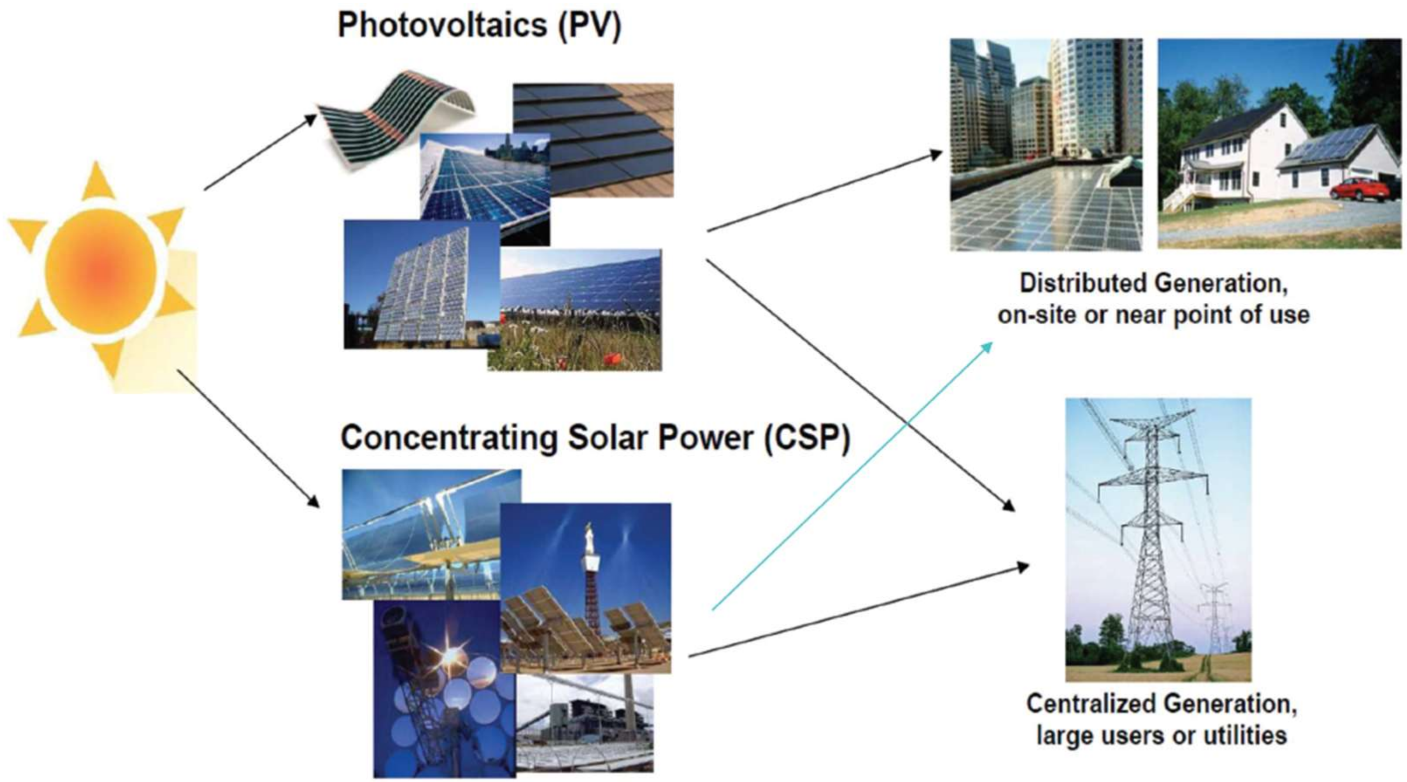
EE4404 : Renewable Energy and Smart Grid

Solar Photovoltaic(PV)

By Dr. Sahoo SK, NUS

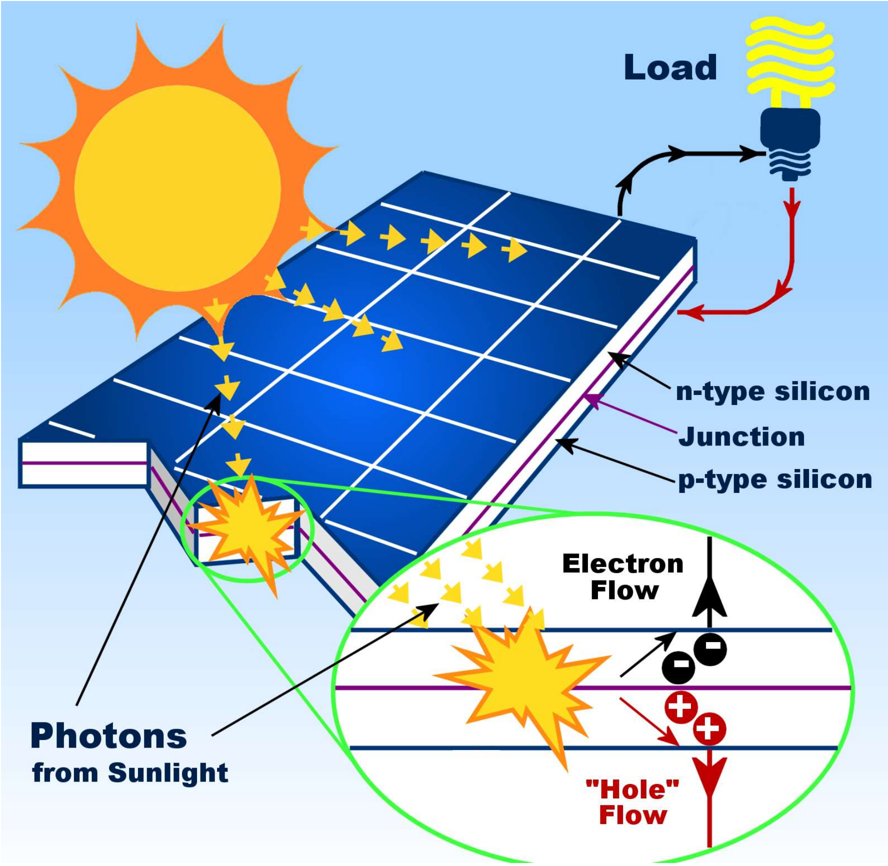
Generating Electricity from the Sun



Every hour the sun beams onto Earth more than enough energy to satisfy global energy needs for an entire year!

Solar Photovoltaics

- A material that can convert the energy in photons of light into an electrical voltage and current is a photovoltaic
- Photovoltaics use semiconductor material, typically Silicon

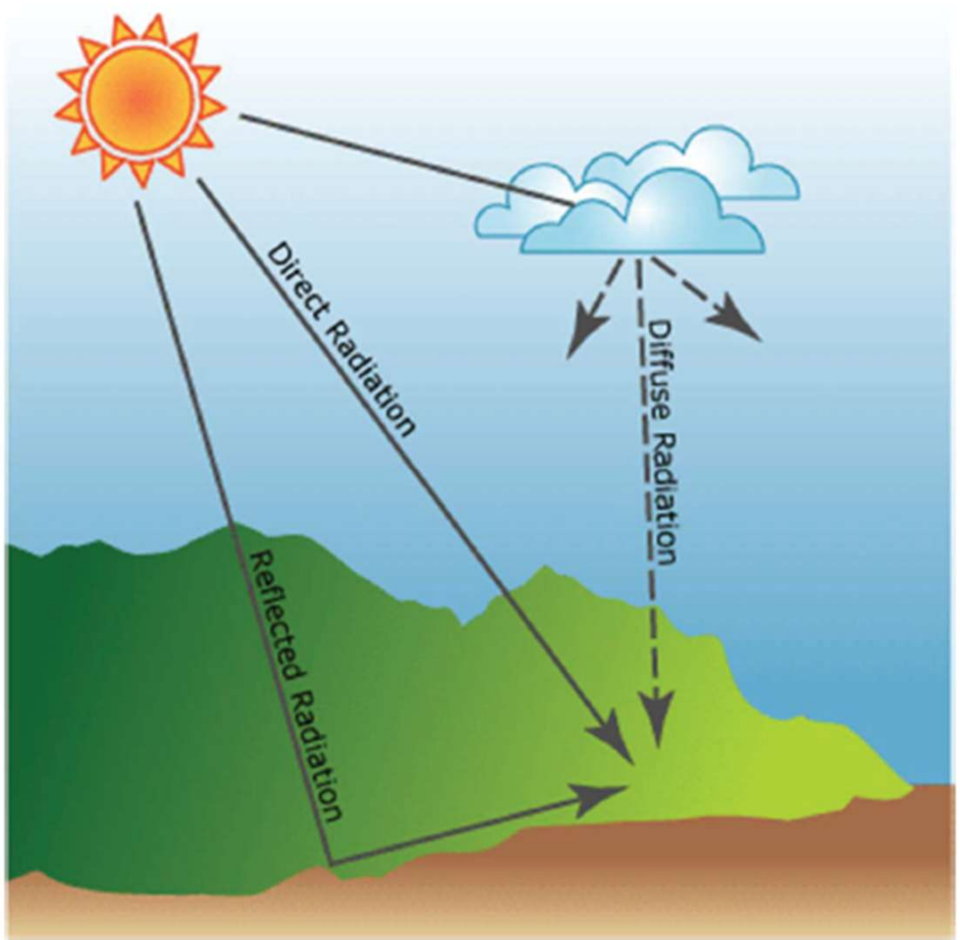


Solar Insolation

Incoming solar radiation (insolation) is intercepted at the earth's surface as direct, diffuse, and reflected components.

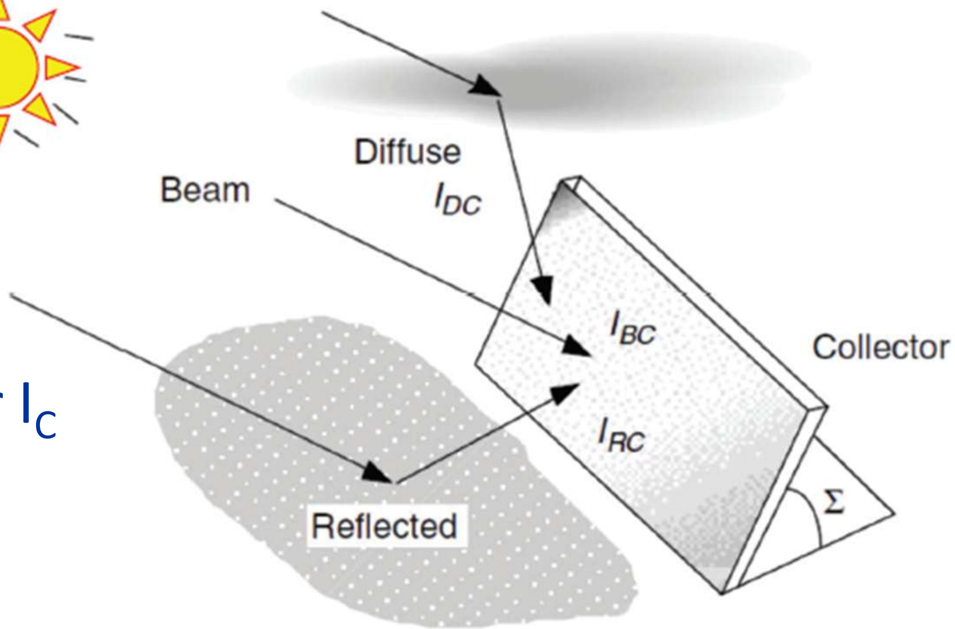
Solar insolation is a measure of solar radiation energy received on a given surface area in a given time

It is commonly expressed as average irradiance Watts per square meter



Clear Sky Direct-Beam Radiation

- Direct Beam radiation, I_{BC}
- Diffuse Beam radiation, I_{DC}
- Reflected Beam radiation, I_{RC}



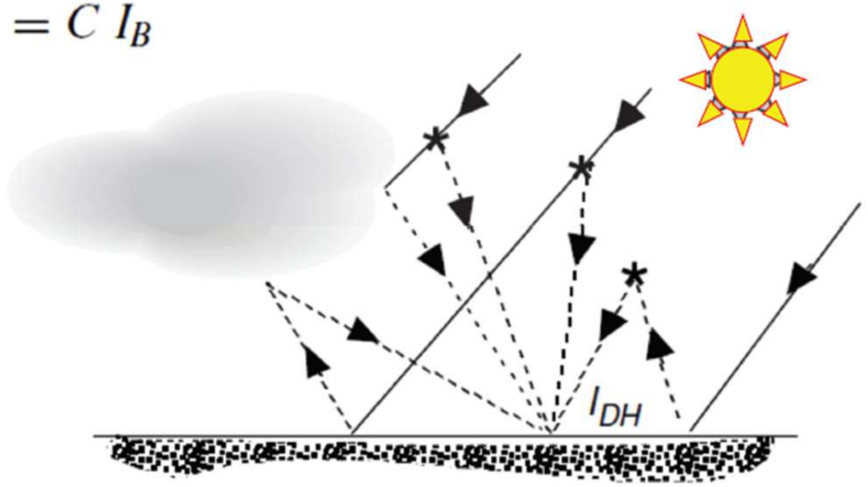
- Solar radiation striking a collector I_C is a combination of direct beam, diffuse, and reflected radiation.

- For sunny days with clear skies, most of the solar radiation is direct beam radiation

Diffuse radiation

- More difficult to estimate
- Scattered radiation from atmospheric particles, moisture, clouds
- Diffuse beam radiation (I_{DH}) on horizontal surface is approximated as (C is sky diffuse factor):

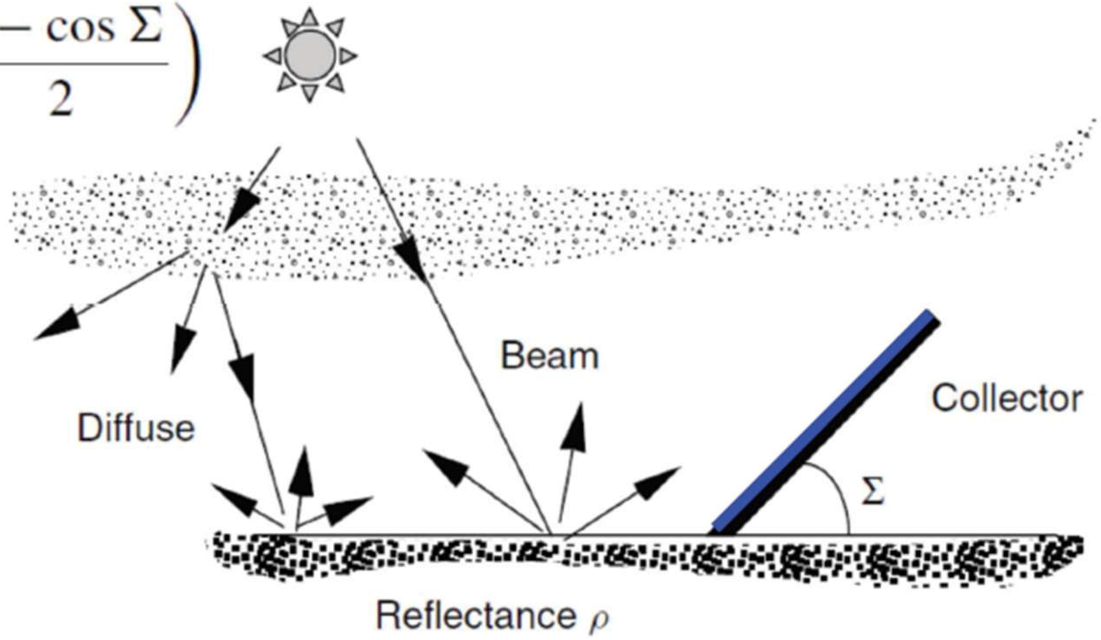
$$I_{DH} = C\ I_B$$



Reflected radiation

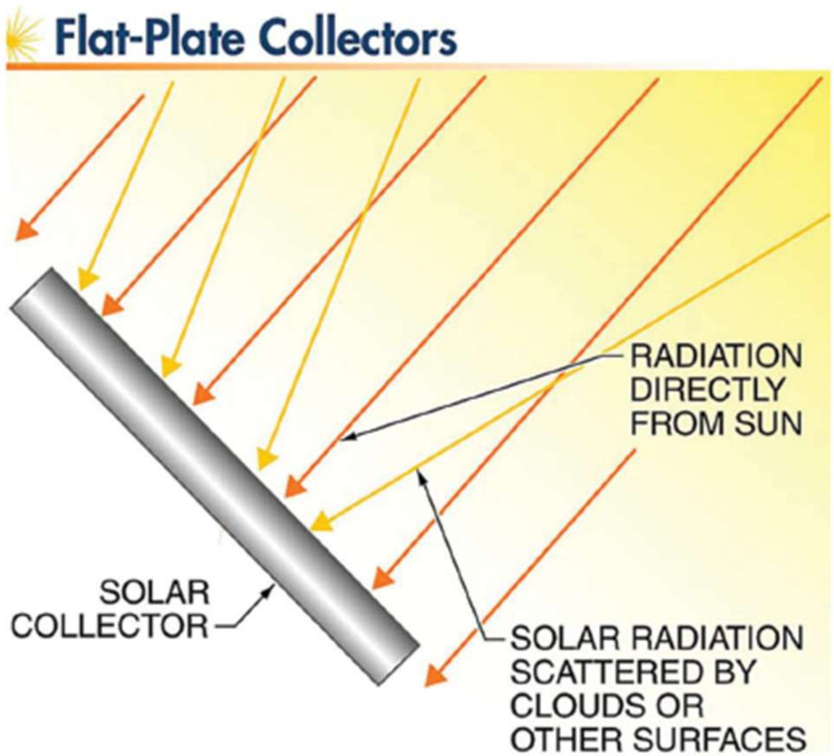
- Radiation that is reflected by surfaces in front of the panel
- Provides considerable boost to the performance on sunny days with snow or water in front of collector

$$I_{RC} = \rho(I_{BH} + I_{DH})\left(\frac{1 - \cos\Sigma}{2}\right)$$



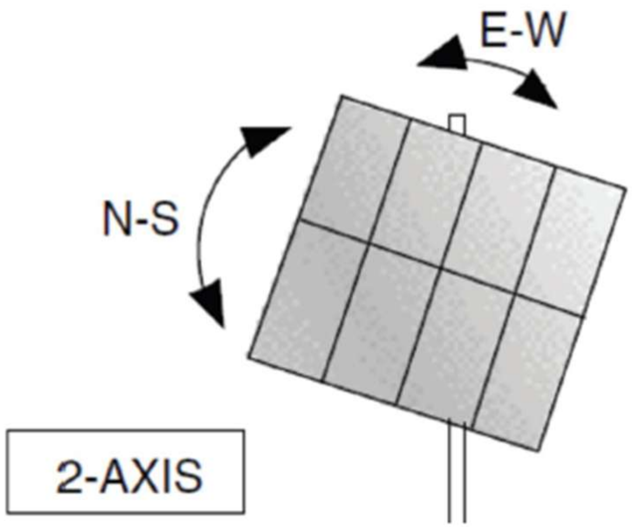
Flat plate collector

- A flat-plate collector can utilize any solar radiation, direct, diffuse or reflected, that strikes its surface.
- Flat-plate collectors may be installed in a fixed orientation or on a sun-tracking mount
- Nearly all commercial and residential solar energy installations use flat-plate collectors



Tracking systems

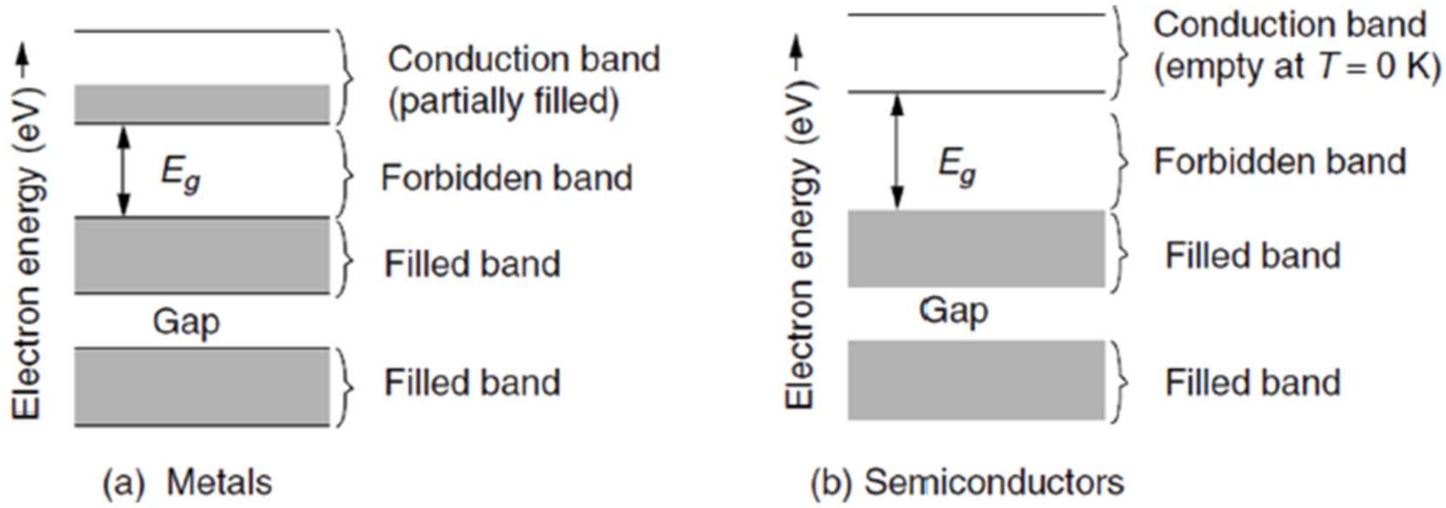
- In many circumstances, racks that allow the collector to track the movement of the sun across the sky are quite cost effective.
- Trackers are described as being either two-axis trackers, which track the sun both in azimuth and altitude angles so the collectors are always pointing directly at the sun, or single-axis trackers, which track only one angle or the other.



Solar tracking systems can increase annual power production by 20-40% compared to fixed mounted systems

How does a semiconductor material convert sunlight into electricity?

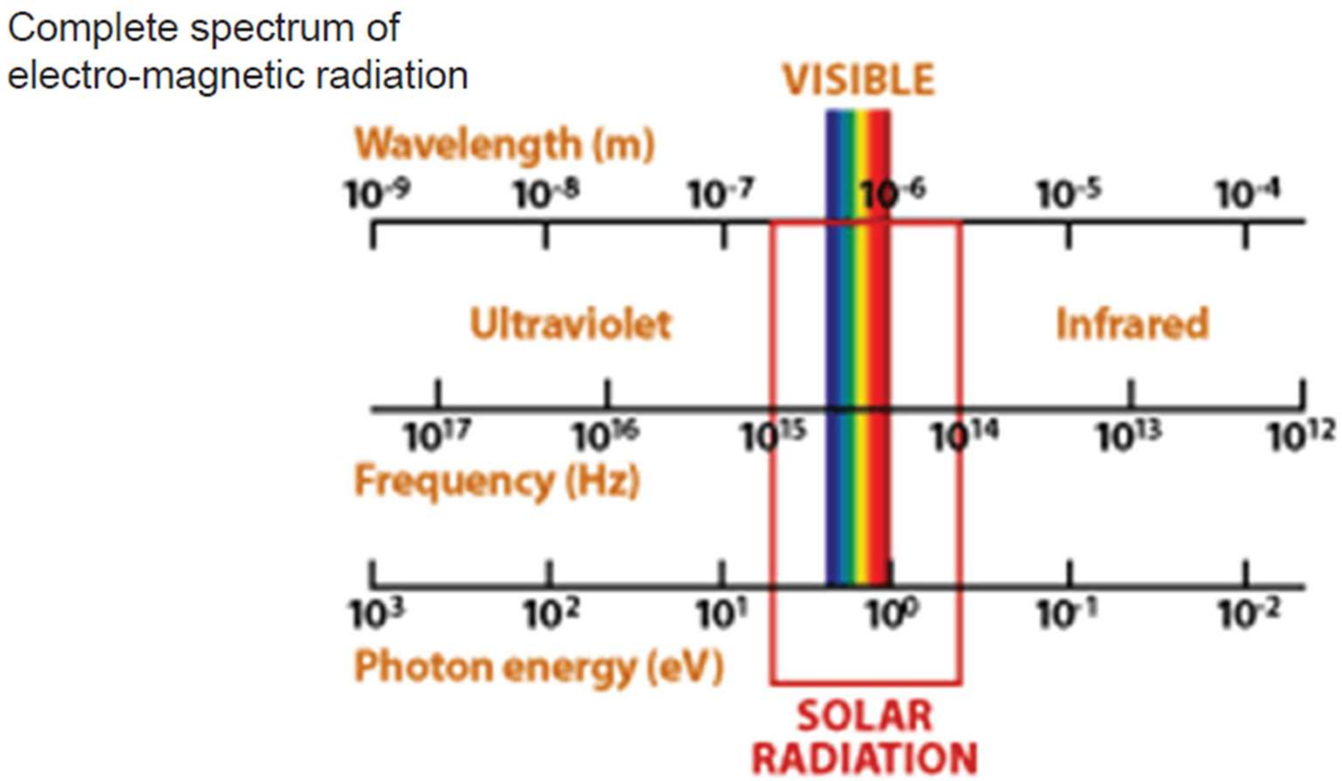
Energy bands for metals and semiconductors



Band gap energy for silicon is 1.12 eV, i.e. the energy required to jump to conduction band.

Where might this energy come from??

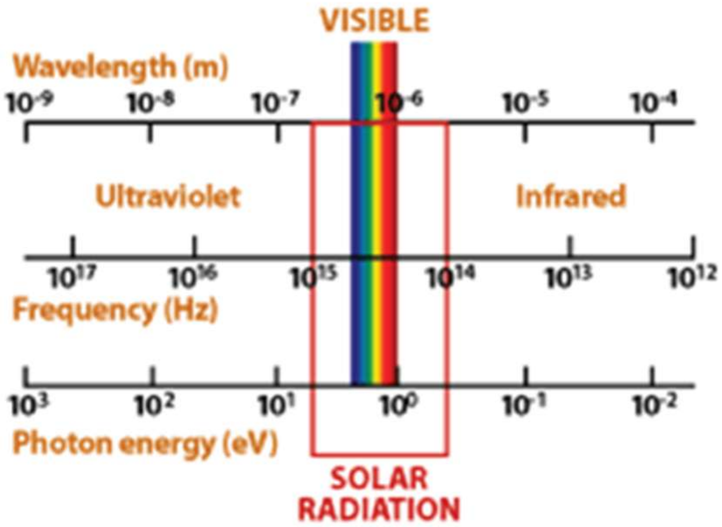
Photon Energy



All the photons in the visible spectrum are strong enough to cause electrons to jump the band gap. Some infrared, all microwave, and all radio waves do not have enough energy and pass right through the solar cell

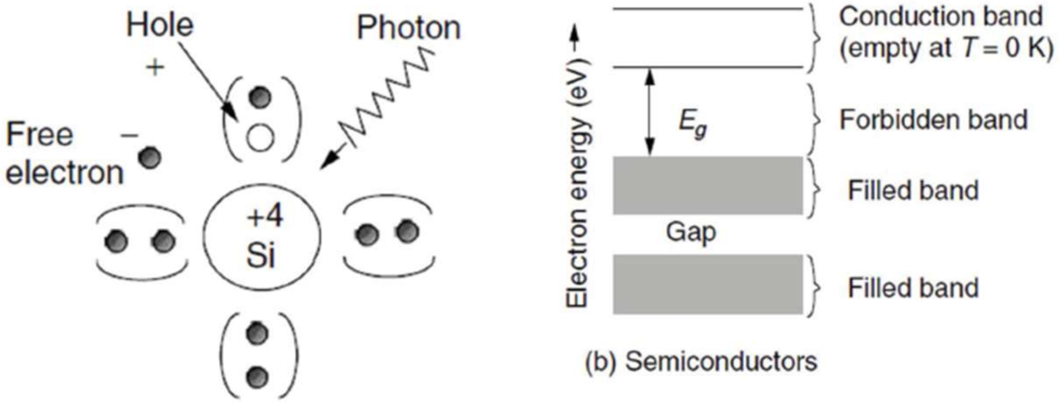
Light & the Photovoltaic Effect

- Certain semiconductor materials absorb certain wavelengths
  - The shorter the wavelength the greater the energy
  - Ultraviolet light has more energy than infrared light
- Crystalline silicon
  - Utilizes all the visible spectrum plus some infrared radiation
- Heat vs electrical energy
  - Light frequencies that is too high or too low for the semiconductor to absorb turn into heat energy instead of electrical energy



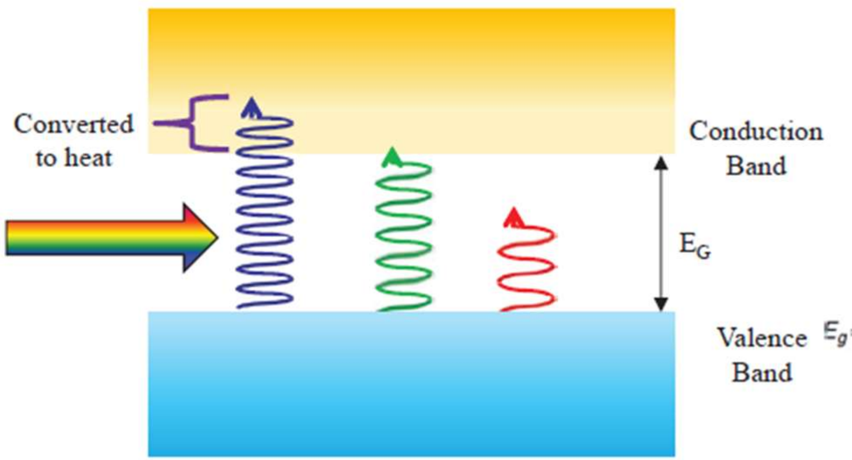
Light & the Photovoltaic Effect

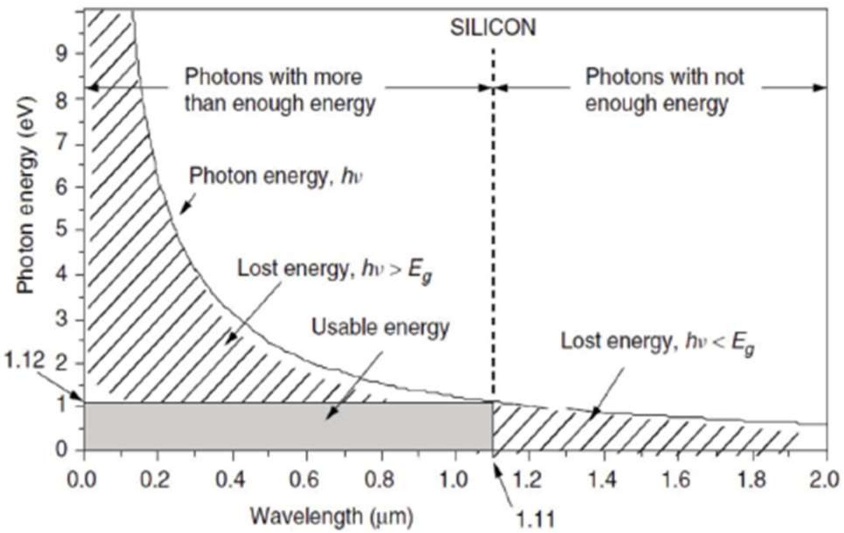
- In photovoltaics, the energy source is photons of electromagnetic energy from the sun.
- When a photon with more than 1.12 eV of energy is absorbed by a solar cell, a single electron may jump to the conduction band.
- One photon can excite only one electron



Bandgap energy for Silicon

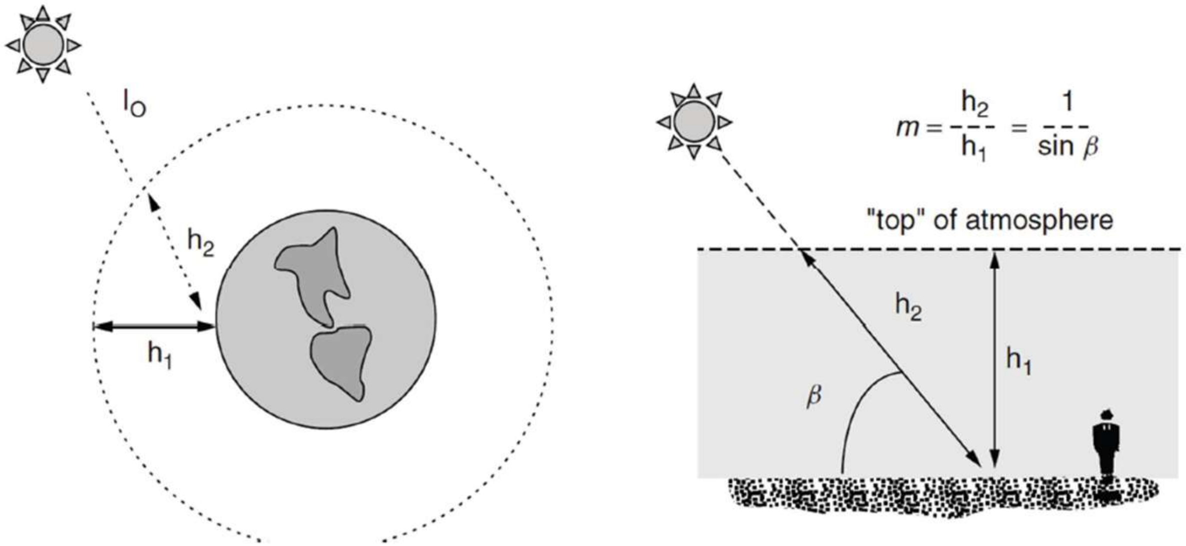
- Band gap of silicon : 1.12 eV corresponding to wavelength of 1.11 μm
- Photons with wavelength < 1.11 μm waste their extra energy
- Photons with wavelength > 1.11 μm cannot send electrons to conduction band



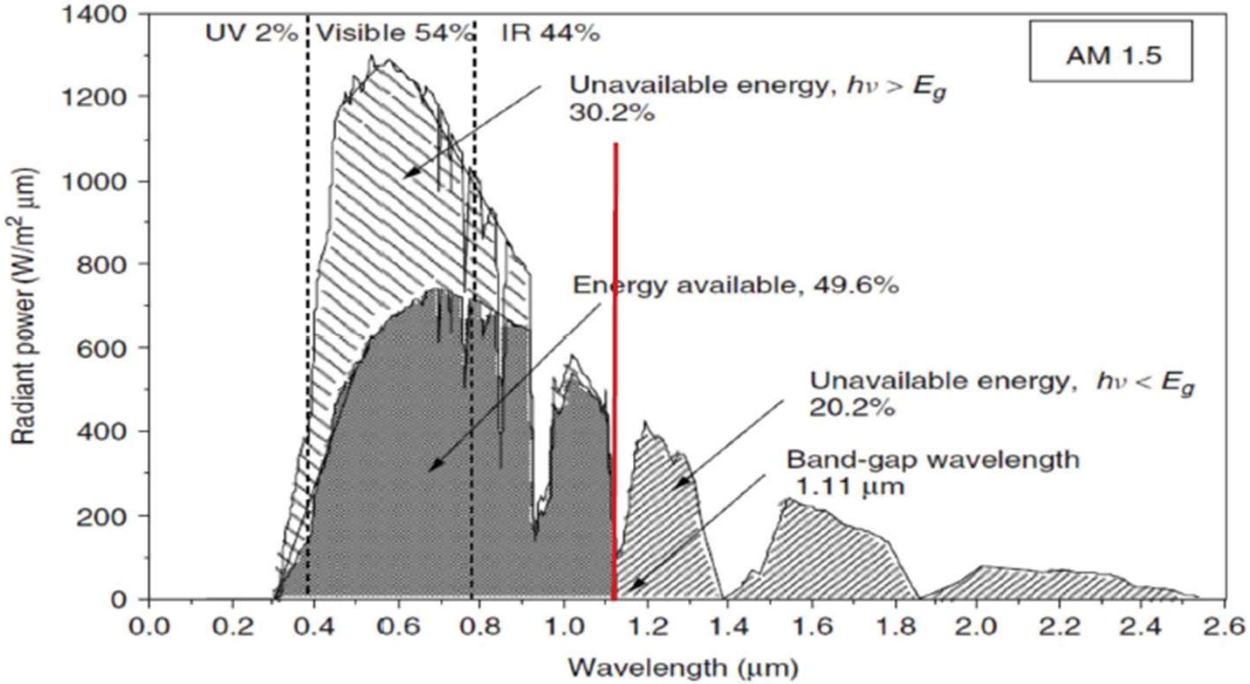


Air mass ratio (AM)

Air mass ratio (AM): length of the path taken by sun's rays through atmosphere to reach a spot on the ground divided by the path length corresponding to the sun directly overhead (an AM of 1 means that the sun is directly overhead, AM=0 means no atmosphere)

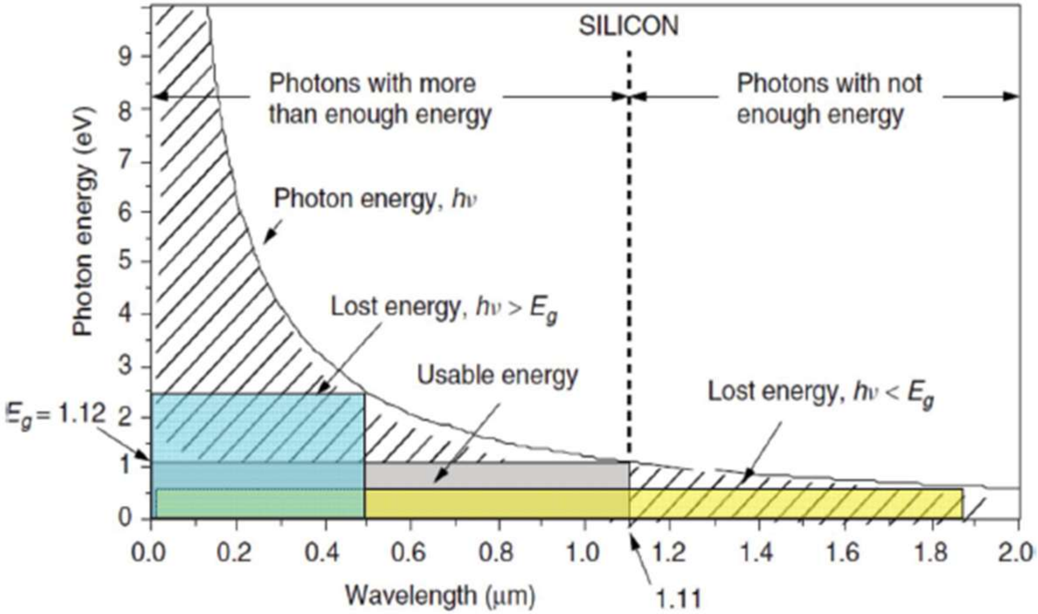


Band gap impact on Photovoltaic Efficiency



The maximum possible fraction of the sun's energy that could be collected with a silicon solar cell is 49.6%!

Important consideration for selection of materials

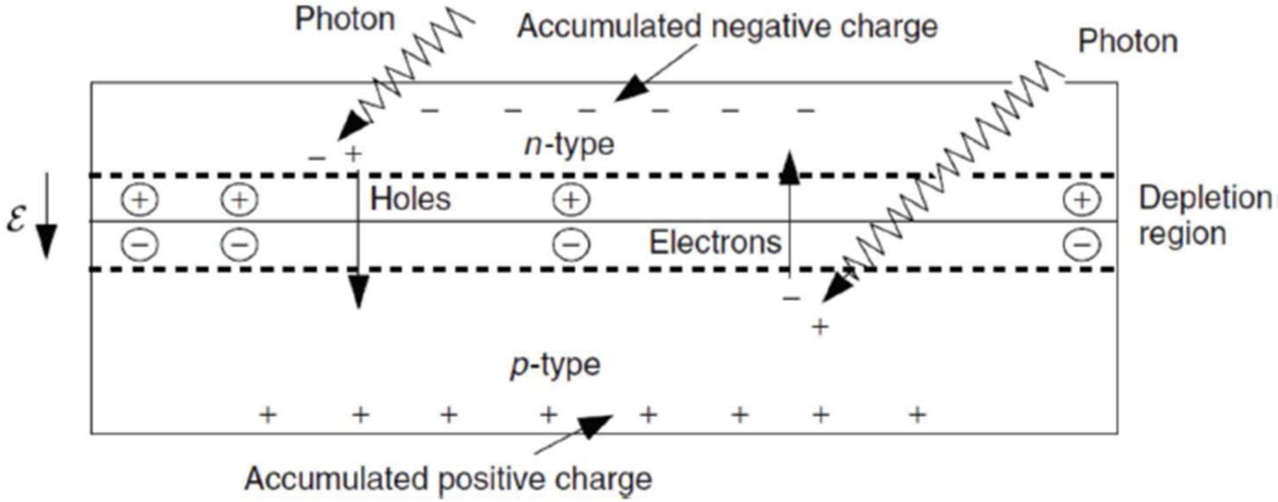


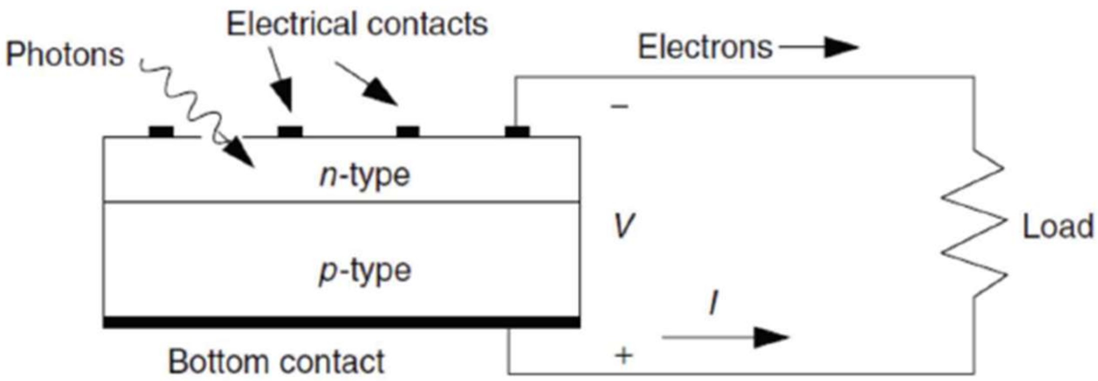
- With smaller bandgap, more photons cross the gap, and high current can be generated but voltage is low
- With larger bandgap, fewer photons cross the gap, which results in higher voltage and lower current

Efficiency of PV Cell

- Efficiency drops to 49.6% due to losses caused by photons with insufficient or too much energy.
- Further drop in efficiency due to:
  1. Recombination of holes and electrons before they can contribute to current flow.
  2. Only about half to two-thirds of the full band-gap voltage across the terminals of the solar cell.
  3. Photons that are not absorbed in the cell
  4. Internal resistance within the cell, which dissipates power.

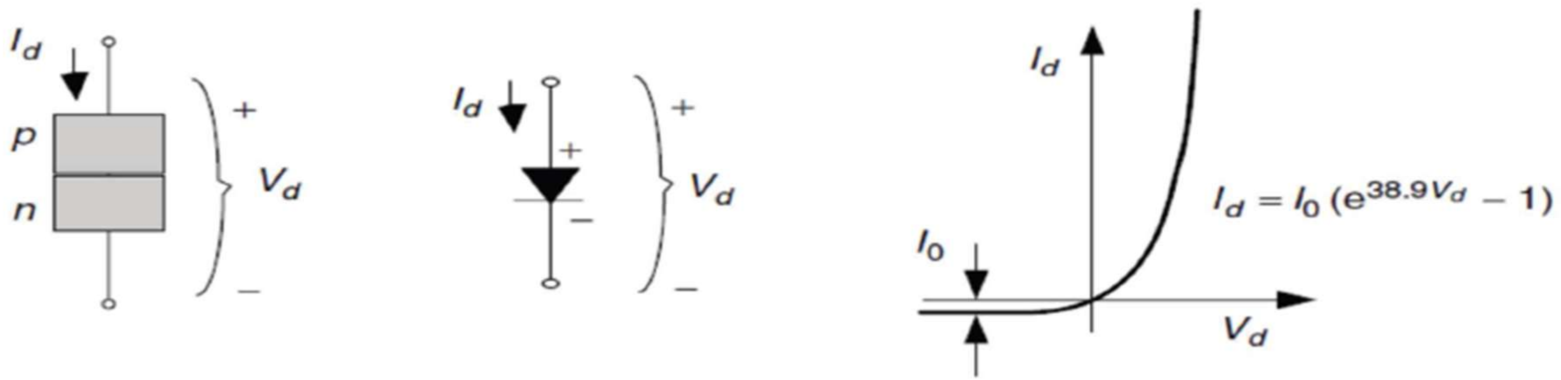
Equivalent Circuit for a Photovoltaic Cell





P-N junction diode

Photovoltaics use p-n junction semiconductor to avoid holes recombining with electrons



(a) p–n junction diode

(b) Symbol for real diode

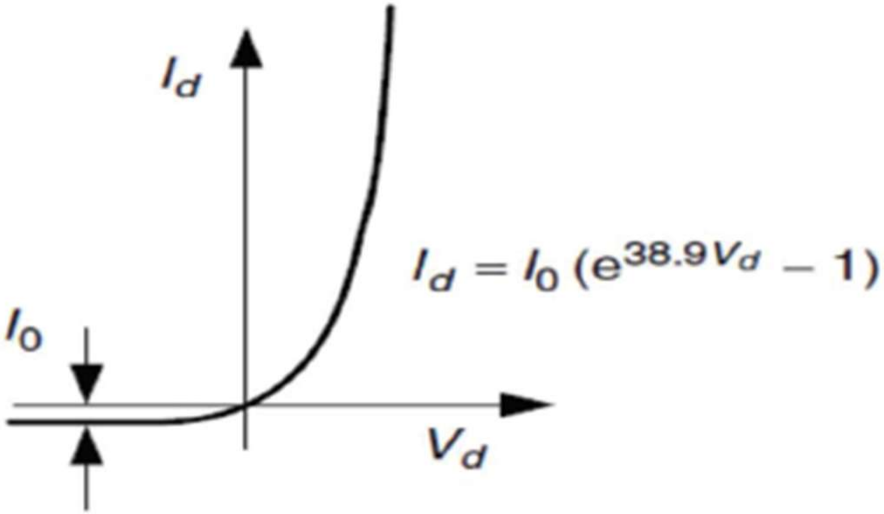
(c) Diode characteristic curve

$$I_d = I_0(e^{qV_d/kT} - 1)$$

Diode I-V characteristic curve

$$I_d = I_0\left(e^{\frac{qV_d}{kT}} - 1\right)$$

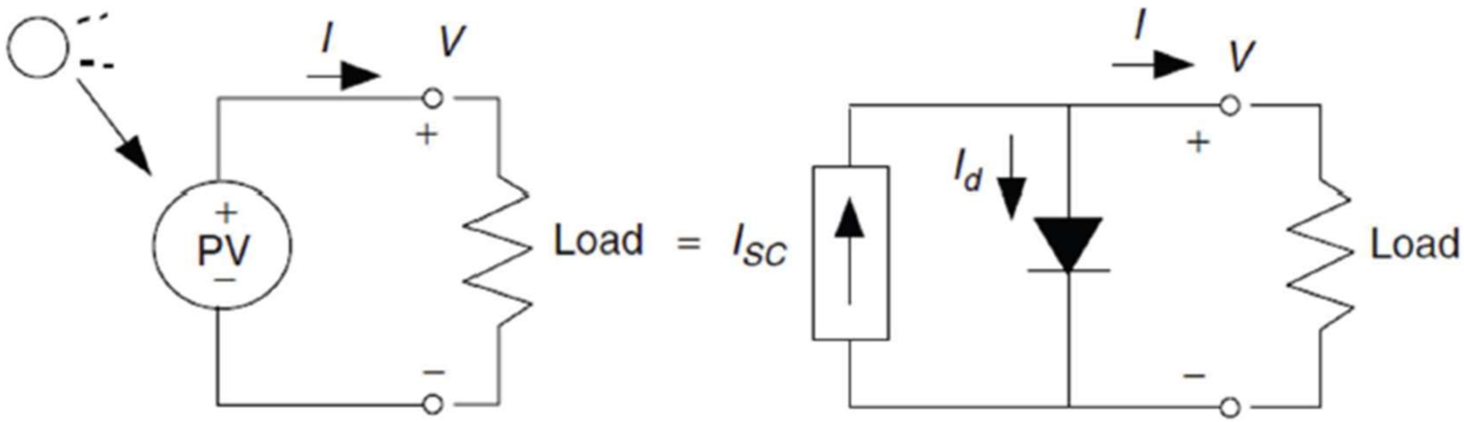
- I_d is the diode current (A),
- V_d is diode voltage (V),
- I_0 is the reverse saturation current (A),
- q is the electron charge (C),
- k is the Boltzmann's constant (J/K), and
- T is the junction temperature (K)



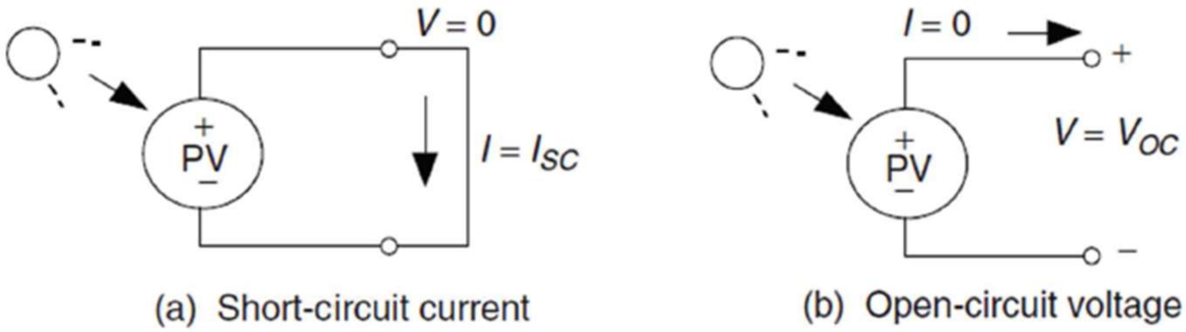
$$I_d = I_0(e^{38.9V_d} - 1)$$

(at $T = 25^oC$)

Equivalent Circuit for a Photovoltaic Cell



Voltage and current equations for the PV cell



Current I: $$I = I_{SC} - I_d$$

From the diagnode characteristics, substituting for I_d: $$I = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$$

Current I:Open circuit voltage (when I = 0): $$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

At 25^0 C, the equations become:

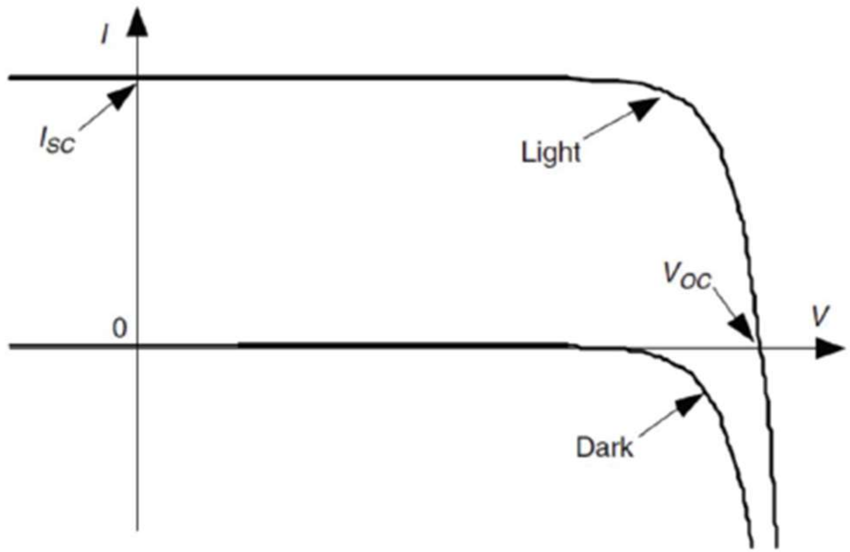
$$\boxed{I = I_{SC} - I_0(e^{38.9\ V} - 1)}$$

$$\boxed{V_{OC} = 0.0257\ln\left(\frac{I_{SC}}{I_0} + 1\right)}$$

I-V characteristic of a Photovoltaic (PV) cell

$$\boxed{I = I_{SC} - I_0(e^{38.9\,V} - 1)}$$

$$\boxed{V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right)}$$



- In both these equations, short circuit current is directly proportional to solar insolation, hence we can now plot current-voltage curves for varying sunlight.
- The dark (no sunlight) curve is just the diode curve turned upside-down. The light (illuminated cell) curve is the dark curve plus I_{SC}

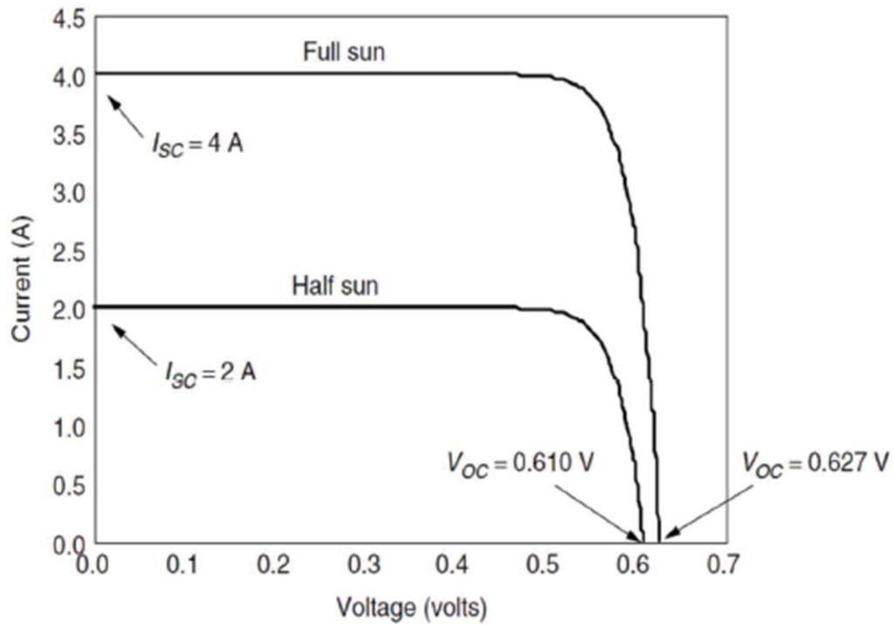
Example

Consider a 100-cm^2 photovoltaic cell with reverse saturation current $I_0 = 10^{-12}\ A/cm^2$. In full sun, it produces a short-circuit current $I_{SC} = 40\ mA/cm^2$ at $25^o C$.

- Find the open-circuit voltage at full sin and again for 50% sunlight.
- Plot the results.

Solution

$$I_0 = 10^{-12} \times 100 = 1 \times 10^{-10}\ A$$



At full sun:

$$I_{SC} = 0.040 \times 100 = 4\ A$$

$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4}{10^{-10}} + 1\right) = 0.627\ V$$

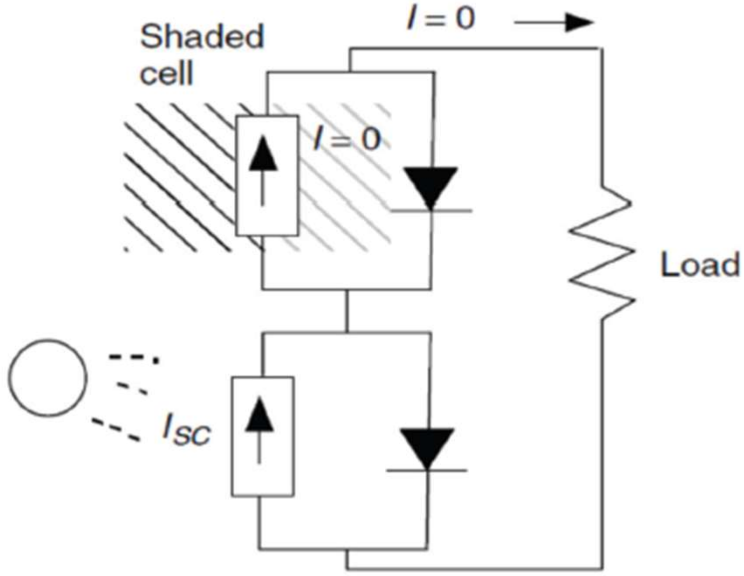
At half sun :

$$I_{SC} = \frac{4}{2} = 2\ A$$

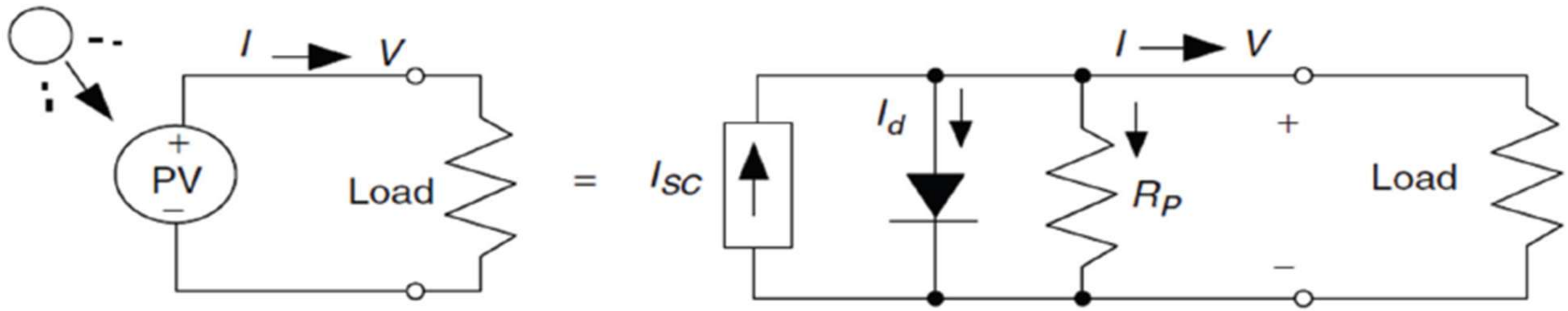
$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610\ V$$

Equivalent circuit of a PV cell…

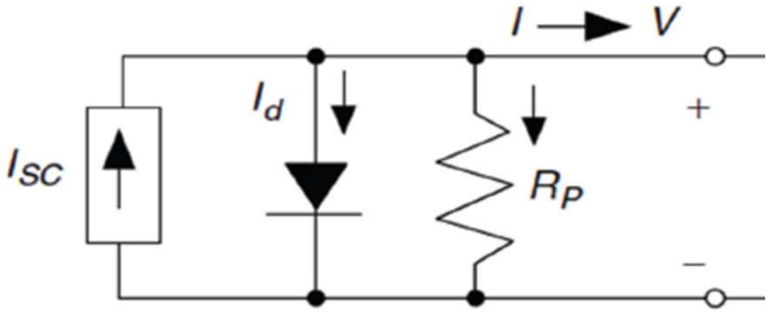
The simple equivalent circuit of a string of cells in series suggests no current can flow to the load if any cell is in the dark (shaded).



A more complex model can deal with this problem



PV equivalent circuit with an added parallel resistance

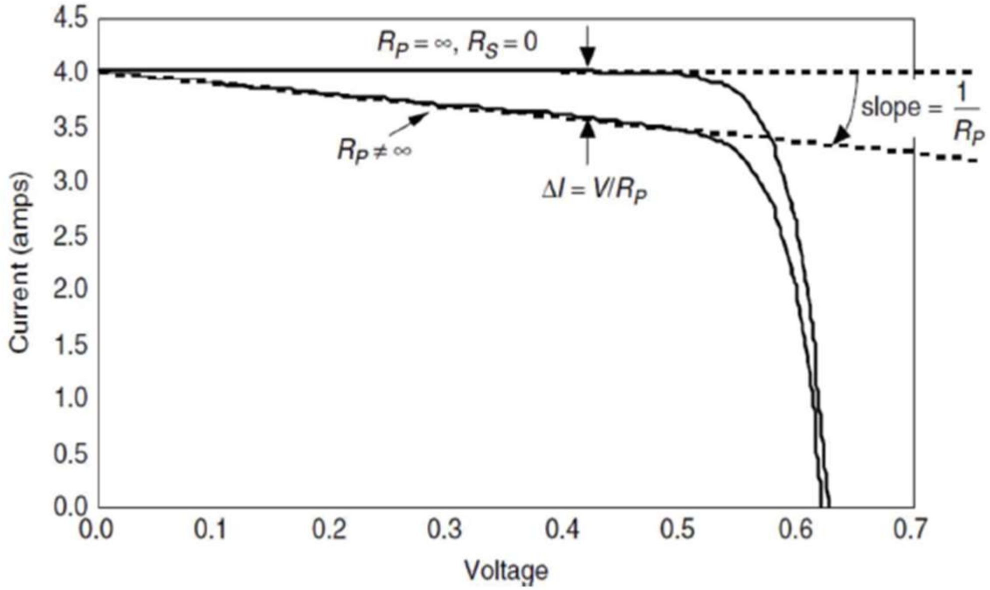


$$I = (I_{SC} - I_d) - \frac{V}{R_p}$$

- For a cell to have losses of less than 1% due to its parallel resistance:

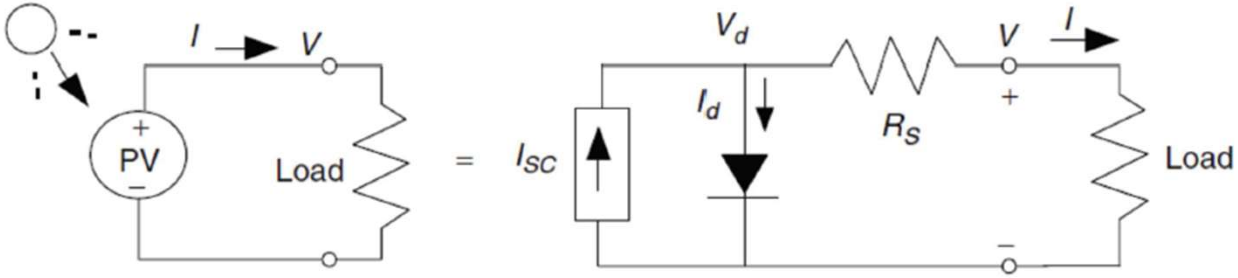
$$\frac{V_{OC}}{R_p} < 0.01\, I_{SC} \Rightarrow$$

$$R_P > \frac{100\, V_{OC}}{I_{SC}}$$



Equivalent circuit for PV cell with series resistance

To incorporate other losses, a series resistor is added to the path of current I:



The original equation: $I = I_{SC} - I_d = I_{SC} - I_0\left(e^{qV_d/kT} - 1\right)$

Modified to include R_S gives $V_d = V + I \cdot R_S$

to give

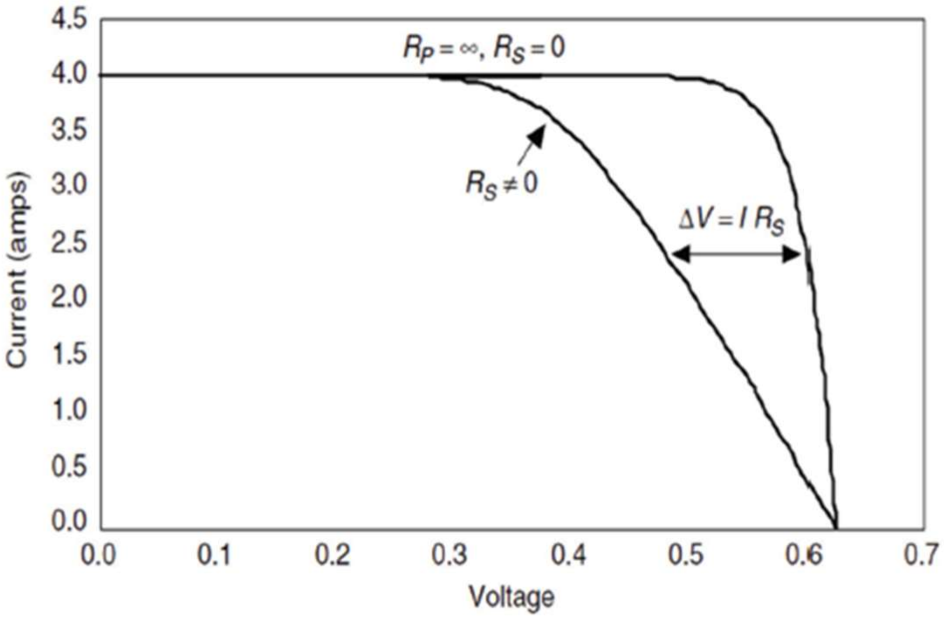
$$I = I_{SC} - I_0\left\{\exp\left[\frac{q(V + I \cdot R_S)}{kT}\right] - 1\right\}$$

Effect of series resistance on PV cell I-V curve

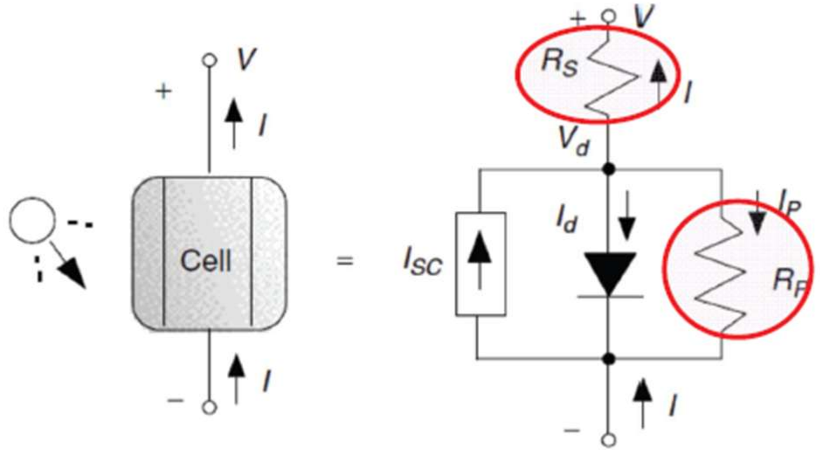
- Adding series resistance to the PV equivalent circuit causes the voltage at a given current to shift to the left by $\Delta V = IR_S$.

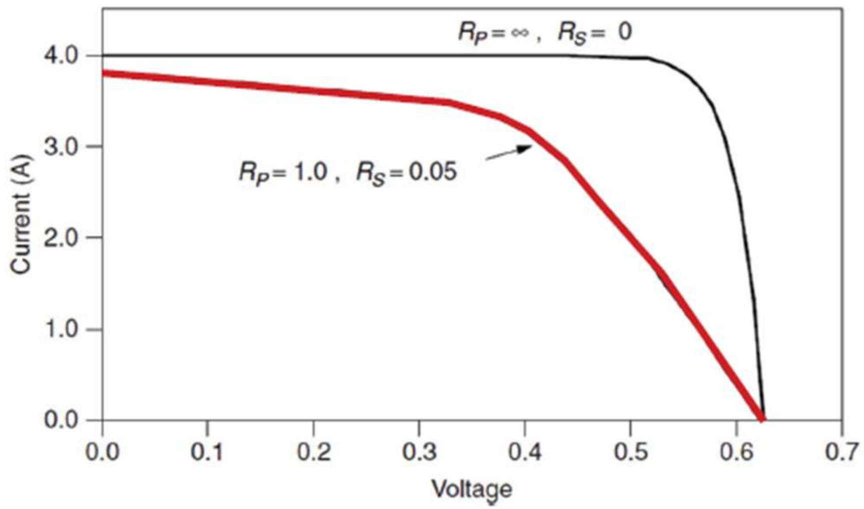
- For a cell to have less than 1% losses due to addition of the series resistance,

$$I_{SC}R_S < 0.01V_{OC}: R_S < 0.01 \times \frac{V_{OC}}{I_{SC}}$$



A more accurate equivalent circuit





$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q(V + I \cdot R_S)}{kT} \right] - 1 \right\} - \left(\frac{V + I \cdot R_S}{R_P} \right)$$

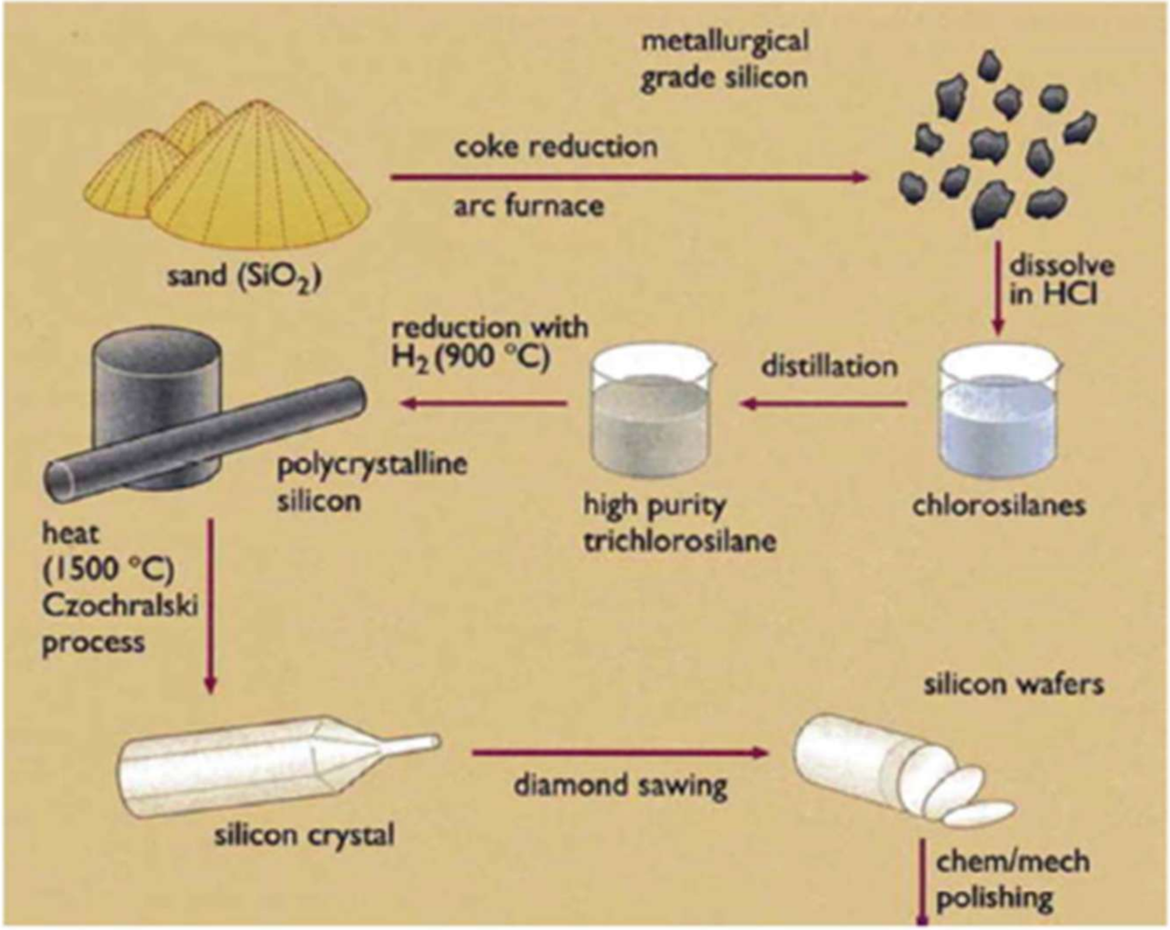
$$I_{SC} = I + I_d + I_P$$

Under the standard test conditions of 25° cell temp,

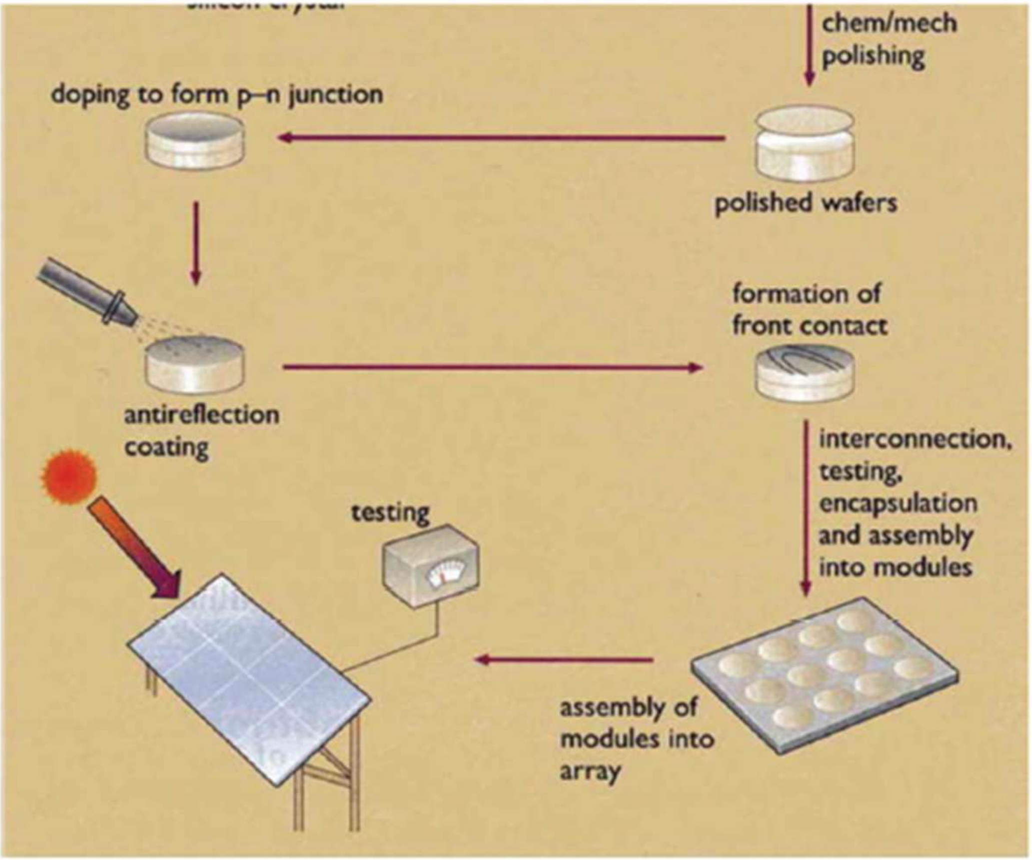
$$I = I_{SC} - I_0 \left[e^{38.9(V + I R_S)} - 1 \right] - \frac{1}{R_P}(V + I R_S) \qquad \text{at } 25^\circ\text{C}$$

Solar Cell Manufacturing process

- Materials
  - Crystalline Silicon or Gallium Arsenide (more expensive)
- Grown into large single-crystal ingots
- Sawed into thin wafers
- Two wafers are bonded together (P-N junction)
- Wafers are grouped into panels or arrays



Creating PV Cells

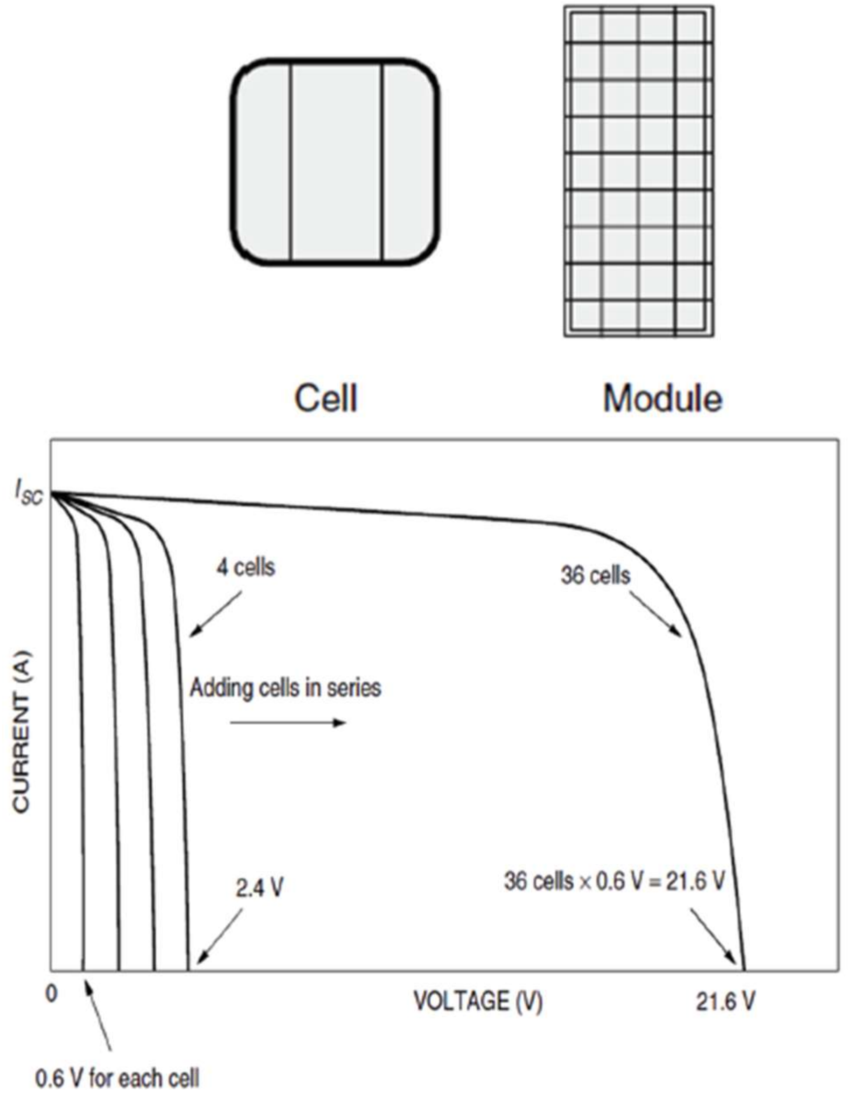


From cells to a module

A typical module has 36 cells

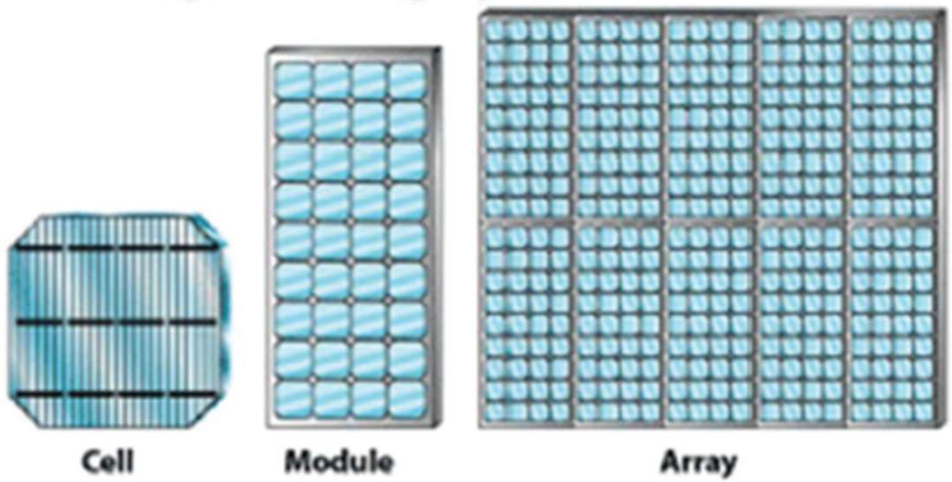
- Often designated as 12-V module
- When wired in series, they carry the same current, but voltages add
- Overall module voltage for n cells:

$$V_{module} = n(V_d - IR_S)$$



Solar PV systems

- Cells are the building blocks of PV systems
  - Typically generate 1.5 – 3 watts of power
- Modules or panels are made up of multiple cells
- Arrays are made up of multiple modules (panels) that comprises the complete PC generating system



Example : Voltage and current from a PV module

A PV module is made up of 36 identical cells, all wired in series. With 1-sun insolation (1 kW/m2), each cell has short-circuit current $I_{SC} = 3.4$ *A and at 25°C its reverse saturation* current is $I_0 = 6 \times 10^{-10}$ *A. Parallel resistance* $R_P = 6.6\ \Omega$ *and series resistance* $R_S = 0.005\ \Omega$.

Find the voltage, current, and power delivered when the junction voltage of each cell is 0.50 V

Solution

Given $V_d = 0.5\ V$

$$I = I_{Sc} - I_0(e^{38.9\times V_d} - 1) - \frac{V_d}{R_P} = I_{Sc} - I_0(e^{38.9\times 0.5} - 1) - \frac{0.5}{6.6} = 3.16\ A$$

For a 36-cell module, voltage produced:

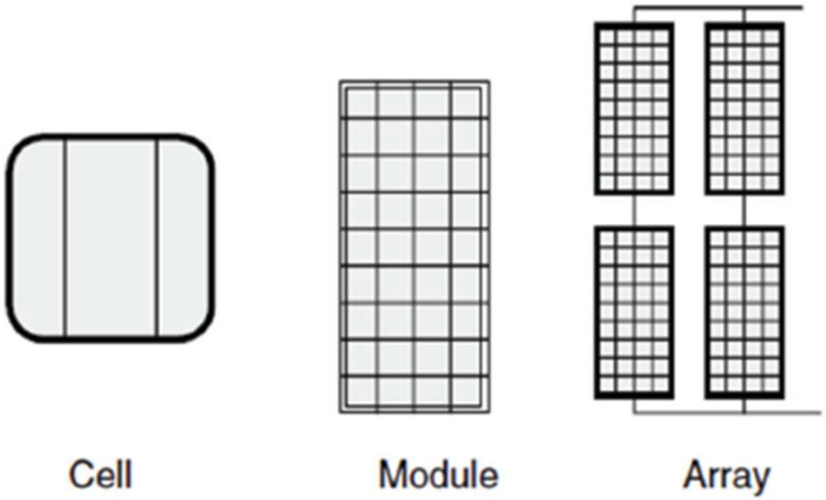
$$V_{module} = n(V_d - IR_S) = 36 \times (0.5 - 3.14 \times 0.005) = 17.43\ V$$

Power delivered by the module:

$$P = V \times I = 17.43 \times 3.16 = 55\ W$$

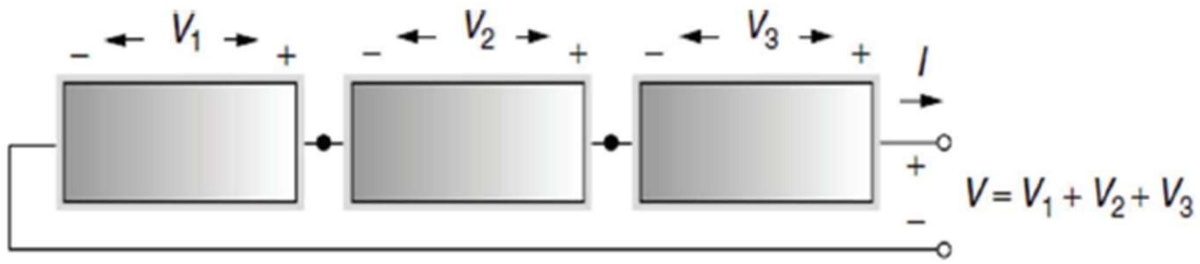
From modules to arrays

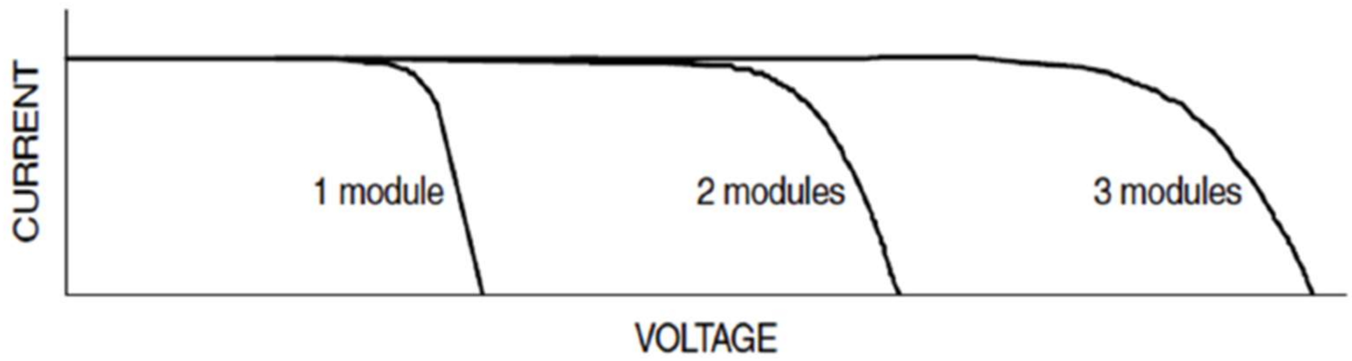
- Modules can be wired in series to increase voltage
- Modules can be connected in parallel to increase current
- Series and parallel connection increases power



Modules connected in series

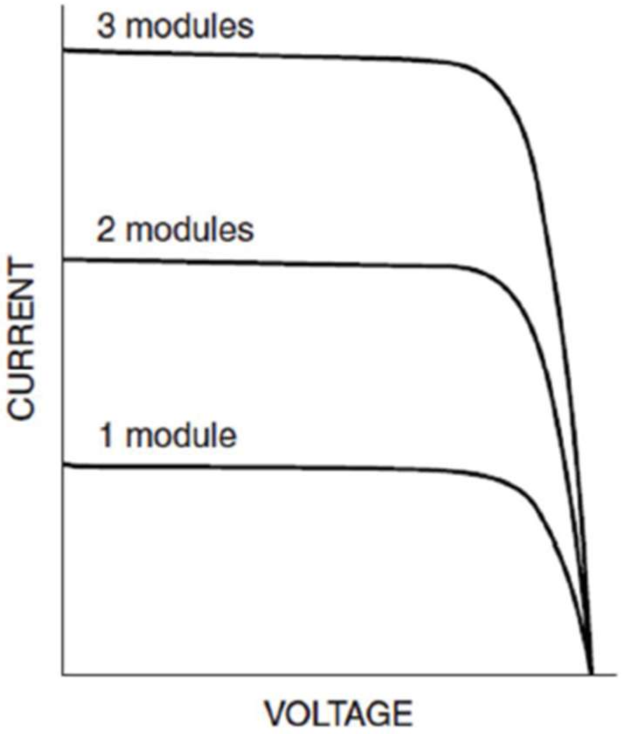
- The voltages produced are added
- Same current flows through all

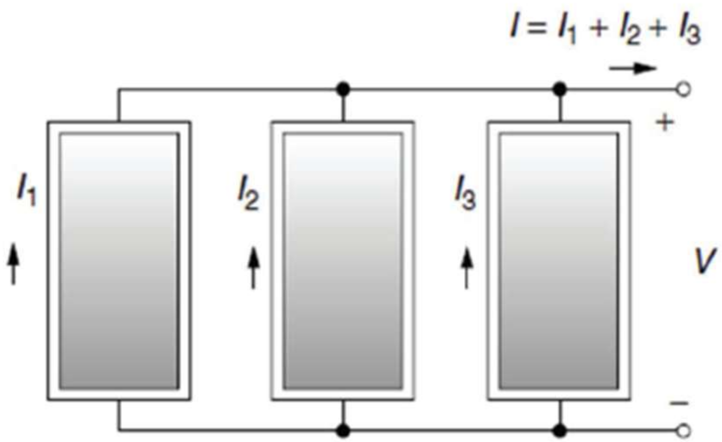




Modules connected in parallel

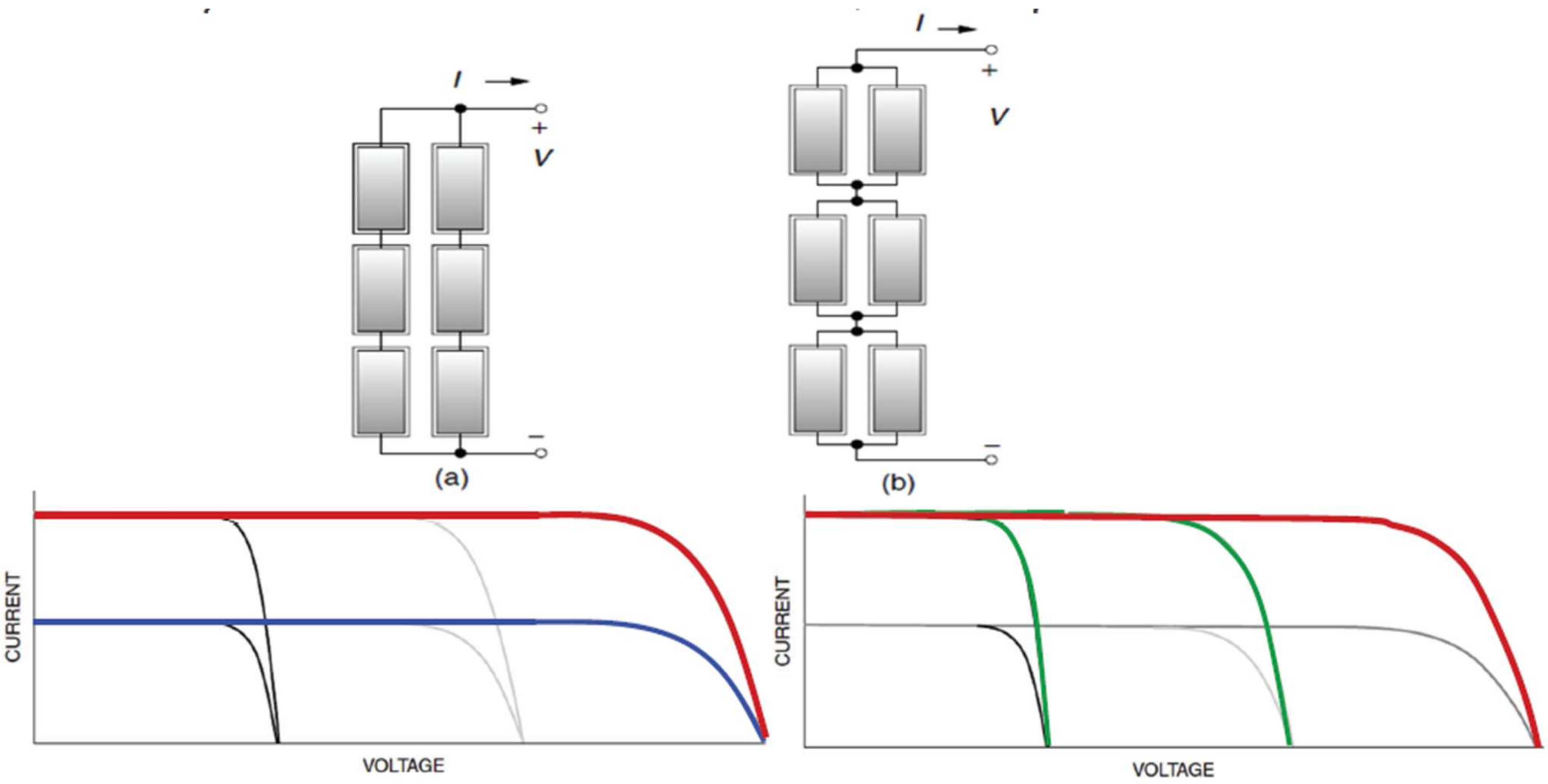
Currents add, while voltage remains the same



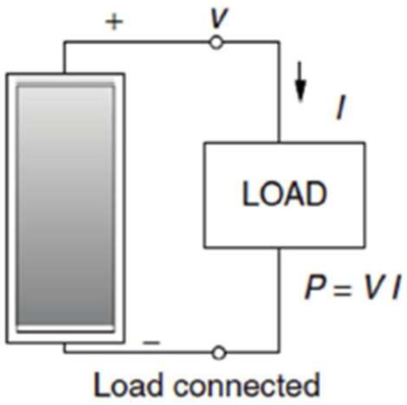


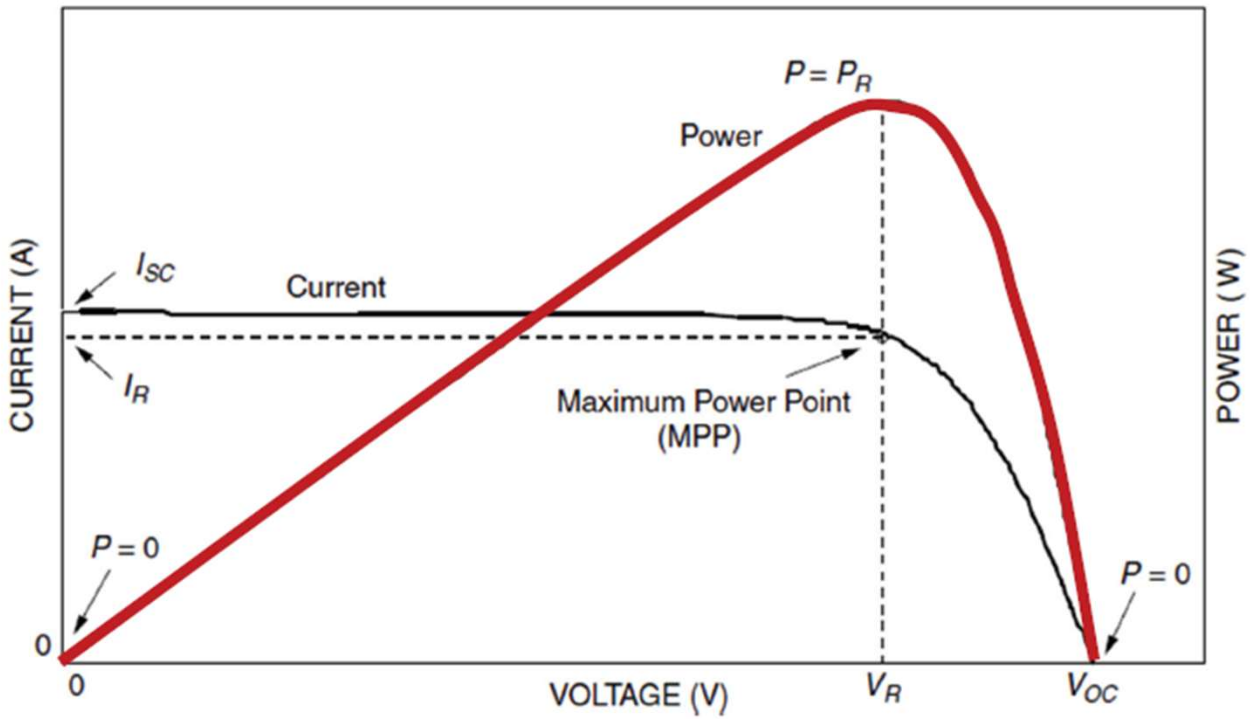
Modules in series-parallel configuration

Example: Three modules in series, two in parallel (3S2P)



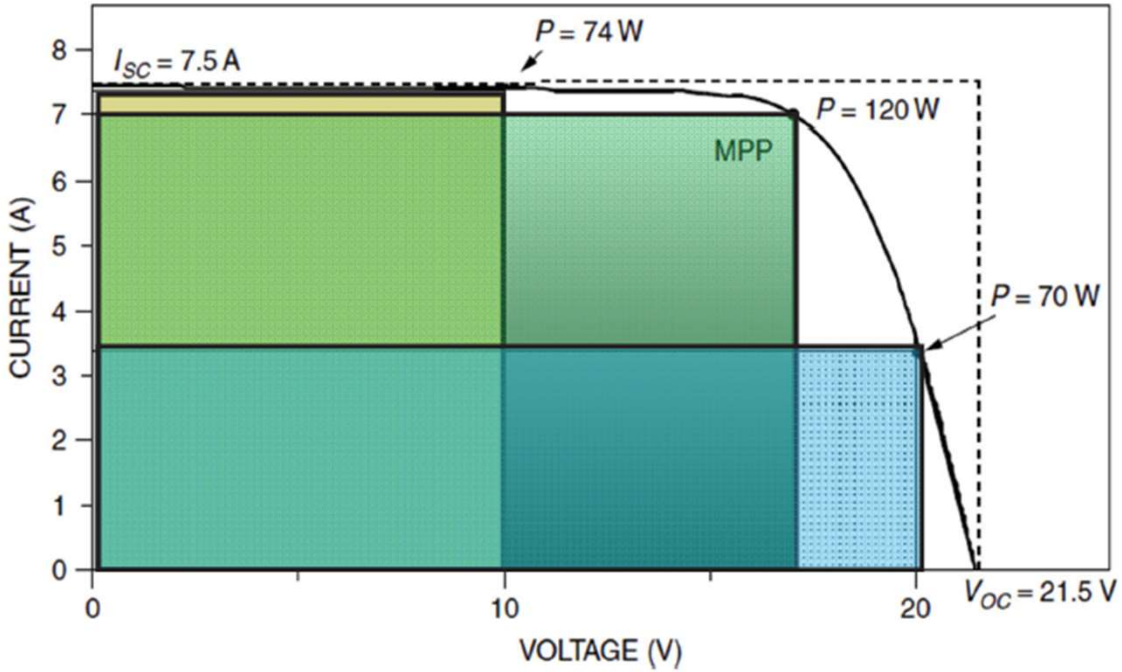
Voltage, Current and Power Curves





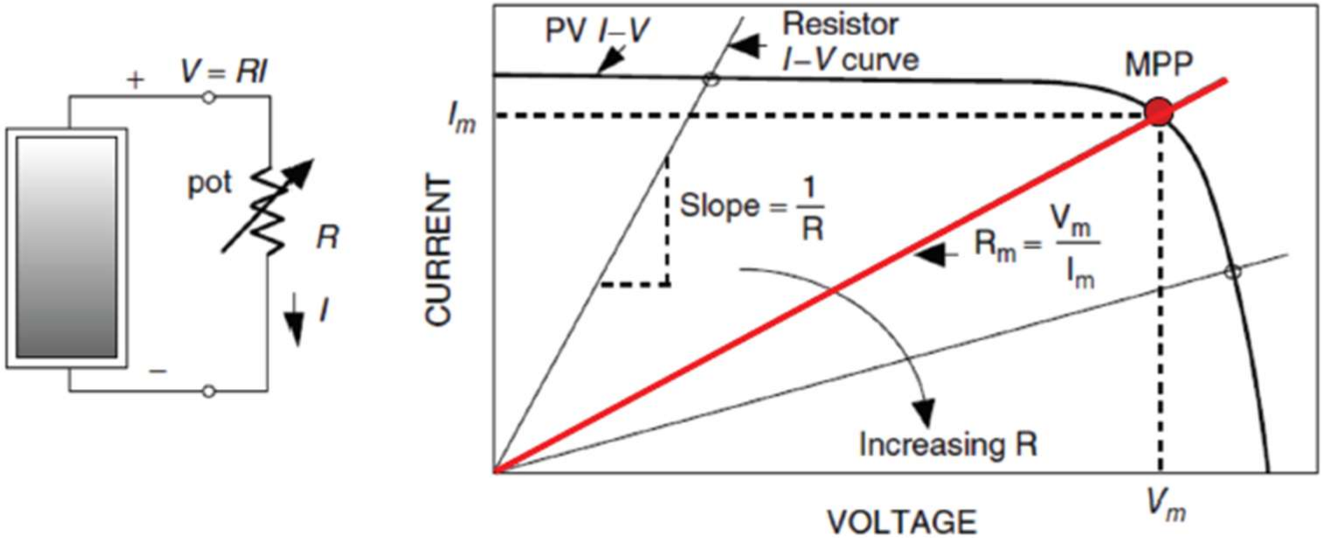
Maximum Power Point (MPP)

At the maximum power point (MPP), the module delivers the most power that it can under the conditions of sunlight and temperature for which the I –V curve has been drawn.



Current-Voltage Curve for Load

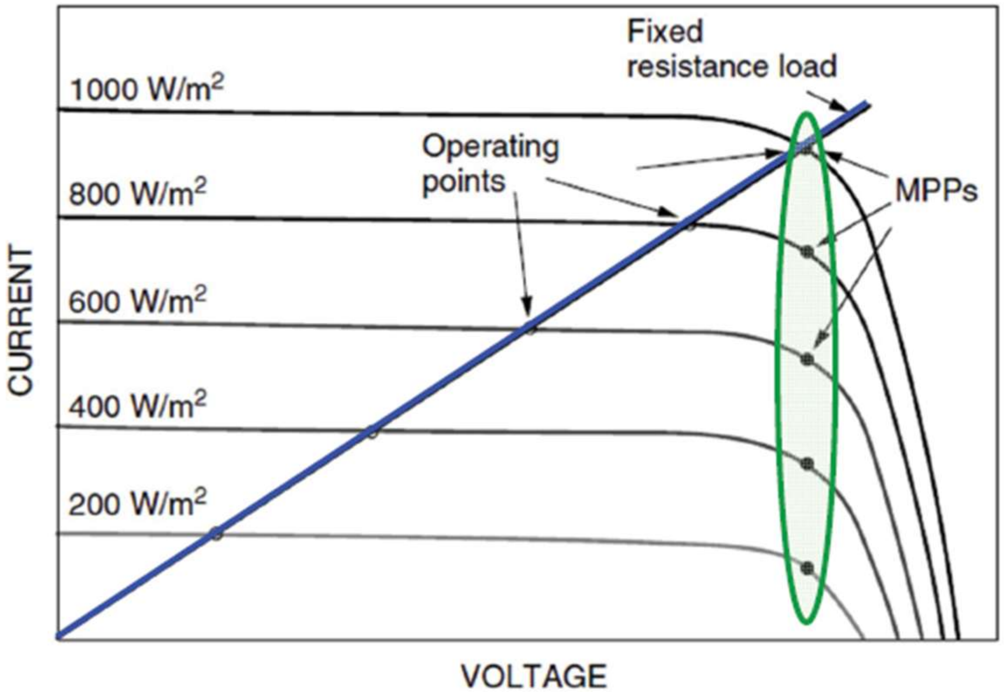
Operating point – intersection of curves where the system will finally operate at,



Resistance corresponding to maximum power: $R_m = \frac{V_m}{I_m}$

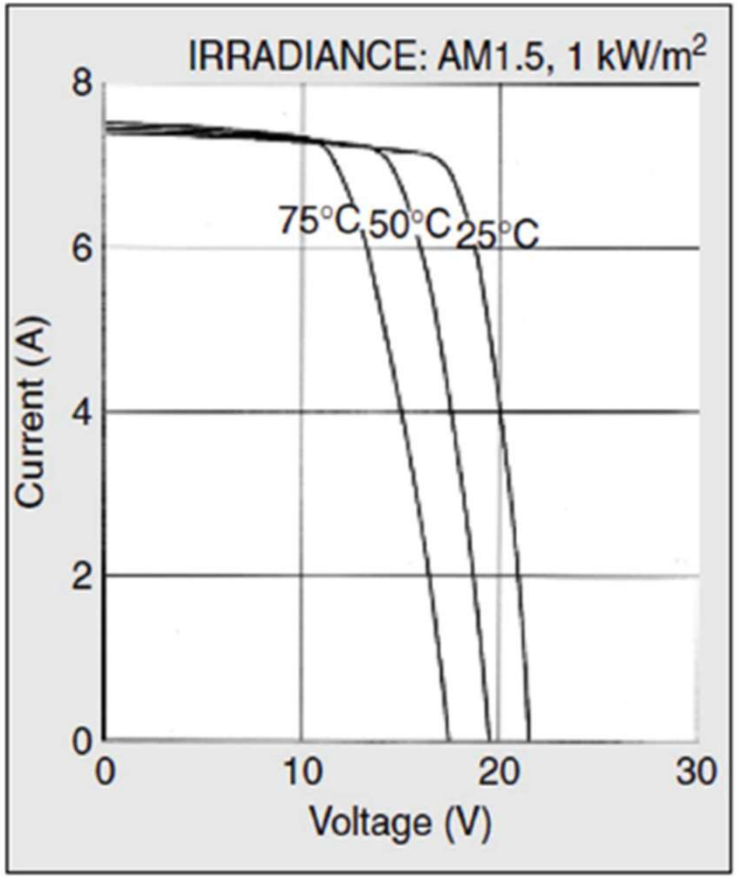
Efficiency of a PV module with fixed resistance load

- The best value of resistance for maximum power transfer under 1-sun, 25°C, 1.5 AM conditions would be V_R/I_R
- The operating point however, slips off MPP if resistance is fixed
- Max power point tracker (MPPT) ensures the module operates at highest efficiency point



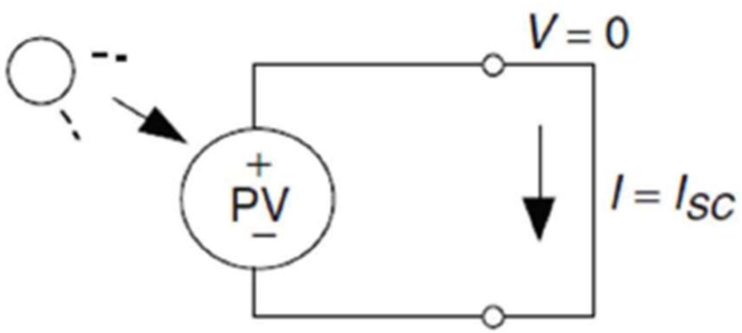
Effect of temperature on I-V curves

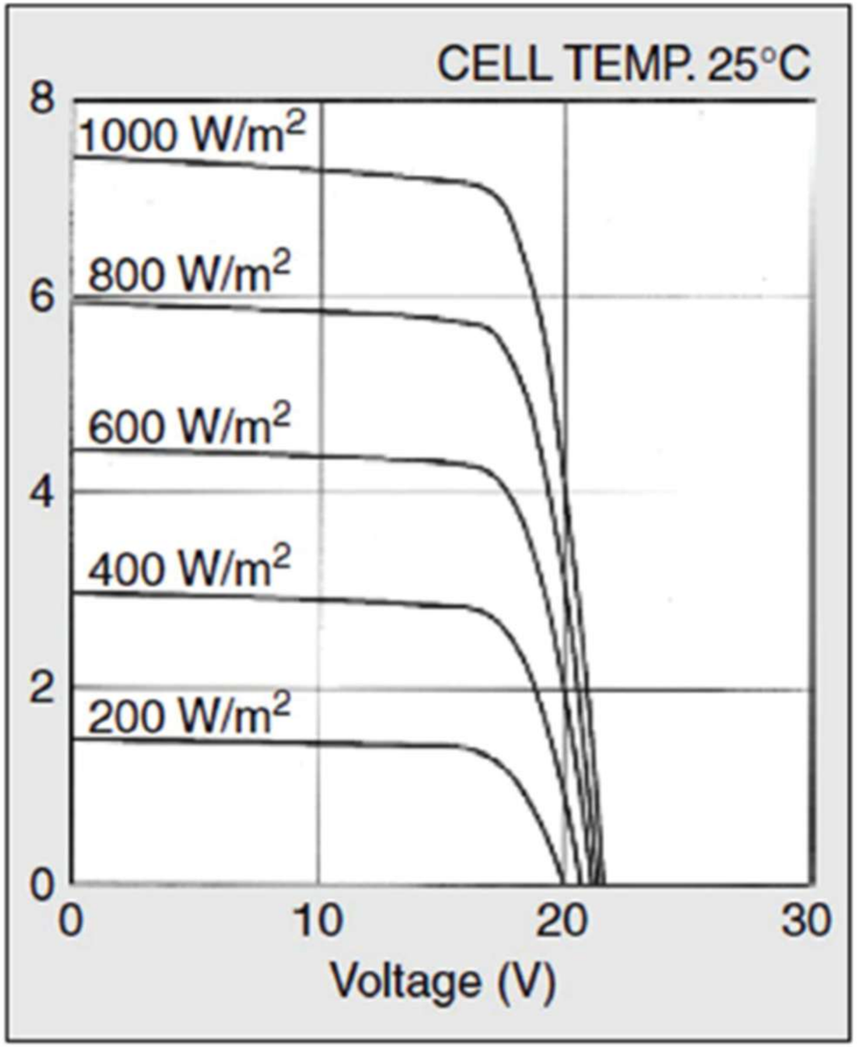
- With increase in temperature, voltage reduces while current increases very slightly
- For crystalline Silicon cells, V_{OC} drops by 0.37% per degree C, and I_{SC} increases by 0.05% per degree C
- MPP drops by approx 0.5% per degree C



Effect of Insolation

- As insolation drops, I_{SC} drops proportionately
- V_{OC} drops very slightly



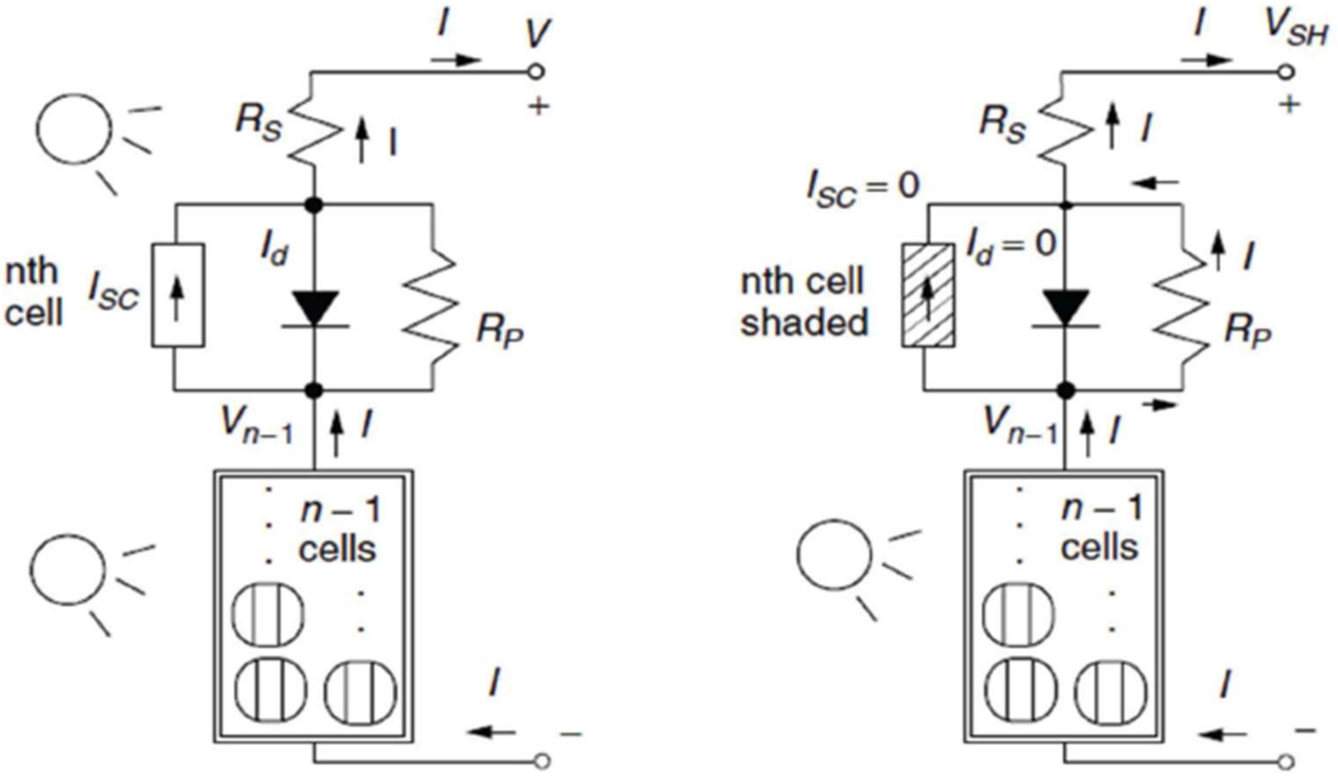


Standard test conditions (STC)

- Solar irradiance – 1 kW/m^2 (sun)
- Air mass ratio of 1.5 AM
- Cell temperature 25^oC

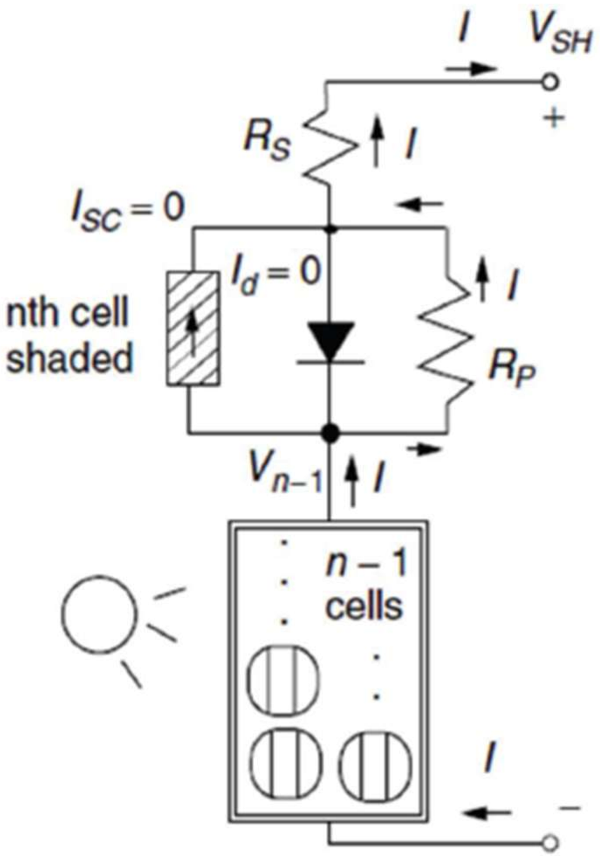
Effect of Shading

Even if one cell is shaded, since its short circuit current is now zero, the main current I causes the diode to be reserve biased, hence $I_d = 0$ and total voltage is reduced by IR_P



(a) All cells in the sun (b) Top cell shaded

Effect of shading..



Output voltage of the module becomes

$$V_{SH} = V_{n-1} - I(R_P + R_S)$$

For the remaining cells, $V_{n-1} = \left(\frac{n-1}{n}\right)V$

Substituting, $$V_{SH} = \left(\frac{n-1}{n}\right)V - I(R_P + R_S)$$

The drop in voltage due to shading of one cell:

$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right)V + I(R_P + R_S)$$

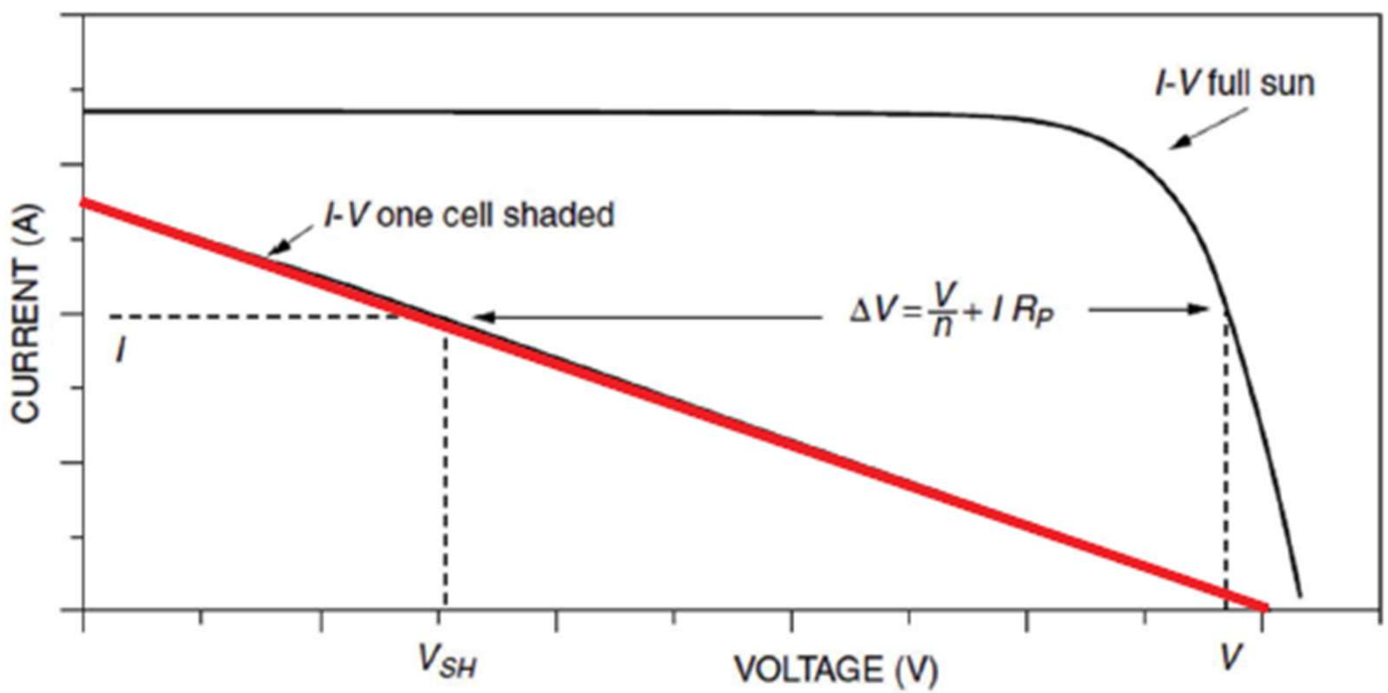
$$\Delta V = \frac{V}{n} + I(R_P + R_S)$$

Since Rs is very small,

$$\Delta V \cong \frac{V}{n} + IR_P$$

Effect of shading..

$$\Delta V \cong \frac{V}{n} + I R_P$$



Example

The 36-cell PV module described in previous example had a parallel resistance per cell of $R_P = 6.6\ \Omega$. *In* full sun and at current $I = 2.14$ *A the output voltage was found to be V =*19.*41 V.*

If one cell is shaded and this current somehow stays the same,

a) What would be the new module output voltage and power?
b) What would be the voltage drop across the shaded cell

Solution

The drop in module voltage will be $\Delta V = \frac{V}{n} + IR_P$

$$= \frac{19.41}{36} + 2.14 \times 6.6 = 14.66 \text{ V}$$

The new output voltage will be $19.41 - 14.66 = 4.75$ V

Power delivered by the module with one cell shaded would be

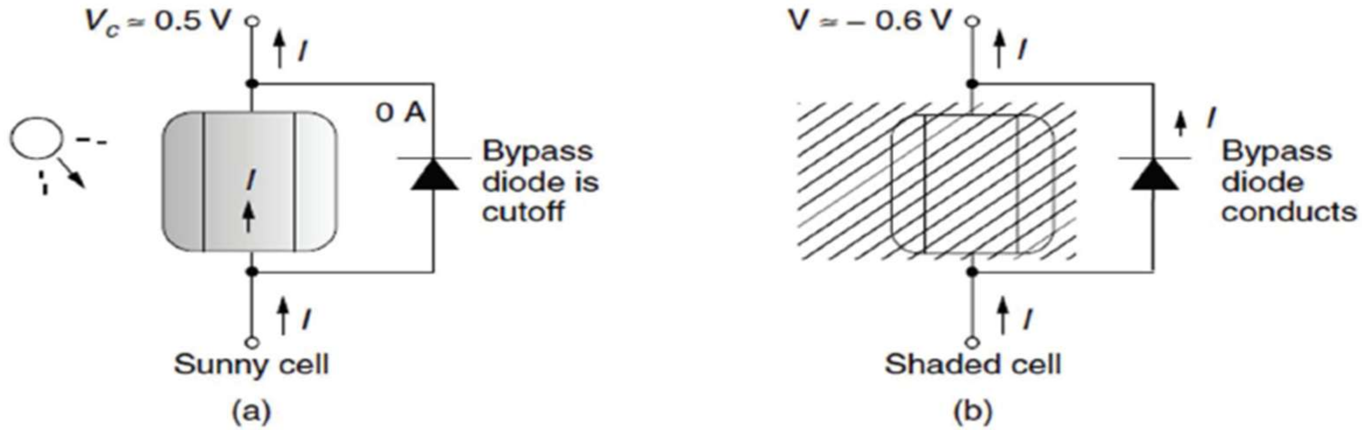
$$P_{\text{module}} = VI = 4.75 \text{ V} \times 2.14 \text{ A} = 10.1 \text{ W}$$

For comparison, in full sun the module was producing 41.5 W

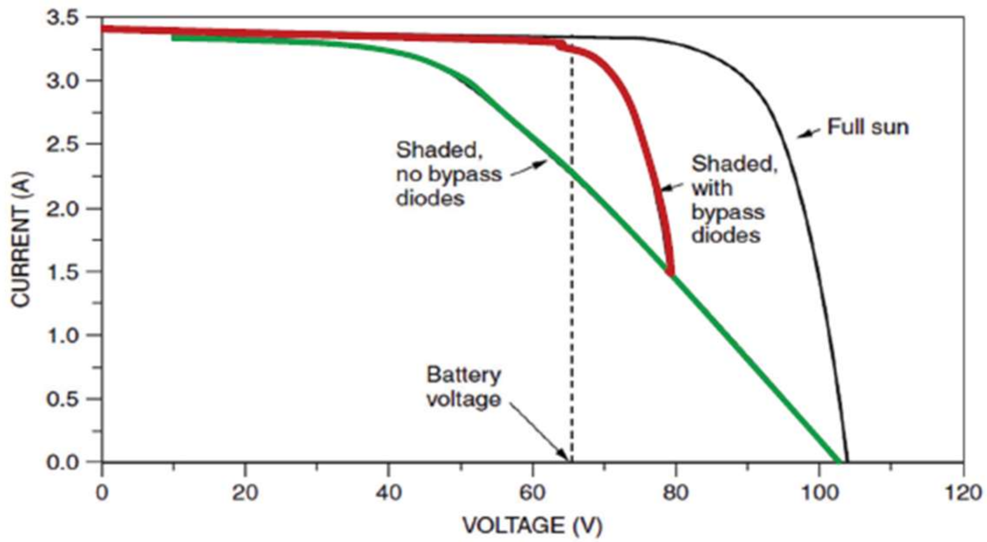
All of that 2.14 A of current goes through the parallel plus series resistance (0.005 Ω) of the shaded cell, so the drop across the shaded cell will be

$$V_c = I(R_P + R_S) = 2.14(6.6 + 0.005) = 14.14\ V$$

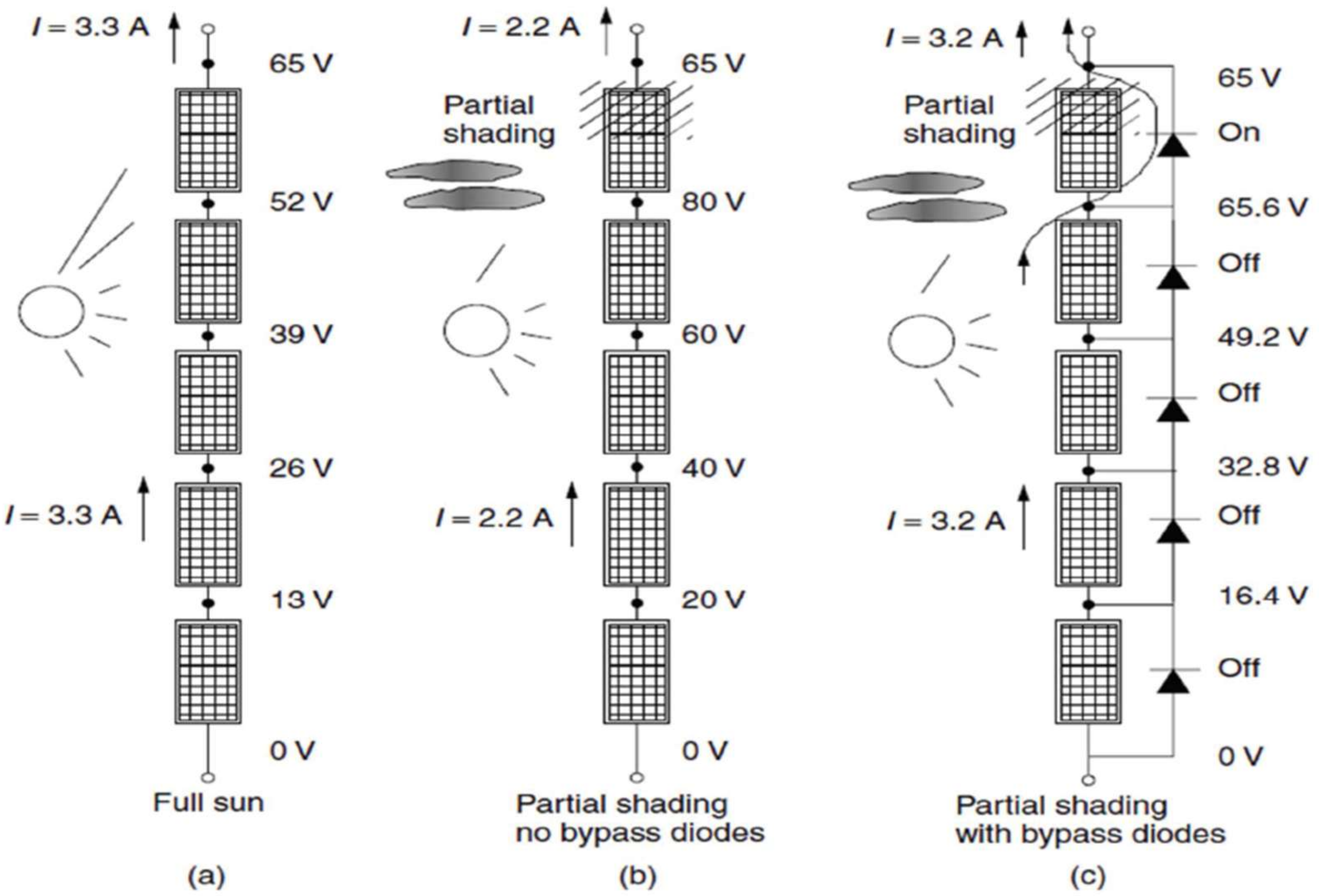
Bypass Diode to mitigate effect of shading



- Typically one bypass diode is provided for each module
- Example I-V curve for a string of 5 modules when one module has two cells completely shaded



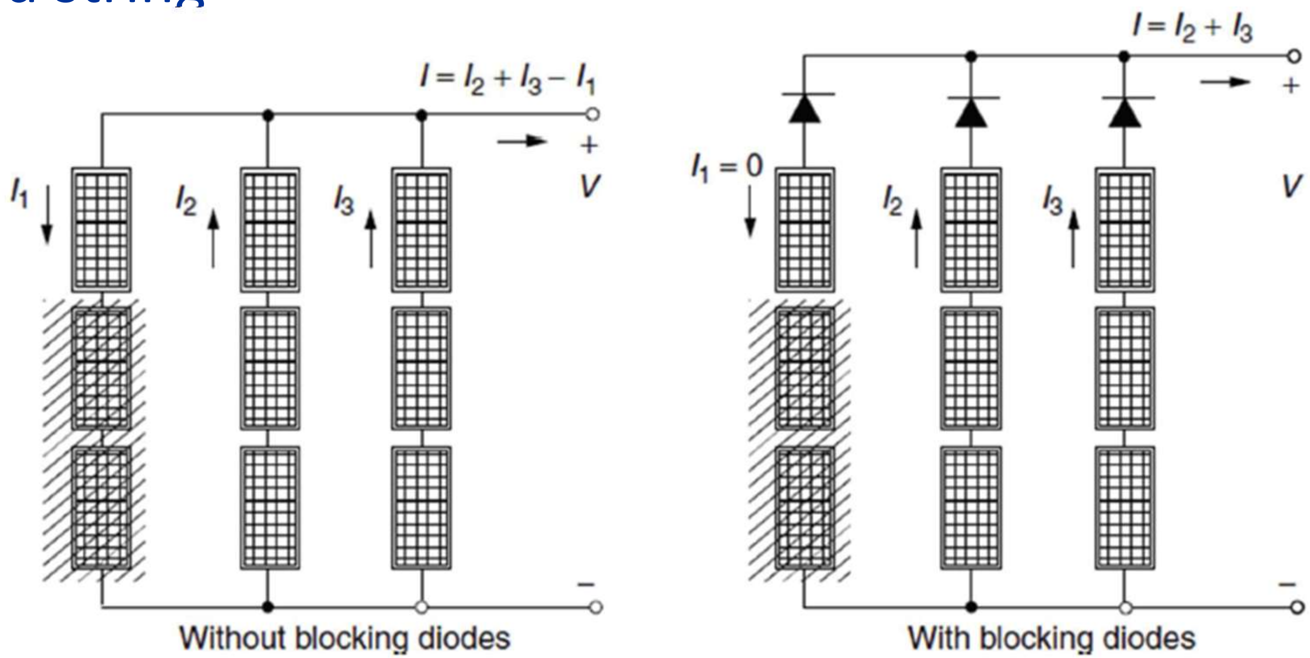
Bypass Diode to mitigate effect of shading..



With bypass diodes, current is diverted around the shaded module.

Blocking Diodes

- For strings of modules connected in parallel, if one of the strings is not performing well, it tends to draw current
- Blocking diodes can prevent the reverse current drawn by shaded string



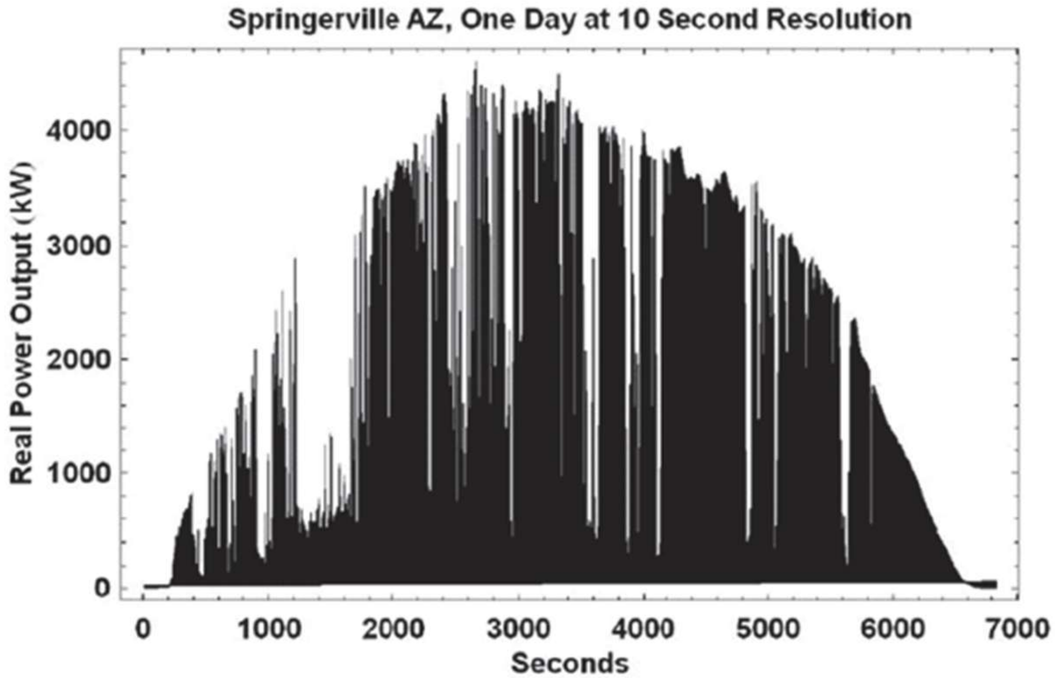
Conclusion

- Sunlight provides an abundant resource to meet our future energy demands
- Photovoltaics is the technology to capture light and generate electricity
- Cells can be connected in series to increase voltage and in parallel to increase current
- Modules can be connected in series to increase voltage and in parallel to increase current, and a combination to increase power

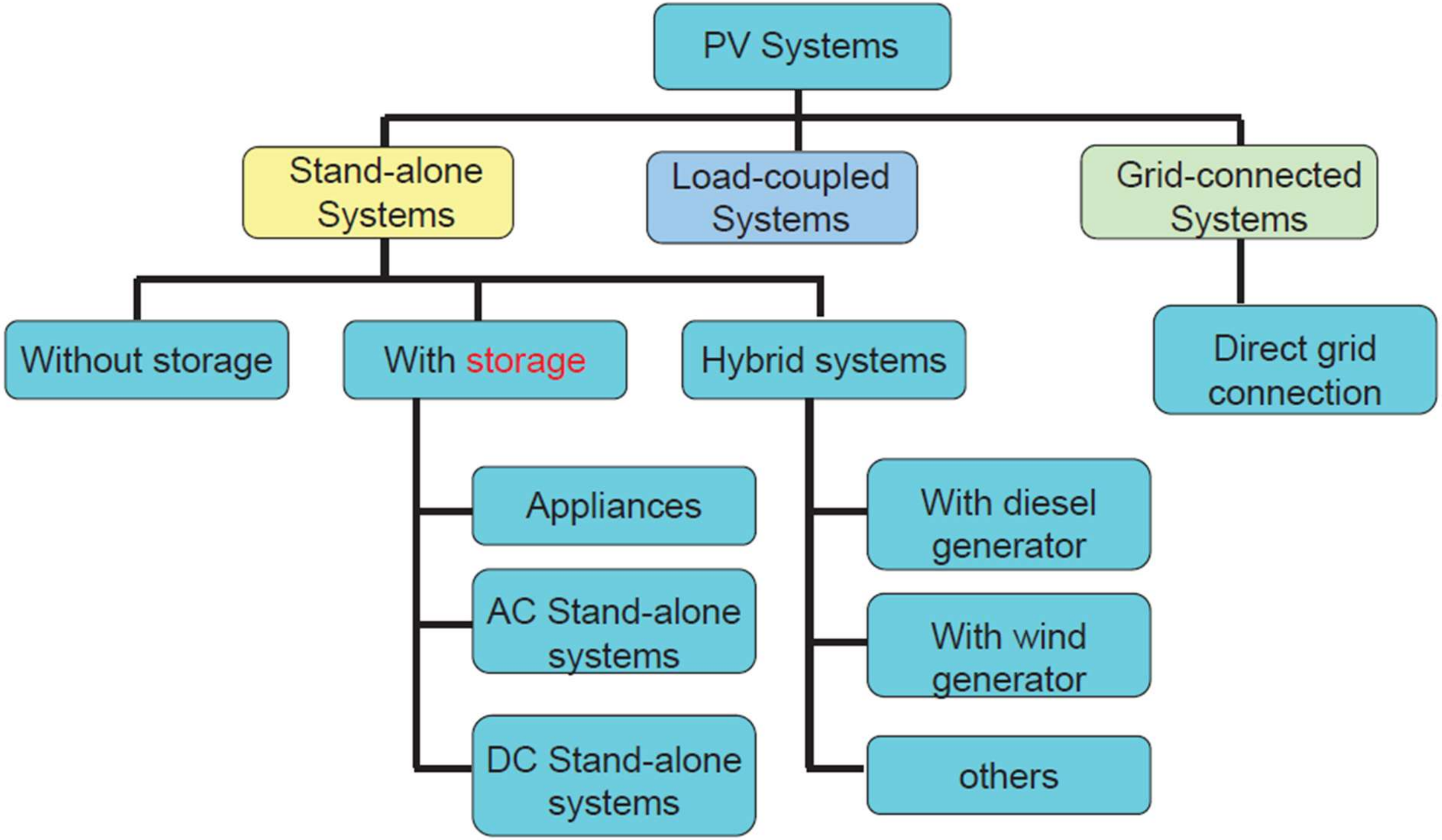
Solar PV Systems

Variability of solar power output – Motivation for Storage

- Variations in power generating capacity – temporal fluctuations are large on a daily and seasonal basis
- Without energy storage, solar power will only be available when the sun is shining
- Storage allows optimal operation and utilization of energy

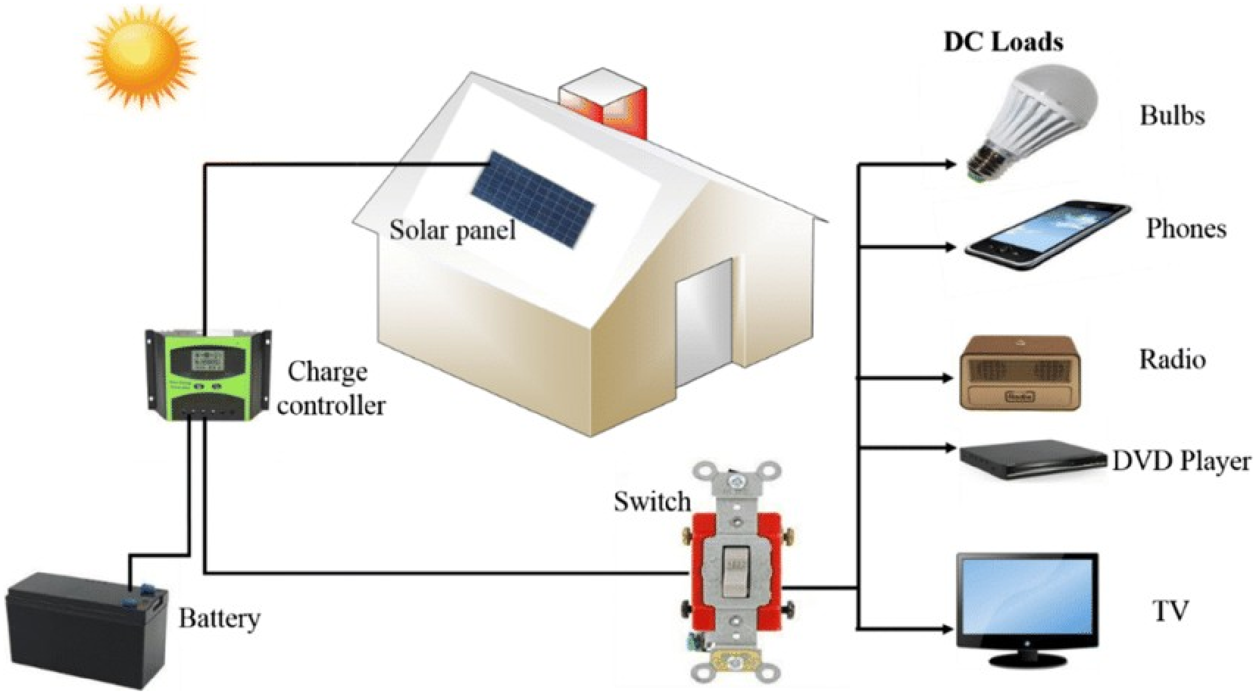


Types of Solar PV Systems



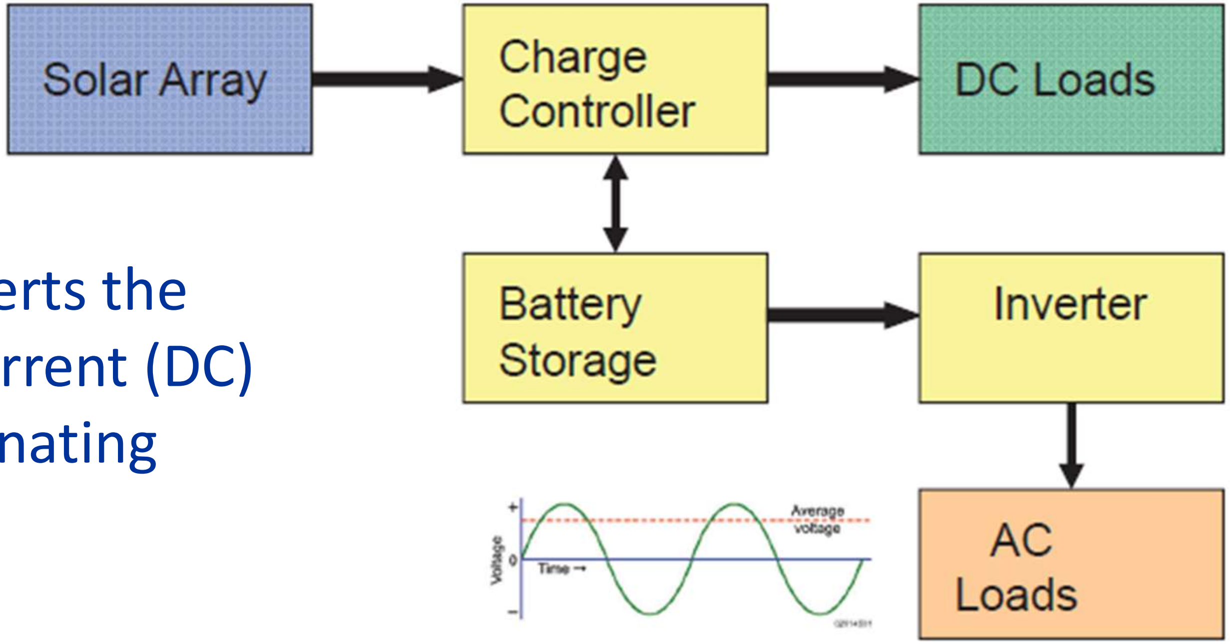
Stand-alone DC-only PV System

- In simple systems, all loads can be directly run on DC and no inverter may be necessary
- Cost-effective in remote locations



Stand-alone solar power systems

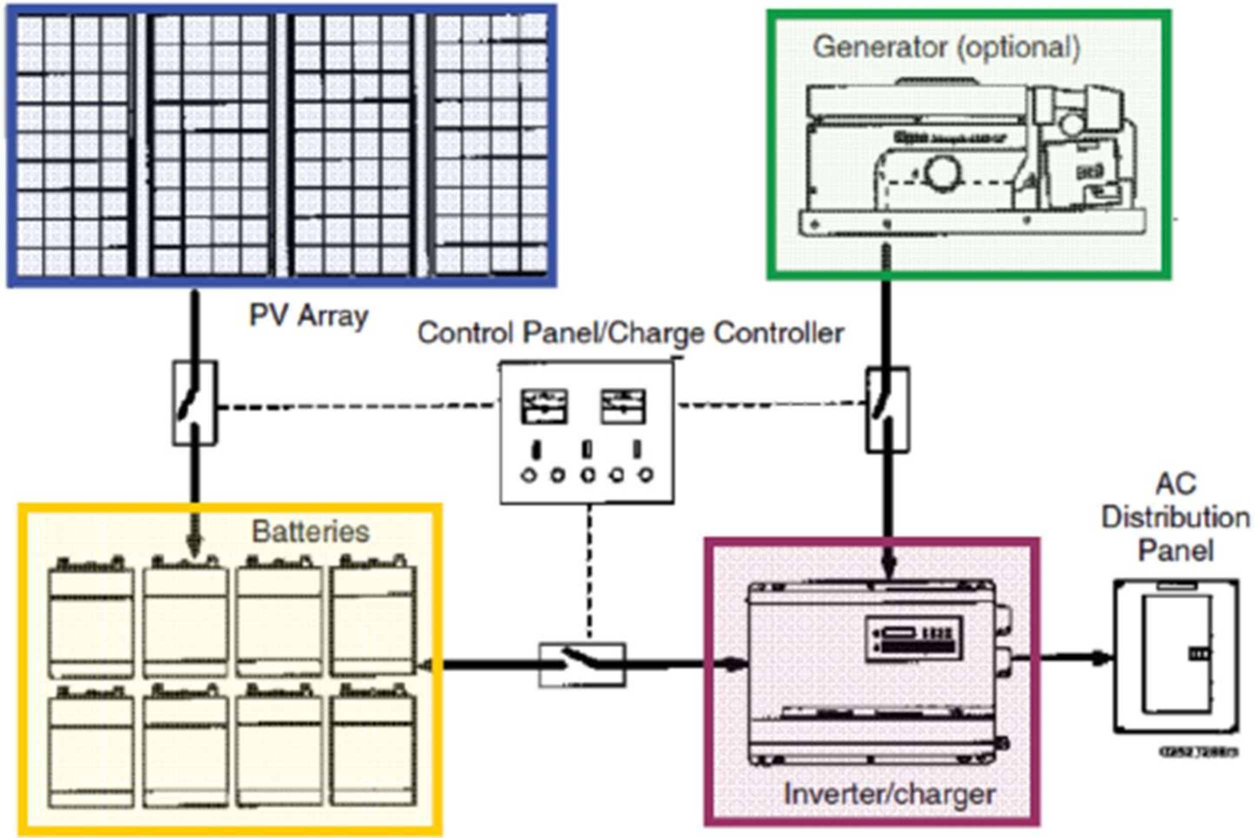
Typical stand-alone system powering DC and AC loads:



- The inverter converts the system's direct-current (DC) electricity to alternating current (AC)

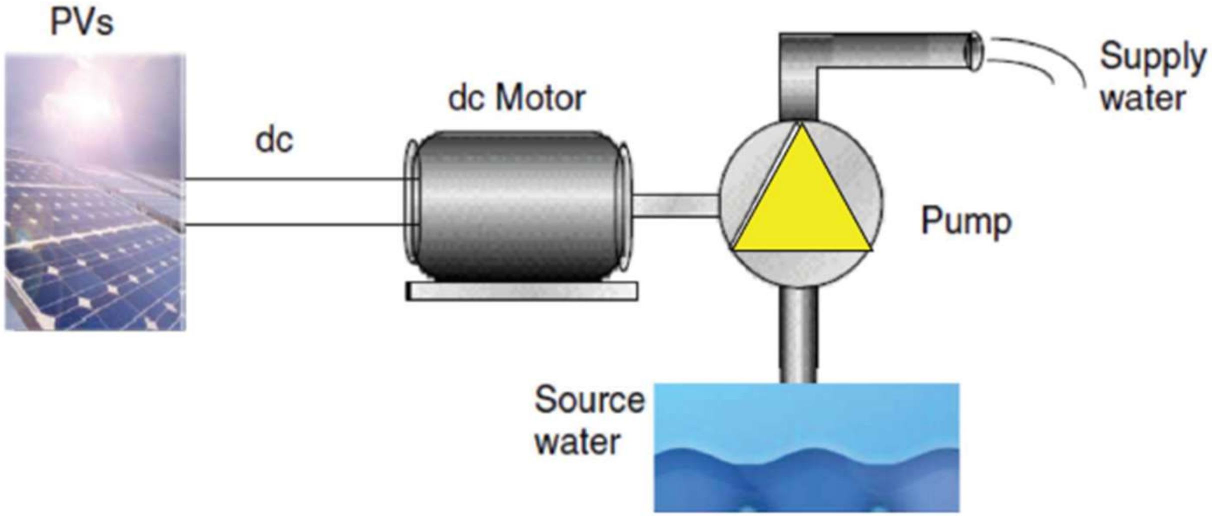
- Charge controller regulates the battery charging/discharge

Stand-alone PV systems with Generator



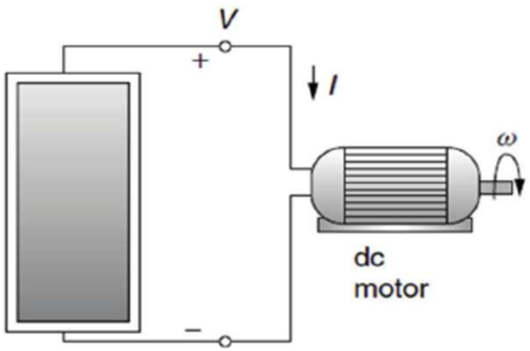
Load-coupled PV Systems

- PV modules are directly connected to their loads
- No batteries or power conditioning equipment
- Most common – for water pumps
- No electric storage (storage in terms of potential energy of water pumped)
- Very simple and reliable



Load-coupled PV Systems – DC Motor for pumps

- Typical motor for water pumping applications

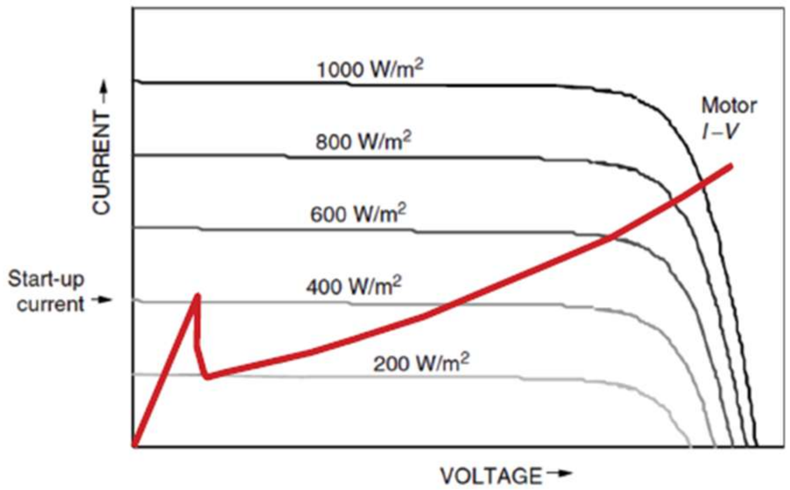


$V = IR_a + E_b$

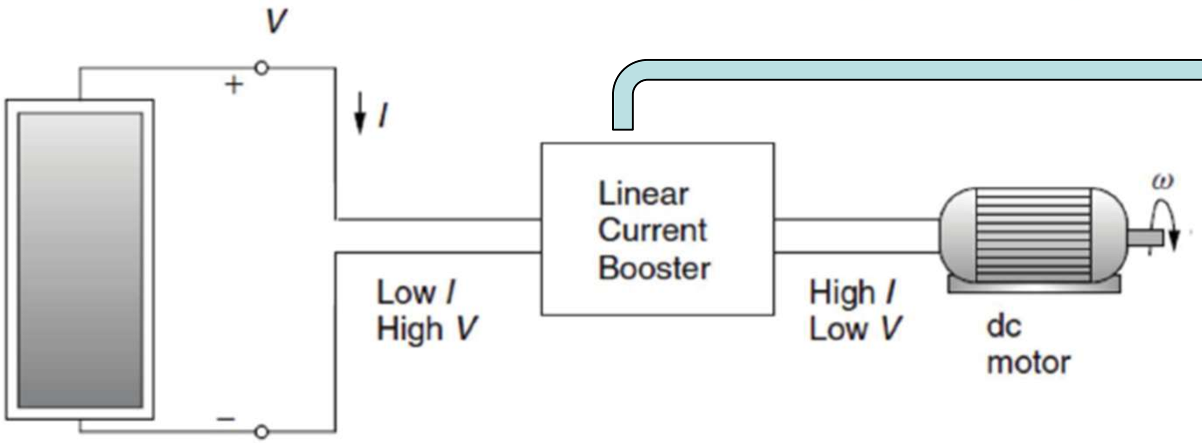
- **The motor will not start pumping until insolation reaches 400 W/m^2**

The system has to be carefully designed!

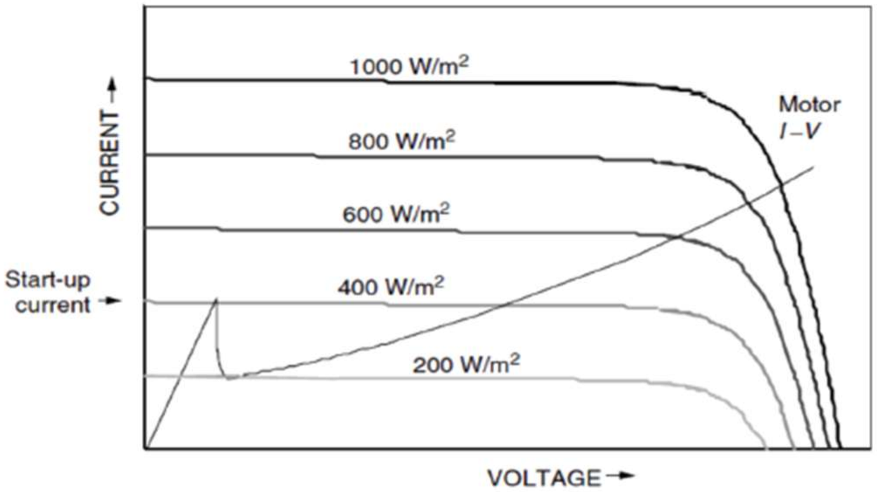
Insufficient insolation in the mornings results in lower efficiency



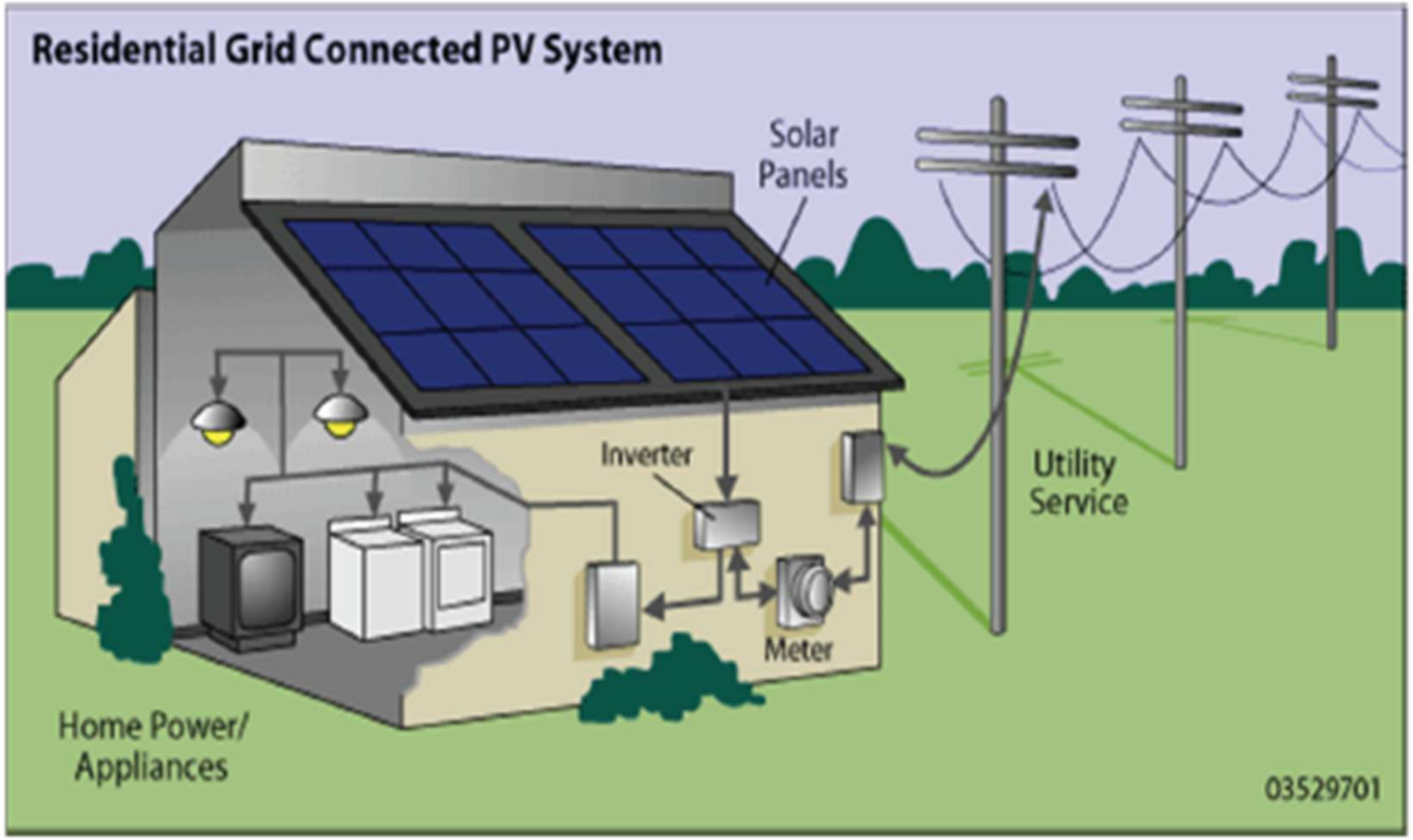
Linear current booster (LCB)



A linear current booster (LCB) increases current to help start or keep the motor running in low sunlight



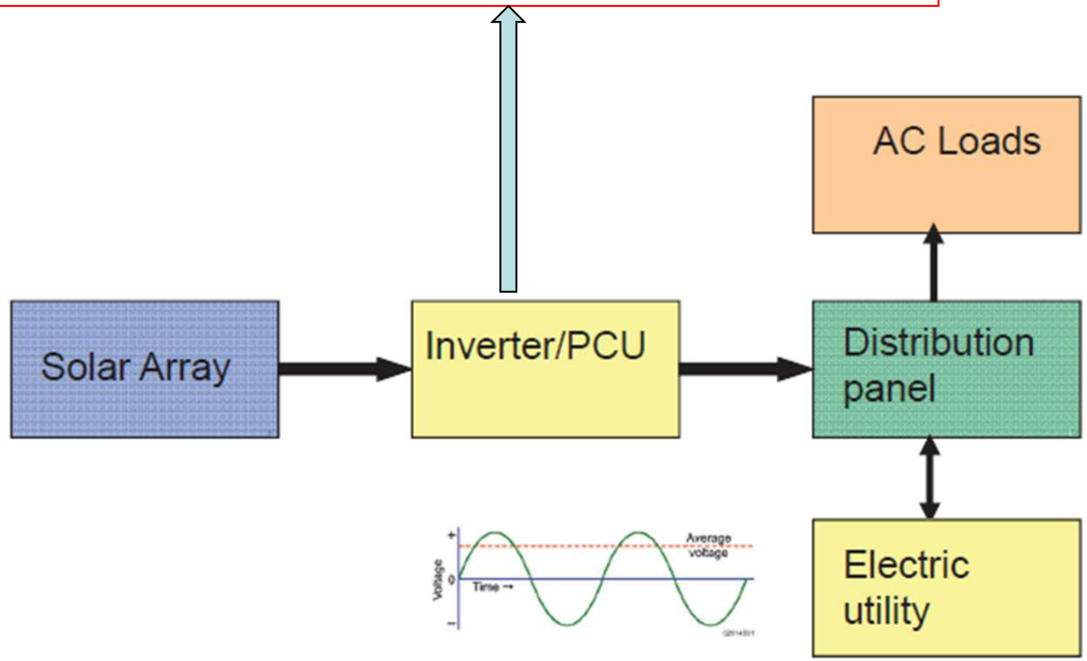
Grid-connected PV Systems



Grid-connected PV Systems…

- The components of a grid-connected PV system include:
    - PV modules/arrays
    - An inverter and power conditioning unit (PCU)
    - A safety device to power down at failures in the grid and an electricity meter
- Designed to operate in parallel with, and interconnected, with the electric utility grid

The primary component in grid-connected systems is the inverter/PCU which converts the DC power into AC power consistent with the voltage and power quality requirements of the utility grid

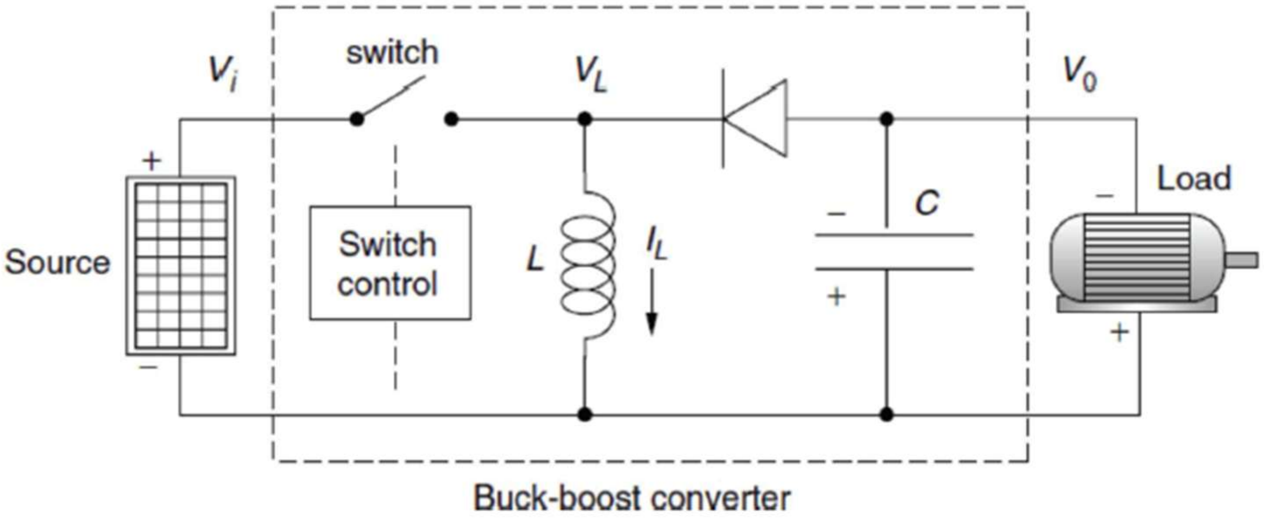


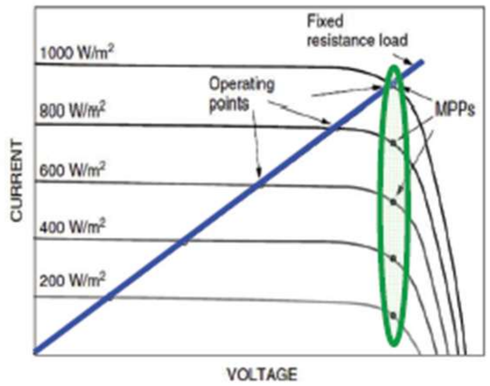
Grid-connected PV Systems..

- Inverter/PCU automatically stops supplying power to the grid when the utility grid is not energized.
- Solar power system back-feeds the grid when the solar power system output is greater than the on-site load demand.
- At night and during other periods when the electrical loads are greater than the solar power system output, the balance of power required by the loads is received from the electric utility.
- The system requires two meters to keep track of these

Maximum Power Point Trackers (MPPT)

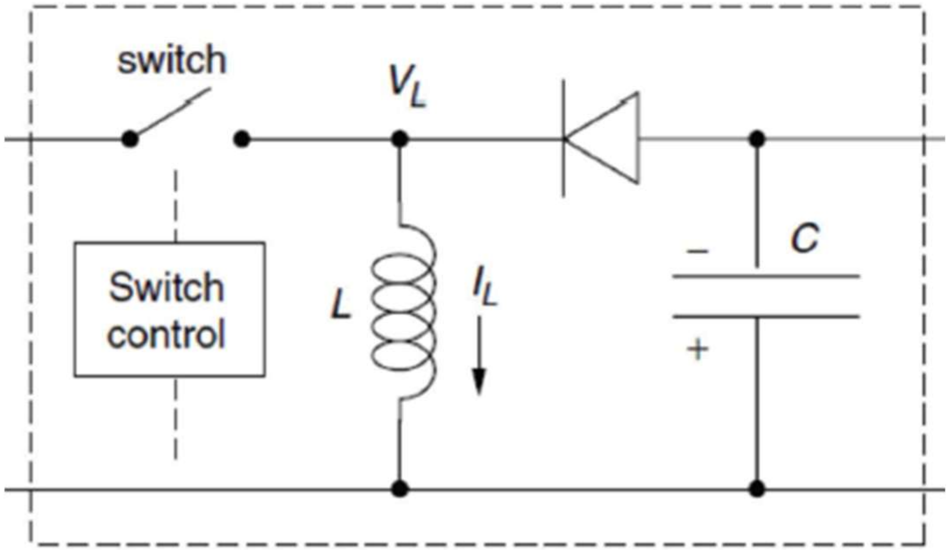
- Standard part of most grid-connected systems
- Commonly use a buck-boost converter (also used in linear current boosters)
- Raises or lowers the voltage to the desired value needed by load





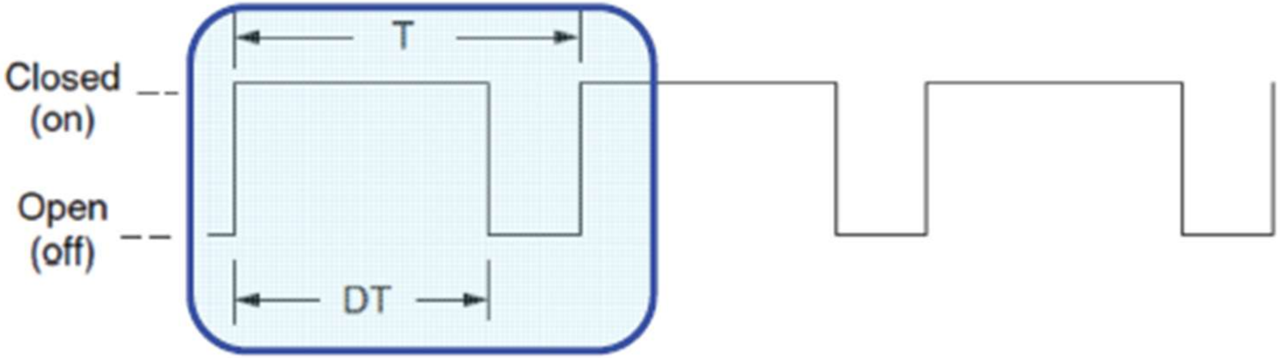
Buck-Boost Converter circuit

- A buck-boost converter is a type of power electronic converter (switch-mode dc-dc converter)
- It comprises of a switch, a diode, an inductor and a capacitor
- Typically, the on-off switch is an IGBT transistor



Buck-boost converter

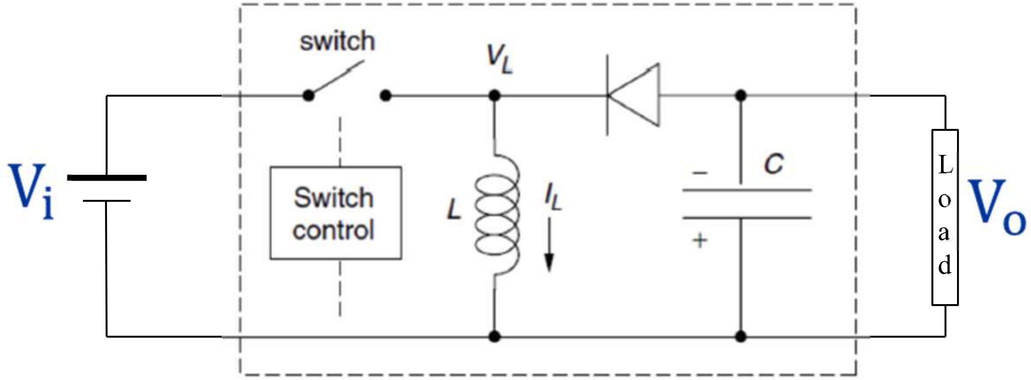
Pulse Width Modulation (PWM), Duty cycle



- The switch is turned ON and OFF at a frequency of a few tens of kilo Hertz.
- Duty cycle: the fraction of time the switch is closed
  - $Duty\ Cycle = \frac{t_{ON}}{T} = D$
  - $0 < D < 1$

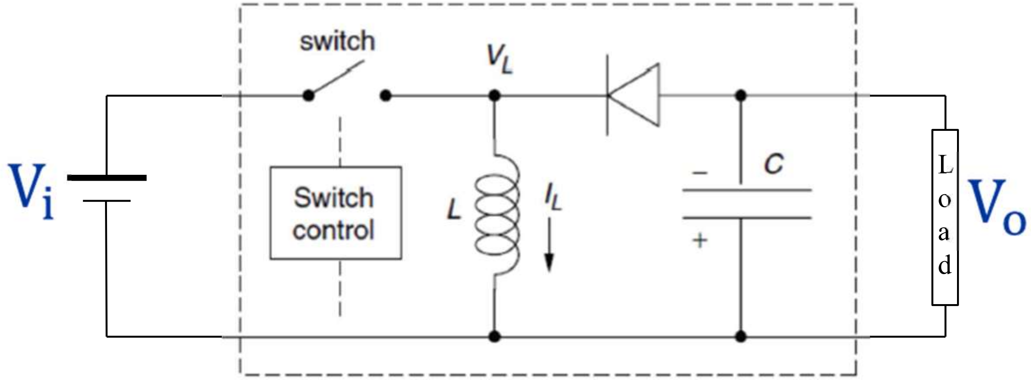
Buck-Boost Converter operation

- When switch is CLOSED: energy supplied to inductor, and I_L builds up
- When switch is OPEN: Inductor current flows through C, load, and diode, and I_L decreases
- As the change in inductor current during two states of the switch, we can use *volt-sec balance of the*



Buck-boost converter

Buck-Boost Converter operation

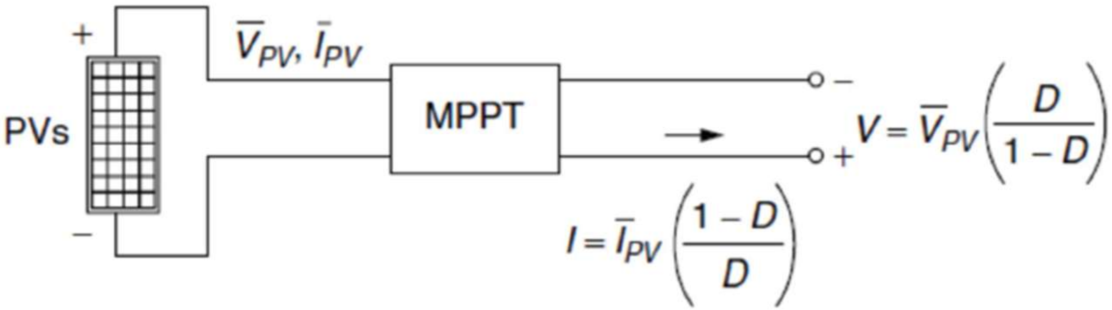


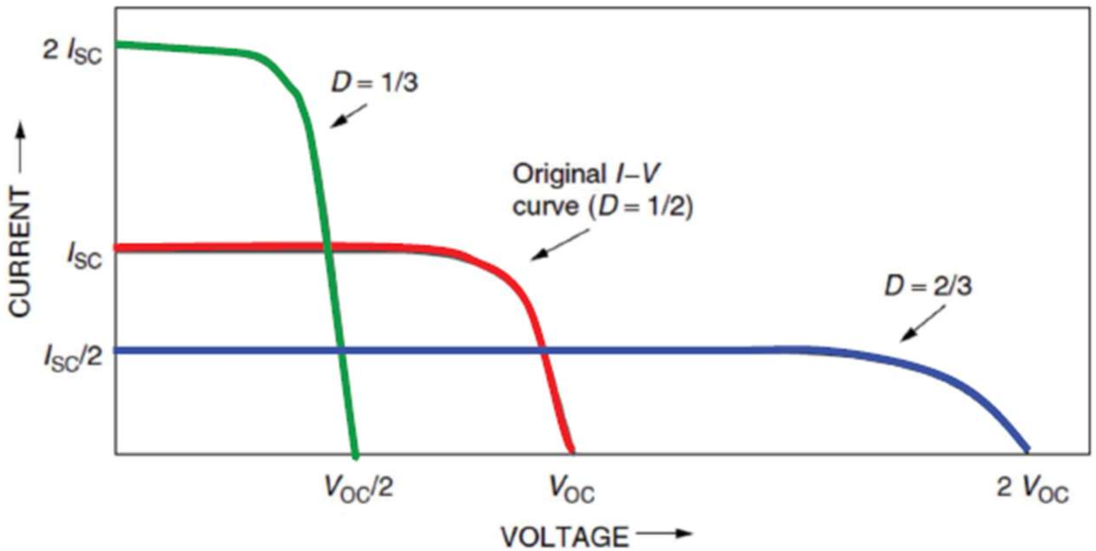
Buck-boost converter

$$\Rightarrow V_o = \frac{D}{1-D} V_i$$

- The converter behaves as boost converter when $D > 0.5$.
- The converter behaves as buck converter when $D < 0.5$.

PV current-voltage curve with MPPT converter





I-V curves drawn using D as a parameter

Example

Under certain ambient conditions, a PV module has its maximum power point at V_m = 17 volts and I_m = 6 A.

What duty cycle should an MPPT have if the module is delivering power to a 10 Ω resistance?

Solution

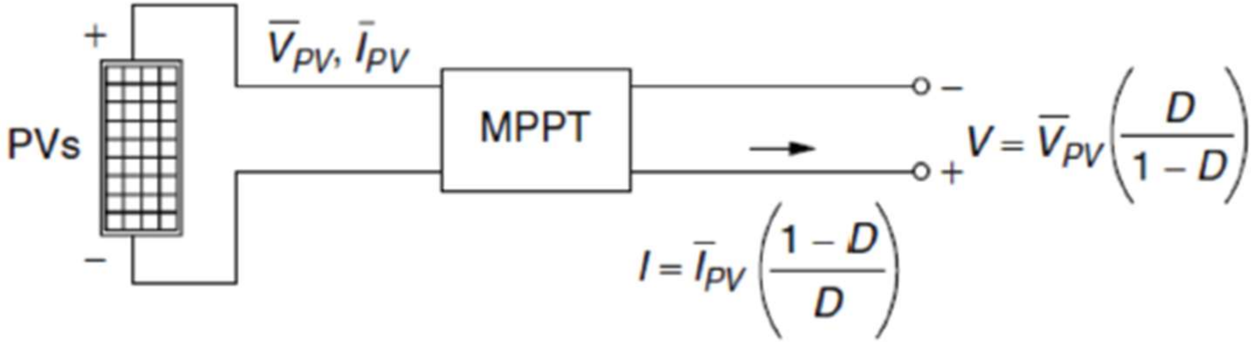
The maximum power delivered by the PVs is: P = 17 V × 6 A = 102 W.

To deliver all of that 102 W to the 10 Ω resistor means the resistor needs a voltage of:

$$P = \frac{V_R^2}{R} = 102 = \frac{V_R^2}{10}$$
$$V_R = \sqrt{102 \times 10} = 31.9\ V$$

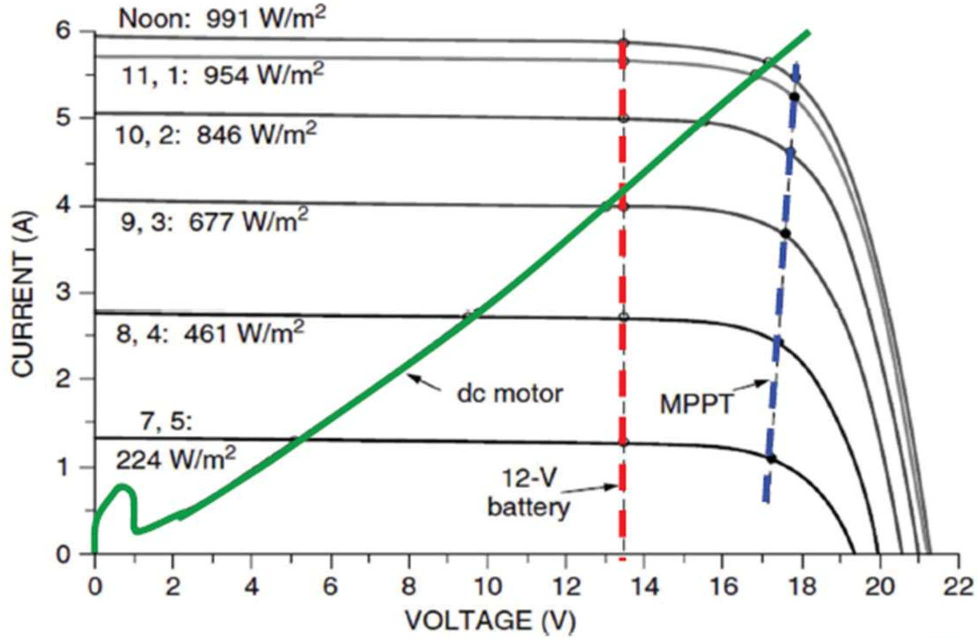
The MPPT must bump the 17-V PV voltage to the desired 31.9V resistor voltage.

$$\frac{31.9}{17} = \left(\frac{D}{1-D}\right) = 1.88$$
$$D = 1.88 - 1.88D$$
$$D = \frac{1.88}{2.88} = 0.65$$



Hourly Current-Voltage curves

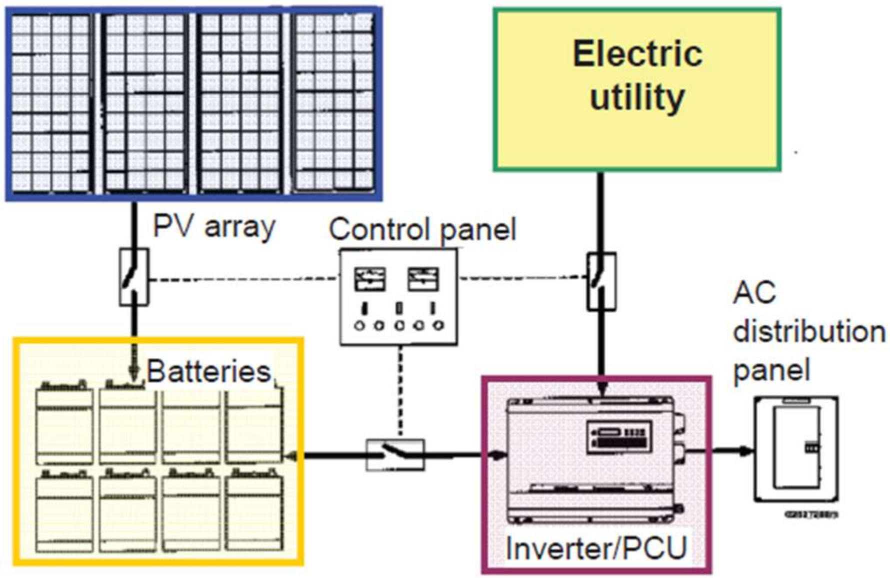
- The 1-sun curve can be scaled up or down in proportion to the insolation to draw hour-by-hour I-V curves (for clear days)
- Example: For three different types of loads – DC motor, 12-V battery, MPPT



DC motor and battery lose about 15% of the available daily energy because
they don’t always operate on maximum power point

Grid-connected PV Systems

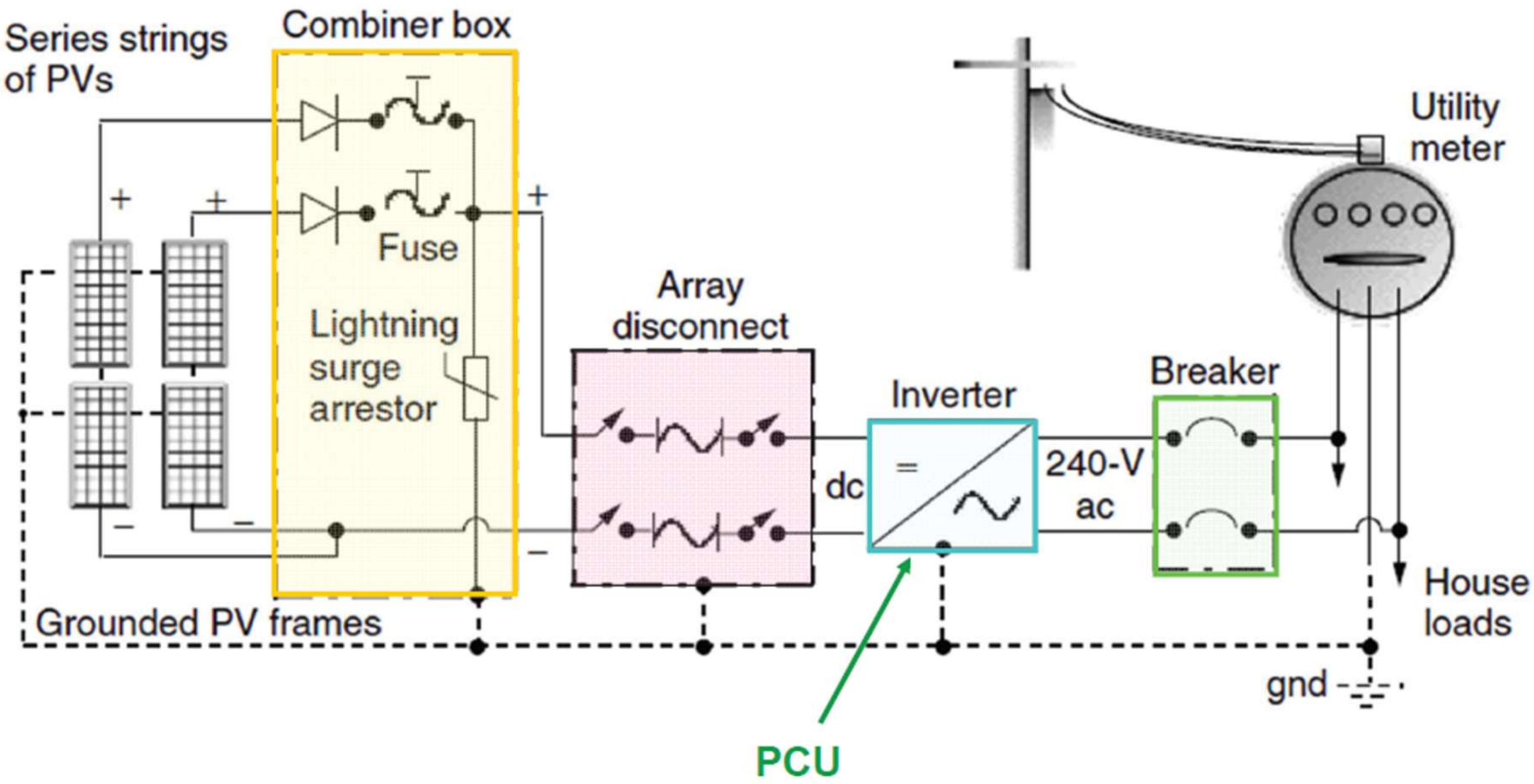
- The power conditioning unit must be designed to quickly and automatically drop the PV system from the grid in the event of utility outage
- A small battery back-up may be included to supply power during such outages



Grid-connected PV Systems

Grid-connected system using a single inverter

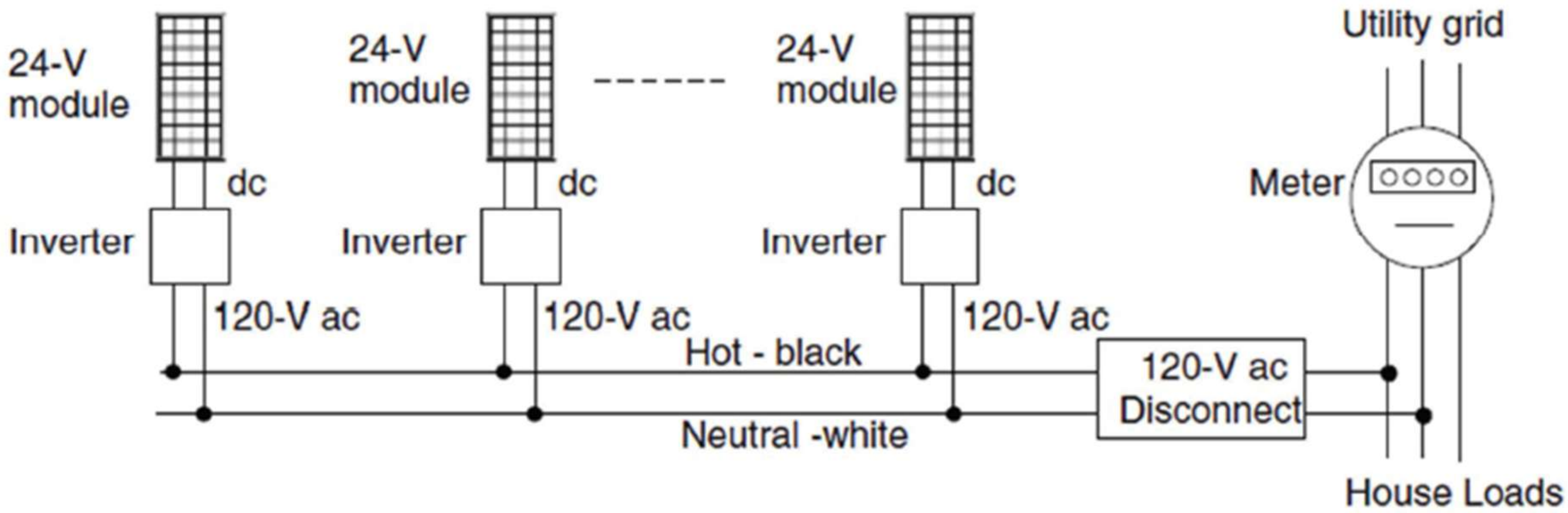
(MPPT, protection circuitry and battery bank are not shown)



Grid-connected PV Systems

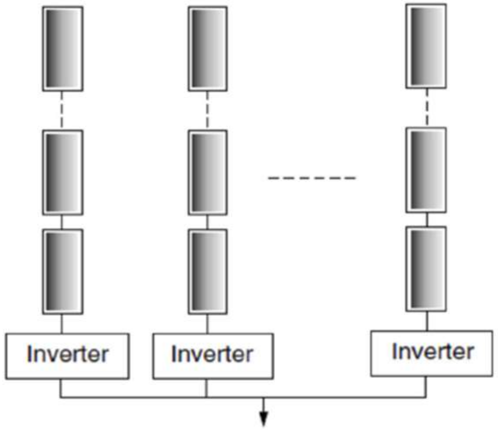
AC modules each with their own inverters

- Allows modular expansion of the system
- Uses simpler, less expensive switches, circuit breakers and wiring

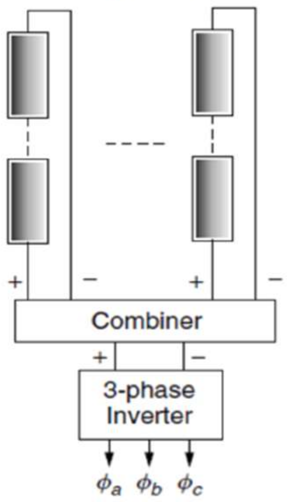


Different inverter configuration

- Large grid-connected systems may use an individual inverter for each string

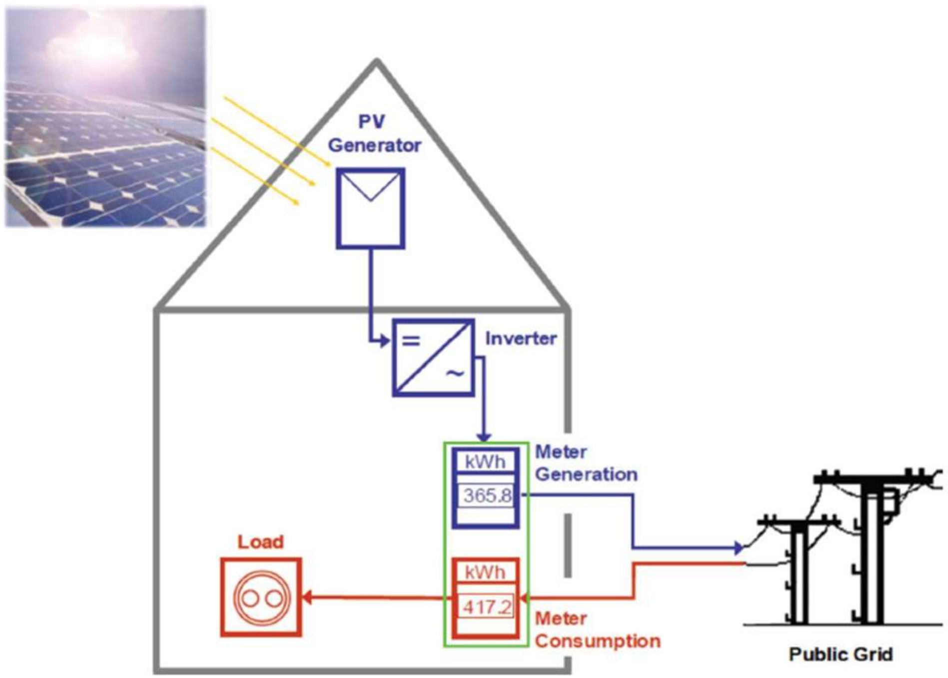


- Or, a large central inverter system can be used to provide three-phase power

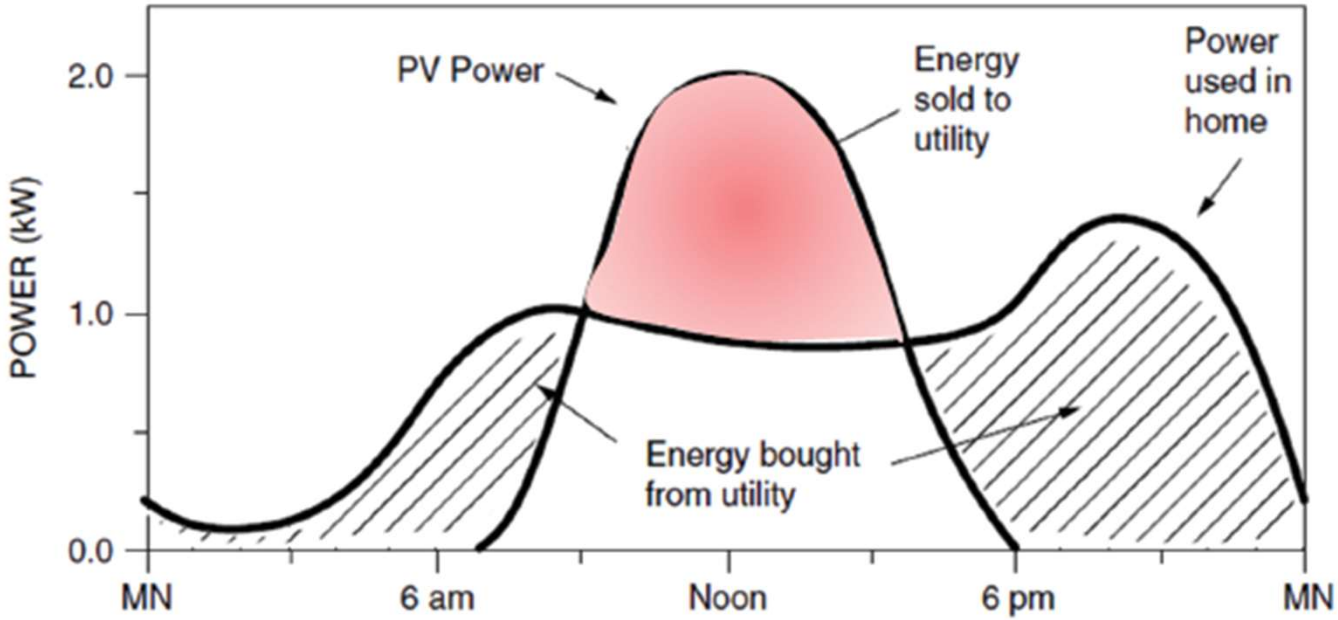


Interfacing with the utility: Net metering

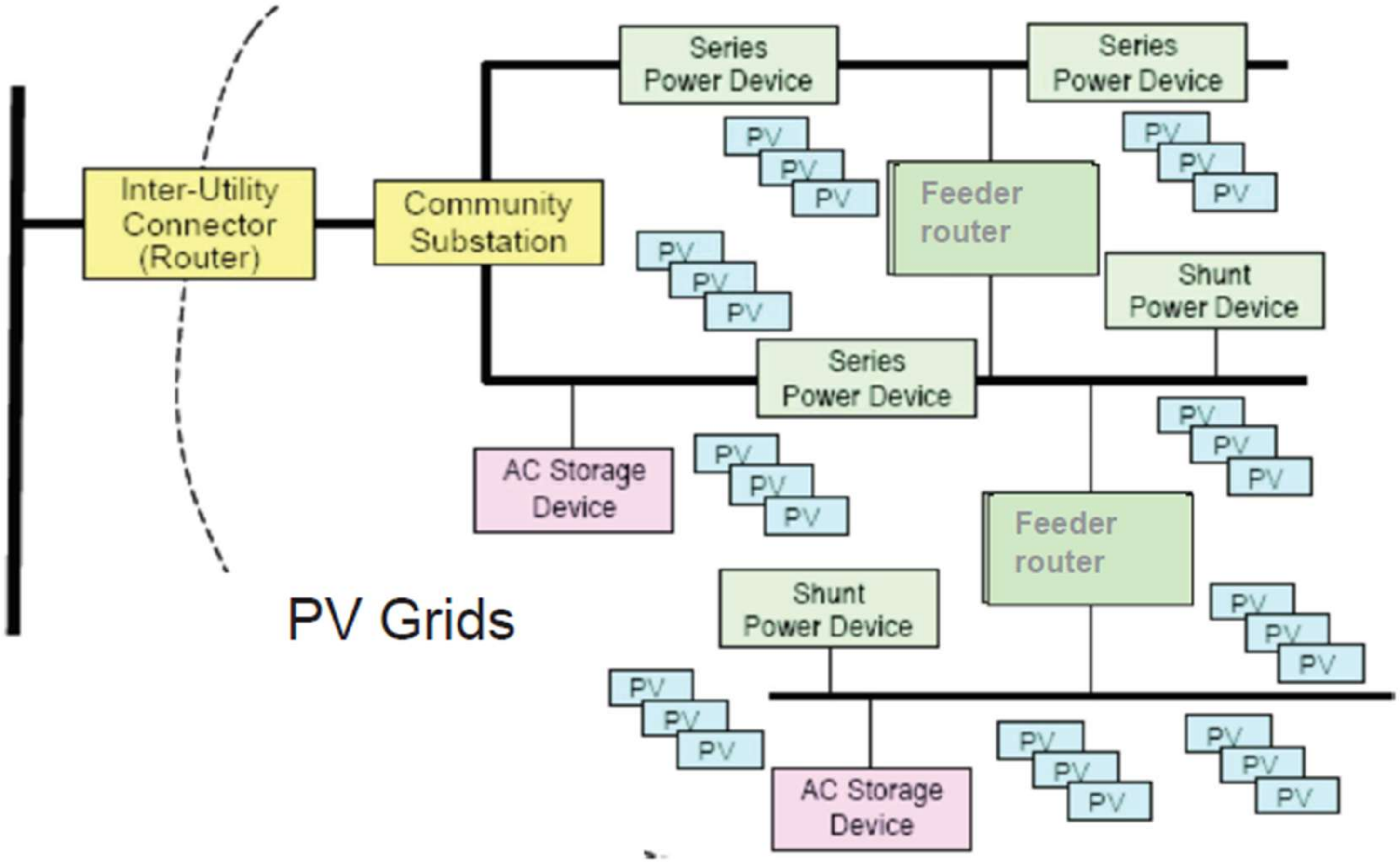
- Whenever PV system delivers more power than demanded by the home, the electric meter runs backwards
- When demand > supply from PV, the grid supplies additional power



Net metering



Grid Connected PV Systems: Large clusters



Estimating PV System Performance

Estimating the system performance

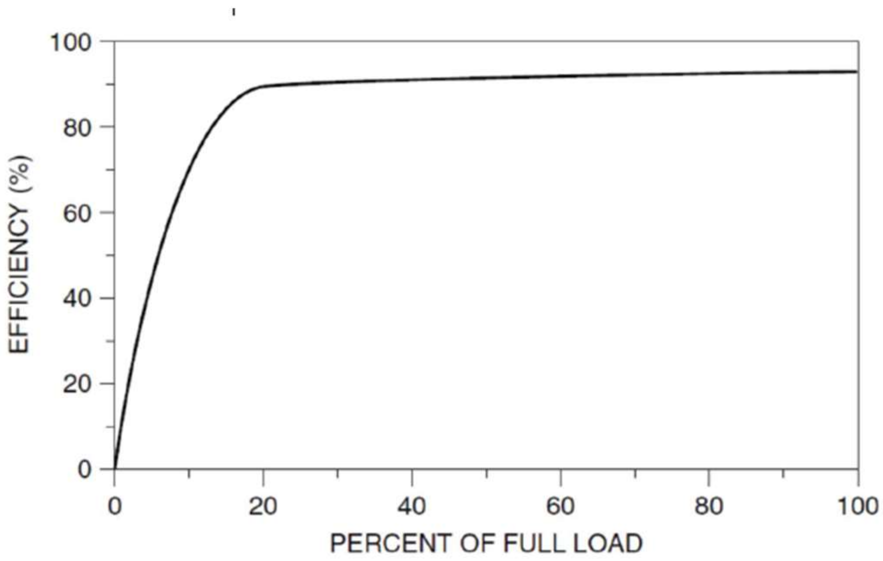
- A good starting point to estimate system performance is the rated DC power output of an individual module under standard test conditions (STC)—that is, 1-sun, AM 1.5 and 25°C cell temperature. Then we can try to estimate the actual AC power output under varying conditions.
- Actual ac power delivered at 1-sun,

$$P_{ac} = P_{dc,STC} \times (Conversion\ Efficiency)$$

- The conversion efficiency accounts for inverter efficiency, dirty collectors, mismatched modules, and differences in ambient conditions. Even in full sun, the impact of these losses can easily derate the power output by 20– 40%.

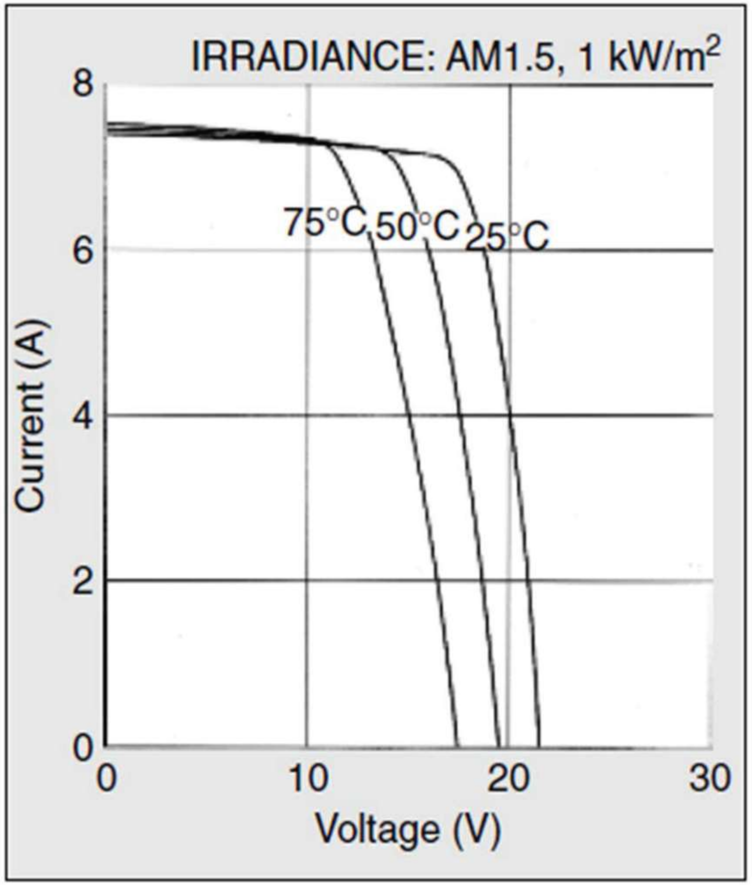
Efficiency of the inverter

- Efficiency of the inverter depends on the load
- Typical grid-connect inverters have efficiencies above 90% for upto 20% loading



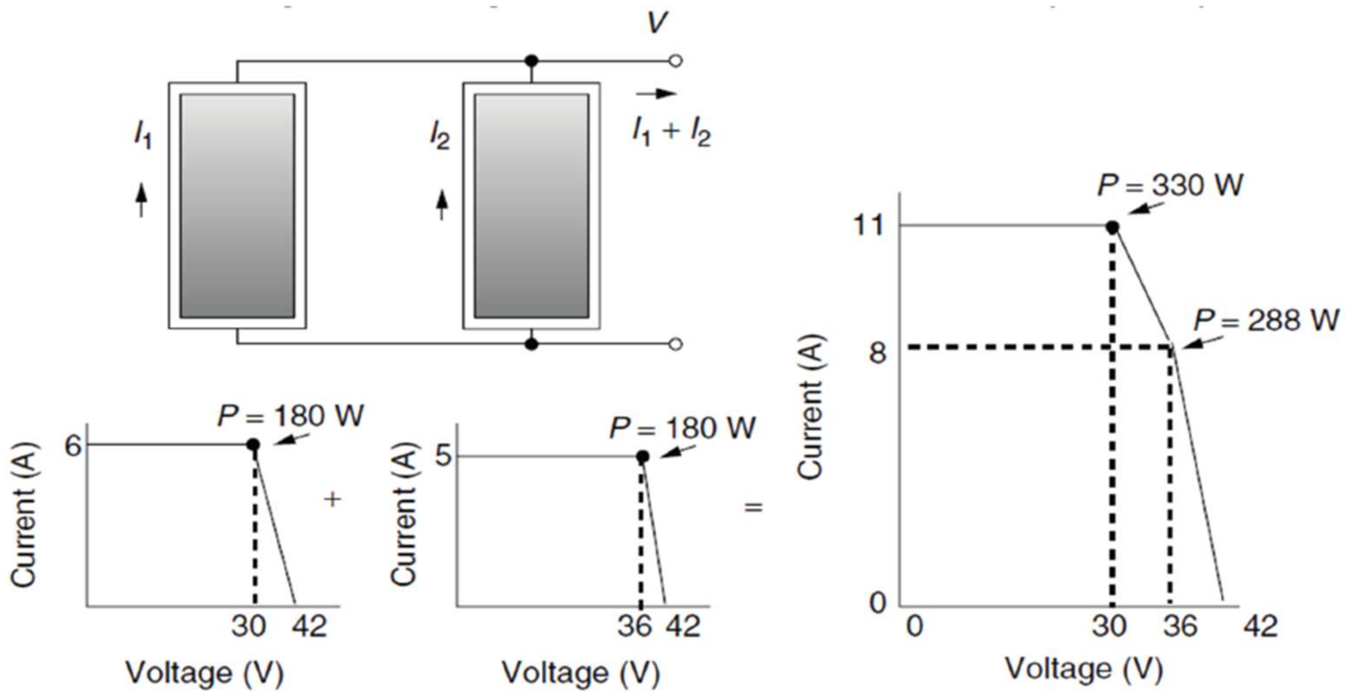
Effect of temperature

- With increase in temperature, voltage reduces while current increases very slightly
- For crystalline Silicon cells, V_{OC} drops by 0.37% per degree C, and ISC increases by 0.05% per degree C
- MPP drops by approx 0.5% per degree C



Effect of variation in I-V curves

Example: Each module is rated at 180 W, but the parallel combination yields only 330 W at the maximum power point



Example

Consider a PV array rated at 1 kW under standard test conditions. Module cell temperature is 53.8^oC . DC power output at the MPP drops by 0.5%/^oC above the STC temperature of 25^oC.

Estimate its ac output if there is a 3% array loss due to mismatched modules, dirt loss is 4%, and the inverter has an efficiency of 90%.

Solution

With power loss at 0.5% per degree above 25°C, the DC rated power of the array would be:

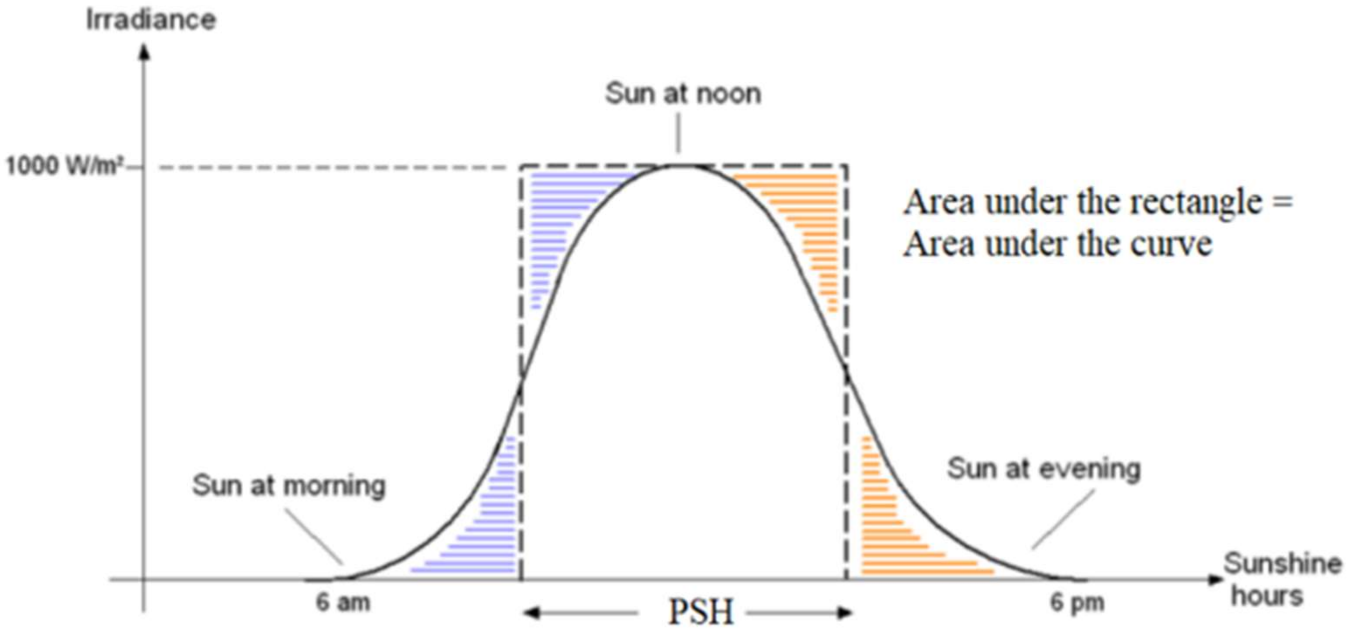
$$P_{DC} = 1\ kW[1 - 0.005(53.8 - 25)] = 0.856\ kW$$

Including mismatch, dirt, and inverter efficiencies will result in an estimated AC rated power:

$$P_{AC} = 0.856\ kW \times 0.97 \times 0.96 \times 0.90 = 0.72\ kW$$

Even though the system would be sold as a “1-kW system”, the array will deliver only 72% of that as ac power to the load under the realistic conditions.

Estimating PV Performance - The "Peak- Hours" Approach



If we know the AC power delivered by an array under 1-sun insolation (P_{AC}), we can just multiply that rated power by the number of hours of peak sun to get daily kWh delivered (energy delivered in a day).

Capacity Factors for PV Grid-Connected Systems

- If the system delivered full, rated power continuously, the capacity factor (CF) would be unity.

$$\text{Energy (kWh/yr)} = P_{ac}\text{(kW)} \cdot \text{CF} \cdot 8760\text{(h/yr)}$$

$$\text{Energy (kWh/day)} = P_{ac}\text{(kW)} \cdot \text{(h/day of “peak sun”)}$$

$$\text{Capacity factor (CF)} = \frac{\text{(h/day of “peak sun”)}}{\text{24 h/day}}$$

Grid-connected PV system design

- Estimate the rated power and area required for the PV array.
- Explore the interactions between the choice of PV modules and inverters and how those impact the layout of the PV array.
- Finally, consider details about voltage and current ratings for fuses, switches, and conductors

Example: System sizing (first cut)

- **An energy efficient house in Singapore is to be fitted with a rooftop PV array that will annually displace all of the 1550 kWh/yr of electricity that the home uses. How many PV panels will be required and what area will be needed? Make assumptions as needed.**
- Using data for Singapore -- 4.1 kWh/m^2-day of annual insolation, using the peak hour approach,
- Energy (kWh/yr) = P_{ac}(kW) · (h/day @1-sun) · 365 days/yr

$$P_{ac} = \frac{1550}{4.1 \times 365} = 1.0357\ kW$$

Considering the impacts of temperature, inverter efficiency, module mismatch, and dirt to come up with conversion efficiency of 75% from dc to ac.

$$P_{dc} = \frac{1.0357}{0.75} = 1.381 kW$$

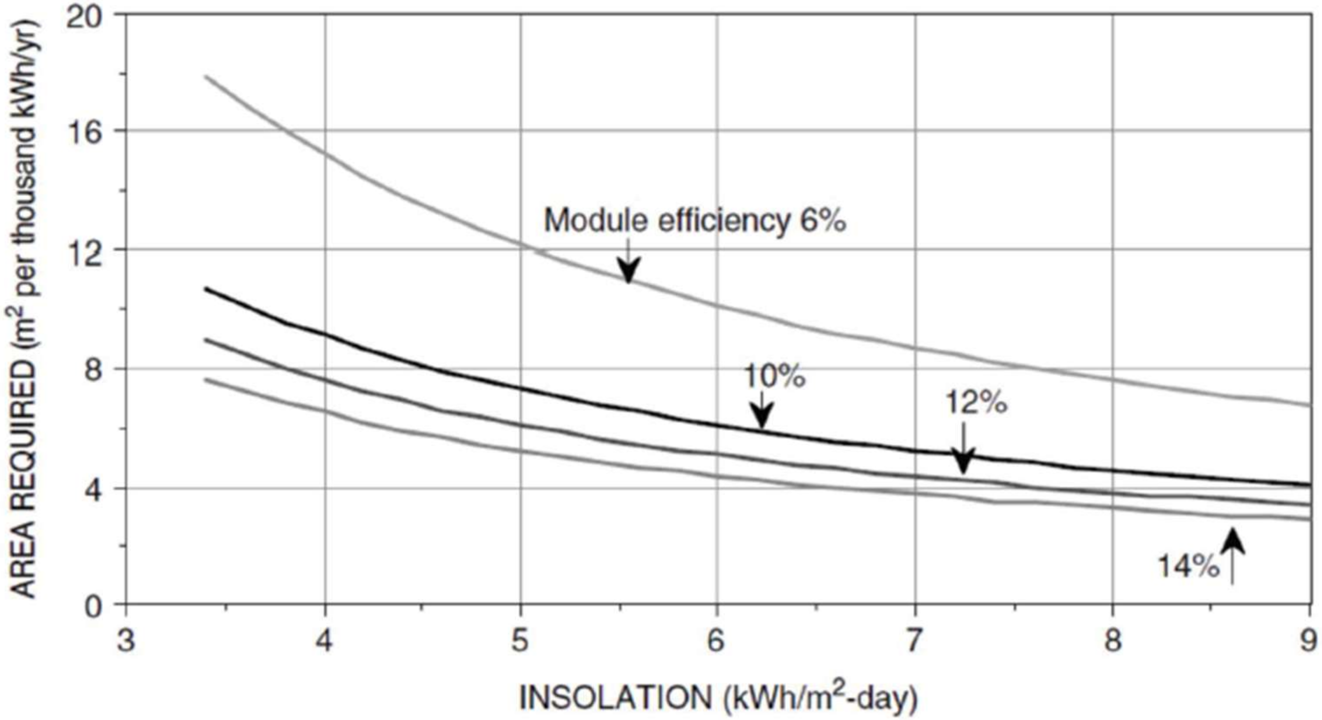
To estimate the collector efficiency, P_{dc} = 1 kW/m^2 insolation · A (m^2) · η

Assuming crystalline silicon modules which typically have an efficiency of about 12.5%, the area required

$$A = \frac{1.381 kW}{1 kW / m^2 \times 0.125} = 11.048 m^2$$

Example: System sizing

- Area required to deliver 1000 kWh/yr with module efficiency as a parameter, assuming a conversion efficiency from DC to AC of 75%.



Example: System sizing (more accurate calculation)

Number of modules required:

Module:	Sharp NE-K125U2	Kyocera KC158G	Shell SP150	Uni-Solar SSR256
Material:	Poly Crystal	Multicrystal	Monocrystal	Triple junction a-Si
Rated power $P_{dc,STC}$:	125 W	158 W	150 W	256 W
Voltage at max power:	26.0 V	23.2 V	34 V	66.0 V
Current at max power:	4.80 A	6.82 A	4.40 A	3.9
Open-circuit voltage V_{OC}:	32.3 V	28.9 V	43.4 V	95.2
Short-circuit current I_{SC}:	5.46 A	7.58 A	4.8 A	4.8
Length:	1.190 m	1.290 m	1.619 m	11.124 m
Width:	0.792 m	0.990 m	0.814 m	0.420 m
Efficiency:	13.3%	12.4%	11.4%	5.5%

$$Number\ of\ modules = \frac{1381W}{158W/module} = 8.74$$

Inverter selection

Manufacturer:	Xantrex	Xantrex	Xantrex	Sunny Boy	Sunny Boy
Model:	STXR1500	STXR2500	PV 10	SB2000	SB2500
AC power:	1500 W	2500 W	10,000 W	2000 W	2500 W
AC voltage:	211–264 V	211–264 V	208 V, 3Φ	198–251 V	198–251 V
PV voltage range MPPT:	44–85 V	44–85 V	330–600 V	125–500 V	250–550 V
Max input voltage:	120 V	120 V	600 V	500 V	600 V
Max input current:	—	—	31.9 A	10 A	11 A
Maximum efficiency:	92%	94%	95%	96%	94%

With three modules per string, rated voltage= 3 × 23.2 = 69.6 V, which is in the MPPT range.

This suggests using an array with three strings of three modules each, for a total of 9 modules

Roof area required = 9 x 1.29 x 0.99 = 11.49 m^2 (very close to the initial estimate)

System sizing

- The short-circuit current for each string of panels is 7.58 A.
- Applying the 125% factor to afford a safe oversizing margin, results in combiner fuses that must allow at least

  Combiner fuses > 7.58 A × 1.25 = 9.475 A
- The array disconnect fuse must accommodate three such strings, so it must handle

  Array disconnect fuse > *9.475 x 3* = 28.425 A
- $$\text{Inverter fuse} > 1.25 \times \frac{2500\ \text{W}}{240\ \text{V}} = 13\ \text{A}$$

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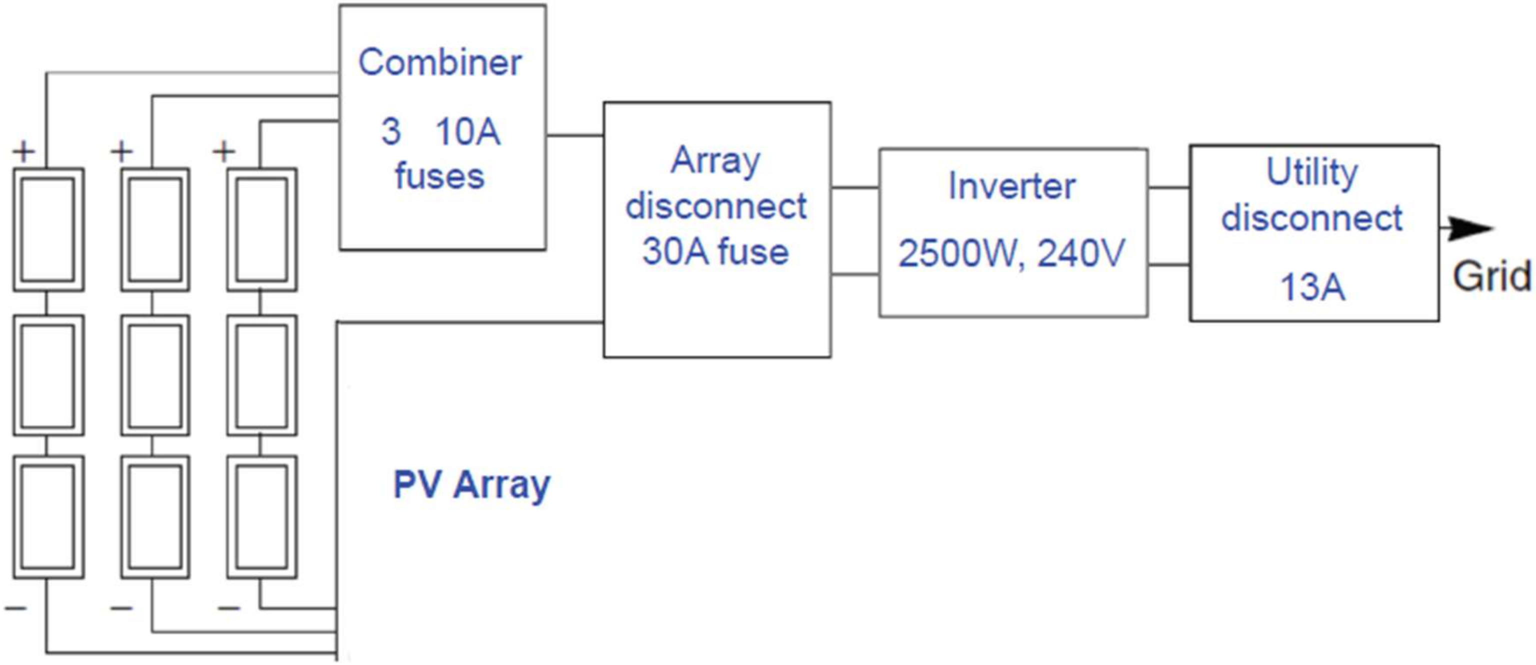
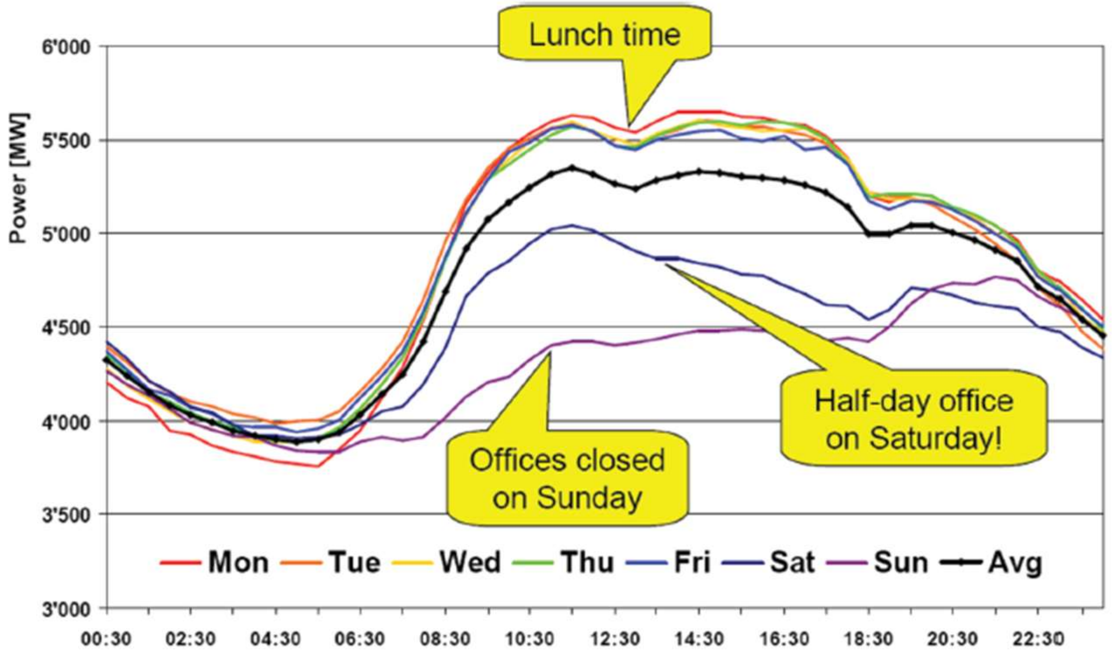
Complete system



PV System Integration Parameters

- Net load duration curve
- Capacity displacement
- Emissions reductions
- Fossil fuel use reductions
- Cost of electricity

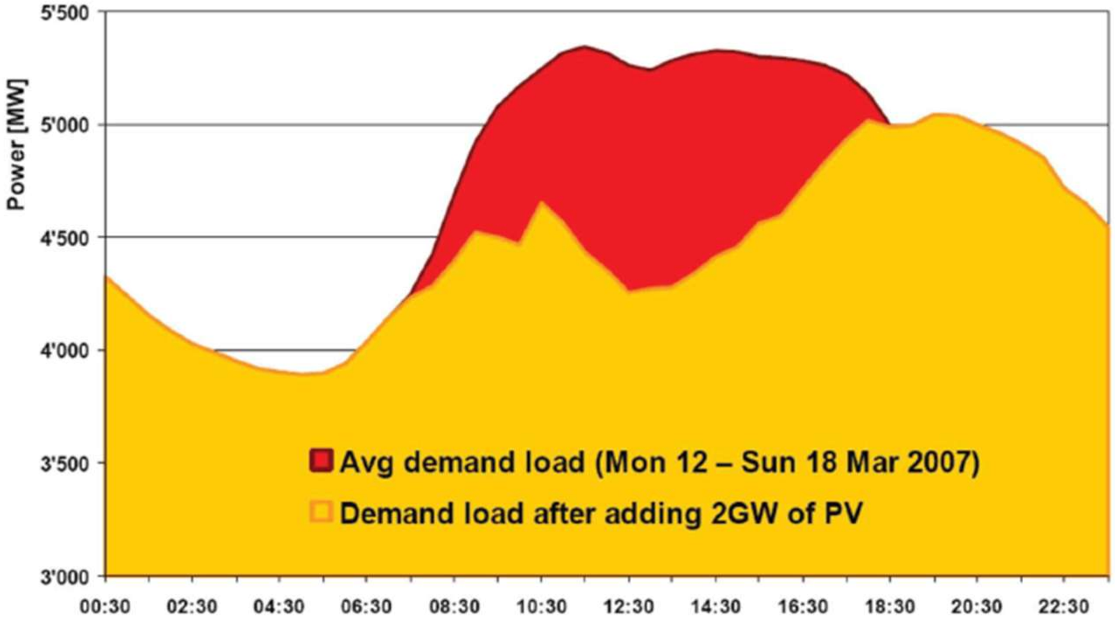
Load profile for Singapore



(source: EMA)

Capacity displacement

Capacity displacement means overall reduction in the power to be generated

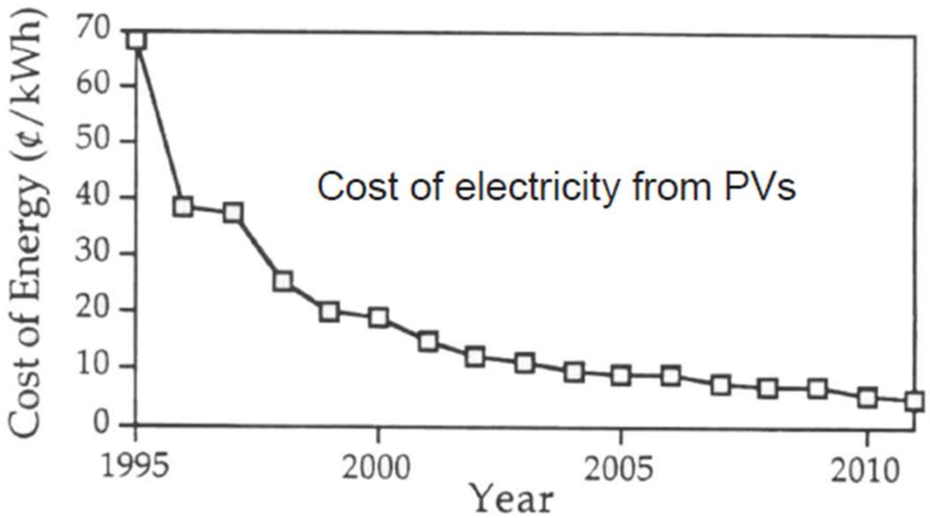


(Source: Phoenix Solar)

Cost of electricity

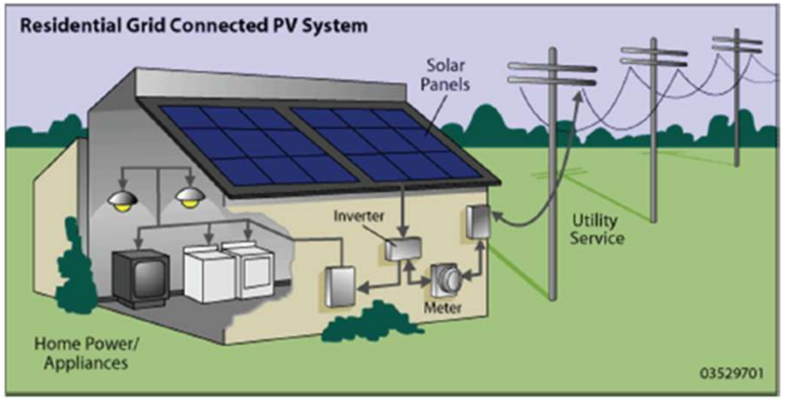
The energy output of such PV plants reaches it's peak at midday, meeting the daily energy consumption peak, when the spot prices on energy are highest

- Grid parity: the point at which the costs are equal to grid power
- PV-generated electricity is usually more expensive than conventional utility-supplied electricity.
- PV power requires a high initial investment but very low running costs



Integration of PV: Issues

- Why does industry resist inclusion of small-scale generation?
  - First problem – local instability in the distribution system
  - Second problem – schedule mismatches and decentralized control in the transmission system
- How would an owner get paid for the benefits provided by installing PV power system?
- Can PV power systems be part of the competitive markets



Source: GE Energy

Technical issues for system integration of PV

Long term planning

- Pros: modular, low emissions, small footprint
- Cons: non-dispatchable, requires different planning frameworks

Short term operations

- Do not fit into the existing or emerging institutional structures (system operation, market rules)

Cost-Effectiveness of Installation

- Tracking arrays of modules gather more energy (perhaps 35%) but add to the cost; one could just increase array area in a fixed mount
- Reduce load demand by conserving energy and efficiency – the rule is that saving a watt in conservation is worth saving three watts in conversion
- Compare installation & utility line extension costs
- Consider adding wind turbine for hybrid energy
- Use fueled generator occasionally to decrease cost of PV
- Modules can be placed vertically on the side of a building at high latitudes or flat on the roof at low latitudes

Flat Roof and Wall Installations

Credit: PV Energy Systems, Inc.

Credit: Pilkington Solar

Conclusion

- Solar PV cells tend to lose capacity due to darkening of the cover glass; use more area than needed at first
- While PV is expensive at $2.0/W to $16/W, the low maintenance costs reduce the overall cost
- Lasts perhaps 30 years and usually warranted for 20 years
- Research similar installations to gain understanding
- Evaluate intended loads closely
- Use spreadsheets to change system parameters readily
- Isolated sites have no alternative power and some assumptions are warranted