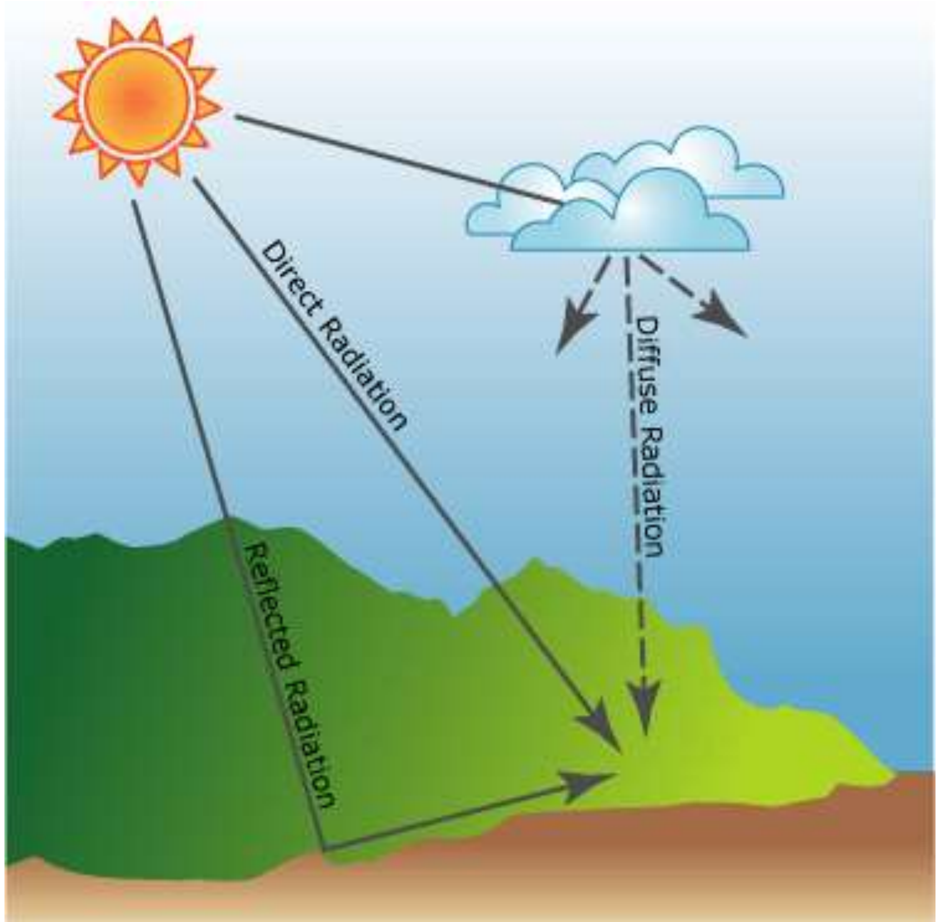
Solar PV Systems

Reference - Chapter 8: GM Master’s Book

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

Solar Insolation

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



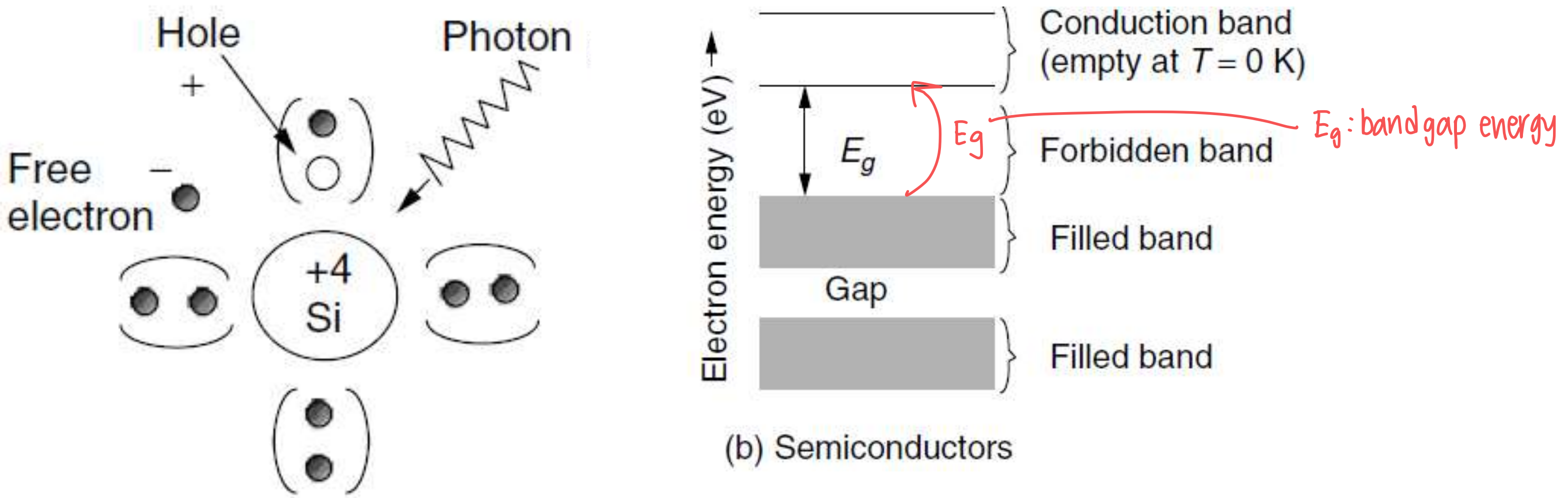
> - *Solar insolation is a measure of solar radiation energy received on a given surface area in a given time*
> - *It is commonly expressed as average irradiance Watts per square meter*

How does a semiconductor material convert sunlight into electricity?

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

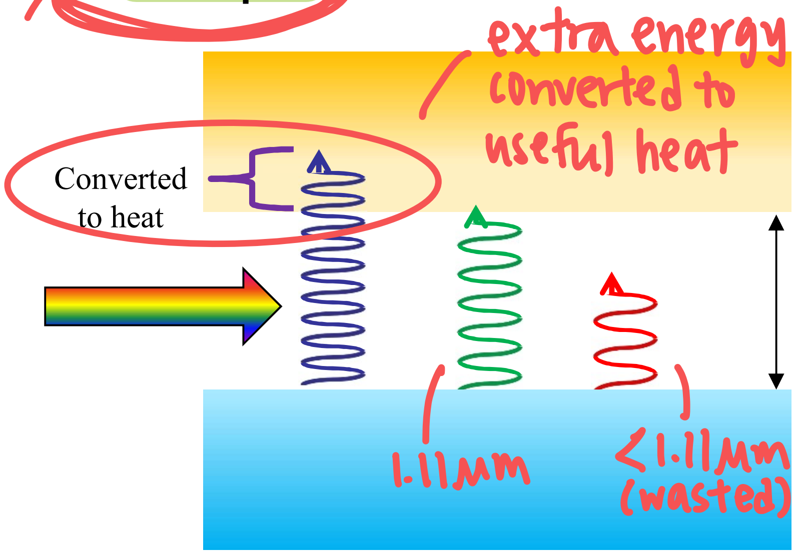


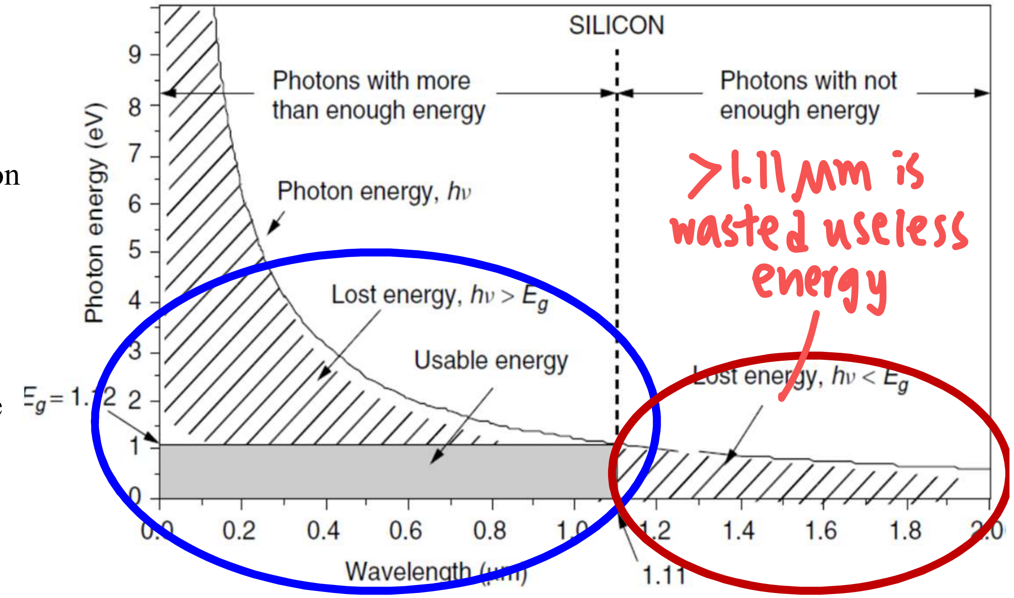
(b) Semiconductors

Refer to Chapter 8: GM Master's book

Bandgap energy for Silicon

- Band gap of silicon : 1.12 eV corresponds to wavelength of 1.11μm

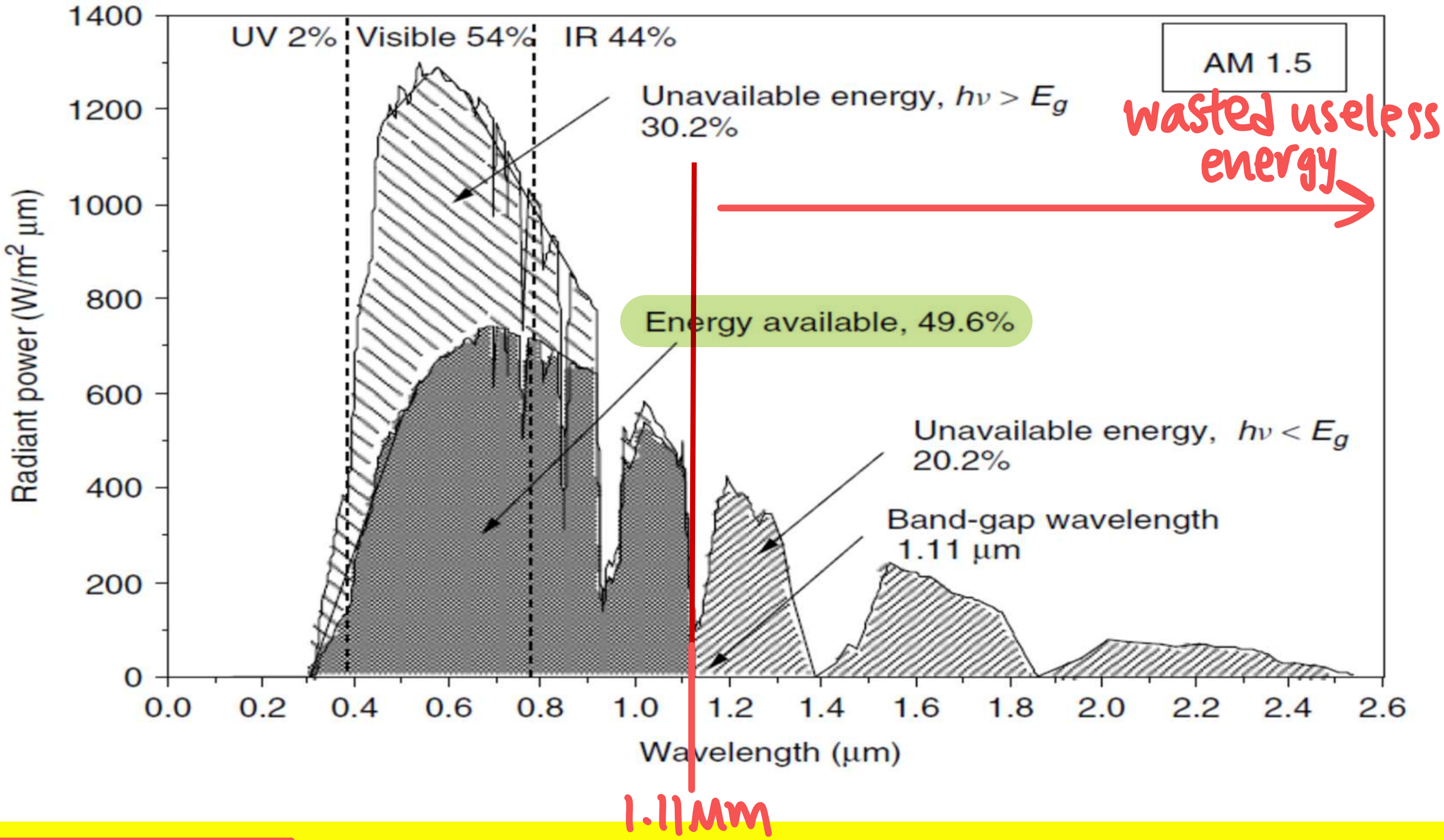




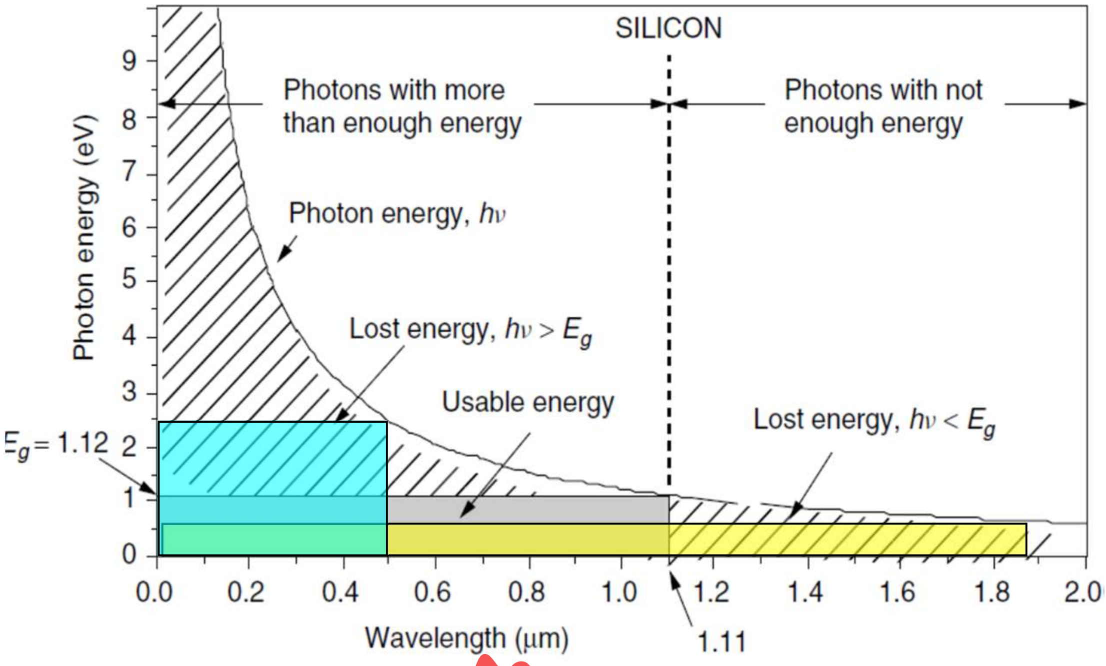
Photons with wavelength < 1.11μm waste their extra energy

Photons with wavelength > 1.11μm cannot send electrons to conduction band

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

the yellow graph

- With larger bandgap, fewer photons cross the gap, which results in higher voltage and lower current

Efficiency of PV Cell

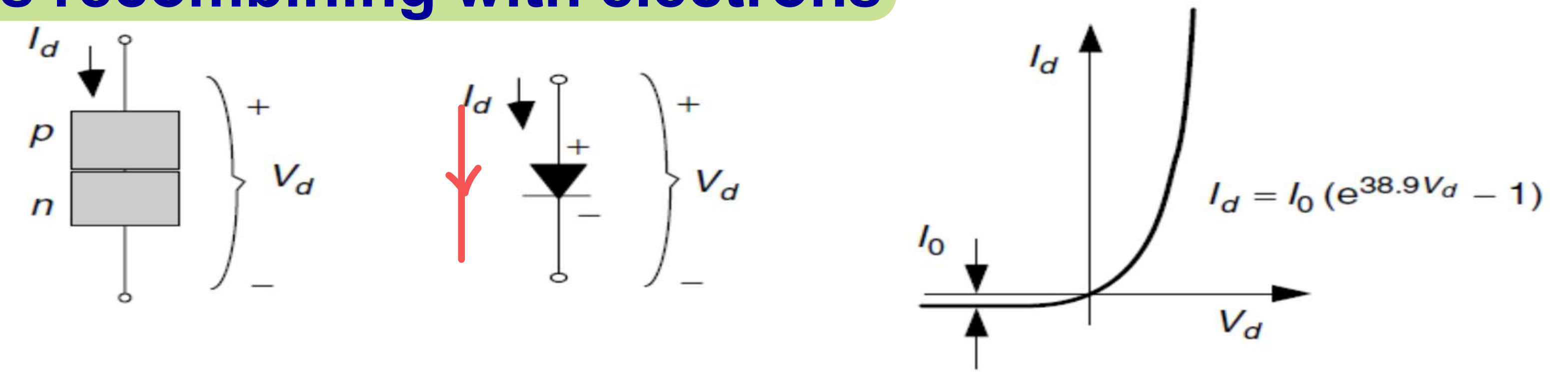
Efficiency drops to 49.6% due to losses caused by photons with **insufficient or too much energy**.

- **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.

P-N junction diode

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

current only flows in 1 direction.



(a) p–n junction diode (b) Symbol for real diode (c) Diode characteristic curve

in K.

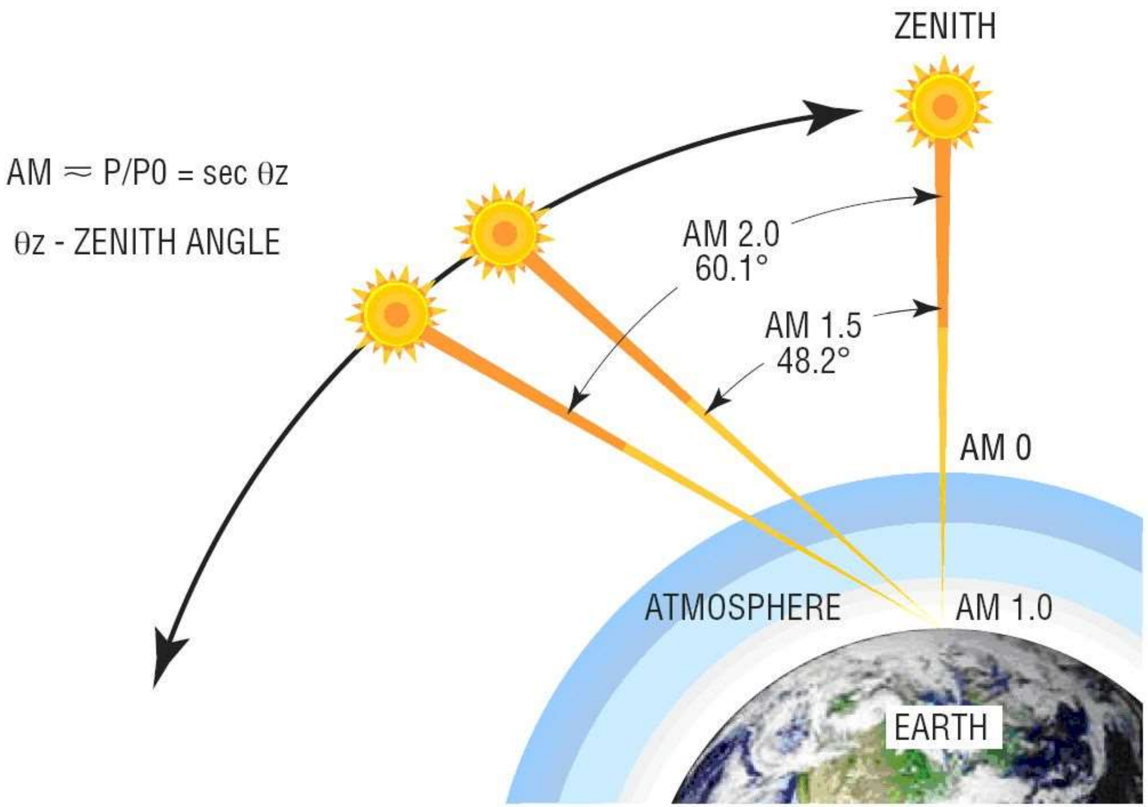
$$I_d = I_0(e^{qV_d/kT} - 1)$$

$$\boxed{I_d = I_0(e^{38.9V_d} - 1) \qquad \text{(at } 25^\circ\text{C)}}$$

where I_d is the diode current in the direction of the arrow (A), V_d is the voltage across the diode terminals from the p-side to the n-side (V), I_0 is the reverse saturation current (A), q is the electron charge (1.602×10^{-19}C), k is Boltzmann's constant (1.381×10^{-23} J/K), and T is the junction temperature (K).

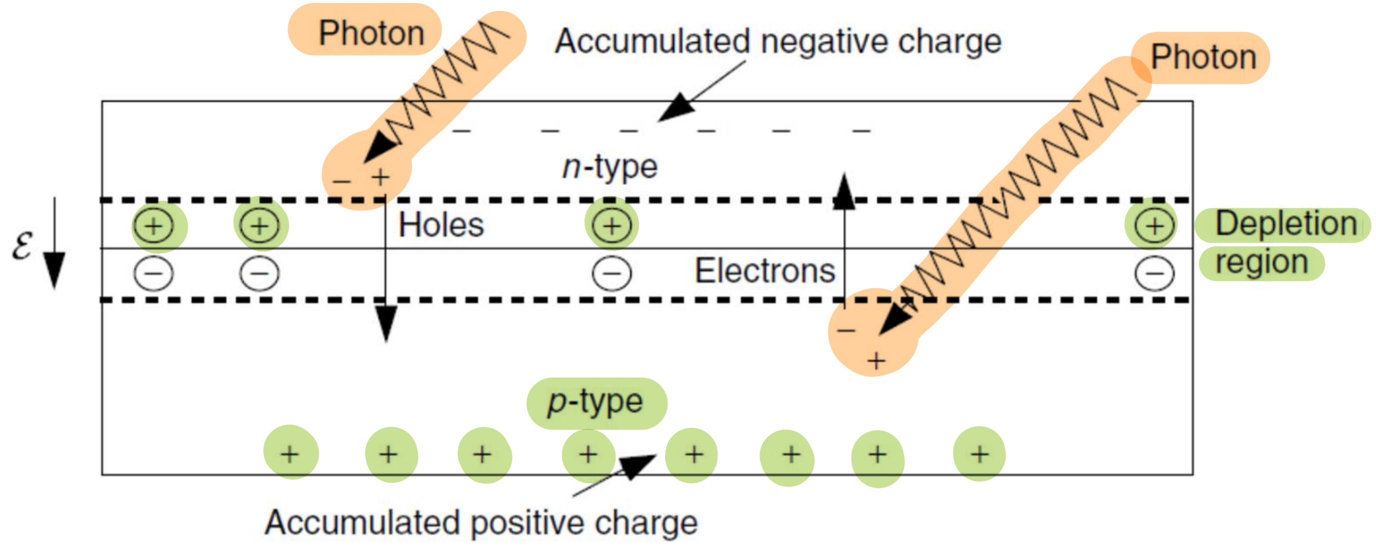
What is meant by "1 Sun"?

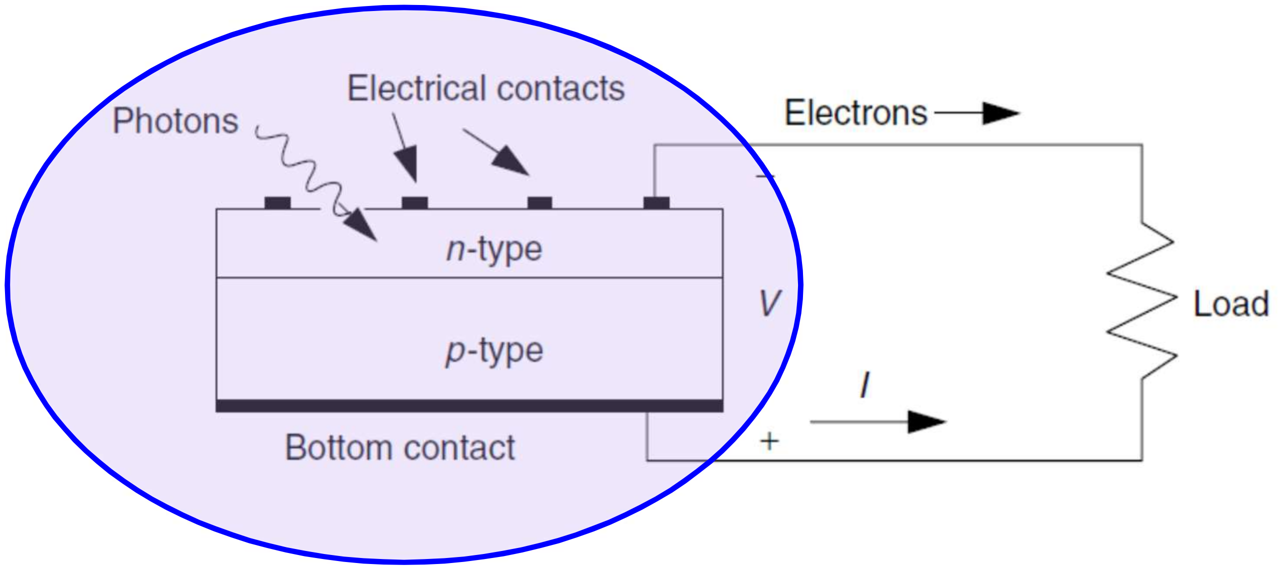
At air mass AM 1.5, 1 sun is defined as equal to $1 kW/m^2$ of irradiance

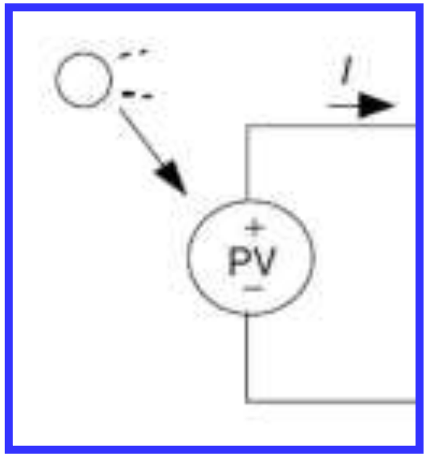


1 sun = $1 kW/m^2$ irradiance

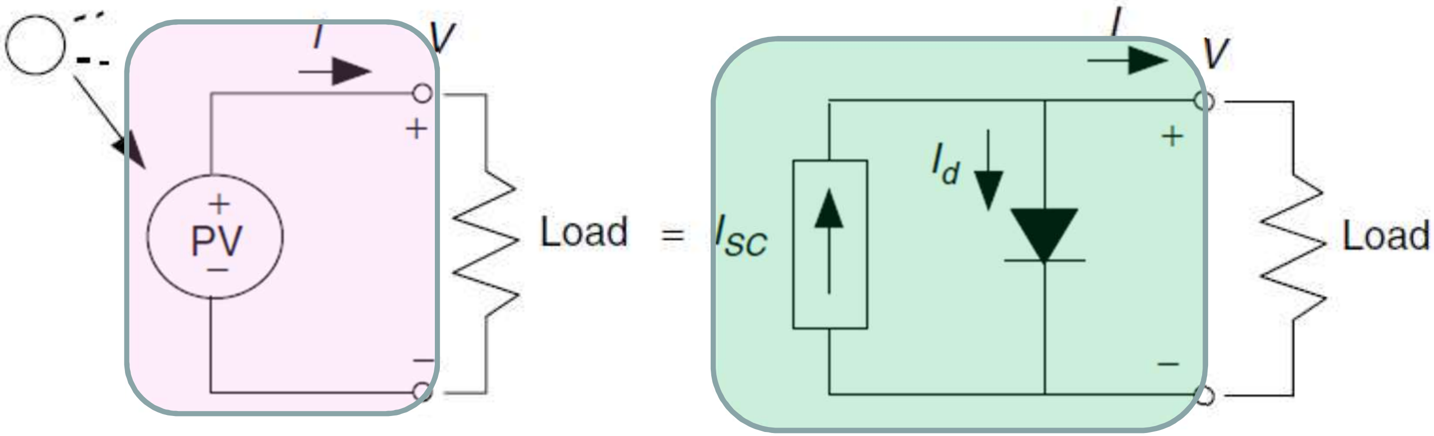
Equivalent Circuit for a Photovoltaic Cell



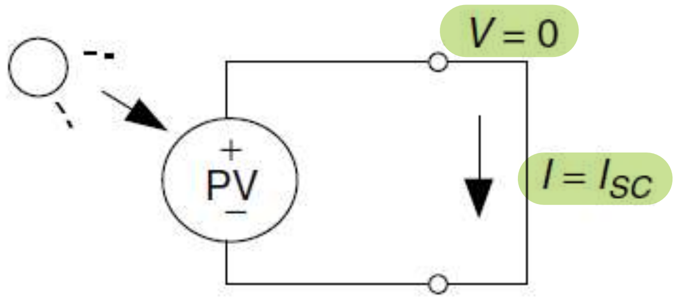




Equivalent Circuit for a Photovoltaic Cell



Voltage and current equations for the PV cell

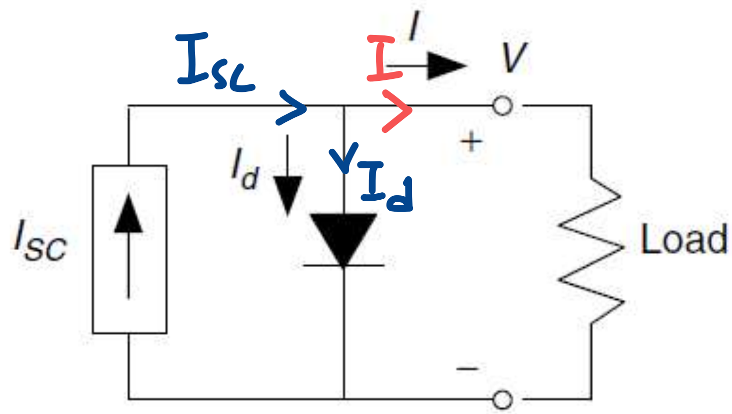


(a) Short-circuit current

Hence the magnitude of ideal current source = I_{SC} — ALL current collected (ideal)

$I_{sc} = I$

Voltage and current equations for the PV cell



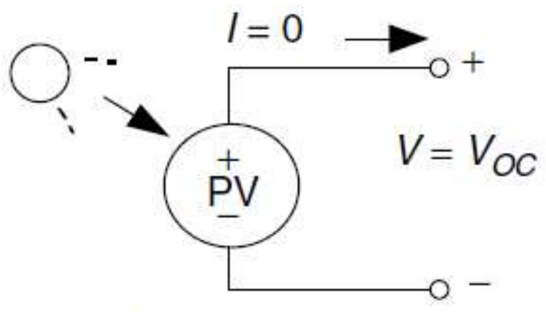
*Current **I***: $I = I_{SC} \underbrace{- I_d}_{\text{current drop due to losses}}$

From the diode characteristics, substituting for I_d:

$$I = I_{SC} - I_0 \left(e^{qV/kT} - 1\right)$$

Voltage and current equations for the PV cell

$$I = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$$



(b) Open-circuit voltage

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:

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

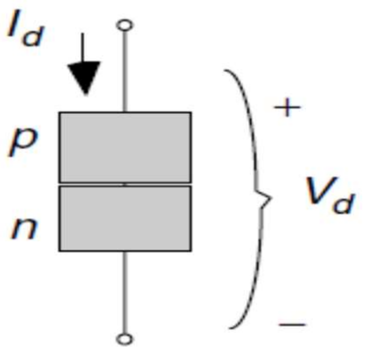
$$\boxed{V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right)}$$

under OPEN CIRCUIT conditions!!

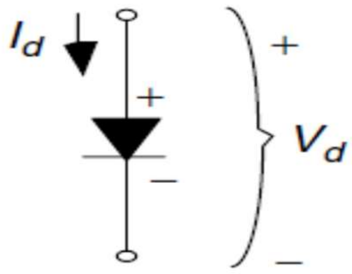
↳ $I = 0$

↳ $V = V_{oc}$

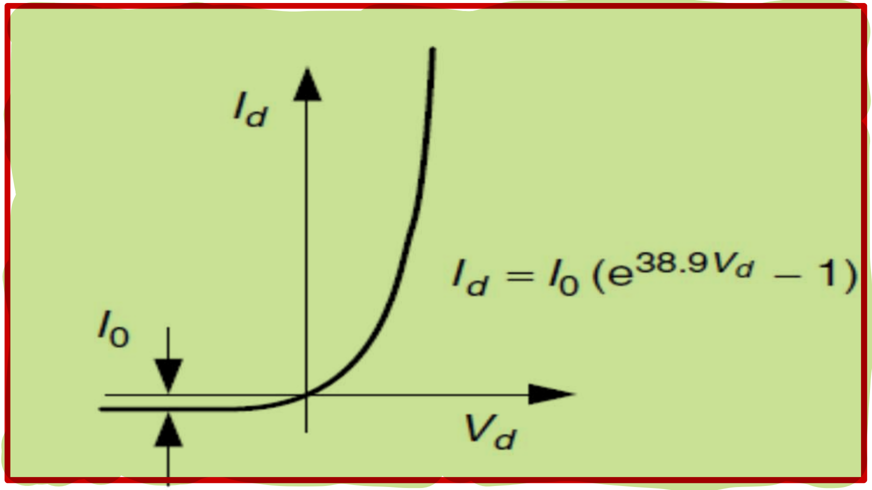
P-N junction diode



(a) p–n junction diode



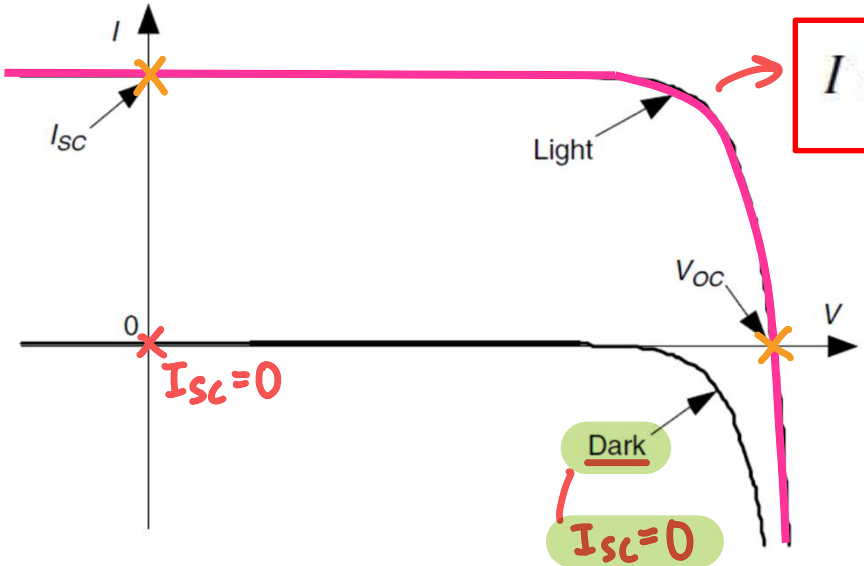
(b) Symbol for real diode



(c) Diode characteristic curve

Photovoltaic current–voltage relationship

- 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}



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

Example **The $I-V$ Curve for a Photovoltaic Cell.** 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 of 40 mA/cm^2 at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

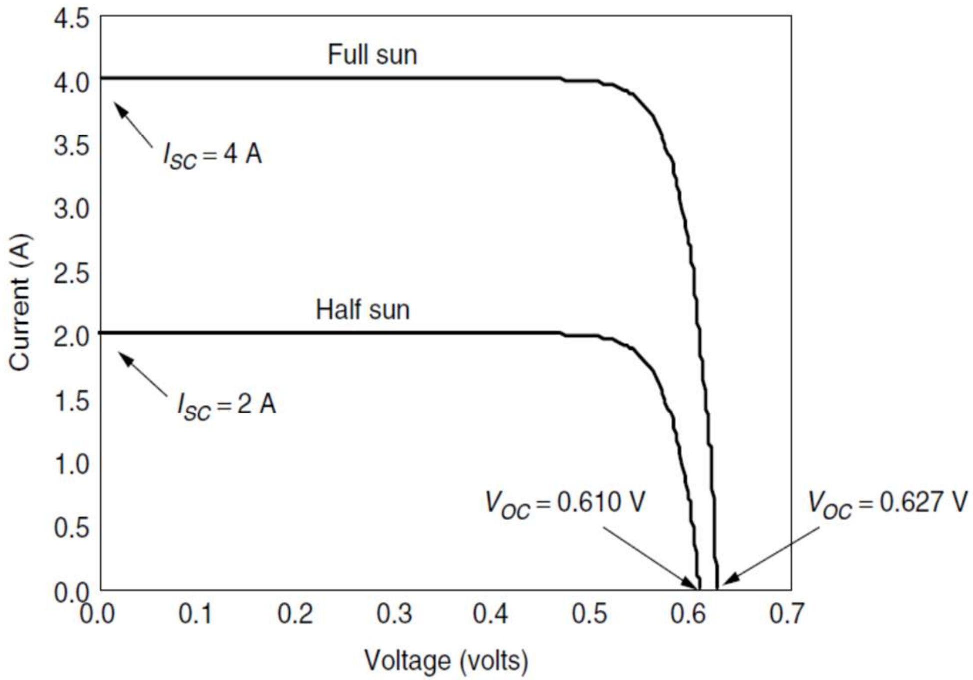
Solution. The reverse saturation current I_0 is 10^{-12} A/cm^2 × 100 cm^2 = 1 × 10^{-10} A. At full sun I_{SC} is 0.040 A/cm^2 × 100 cm^2 = 4.0 A.

$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627 \text{ V}$$

Since short-circuit current is proportional to solar intensity, at half sun $I_{SC} = 2$ A and the open-circuit voltage is

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

$I_{sc} \propto$ sunlight intensity

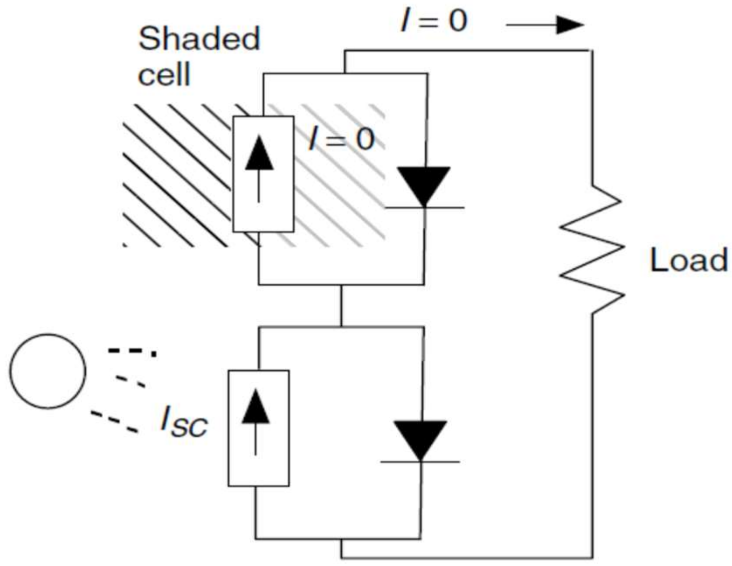


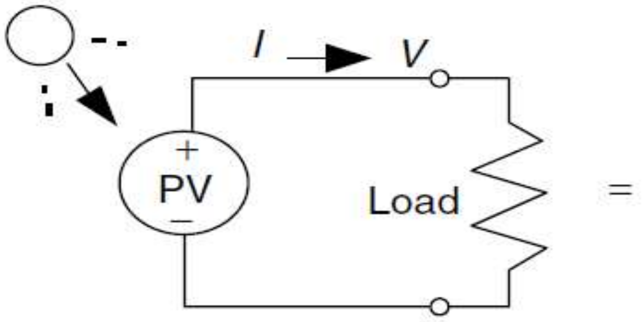
A more accurate Equivalent Circuit for a PV Cell

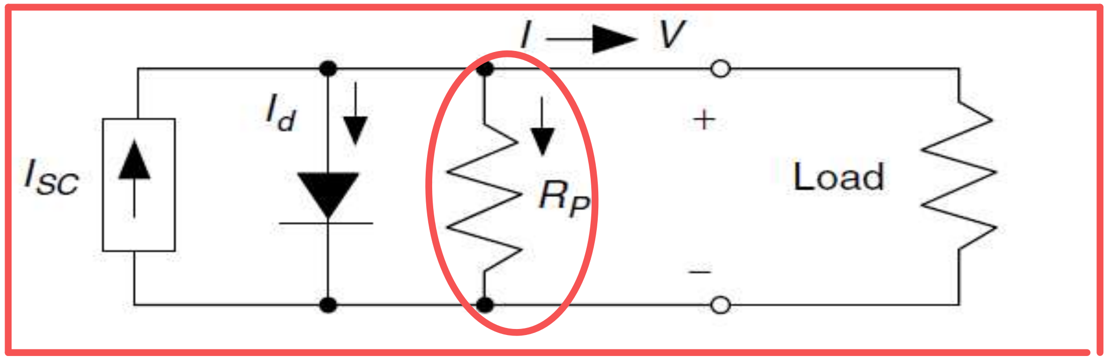
Equivalent circuit of a PV cell…

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.





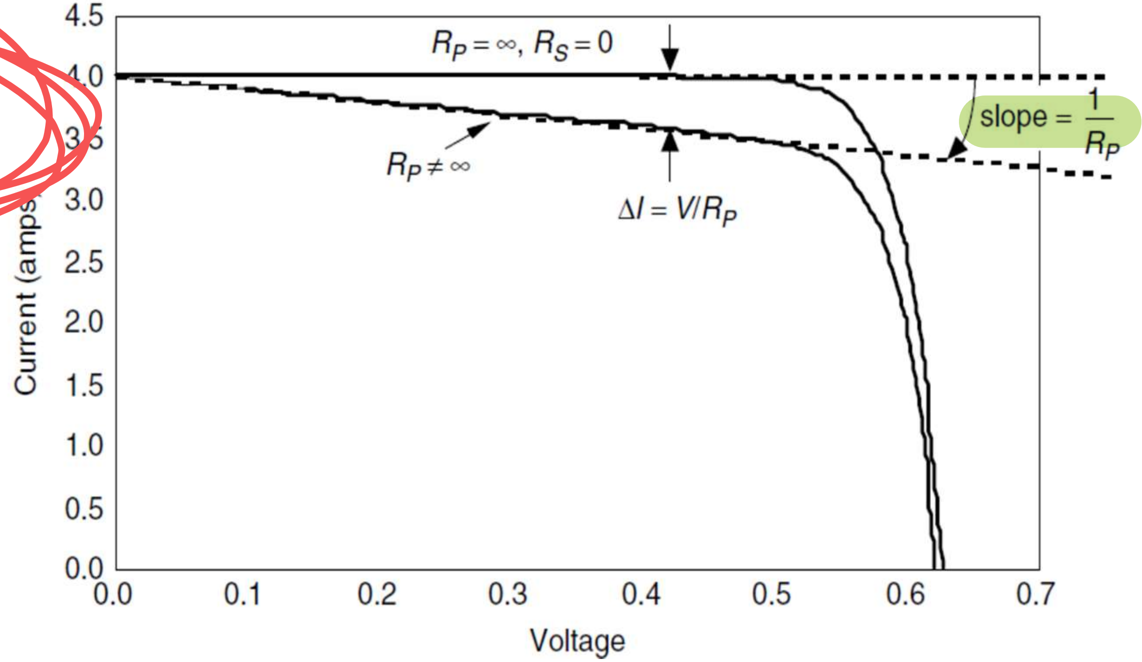


$$I = (I_{SC} - I_d) - \frac{V}{R_p}$$

Simple PV equivalent circuit with an added parallel resistance

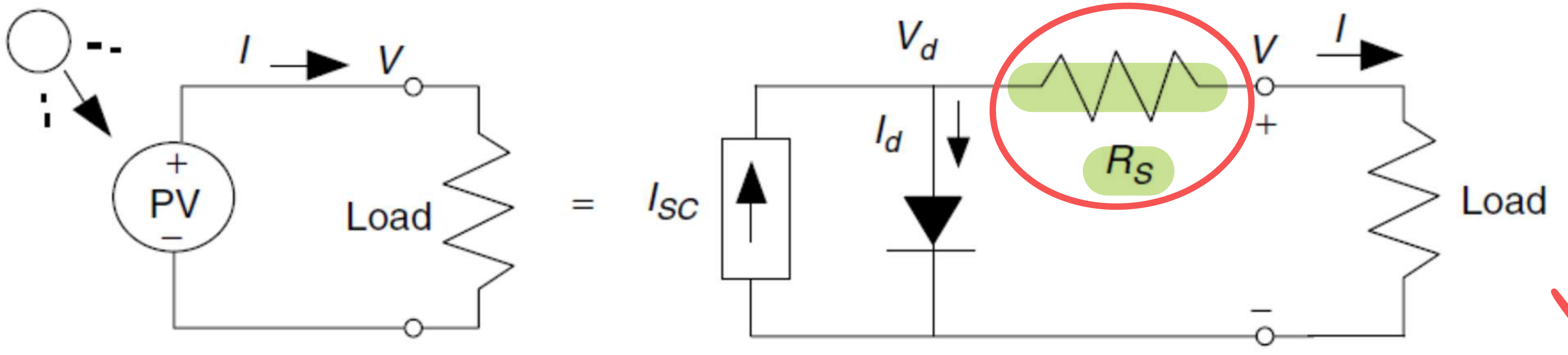
- Modifying the idealized PV equivalent circuit by adding parallel resistance causes the current at any given voltage to drop by V/R_P .

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



- A more accurate equivalent circuit includes series resistance to incorporate other losses
- **If only series resistance is included,**

$I \cdot R_S$



V_d

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

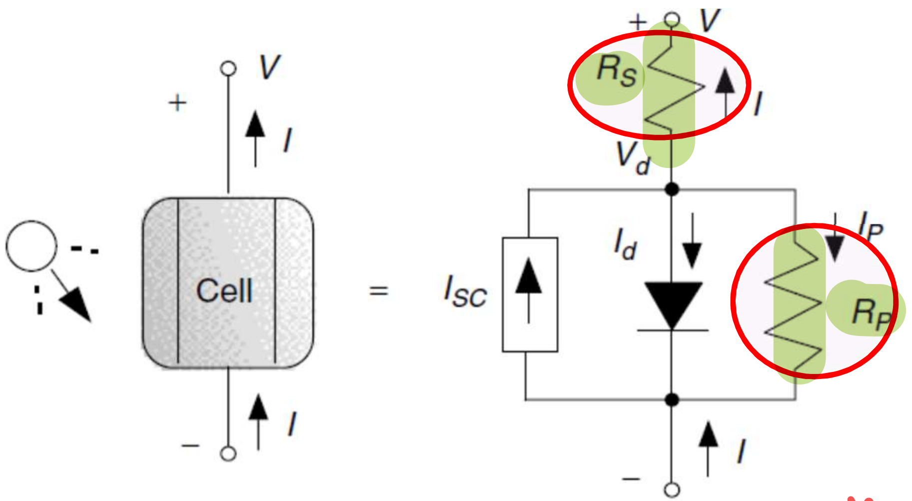
Modified to include R_s gives $V_d = V + I \cdot R_S$

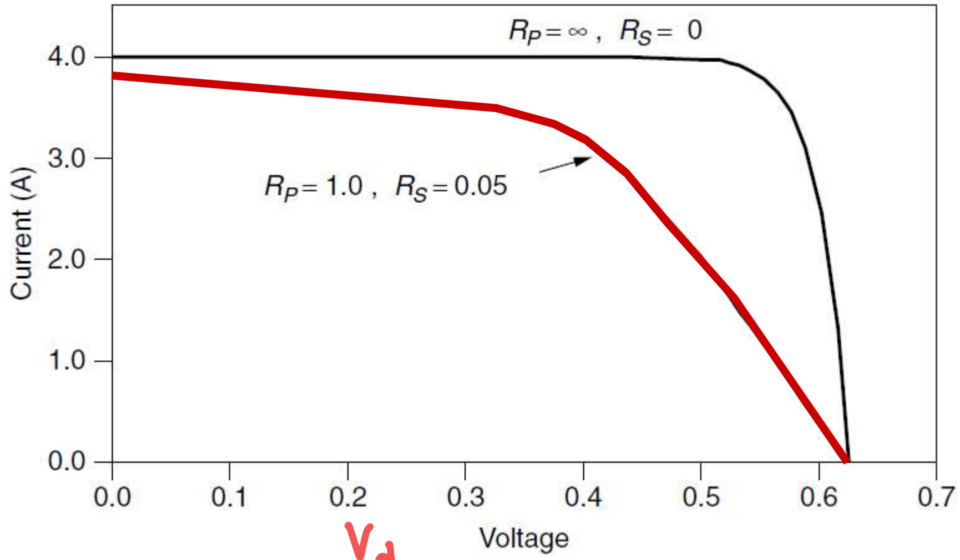
to give

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

Equivalent circuit of a Solar Cell

- A more accurate equivalent circuit includes both series and parallel resistance





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

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

Under the standard test conditions of 25^o cell temp,

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

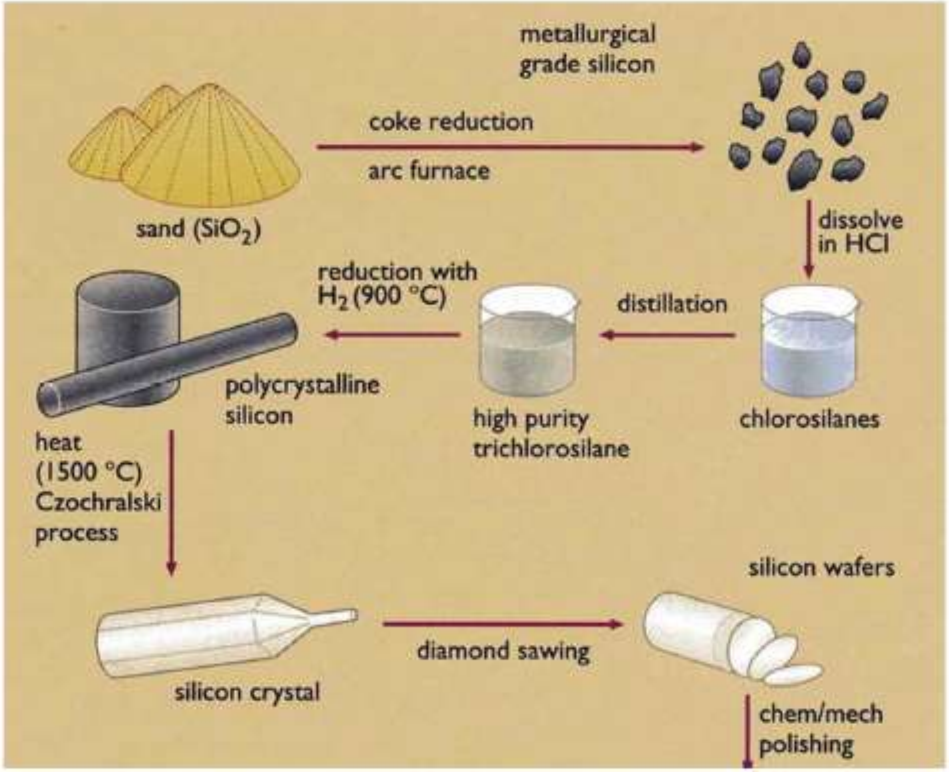
How Solar Cells are made?

Solar Cell Construction

- Materials
  - Crystalline Silicon or Gallium Arsenide (more expensive)
- Grown into large single-crystal ingots
- Sawed into thin wafers

Czochralski Process

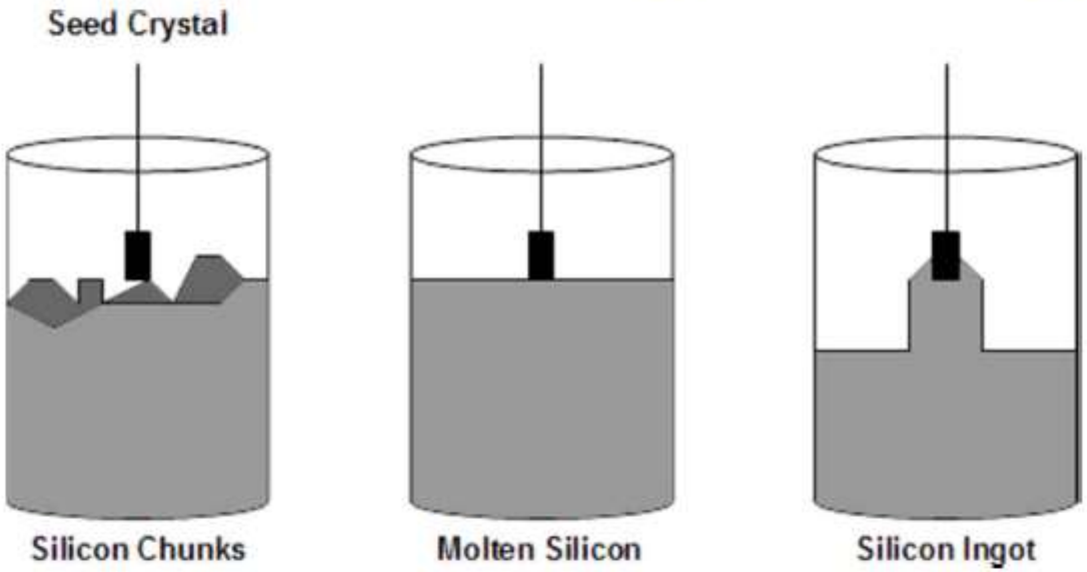
↳ wafers are sliced up to 20-30cm wide, 2m long, few hundreds kg



- 2 wafers are bonded together (p-n junction)
- Wafers grouped into panels or arrays

http://en.wikipedia.org/wiki/Solar_panel

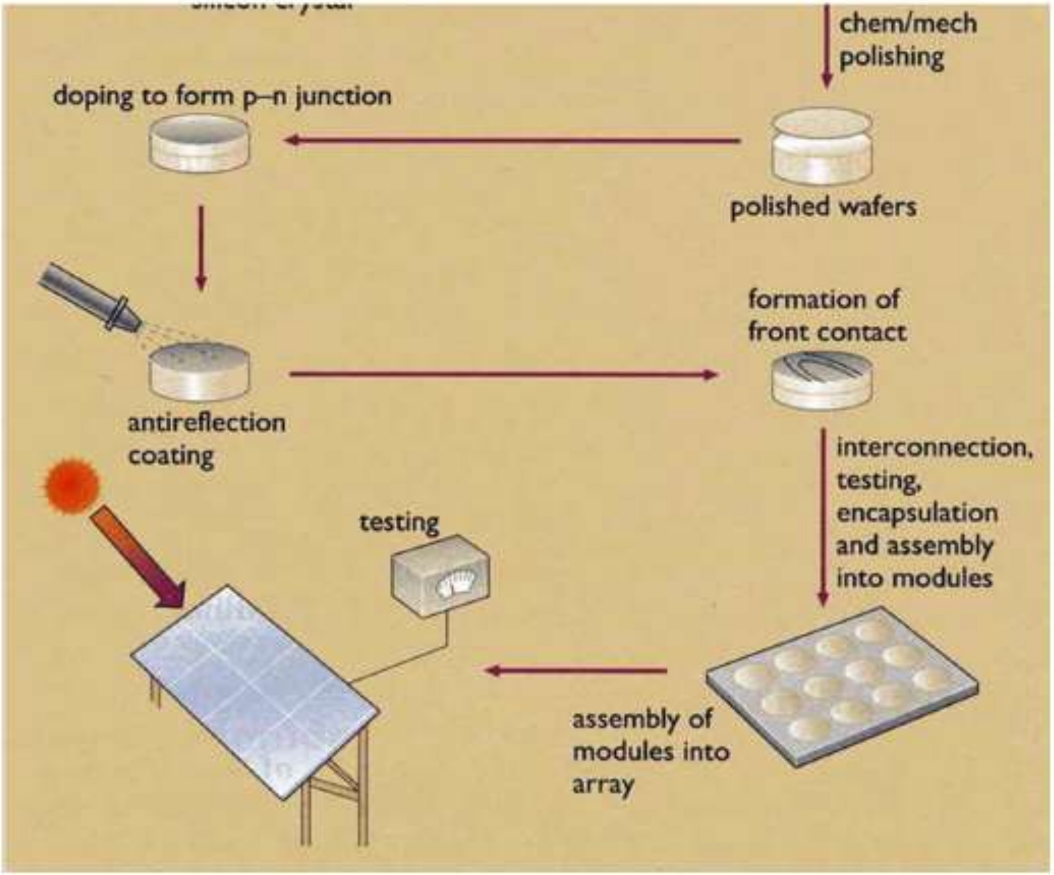
Growing Silicon Ingots

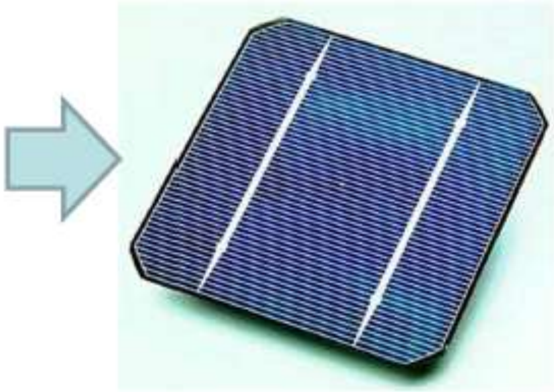


Czochralski Process

Creating PV Cells

generates a lot of CO_2 & emissions in the making process ..

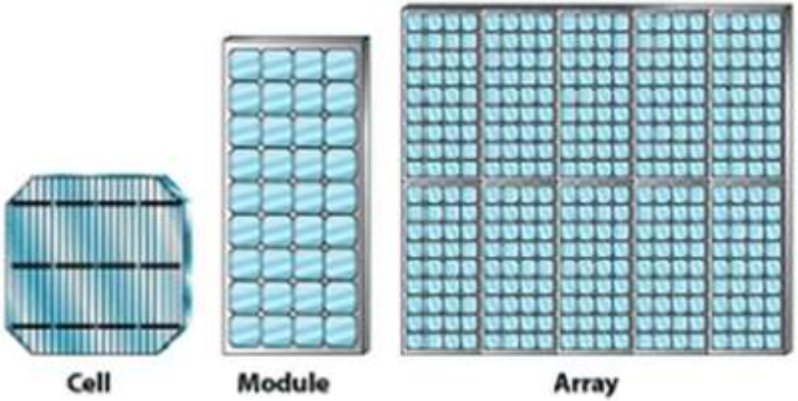


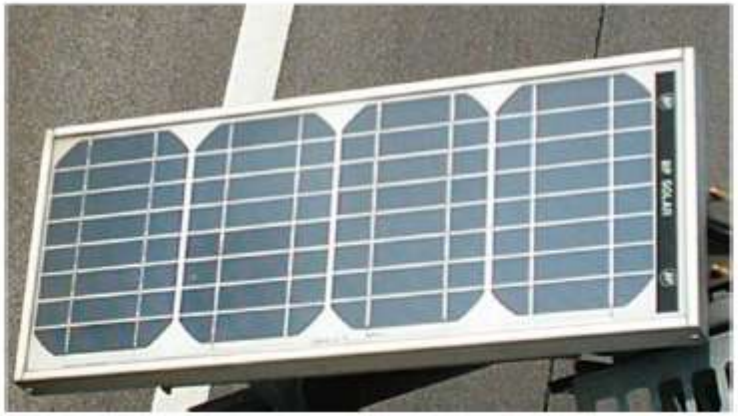


Solar PV Systems

~36x cells

- **Cells** are the building block 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 PV generating system

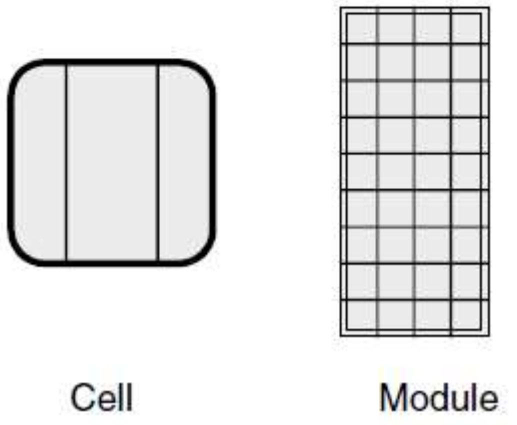




Solar panel by BP Solar at a German autobahn bridge

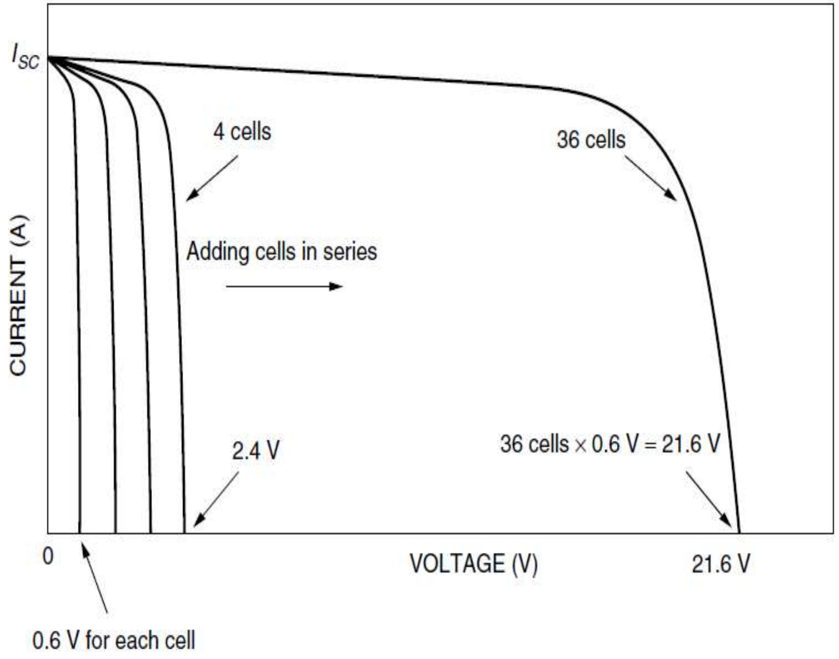
From cells to a module

- 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



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

n=no. of cells



Voltage and current from a PV module

Example: A PV module is made up of 36 identical cells, all wired in series.

With 1-sun insolation (1 kW/m^2), each cell has short-circuit current $I_{SC} = 3.4\ A$

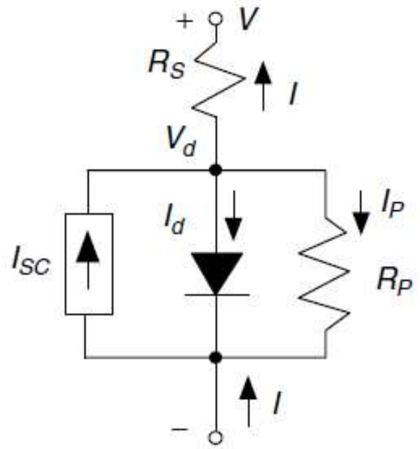
and at 25°C its reverse saturation current is $I_0 = 6 \times 10^{-10}\ A$.

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

V_d



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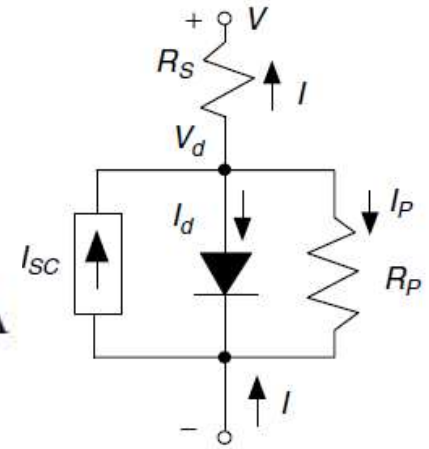


Using the given data, and $V_d = 0.5$V,

$$I = I_{SC} - I_0(e^{38.9V_d} - 1) - \frac{V_d}{R_P}$$

$$= 3.4 - 6 \times 10^{-10}(e^{38.9\times 0.50} - 1) - \frac{0.50}{6.6} = 3.16\text{ A}$$

For a 36-cell module, voltage produced

$$V_{\text{module}} = n(V_d - IR_S) = 36(0.50 - 3.16 \times 0.005) = 17.43\text{ V}$$

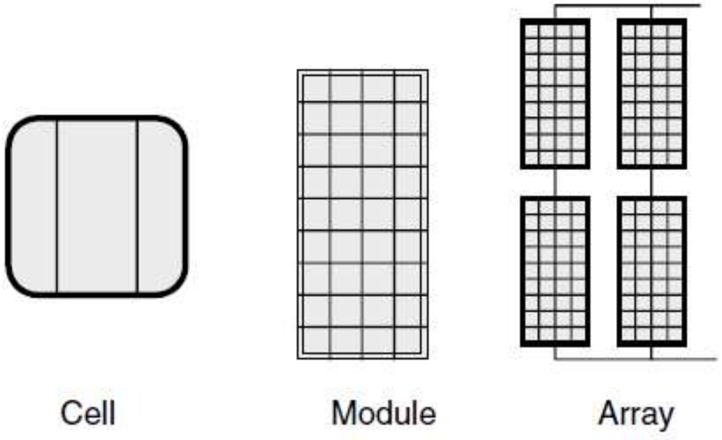
Power delivered is therefore

$$P(\text{watts}) = V_{\text{module}}\, I = 17.43 \times 3.16 = 55.0\text{ W}$$

$$\eta = \frac{\text{output P}}{\text{input P}}$$

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

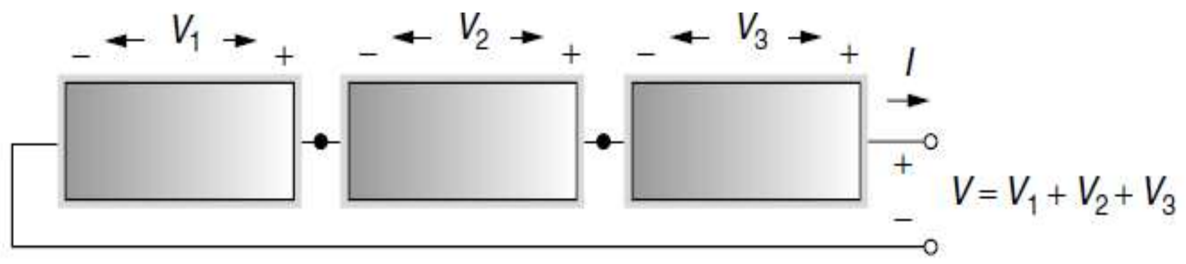


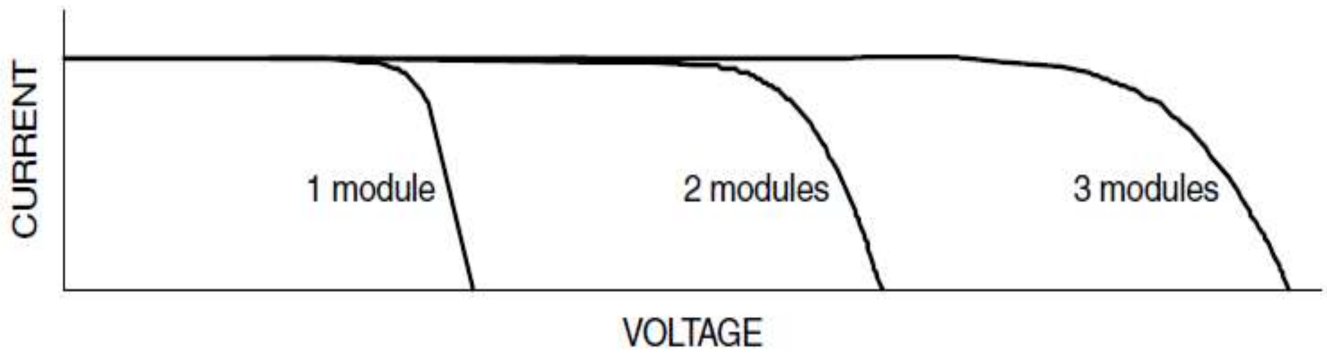
series : ↑V

parallel : ↑I

Modules connected in series

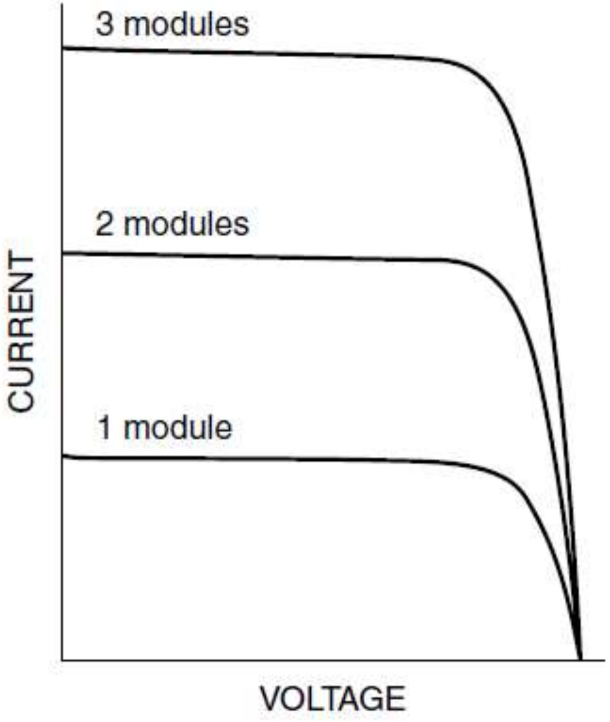
- The voltages produced are added
- Same current flows through all

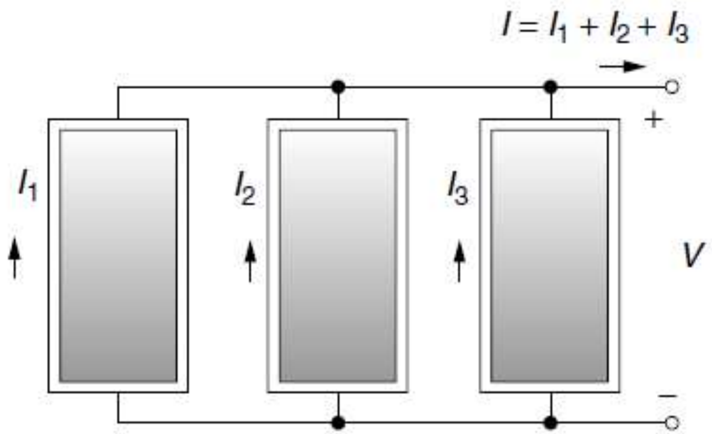




Modules connected in parallel

- Currents add, while voltage remains the same

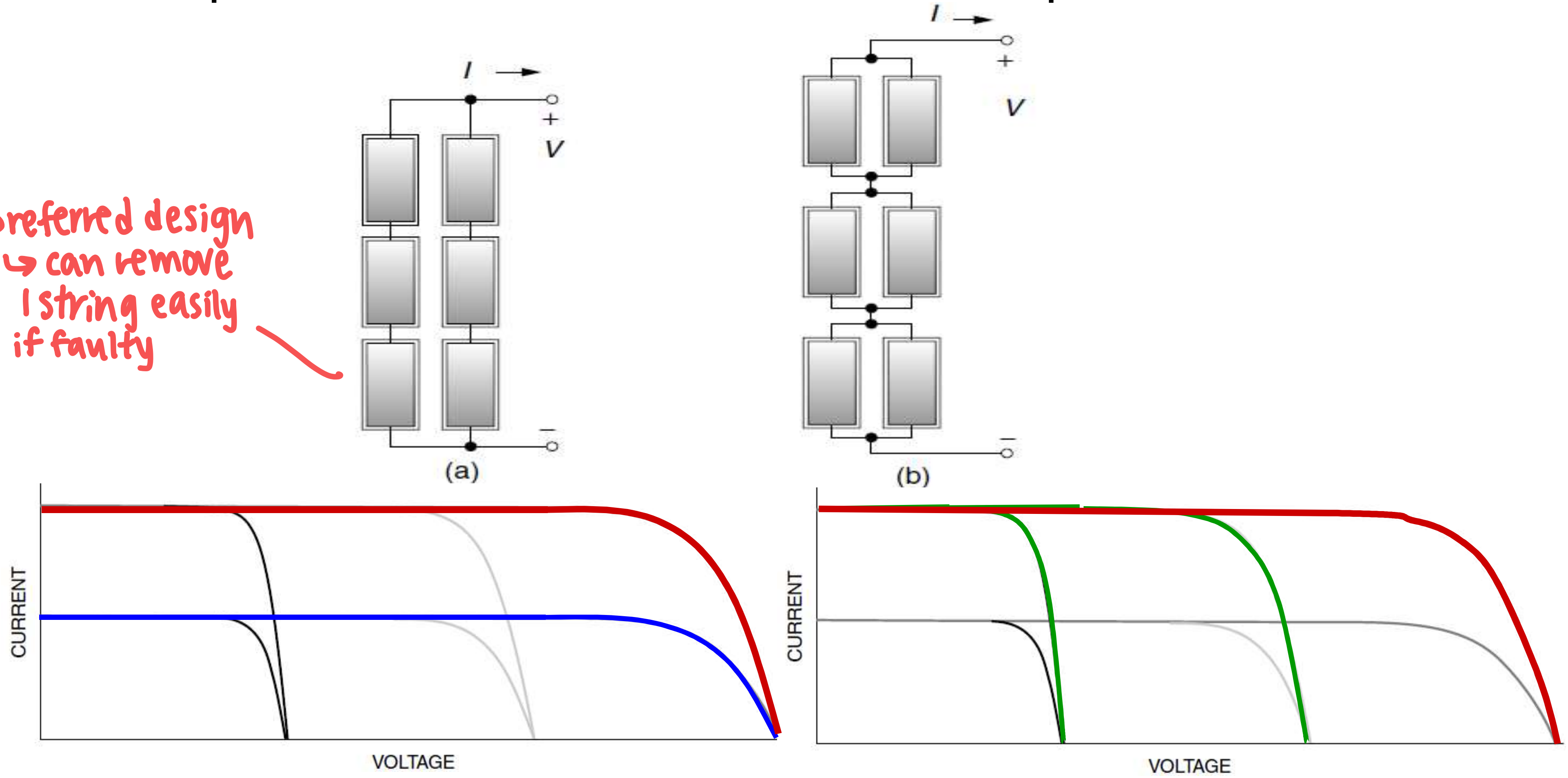




Modules in series-parallel configuration

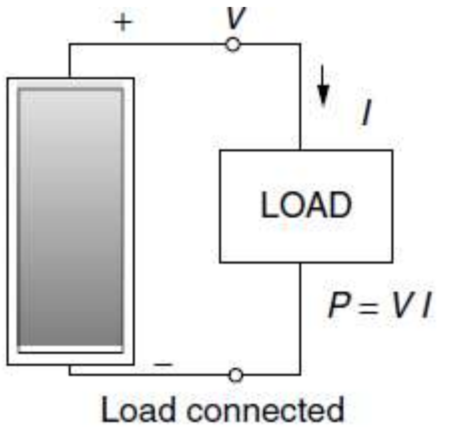
- Example: Three modules in series, two in parallel

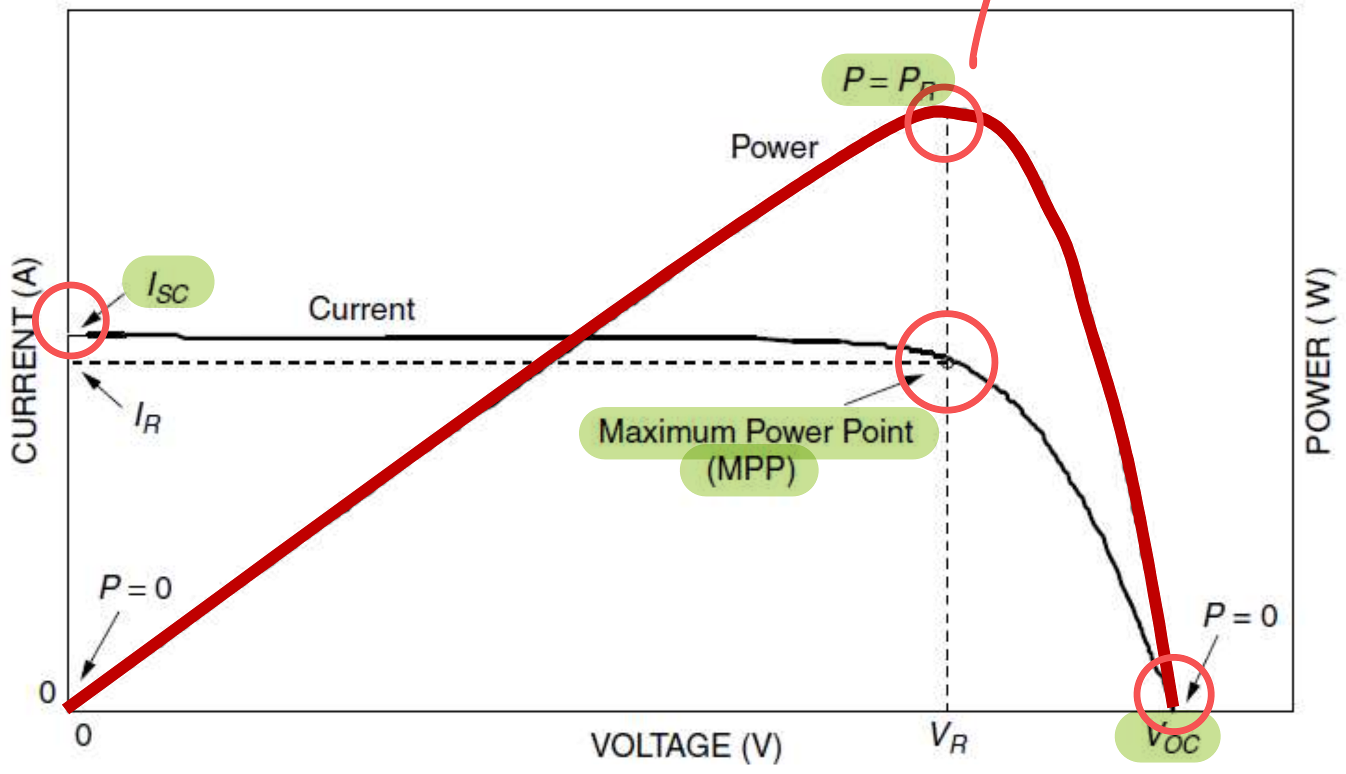
preferred design
↳ can remove 1 string easily if faulty



Voltage, Current and Power Curves

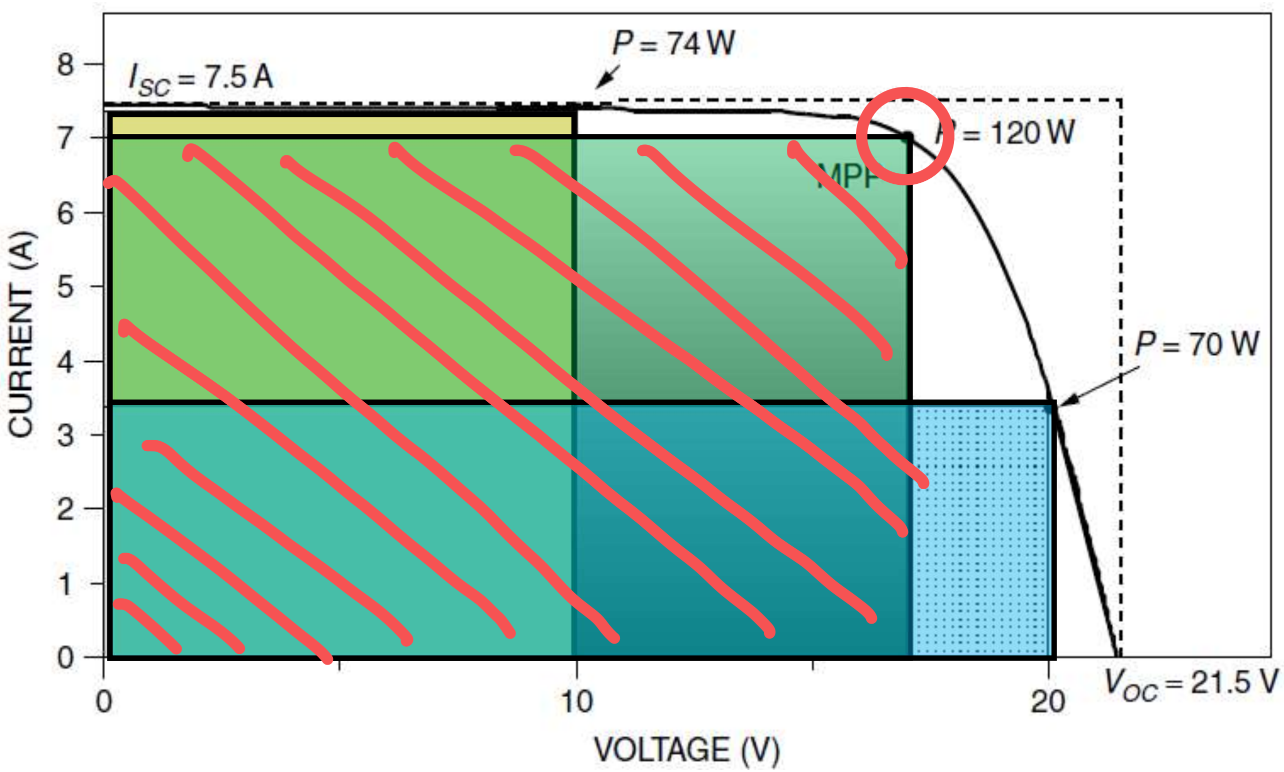
rated power operating at MPP!





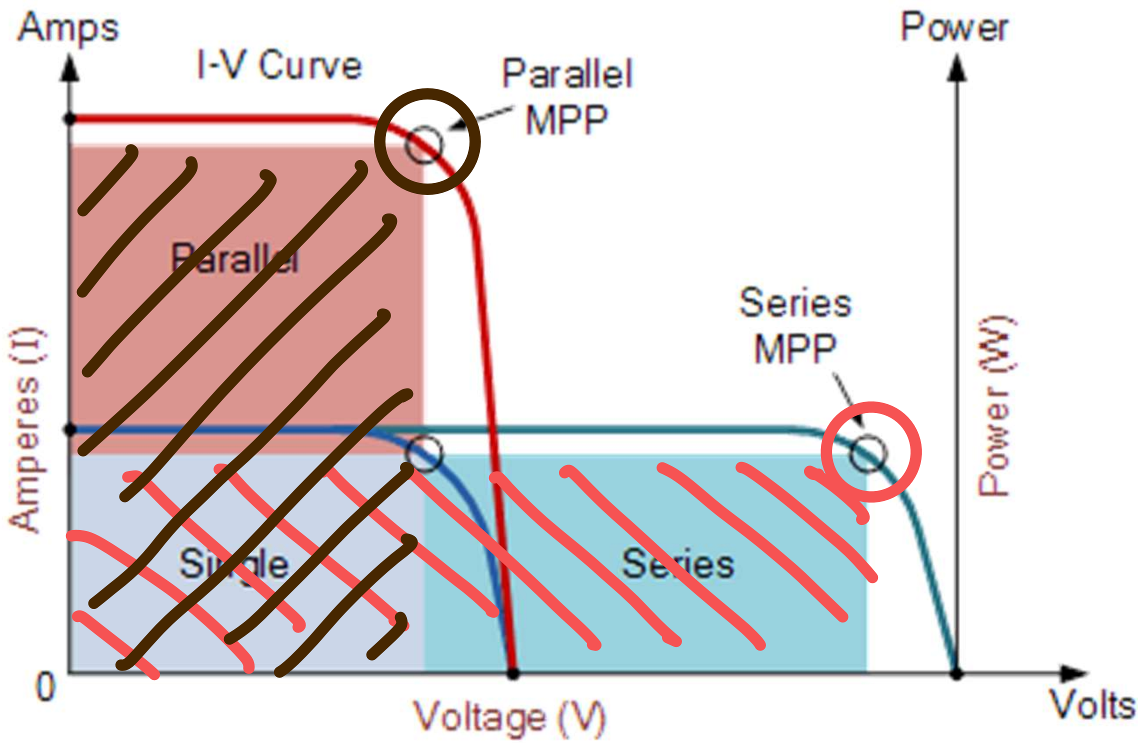
Maximum Power Point (MPP)

- 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



- **MPP corresponds to the biggest rectangle that can fit beneath the $I-V$ curve**

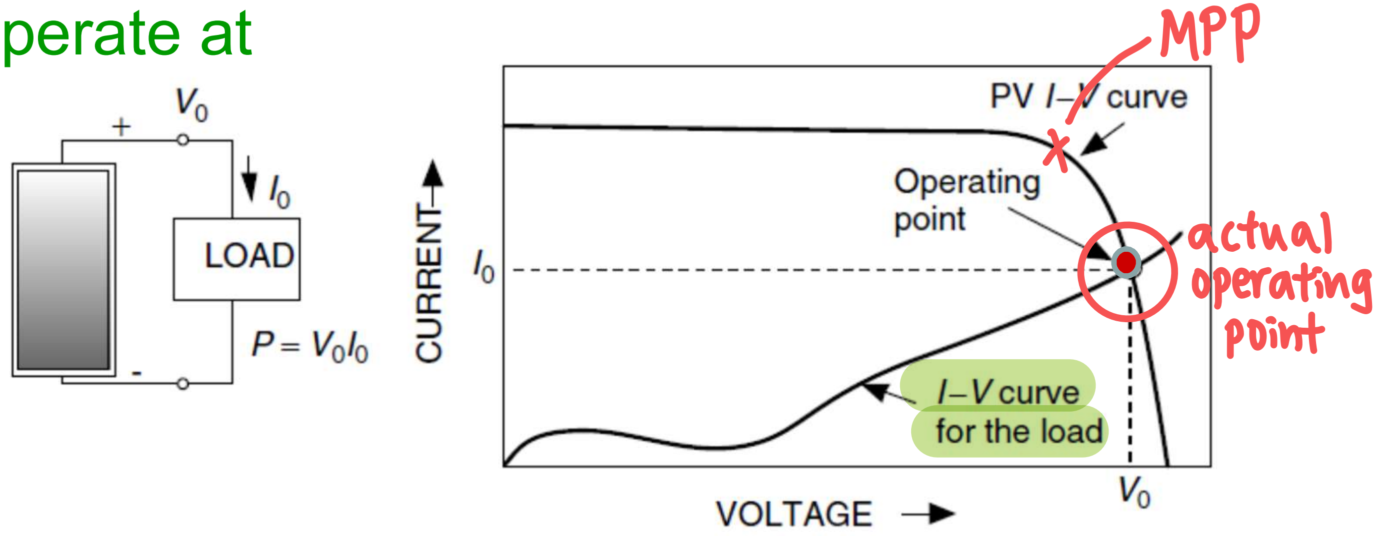
Maximum Power Point (MPP)



What factors can influence the performance of a Solar PV Cell?

Current-Voltage Curve for Load

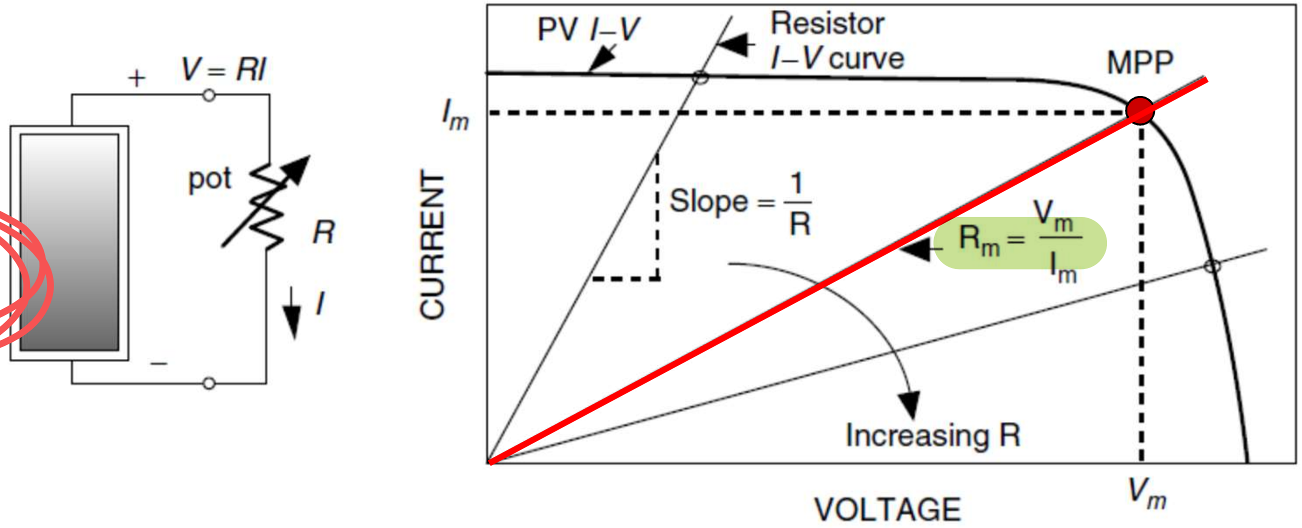
- **Operating point** – intersection of curves where the system will finally operate at



Resistance corresponding to maximum power:

$$R_m = \frac{V_m}{I_m}$$

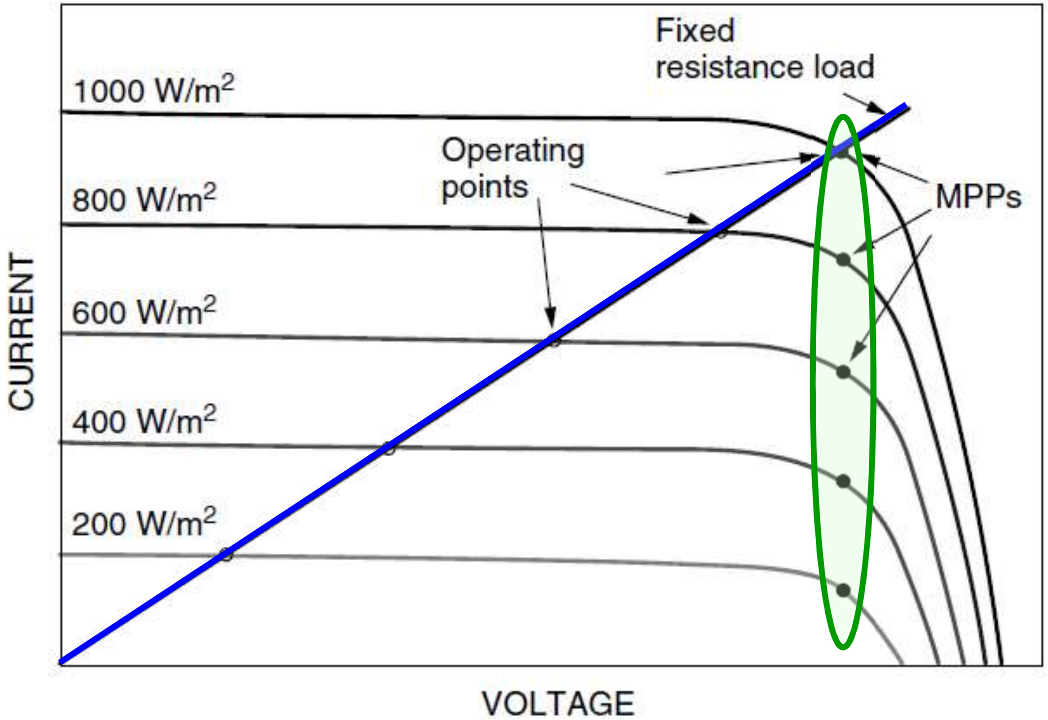
↳R at MPP



Efficiency of a PV module with fixed resistance load

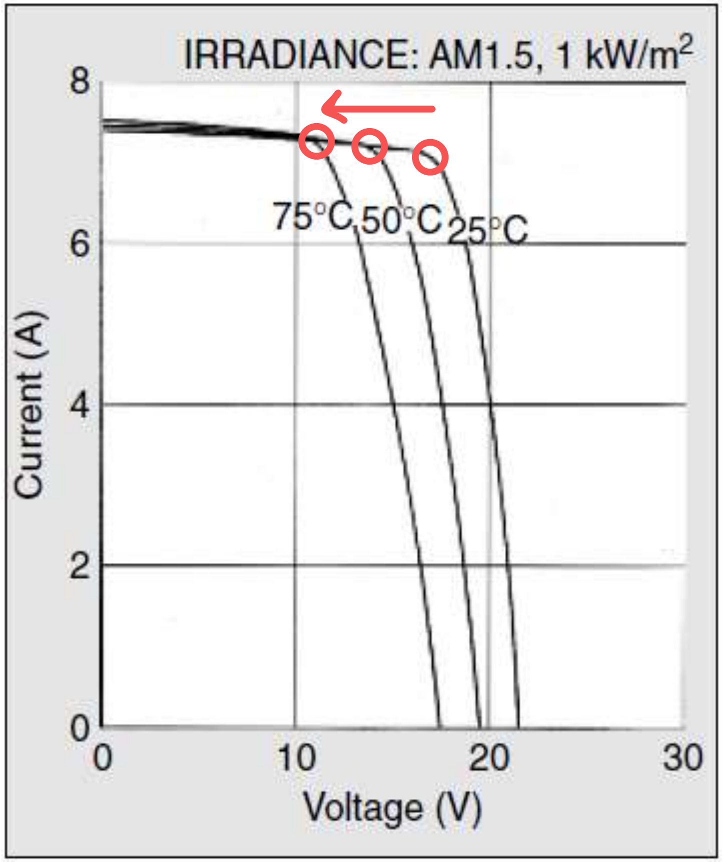
- The best value of resistance for maximum power transfer under 1-sun, 25^{o}C, 1.5 AM conditions would be V_R/I_R — hence varying R would be good
- **The operating point however, slips off MPP if resistance is fixed**

Max power point tracker (MPPT) ensures the module operates at highest efficiency point



Effect of temperature

- **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 deg C**

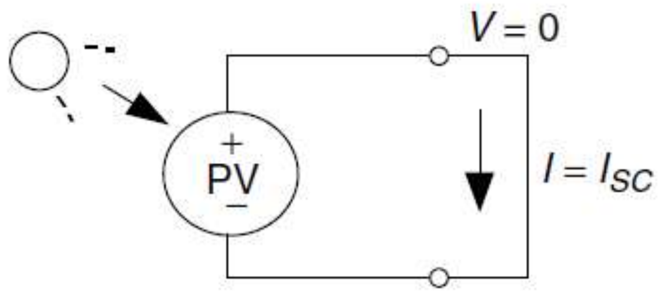


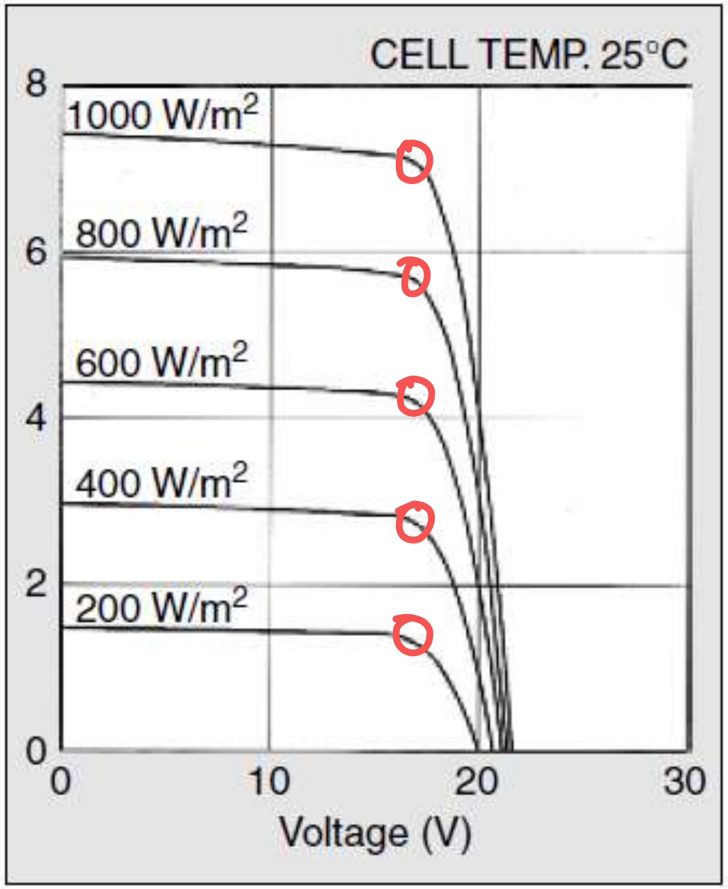
Efficiency drops as the temperature increases

$\uparrow T, \downarrow \eta$

Effect of Insolation

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

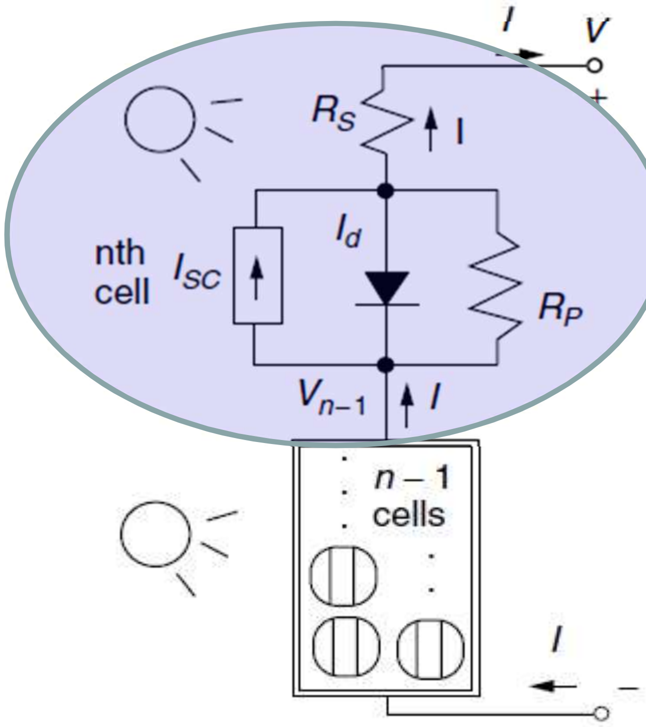




$I_{sc} \propto$ insolation

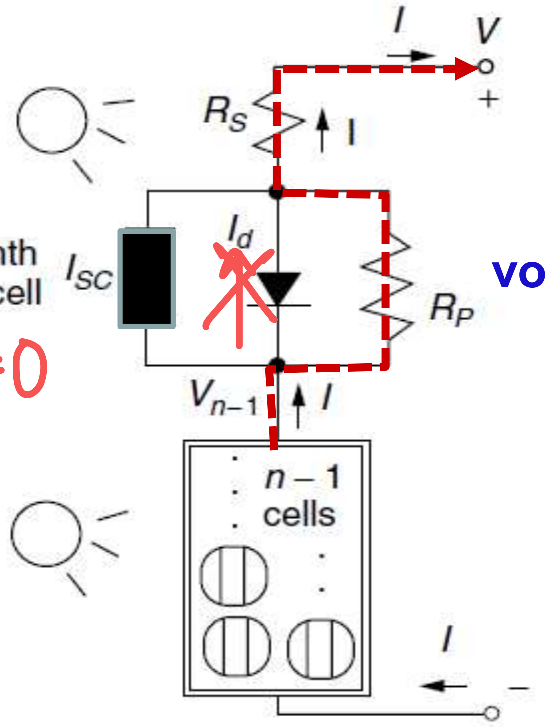
$\downarrow$ insolation, $\downarrow I_{sc}$

Effect of Shading



(a) All cells in the sun

Effect of Shading



$I_{SC} = 0$

shading: $I_{sc}=0$

voltage drop = I R_p

(a) All cells in the sun

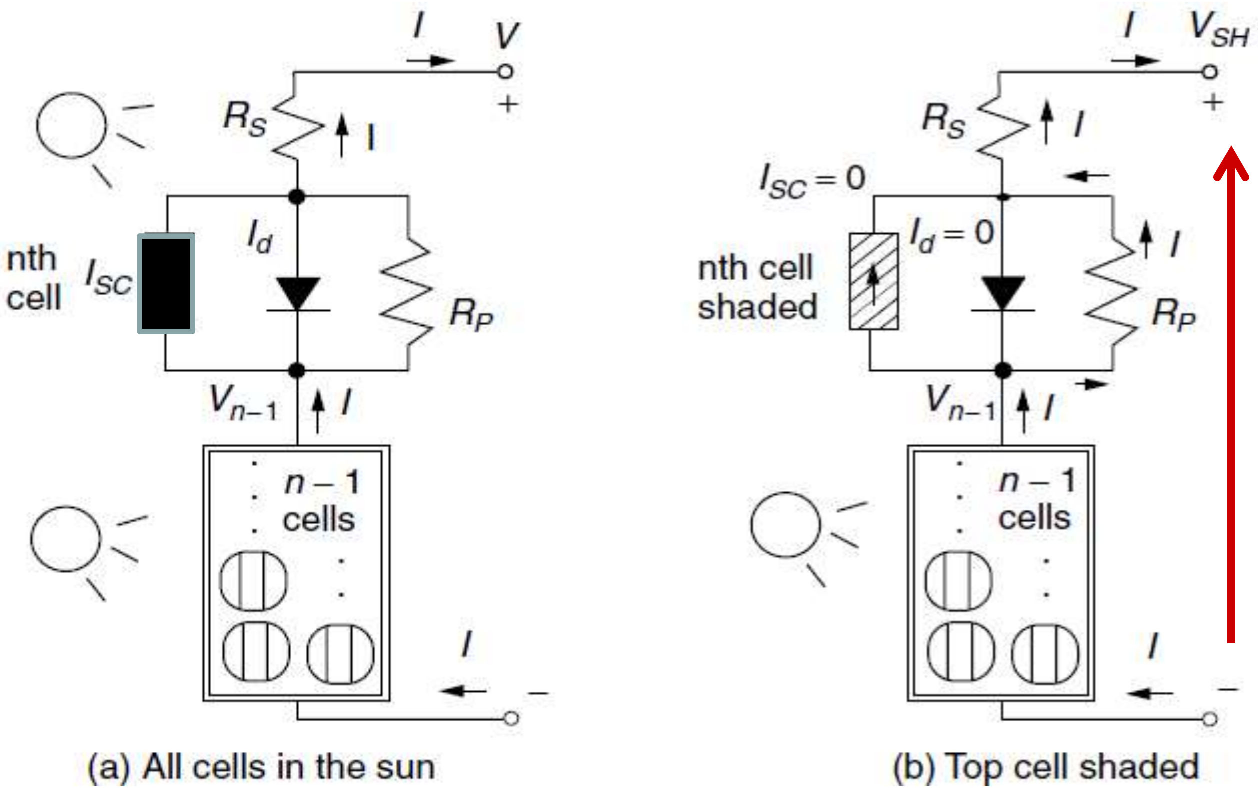
$I_{sc}=0$

- 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

I cannot pass through!

$I_d=0$

Effect of Shading

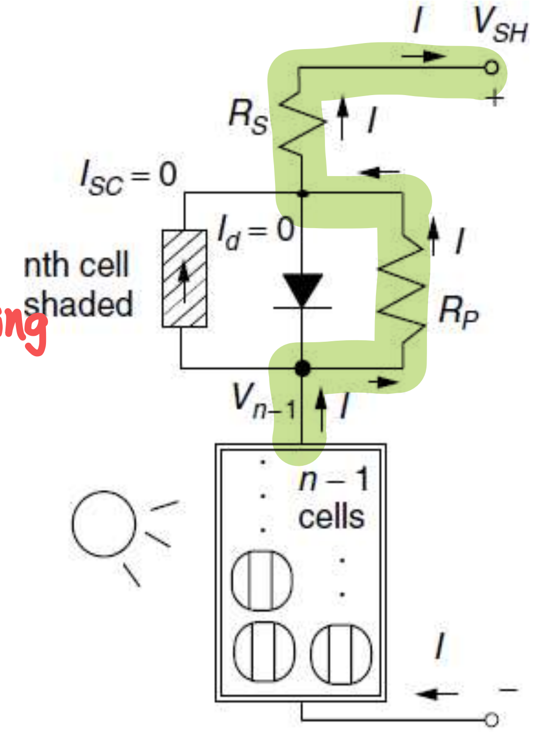


- Even if one cell is shaded, since its short circuit current is now zero, the main current I causes the diode to be reserve biased, hence $I_d = 0$ and total voltage is reduced by IR_p

Effect of shading

Output voltage of the module becomes

$$V_{SH} = V_{n-1} - \underbrace{I(R_P + R_S)}_{\text{V drop due to shading}}$$



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

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

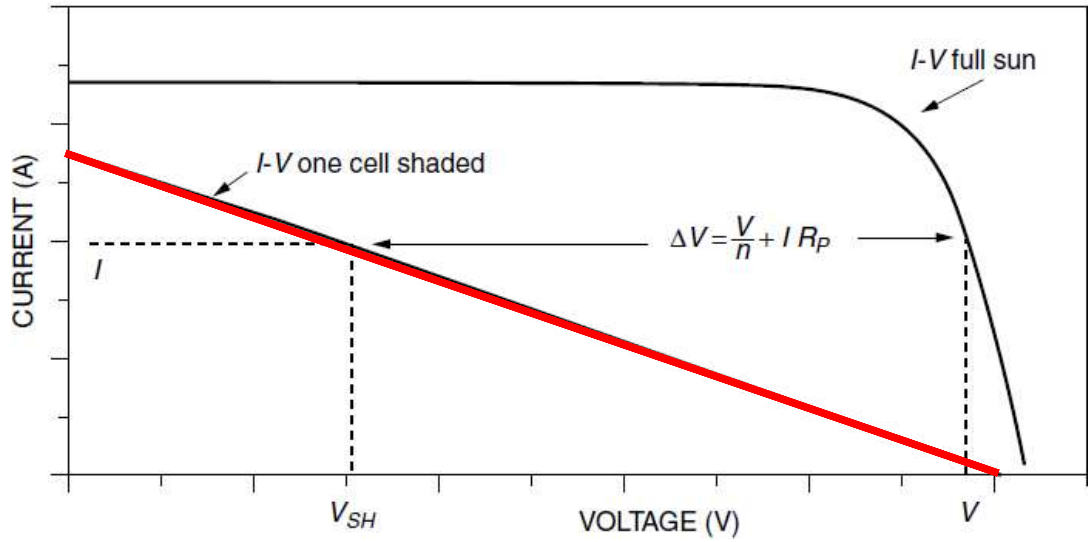
The **drop in voltage** due to shading of one cell:

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

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

Since R_s is very small,

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



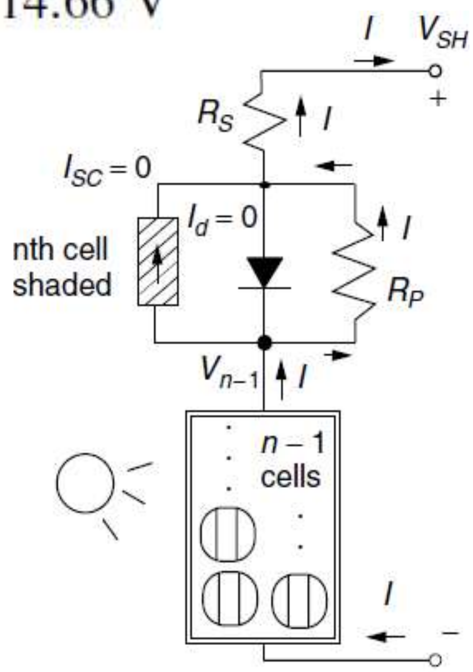
Example: The 36-cell PV module described in previous example had a parallel resistance per cell of $R_P = 6.6\ \Omega$. *In* full sun and at current *I = 2.14 A the output voltage was found to be V =19.41 V.* If one cell is shaded and this current somehow stays the same, then:

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

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

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

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



Example: The 36-cell PV module described in previous example had a parallel resistance per cell of R_P = *6.6 Ω. 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, then:

- a. What would be the new module output voltage and power?
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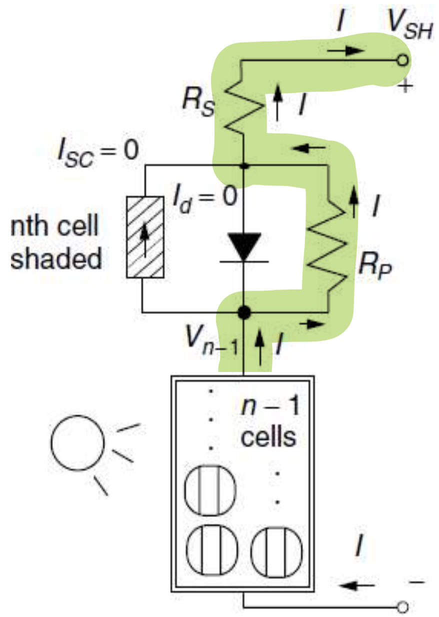


Power delivered by the module with one cell shaded would be

P lost is converted to heat
↳ might damage the PV cell

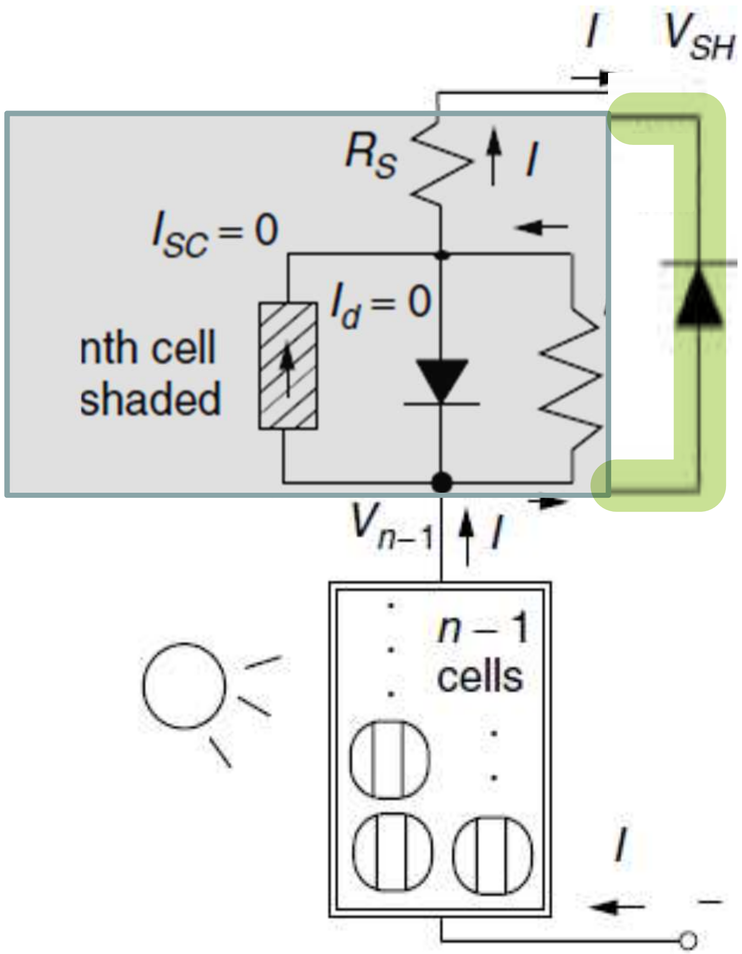
$$P_{\text{module}} = VI = 4.75 \text{ V} \times 2.14 \text{ A} = 10.1 \text{ W}$$

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

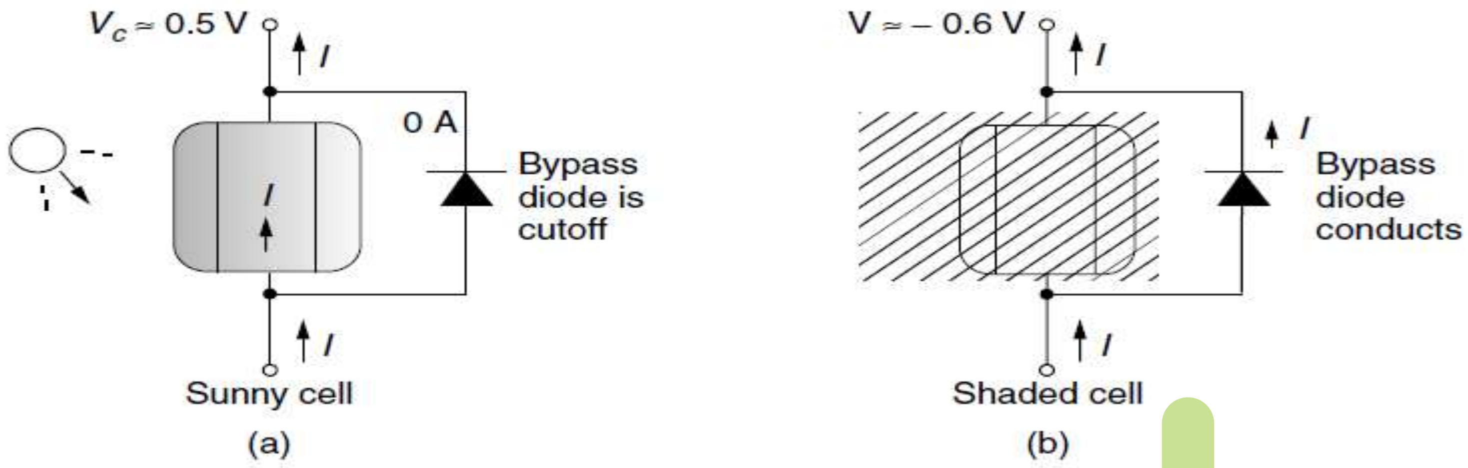
$$V_c = I(R_P + R_S) = 2.14(6.6 + 0.005) = 14.14 \ V$$

Bypass Diode to mitigate effect of shading

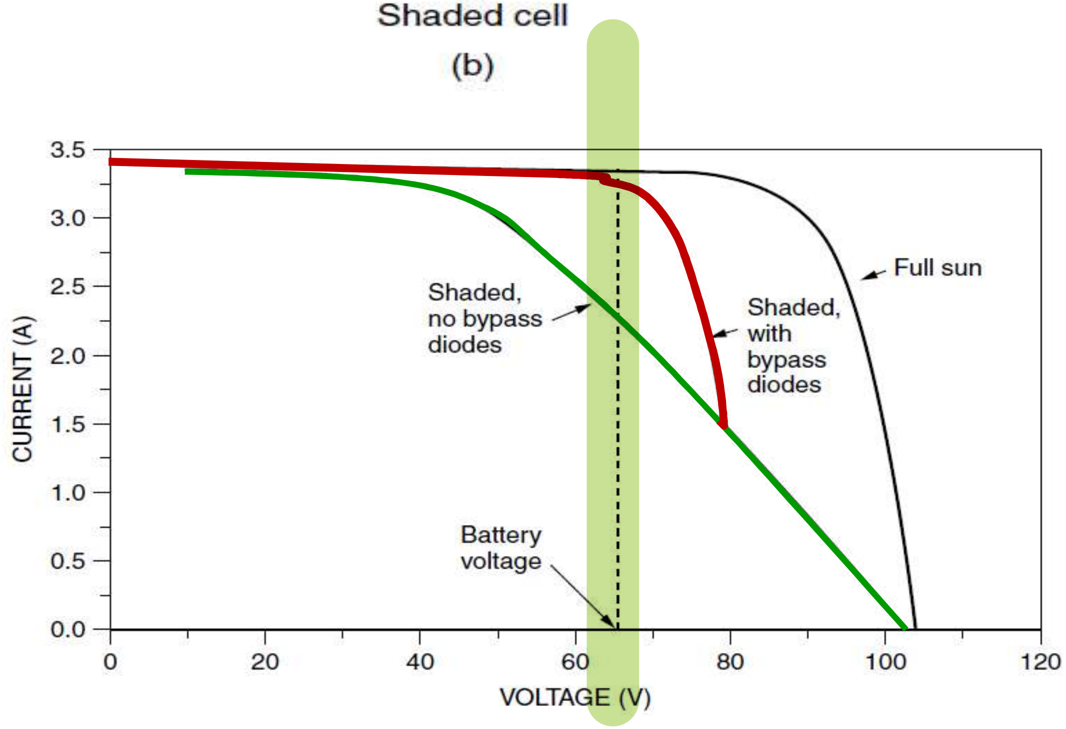


Bypass diode
↳ current passes through this diode instead of the shaded cell
↳ prevents overheating of shaded cell

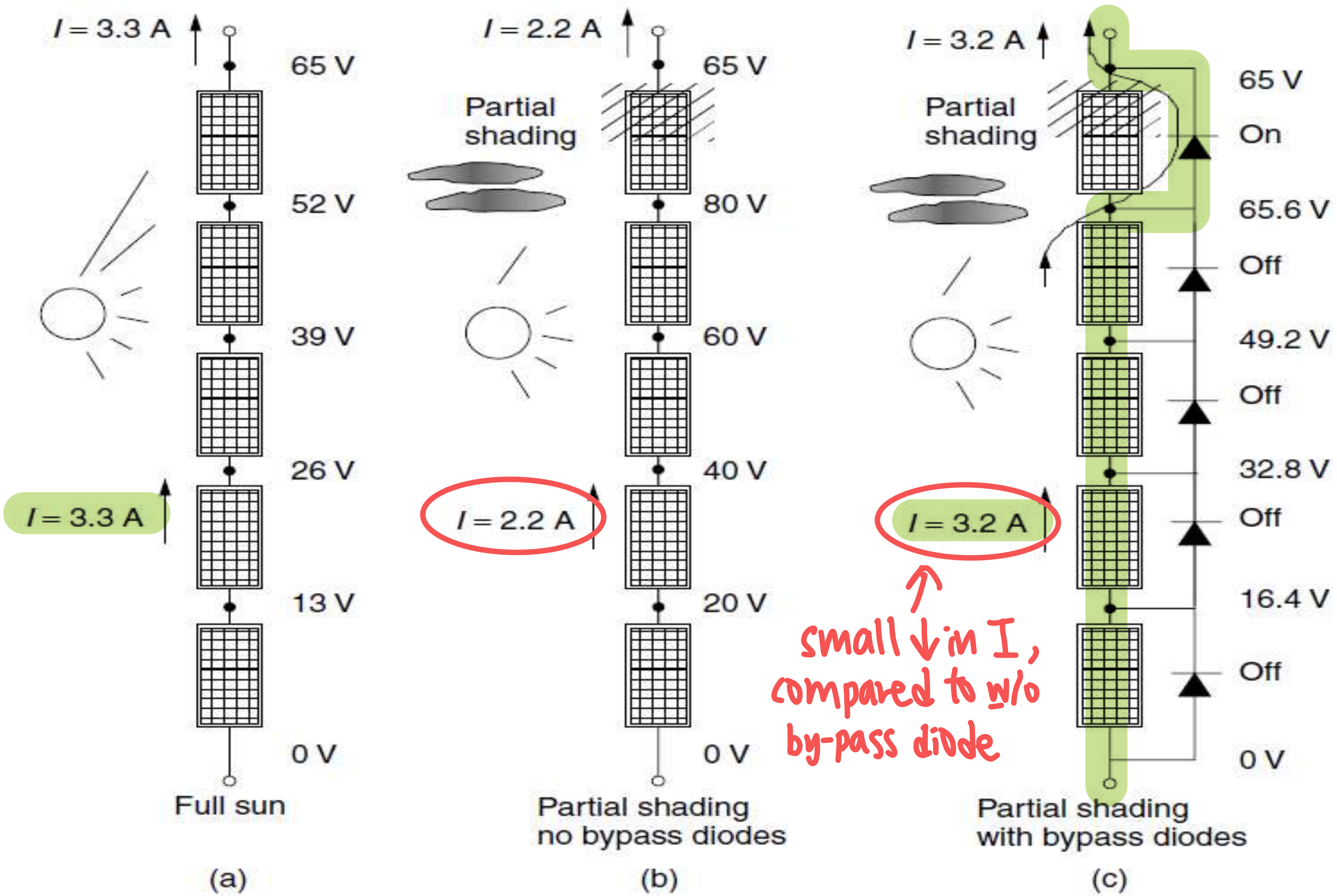
Bypass Diode to mitigate effect of shading



- 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

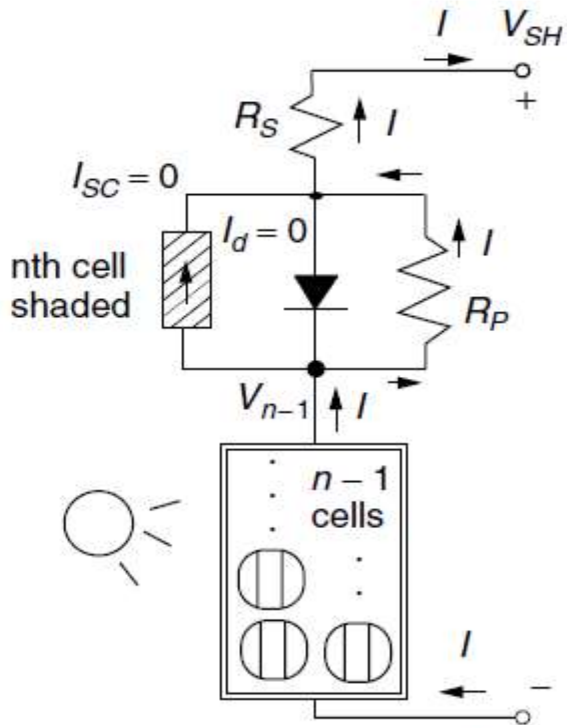


With bypass diodes, current is diverted around the shaded module

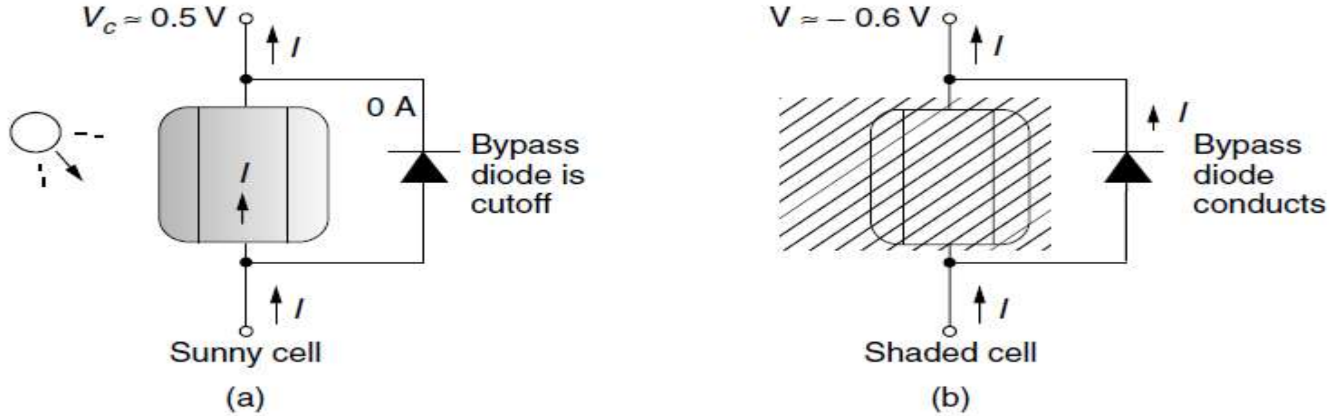


Effect of shading

Shading of even one cell in a module causes severe drop in module voltage and power

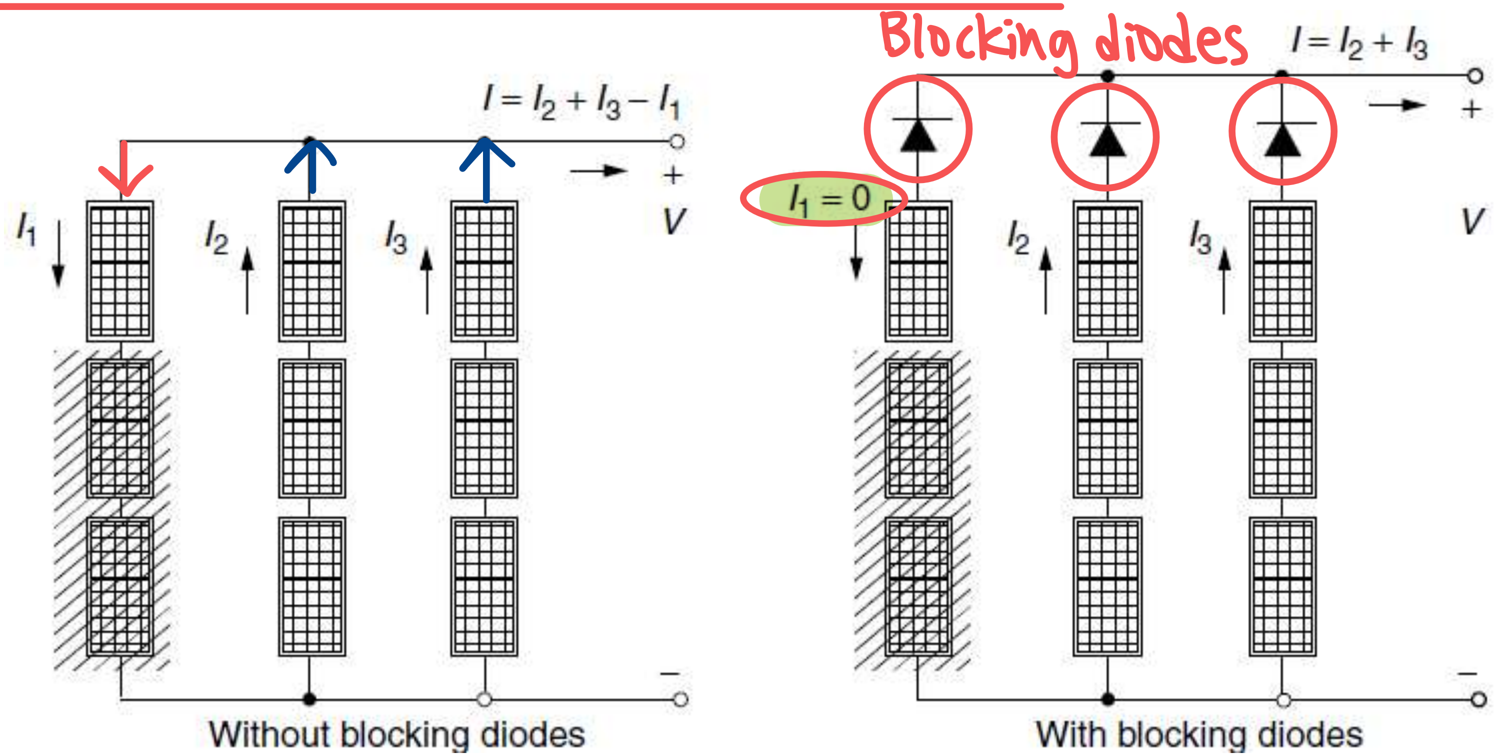


Bypass diode can mitigate the effect of shading



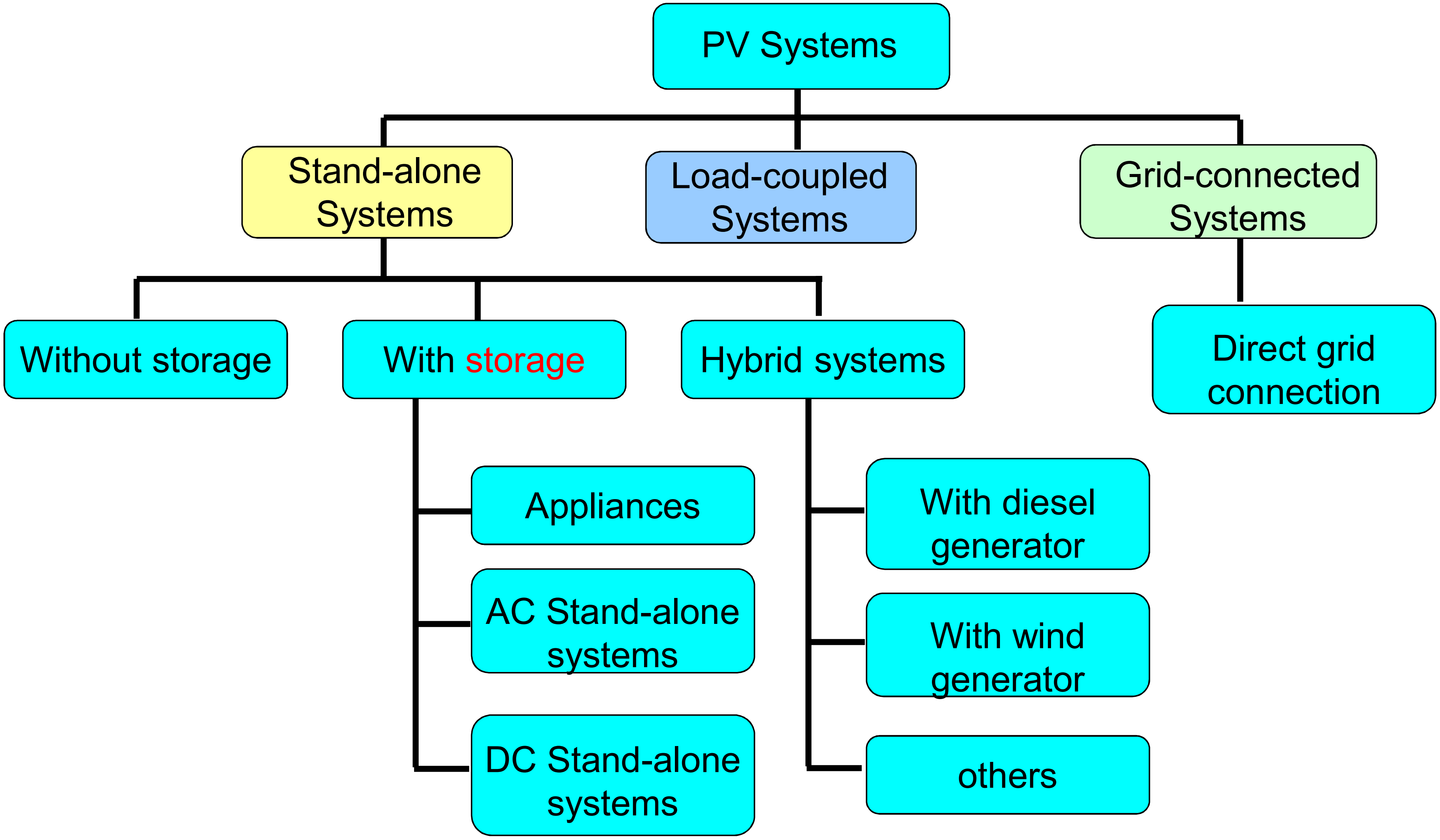
Blocking Diodes

- 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

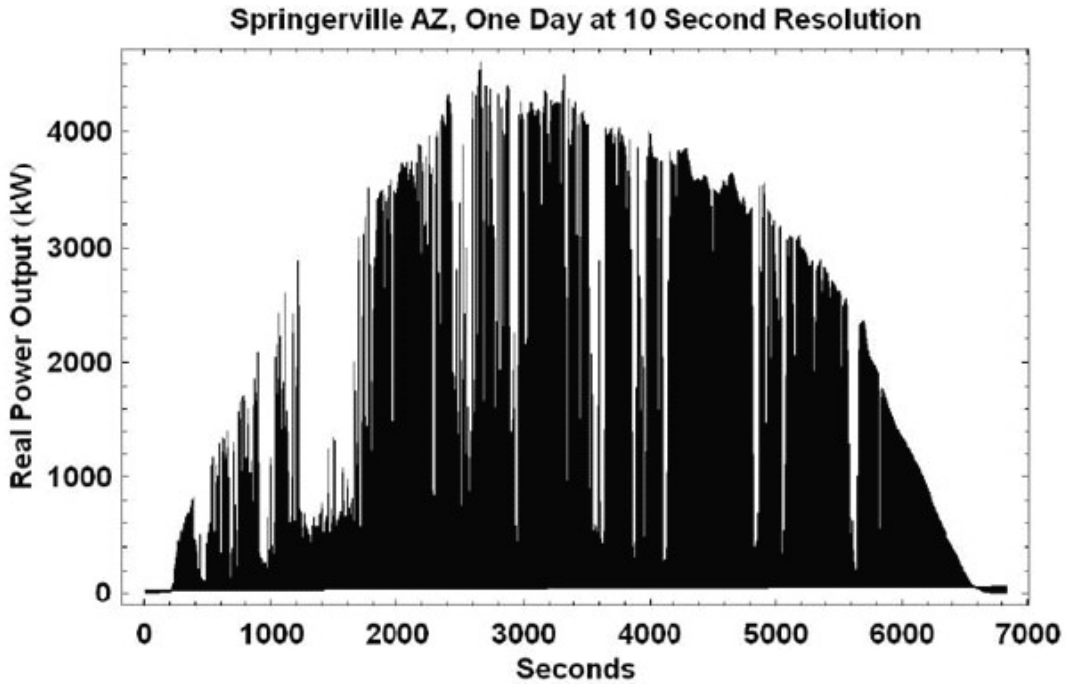


Solar PV Systems

Types of Solar PV Systems



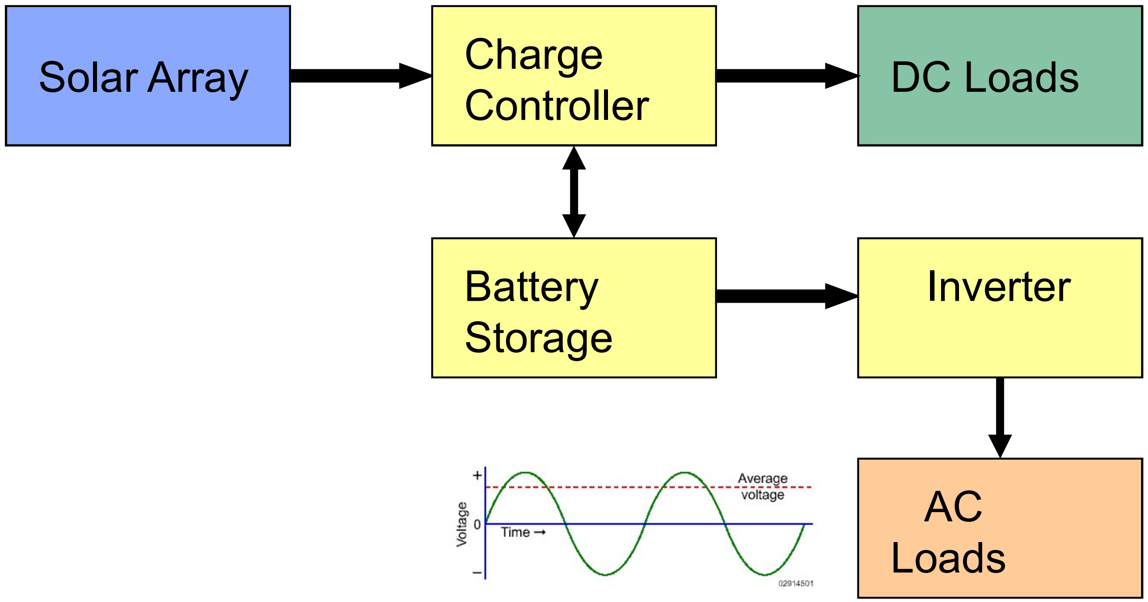
Variability of solar power output – Motivation for Storage



- **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**

Stand-alone solar power systems

Typical stand-alone system powering DC and AC loads:

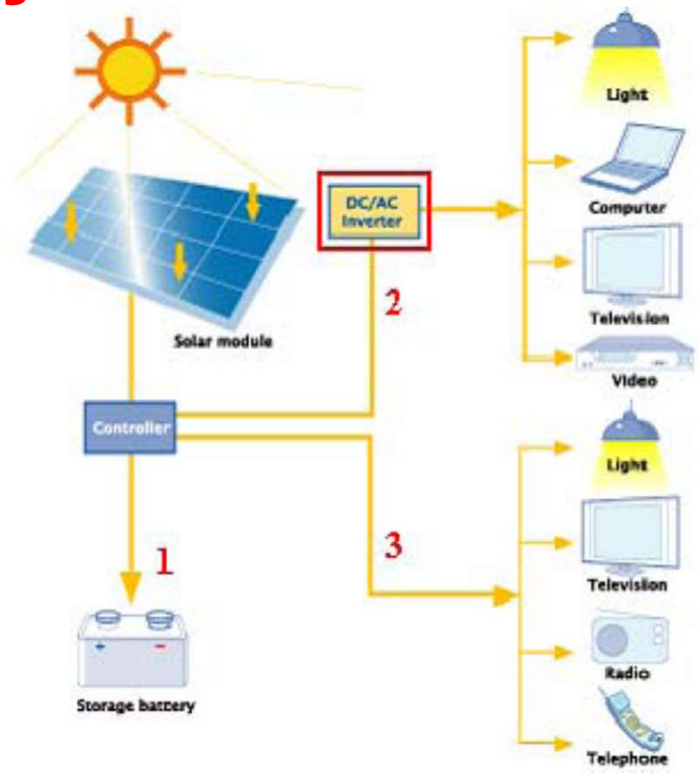


A PV system has these main components:

- One or more PV modules, which are connected to an inverter
- The inverter, which converts the system's direct-current (DC) electricity to alternating current (AC)
- Batteries to provide energy storage or backup power in case of a power interruption
- *Charge controller regulates the battery charging/discharge*

Stand-alone PV System

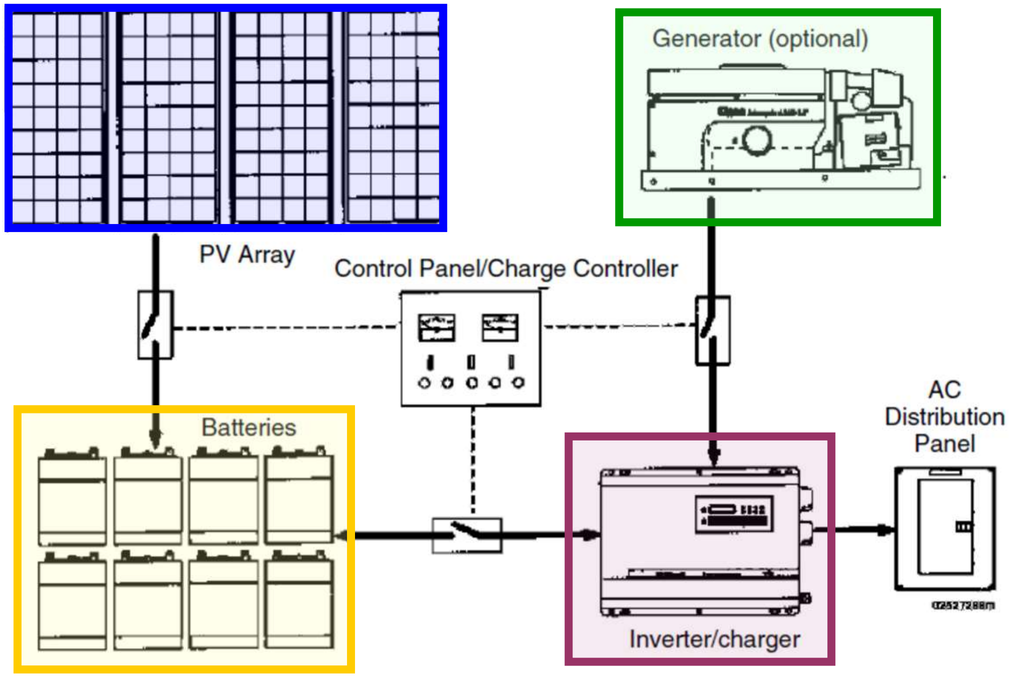
- In simple systems, all loads can be directly run on DC and no inverter may be necessary
- Cost effective in remote locations
- Some loads may run on AC – inverter is therefore needed



Stand-alone PV systems

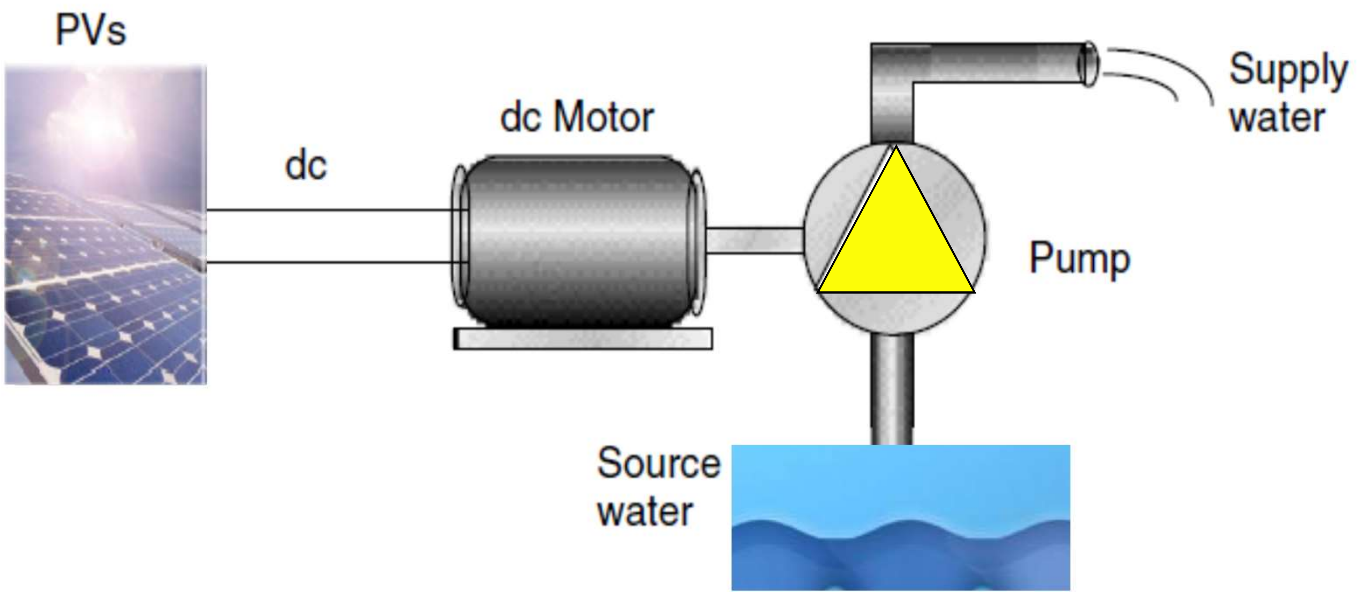
Inefficiencies due to:

- Battery losses
- Operating point typically not the most efficient one
- Steep tilt angle
- Uneven availability of power due to weather variations



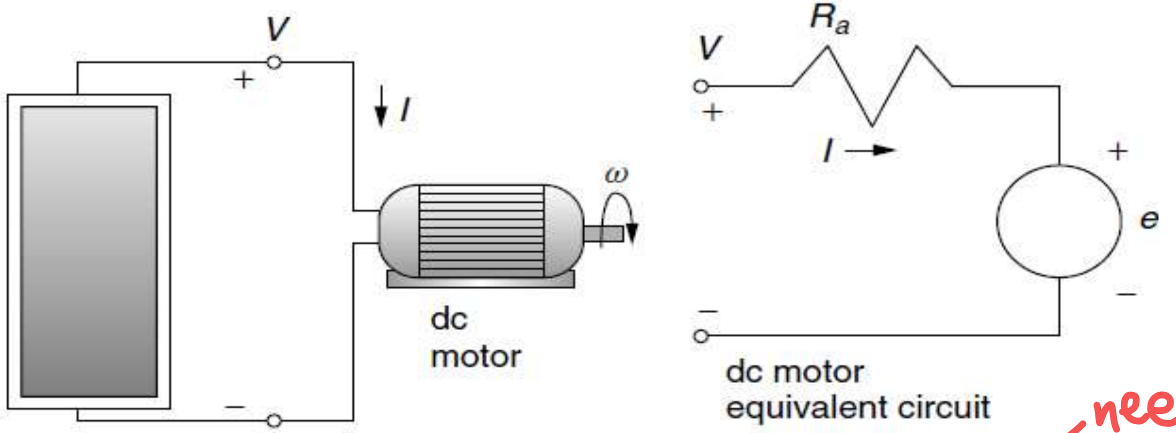
Load-coupled PV Systems

- 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



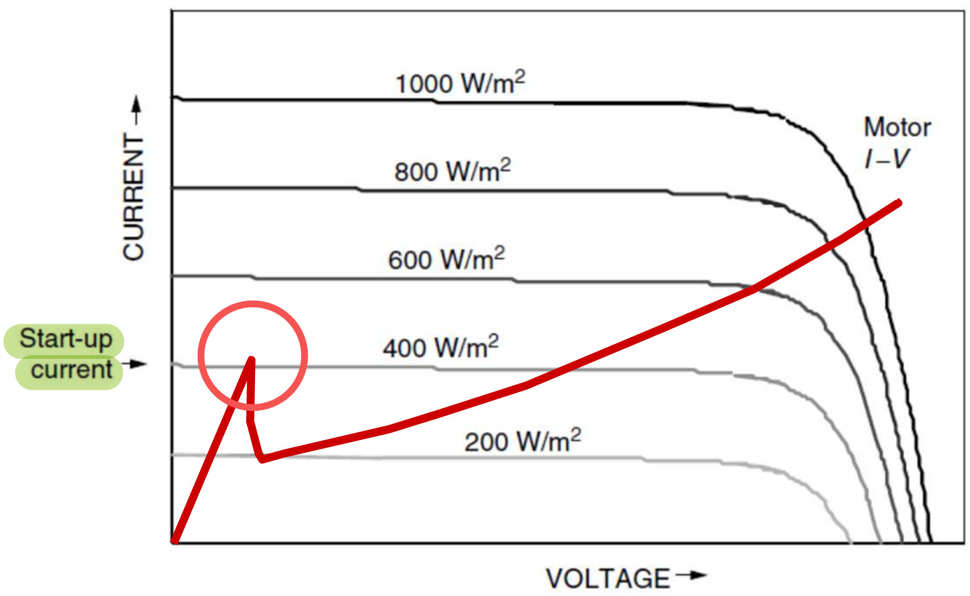
$$V = I\,R_a + E_b$$

needs enough insolation

- **The motor will not start pumping until insolation reaches 400 W/m²**

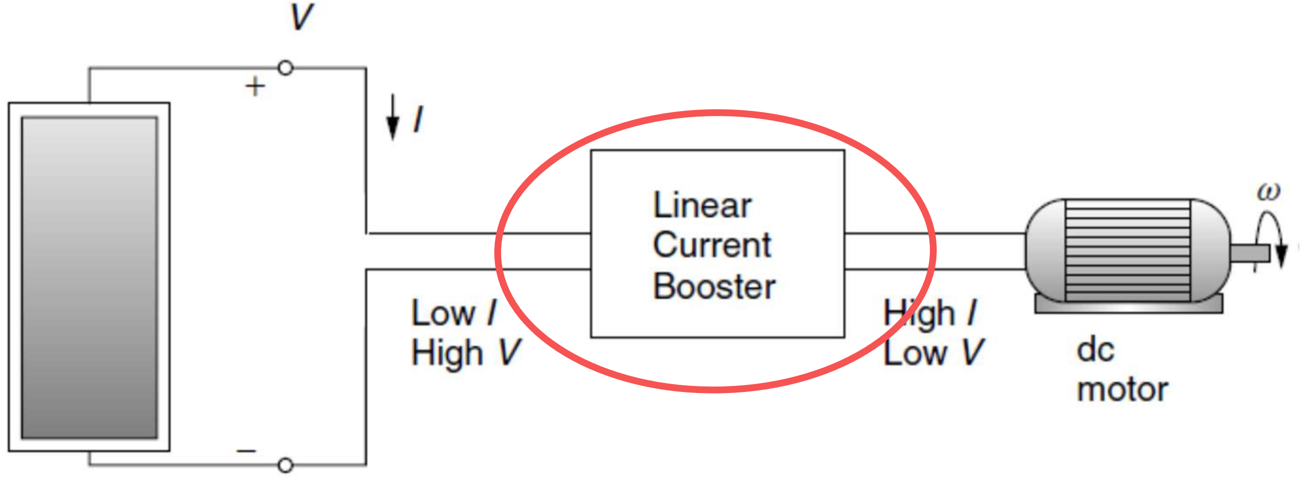
The system has to be carefully designed!

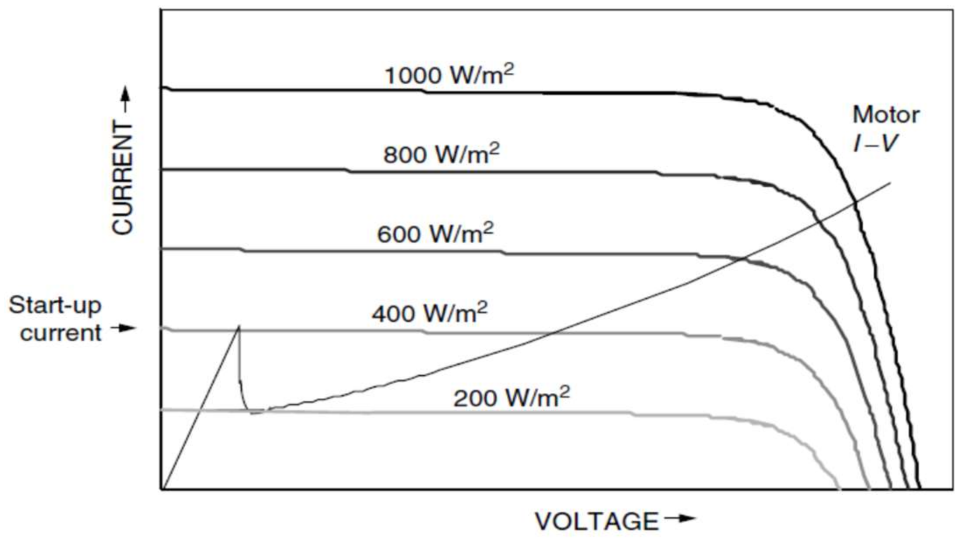
Insufficient insolation in the mornings results in lower efficiency



Load-coupled PV Systems – DC Motor for pumps

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





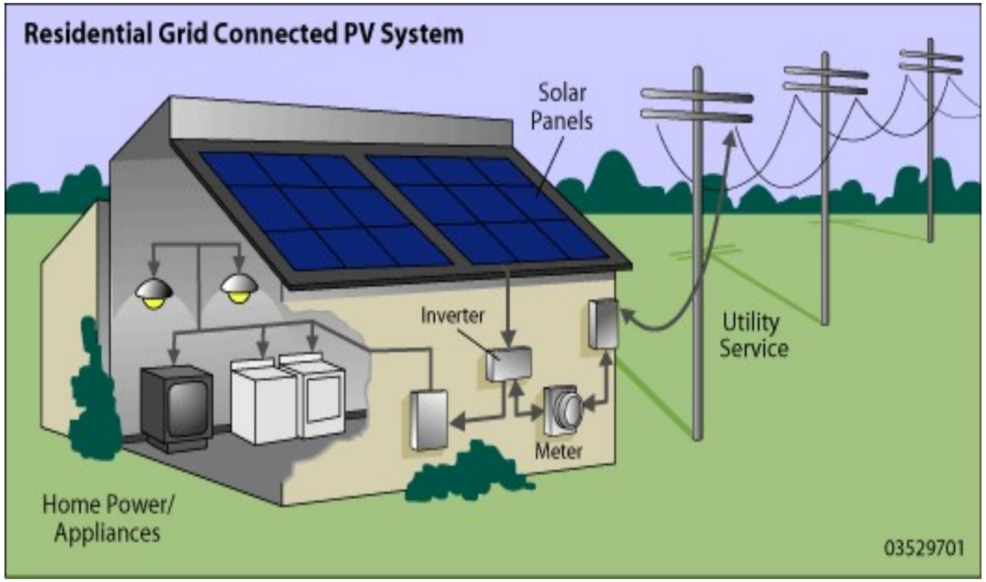
→ needs inverter : DC → AC!!

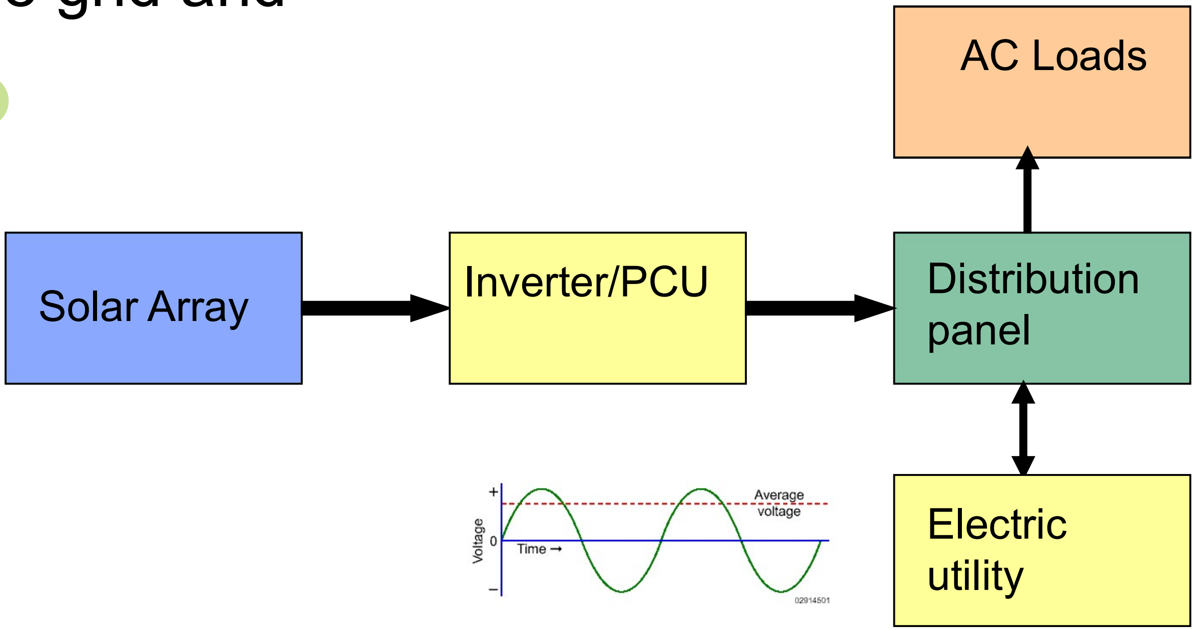
Grid-connected PV Systems

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

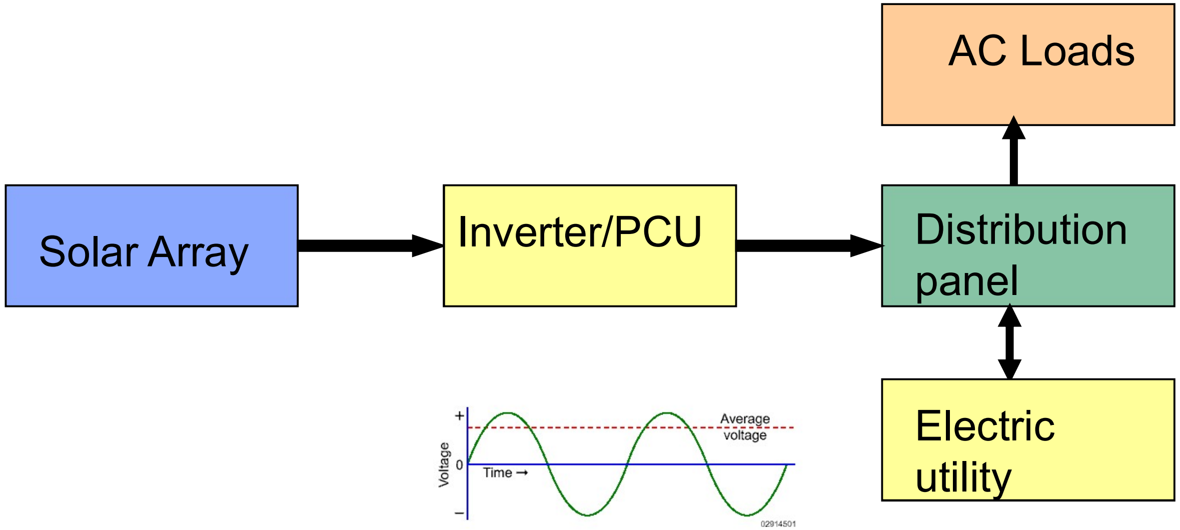
↳ no need external energy storage system





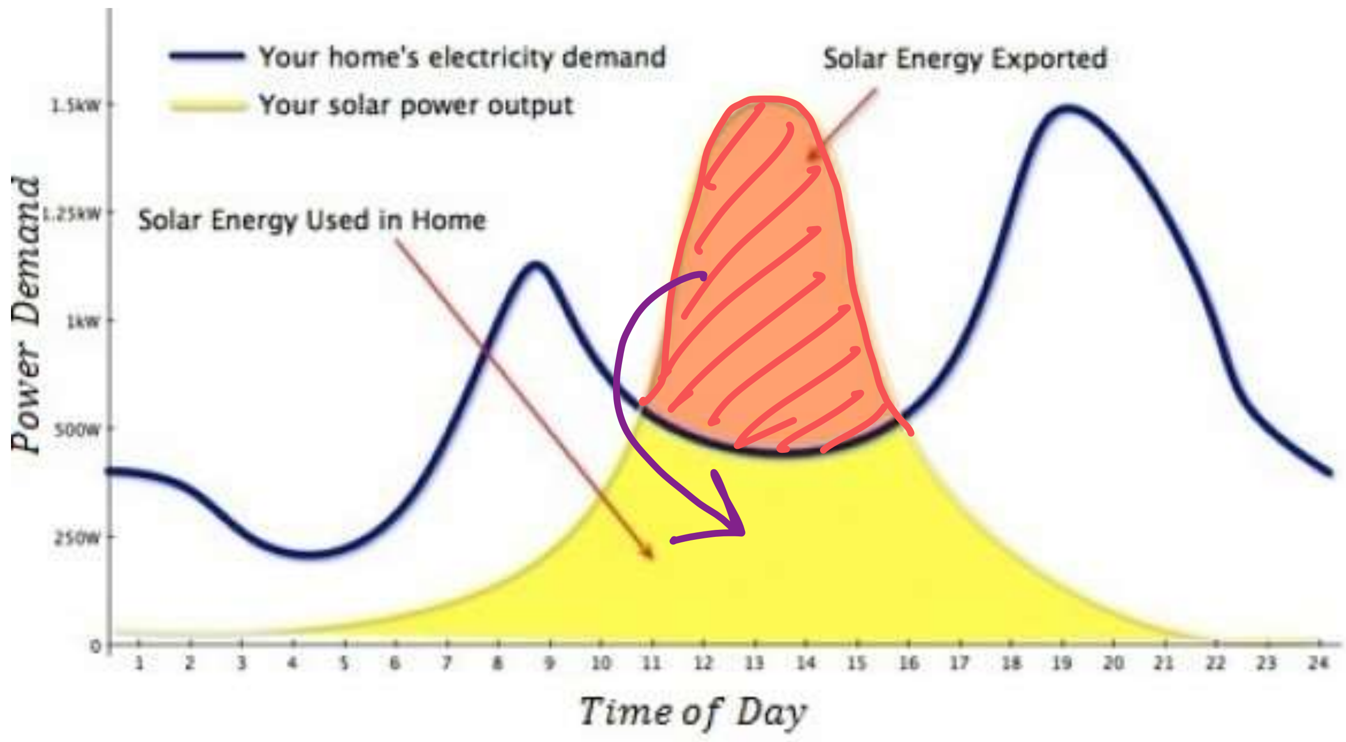
Grid-connected PV Systems

- Designed to operate in parallel with, and interconnected, with the electric utility grid
- The primary component in grid-connected systems is the **inverter**
- **PCU** converts the DC power into AC power consistent with the voltage and power quality requirements of the utility grid
- PCU **automatically stops** supplying power to the grid when the utility grid is not energized.



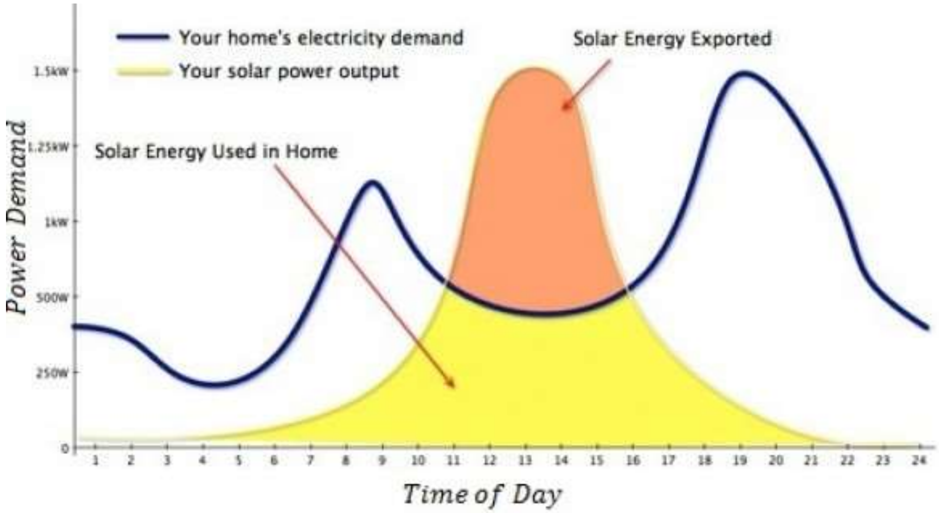
Grid-connected PV Systems

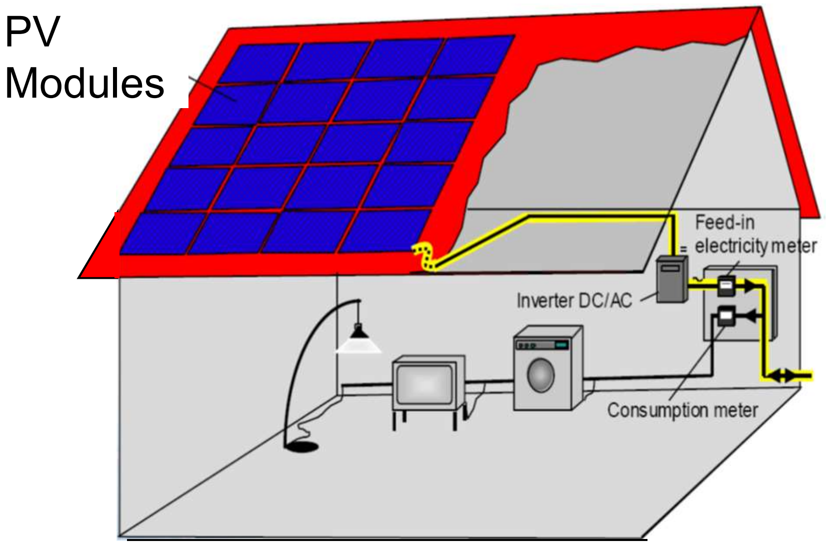
- Solar power system **back-feeds the grid** when the solar power system output is greater than the on-site load demand.



Grid-connected PV Systems

- 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**

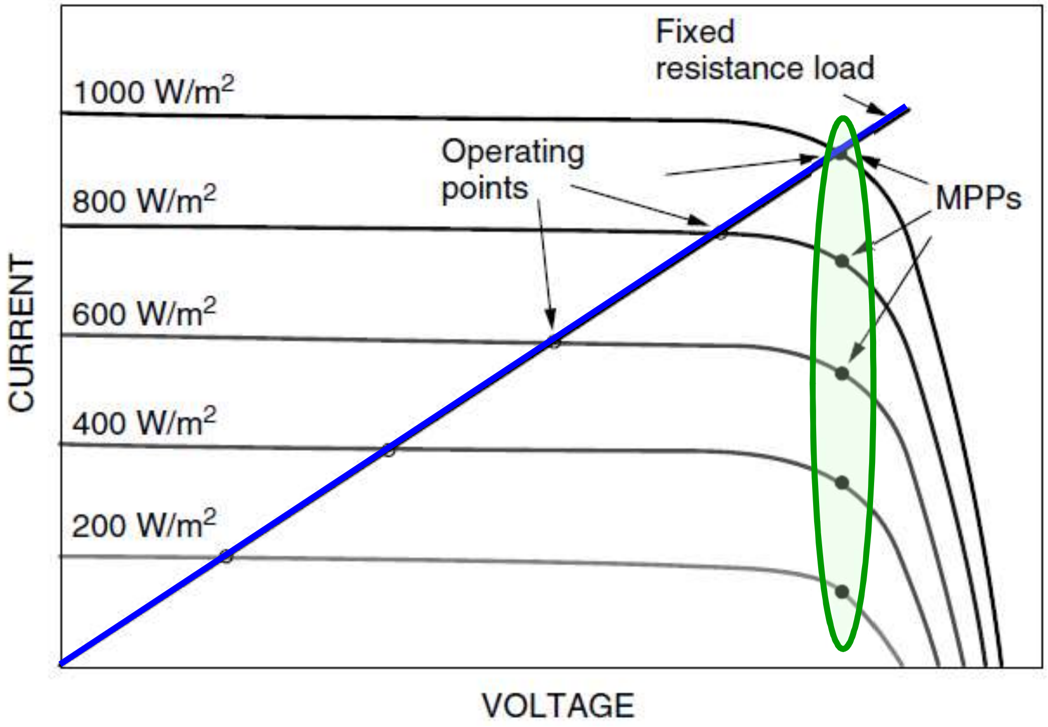




(Source: BSW)

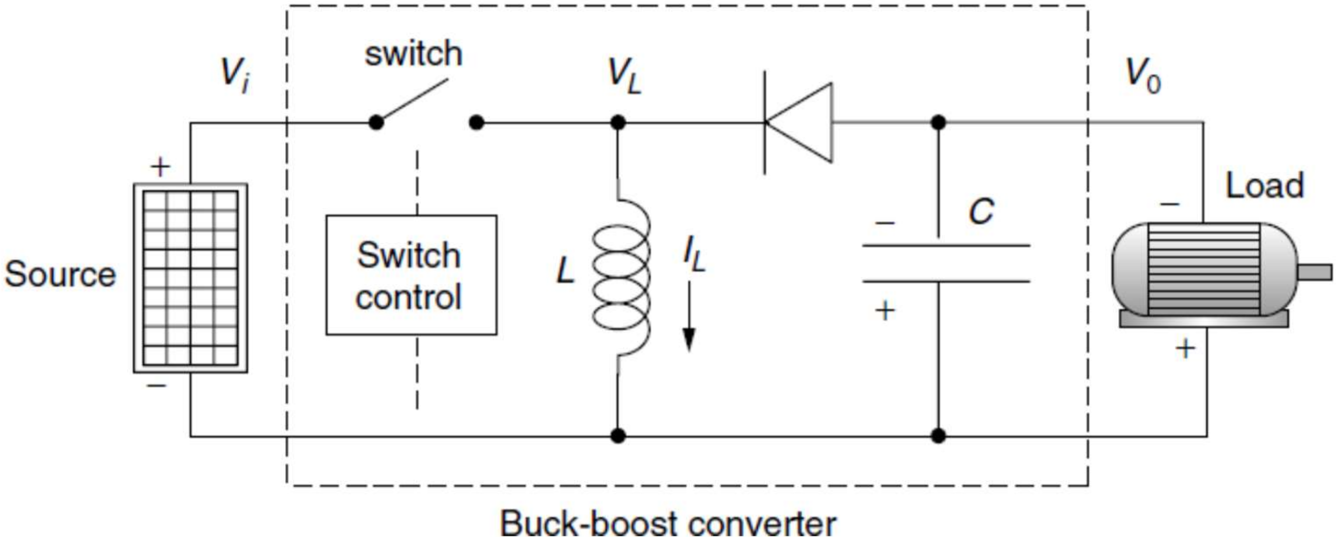
Maximum Power Point Trackers (MPPT)

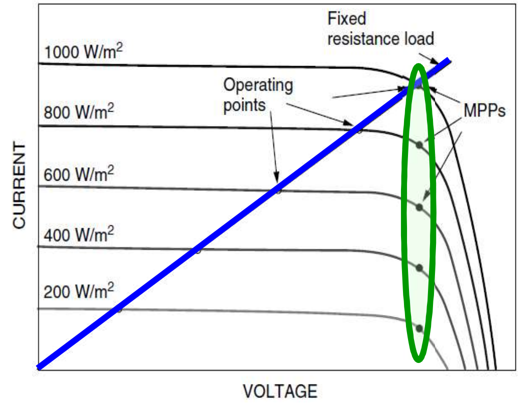
Max power point tracker (MPPT) ensures the module operates at highest efficiency point



Maximum Power Point Trackers (MPPT)

- Standard part of most grid-connected systems
- Commonly use a buck-boost converter (also used in linear current boosters)

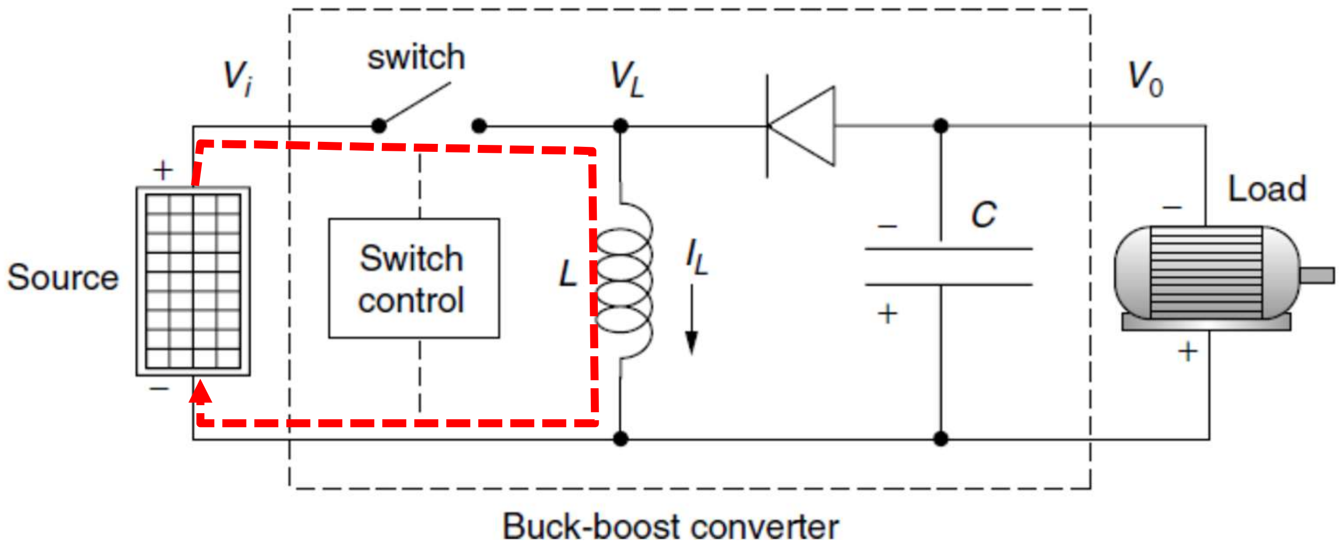




Raises or lowers the voltage to the desired value needed by load

Maximum Power Point Trackers (MPPT)

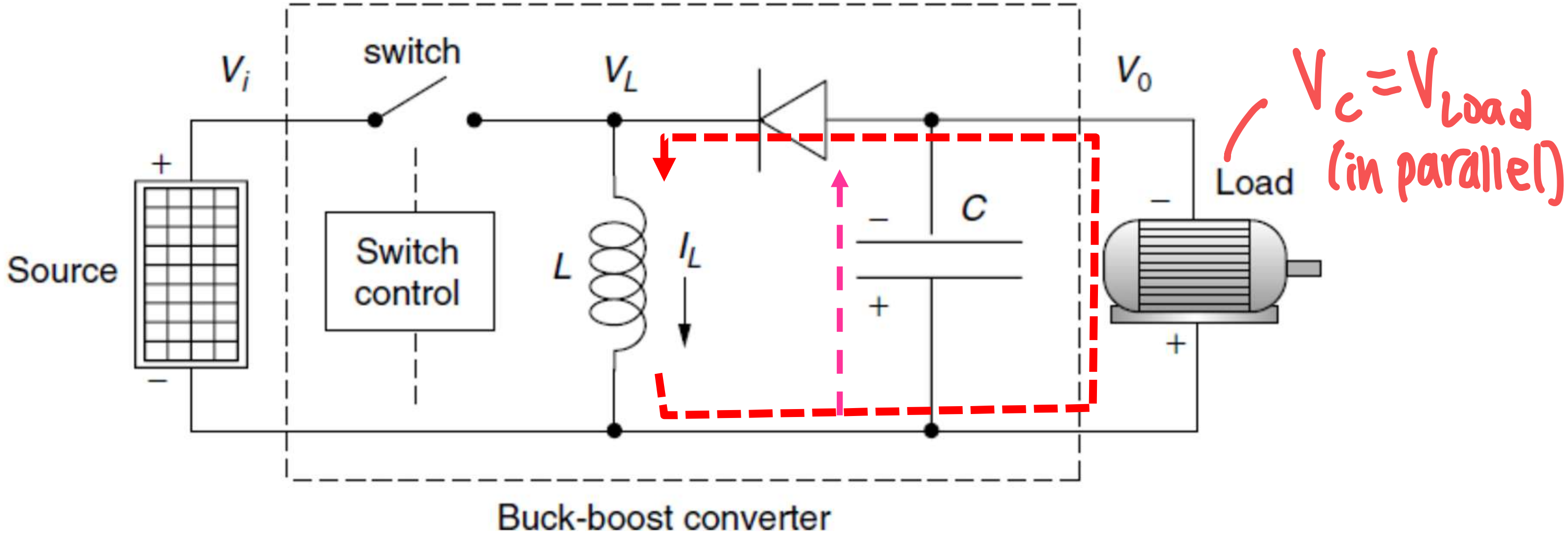
- When switch is **CLOSE**: energy is supplied to inductor, and I_L builds up



Typically, the on-off switch in this switched-mode dc-dc converter is an IGBT transistor

Maximum Power Point Trackers (MPPT)

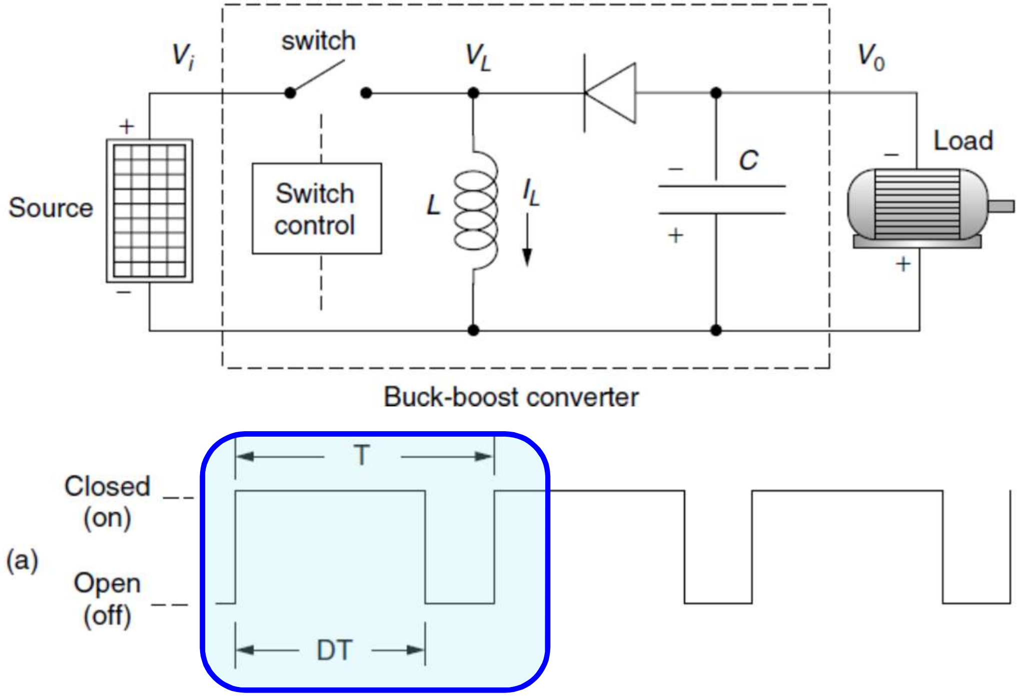
- When switch is **CLOSE**: energy supplied to inductor, and I_L builds up
- When switch is **OPEN**: Inductor current flows through C, load and diode
- With fast switching, inductor current and output voltage are **CONSTANT**



Typically, the on-off switch in this switched-mode dc-dc converter is an IGBT transistor

Maximum Power Point Tracker (MPPT)

Duty cycle: the **fraction** of time the switch is closed



Duty cycle = DT/T

(assume fast charging)

Under the assumption that inductor current is constant, the average power into the inductor is

$$\overline{P}_{L,\text{in}} = \frac{1}{T} V_i I_L \int_0^{DT} dt = V_i I_L D$$

Maximum Power Point Tracker (MPPT)

power into the inductor

$$\overline{P}_{L,\text{in}} = \frac{1}{T} V_i I_L \int_0^{DT} dt = V_i I_L D$$

power delivered by the inductor is

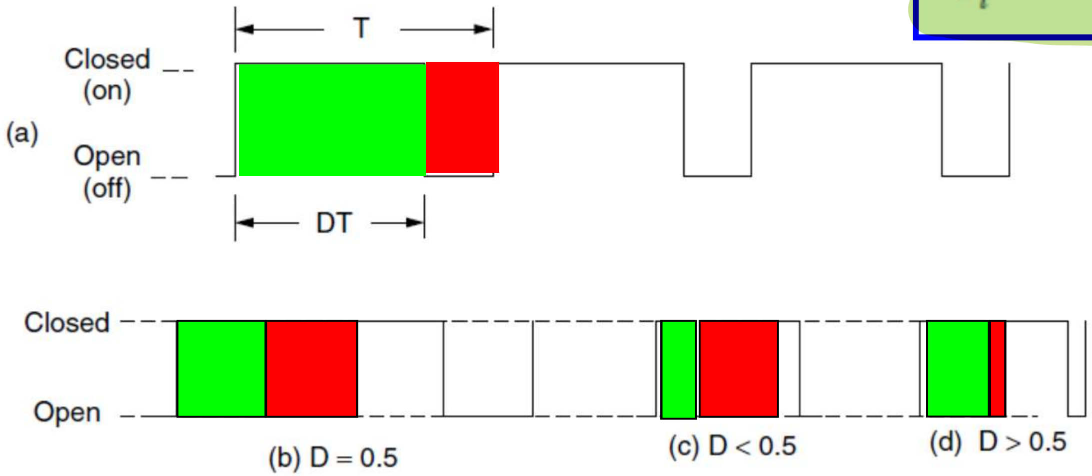
output

$$\overline{P}_{L,\text{out}} = \frac{1}{T} V_0 I_L (T - DT) = V_0 I_L (1 - D)$$

Over a complete cycle, the two are equal. Therefore:

$$\boxed{\frac{V_0}{V_i} = -\left(\frac{D}{1-D}\right)}$$

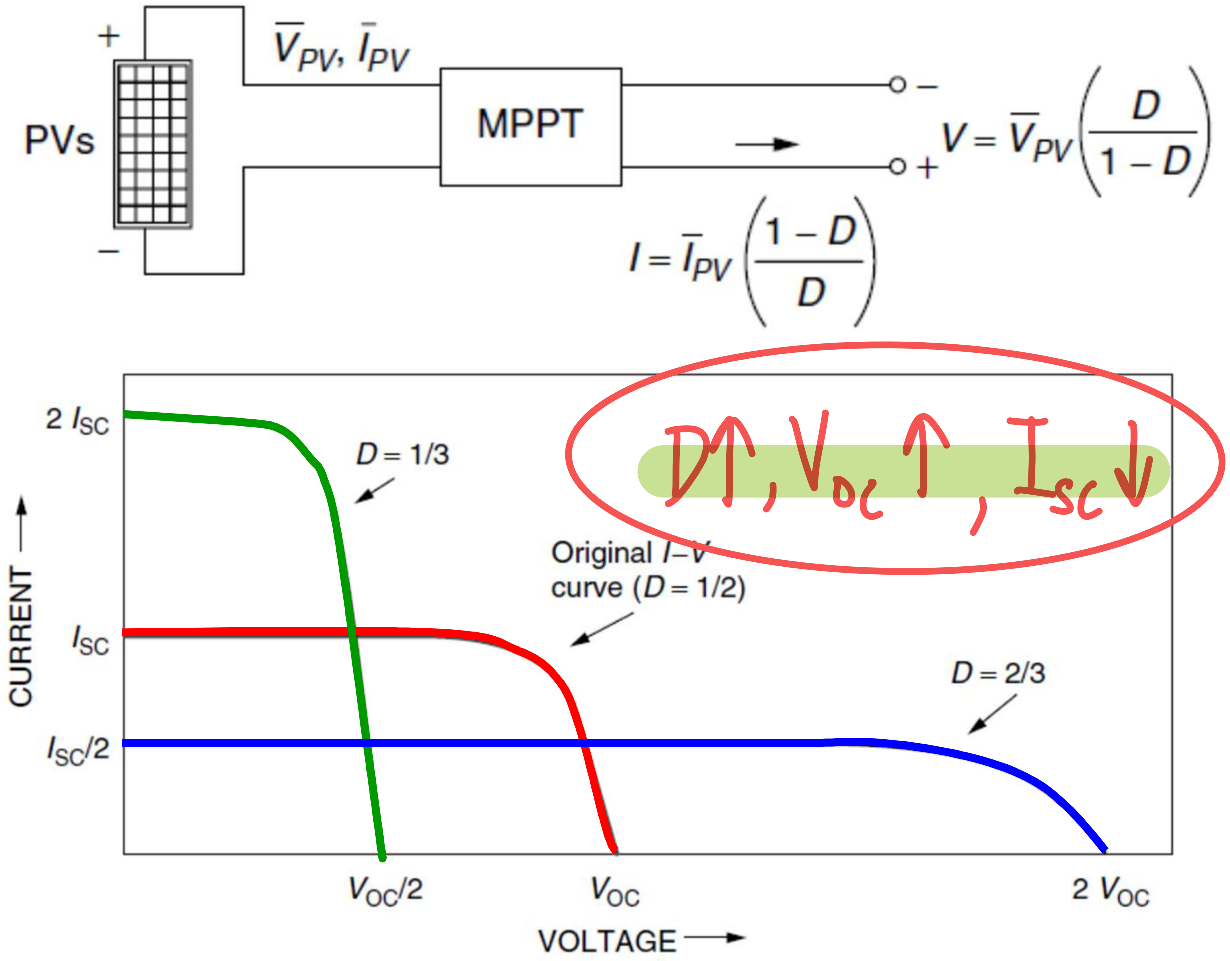
fraction of time that switch is closed



Voltage can be increased or decreased just by varying the duty cycle!

Maximum Power Point Tracker (MPPT)

- PV current-voltage curve with MPPT



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?

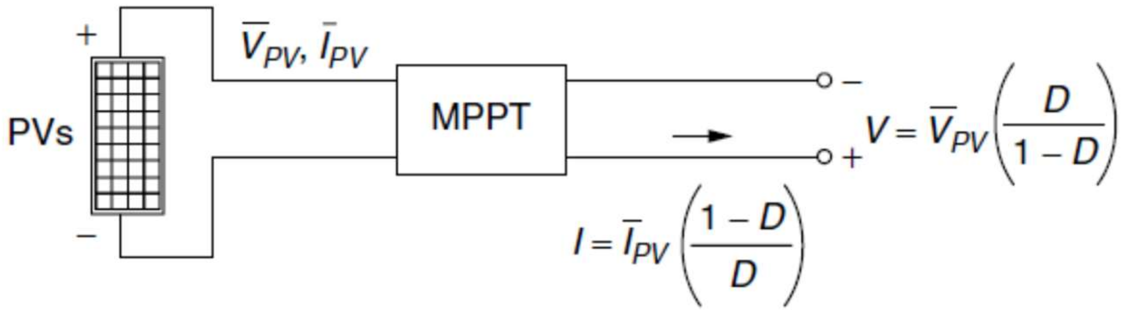
Solution: The maximum power delivered by the PVs is:

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

$$P = \frac{V_R{}^2}{R} \Rightarrow 102 = \frac{V_R{}^2}{10}$$

$$V_R = \sqrt{102 \cdot 10} = 31.9 \text{ V}$$

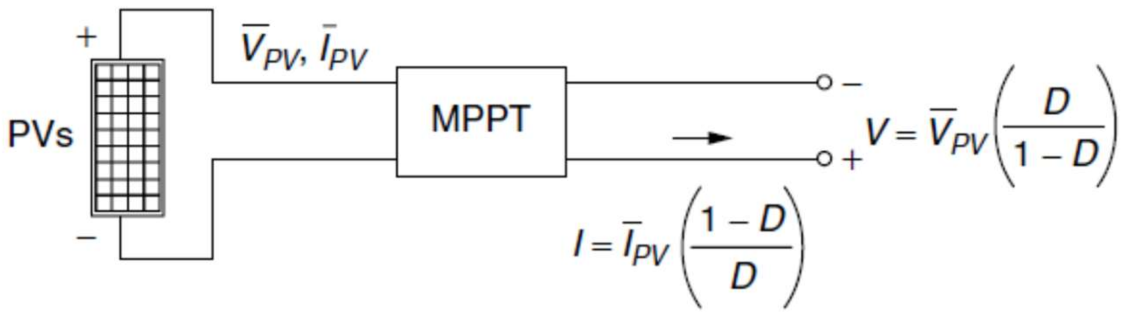


The MPPT must bump the 17-V PV voltage to the desired 31.9-V resistor voltage.

$$\frac{V_i}{V_o} \quad \frac{31.9}{17} = \left(\frac{D}{1-D}\right) = 1.88$$

$$D = 1.88 - 1.88D$$

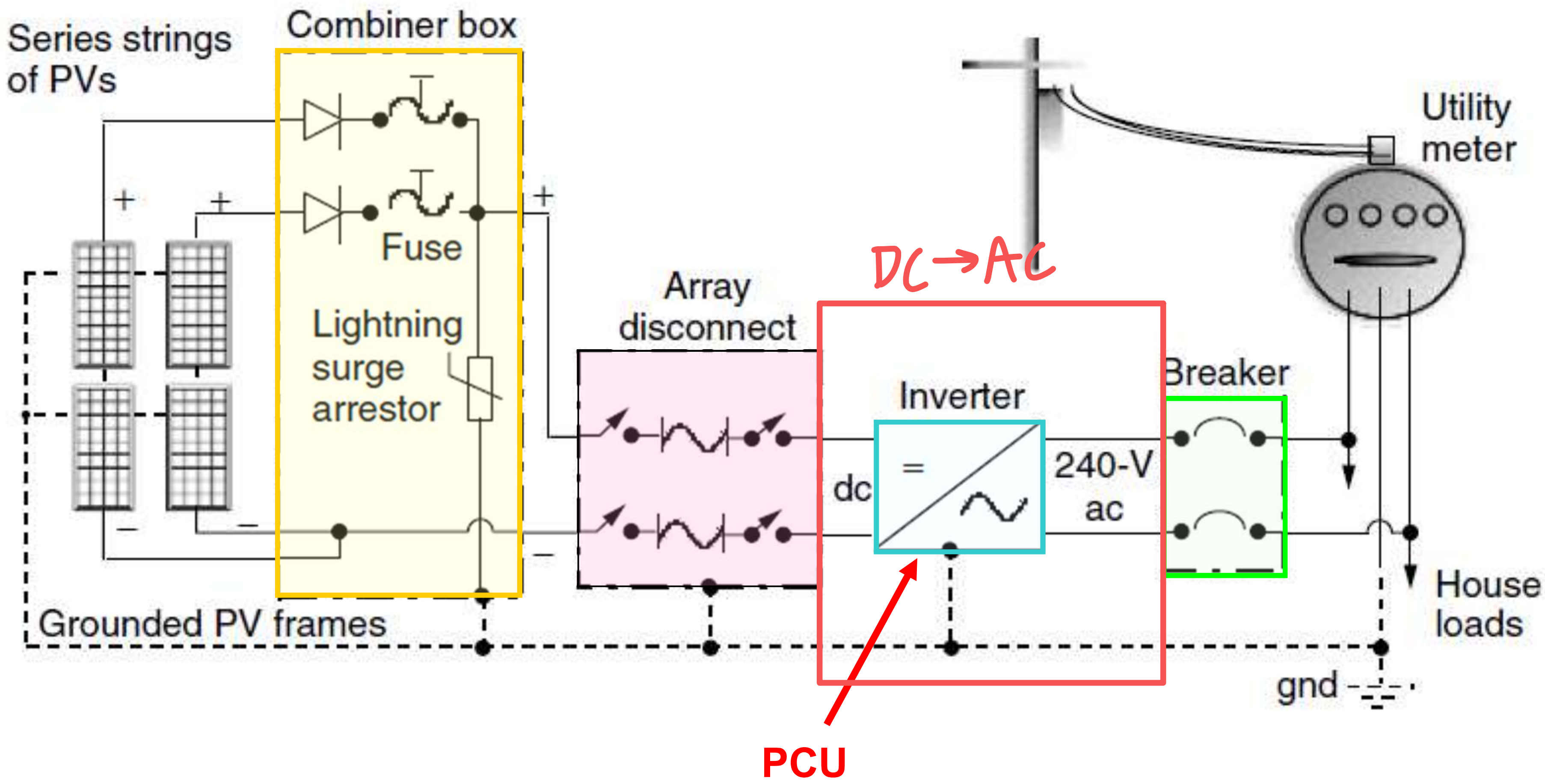
$$D = \frac{1.88}{2.88} = 0.65$$



Grid-connected PV Systems

Grid-connected system using a single inverter

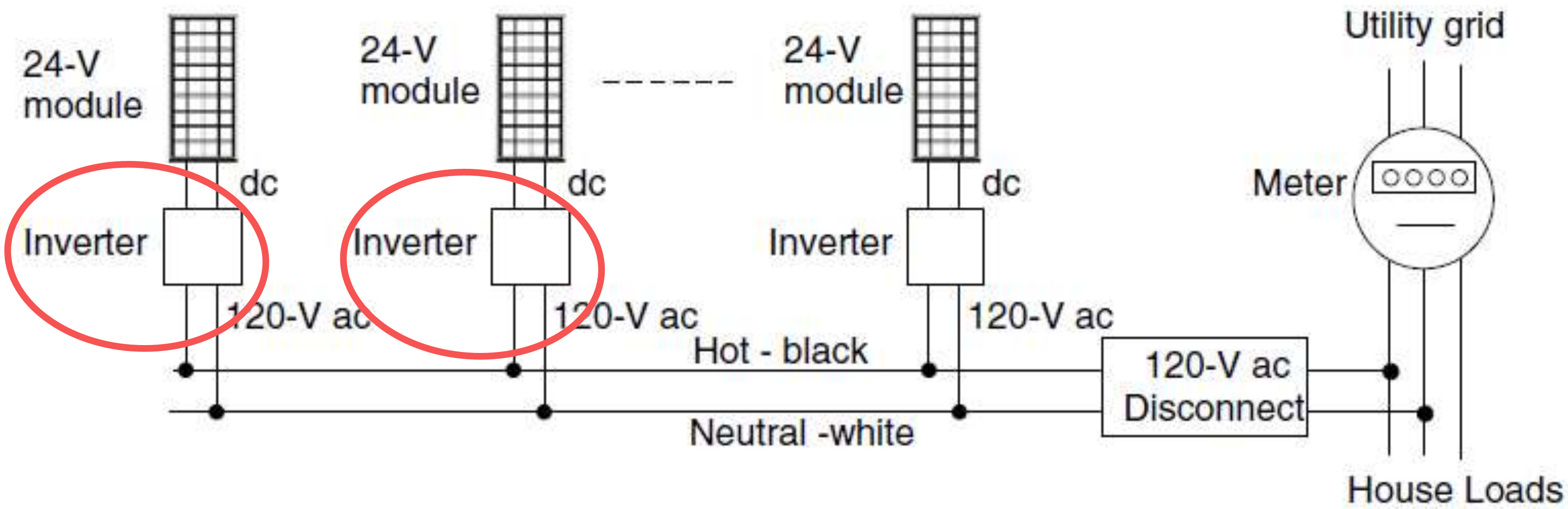
(MPPT, protection circuitry and battery bank are not shown)



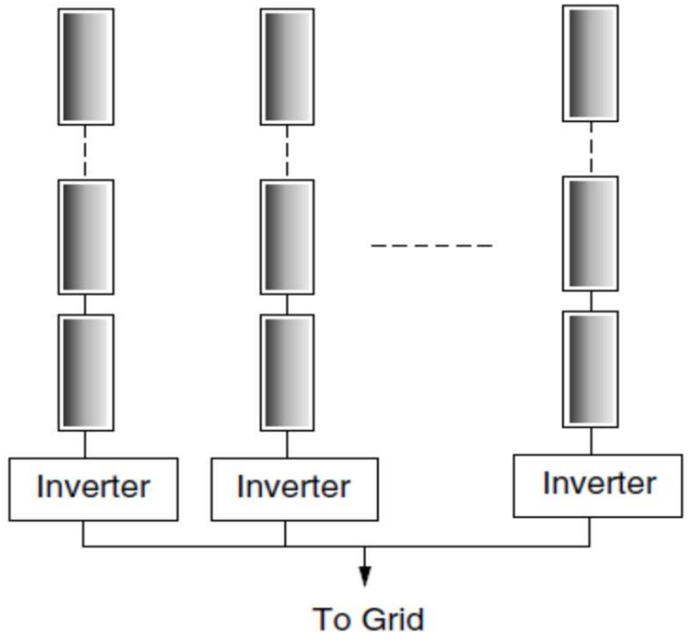
Grid-connected PV Systems

AC modules each with their own inverters can add on modules in // easily

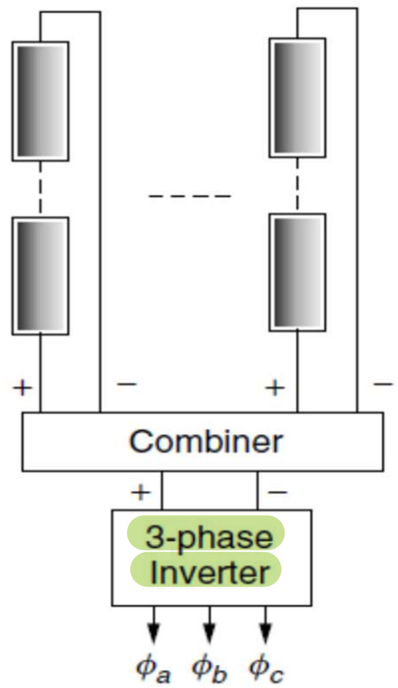
- Allows modular expansion of the system
- Uses simpler, less expensive switches, circuit breakers and wiring



- 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

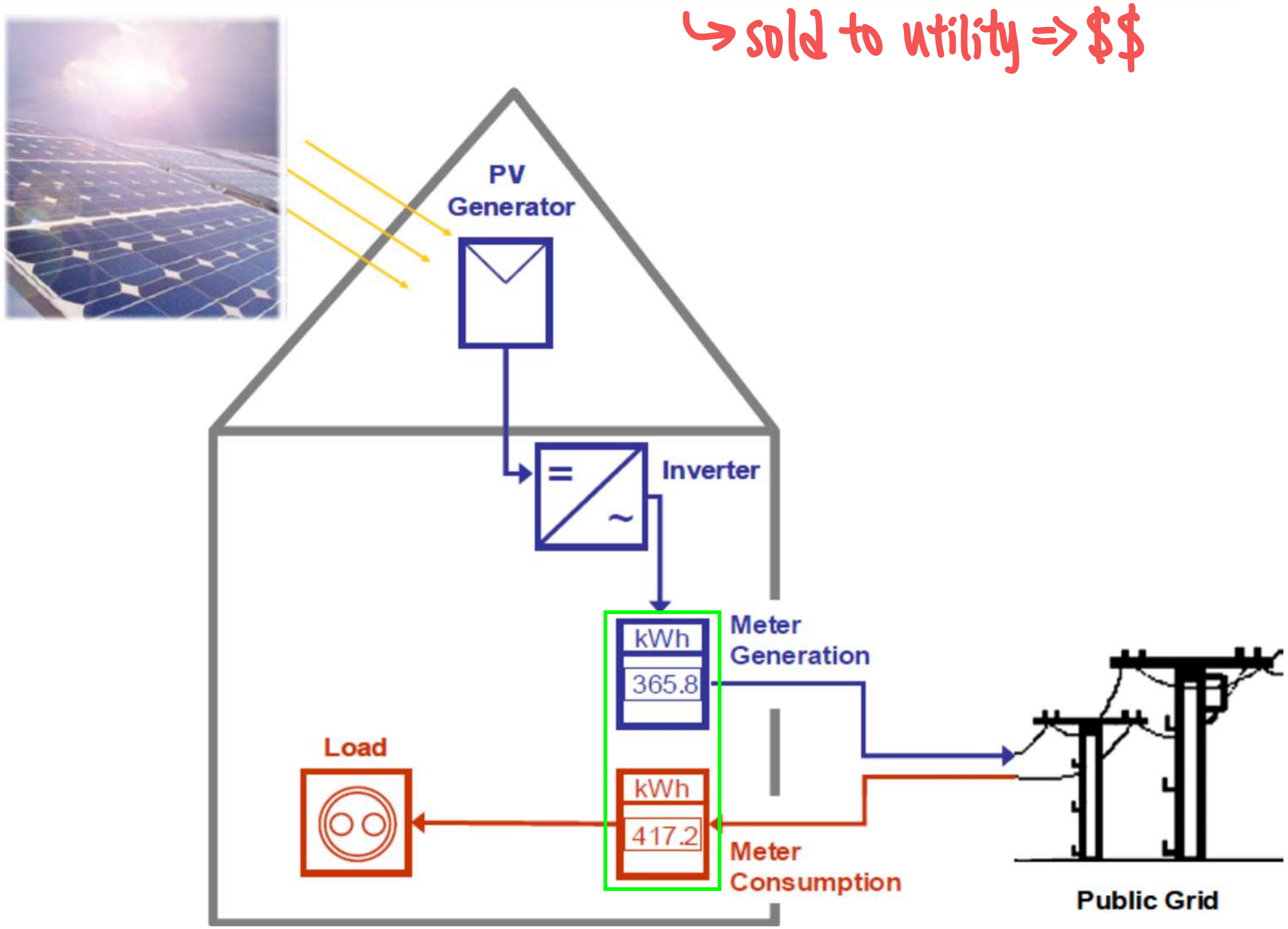


Grid-connected PV Systems

Interfacing with the utility: Net metering

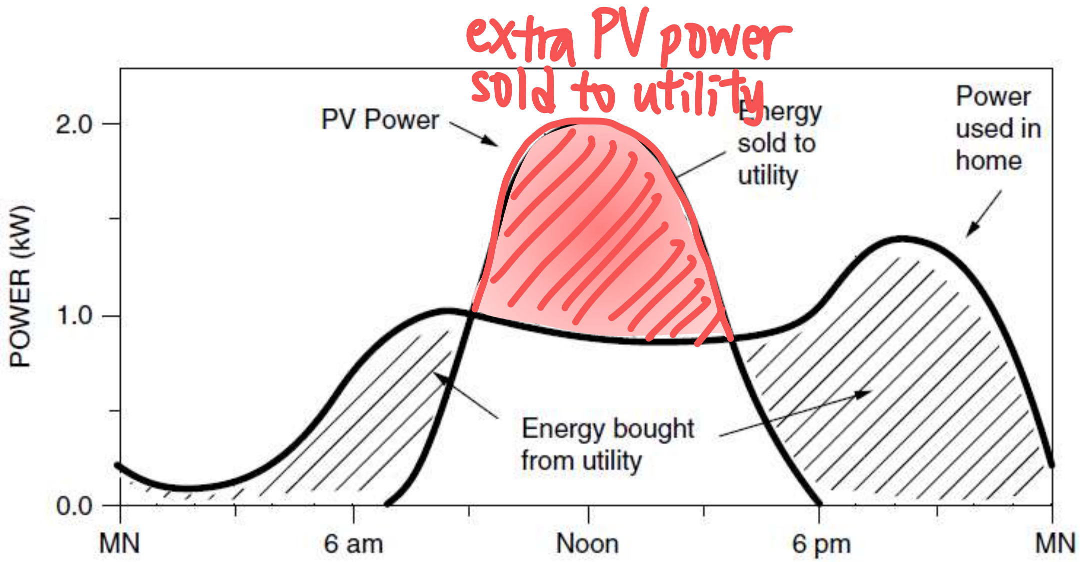
- Whenever PV system delivers more power than demanded by the home, the electric meter runs backwards
- When demand > supply from PV, the grid supplies additional power

↳ sold to utility ⇒ $$



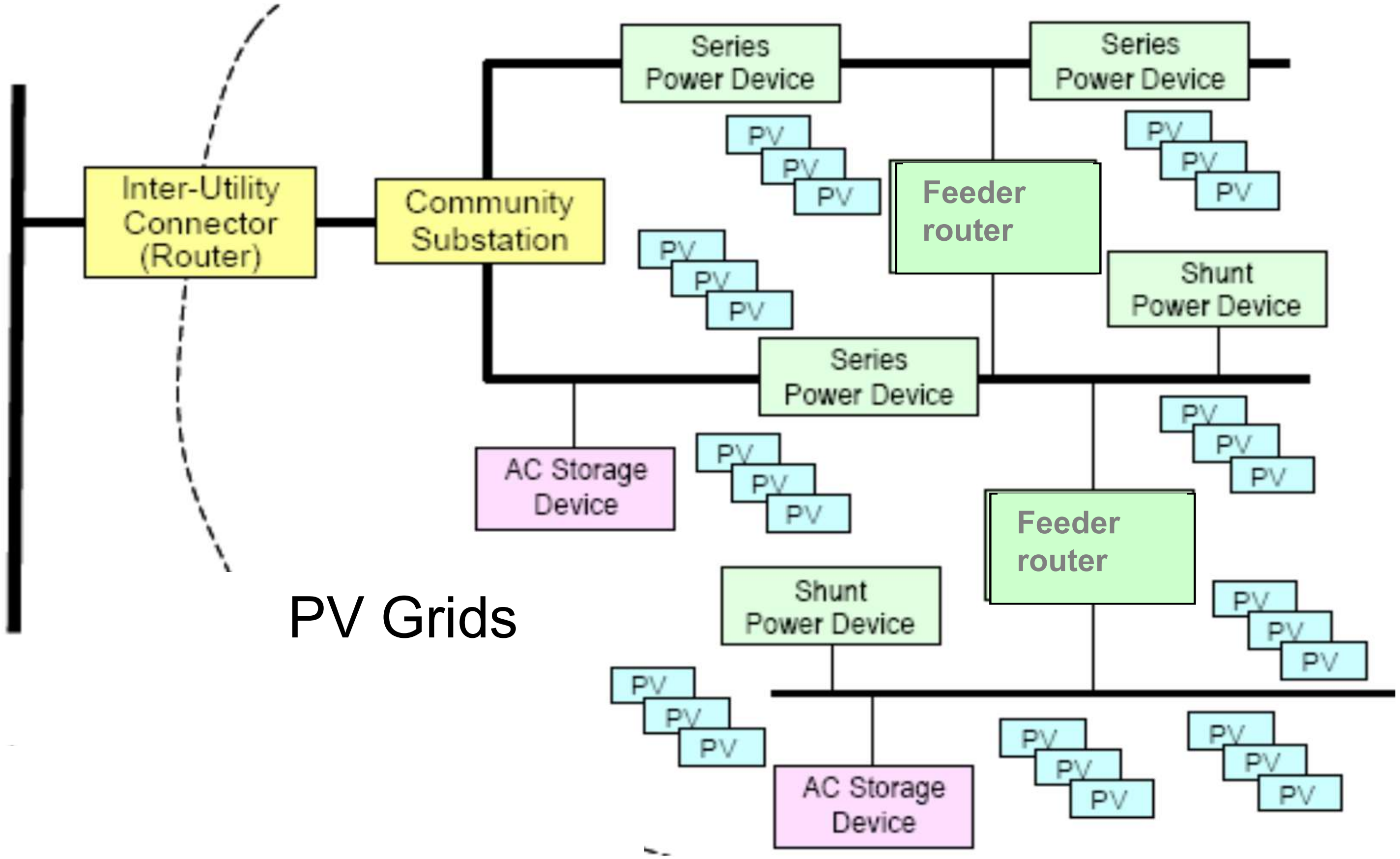
Grid-connected PV Systems

- Example: net metering



Grid Connected PV Systems: Large clusters

- Wide spread PV penetration in the future may have several PV Clusters with power electronic devices and battery storage stations

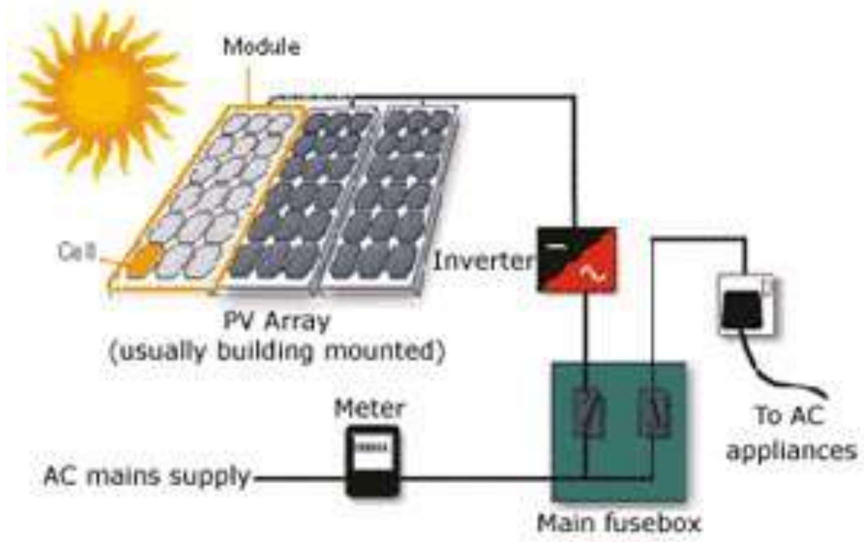


- Estimating PV system performance
- Grid-connected PV system design
- System integration issues

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,

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

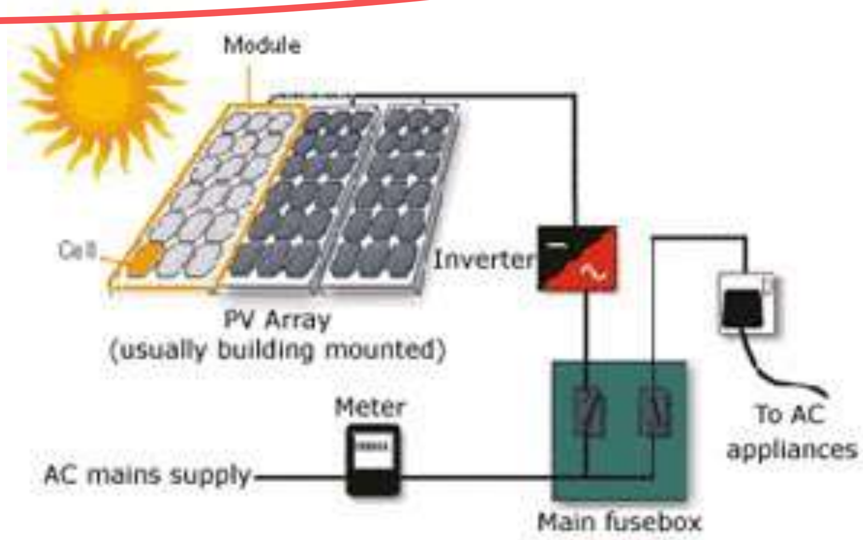


Estimating the system performance

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

The conversion efficiency accounts for

1. inverter efficiency,
2. dirty collectors,
3. mismatched modules, and
4. differences in ambient conditions.

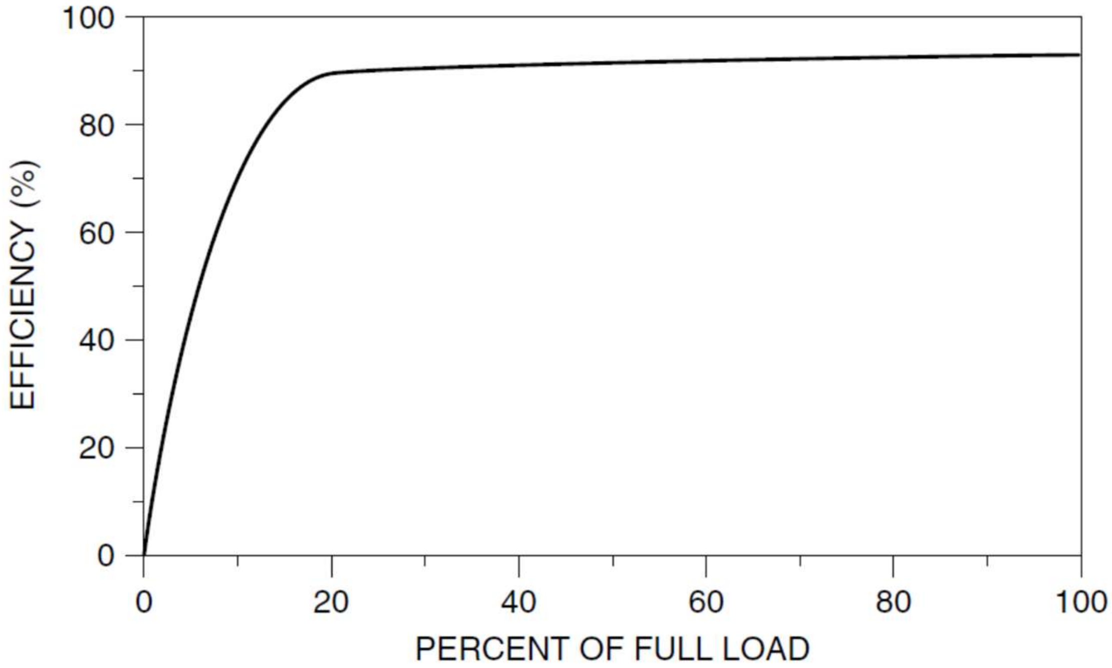


Even in full sun, the impact of these losses can easily derate the power output by 20–40%.

ö emotional damage

Efficiency of the inverter

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

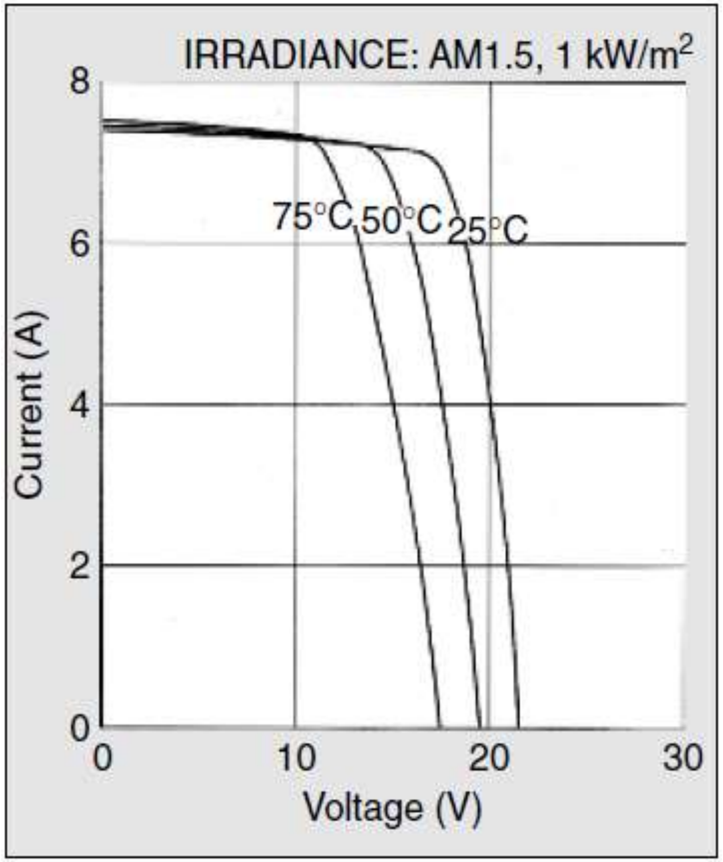


↑ loading, ↑ inverter η

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 I_{SC} increases by 0.05% per degree C
- **MPP drops by approx 0.5% per deg C**

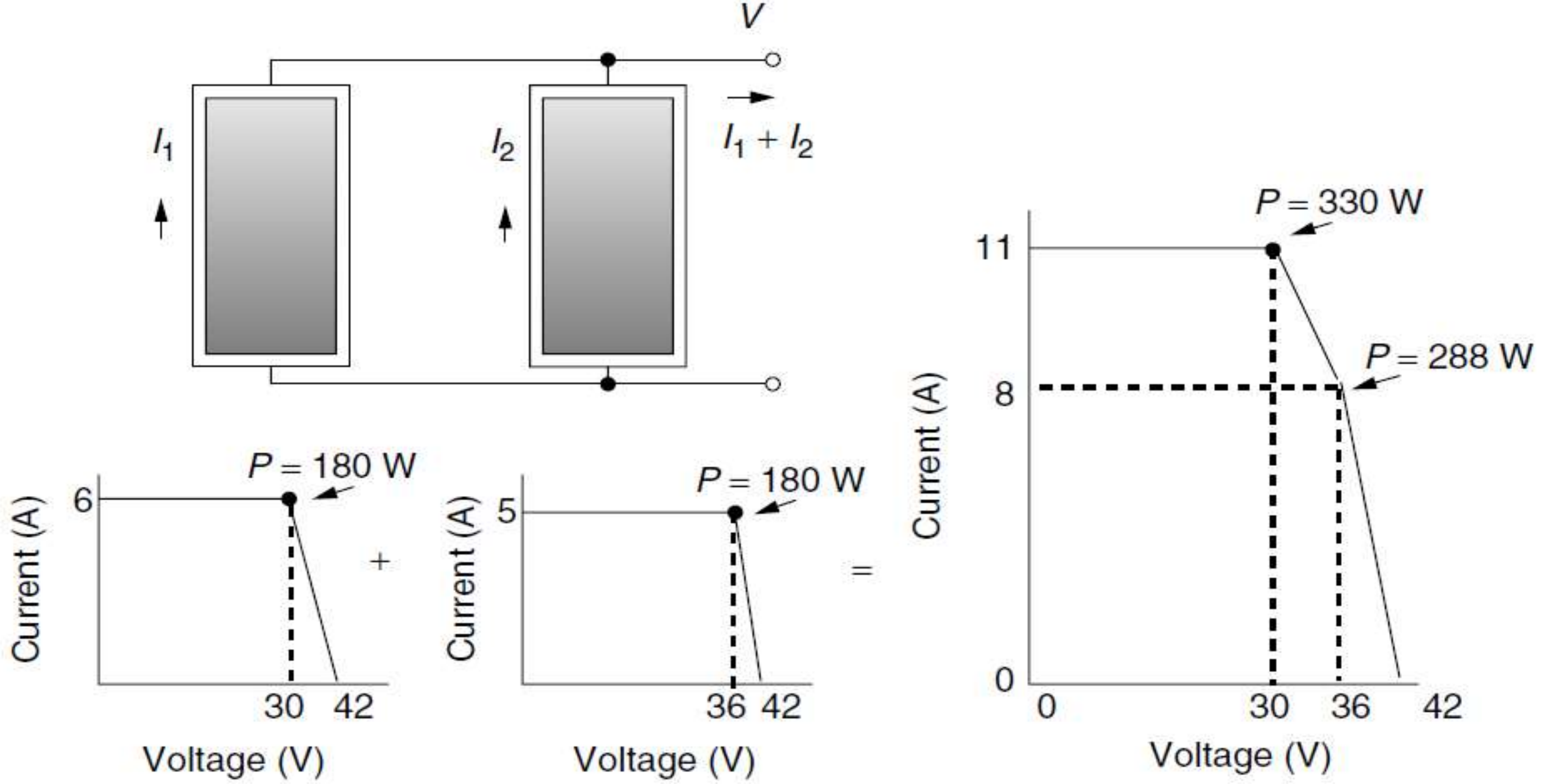
$\uparrow T, \downarrow \eta$



in reality, modules don't add up perfectly...

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◦C . DC power output at the MPP drops by 0.5%/◦C above the STC temperature of 25◦C. 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%.

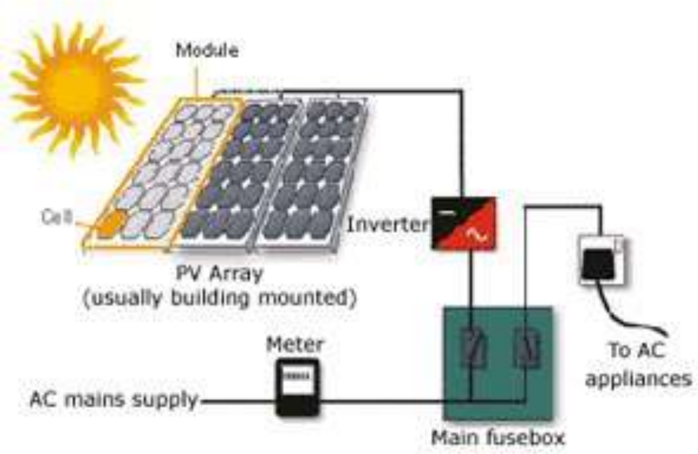
Solution:

With power loss at 0.5% per degree above 25◦C, the dc rated power of the array would be

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

Including mismatch, dirt, and inverter efficiencies will result in an estimated ac rated power at PTC of

$$P_{ac} = 0.856\ \text{kW} \times \underline{0.97} \times \underline{0.96} \times \underline{0.90} = 0.72\ \text{kW}$$

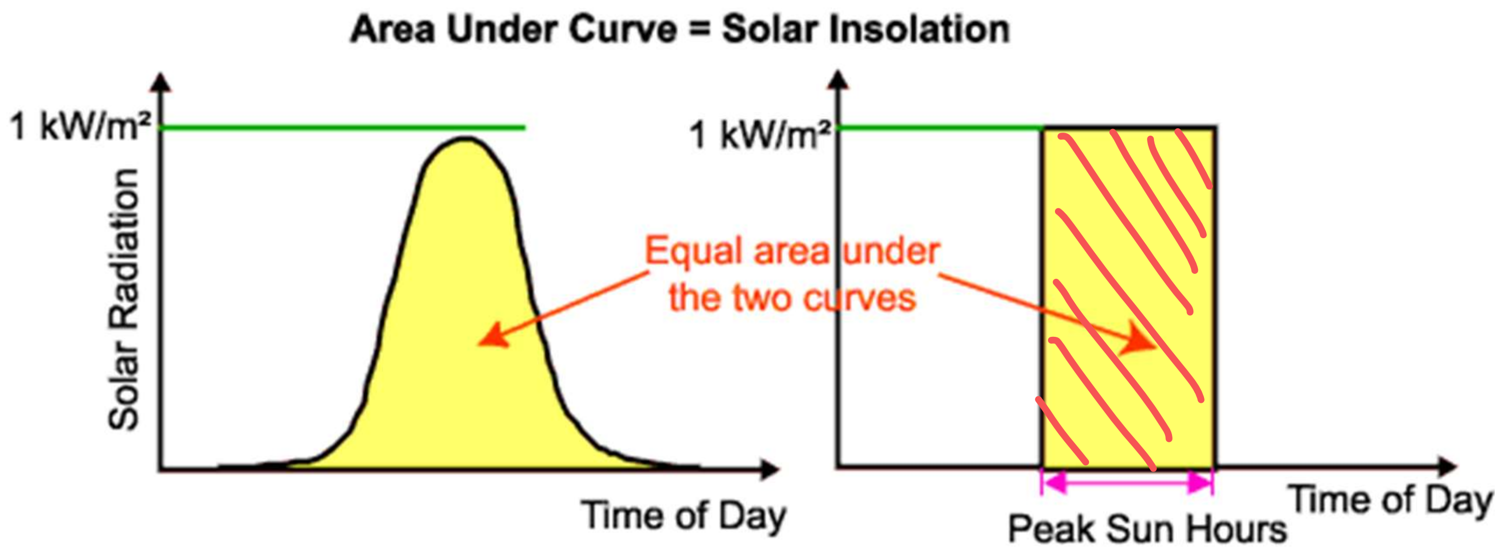


Even though the system would be sold as a “1-kW system”, the array will deliver **only 72%** of that as ac power to the load under realistic conditions

Peak Sun Hours

- **The term "peak sun hours" refers to the solar insolation which a particular location would receive if the sun were shining at its maximum value for a certain number of hours.**

- For example, a location that receives 8 kWh/m^2 per day can be said to have received 8 hours of sun per day at 1 kW/m^2.



↳ we want to know how many sun hours at max. insolation

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

$$\text{Energy (kWh/day)} = \text{Insolation}\left(\frac{\text{kWh/m}^2}{\text{day}}\right) \cdot A\ (\text{m}^2) \cdot \overline{\eta}$$

Capacity Factors for PV Grid-Connected Systems

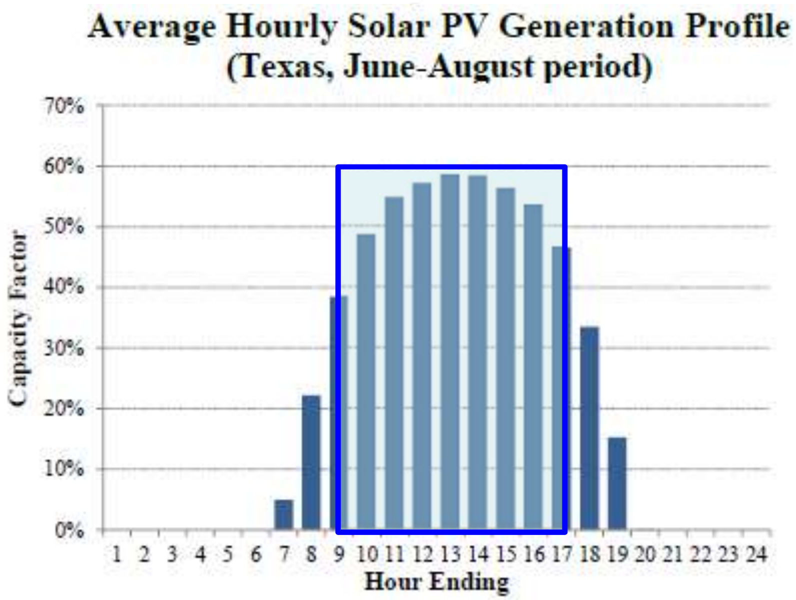
(1)

- If the system delivered full, rated power continuously, the CF would be unity.
- the energy delivered by the system in terms of its rated ac power and capacity factor (CF).

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

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

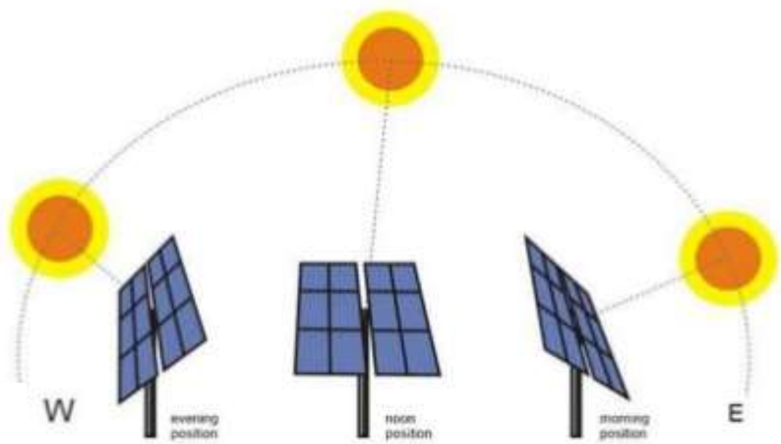
$$\text{Capacity factor (CF)} = \frac{(\text{h/day of “peak sun”})}{24 \text{ h/day}}$$

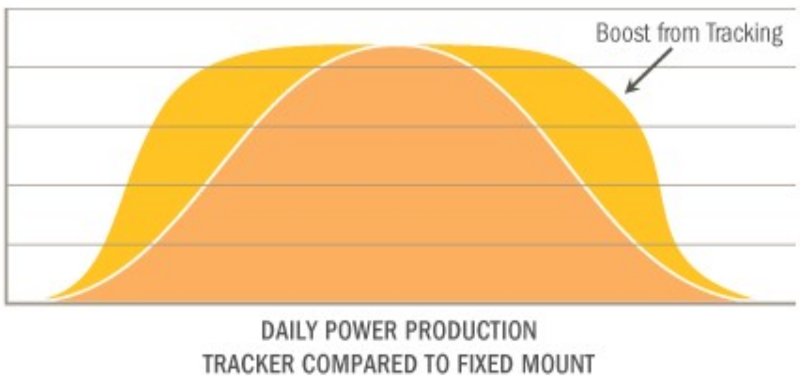


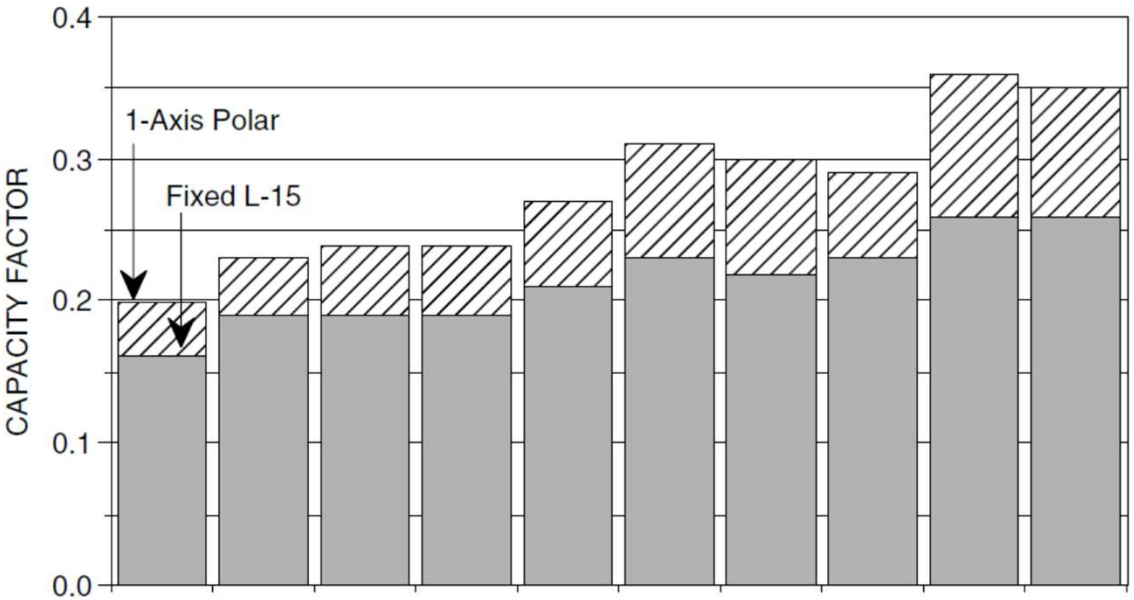
Source: Calculated based on 8,760 hourly generation data from NREL's Solar Advisor Model (SAM) version 2011.6.30.

Capacity Factors for PV Grid-Connected Systems

Single-Axis Solar Tracker







The tracker can substantially increase the power output of a solar PV system

Grid-connected PV system design

1. Estimate the rated power and area required for the PV array.

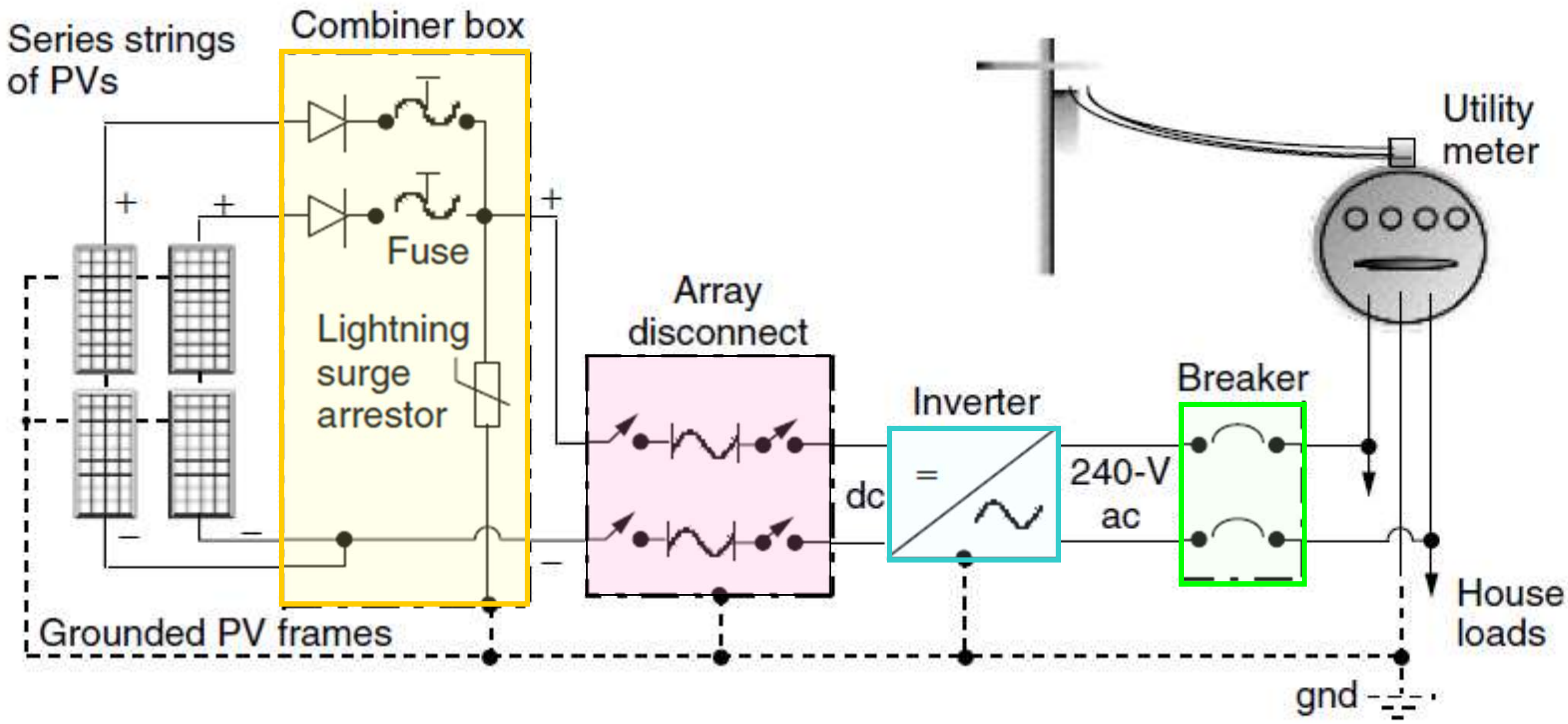
2. Explore the interactions between the choice of PV modules and inverters and how they impact the layout of the PV array.

3. Finally, consider details about voltage and current ratings for fuses, switches, and conductors.

Grid-connected PV Systems

Grid-connected system using a single inverter

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



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.

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

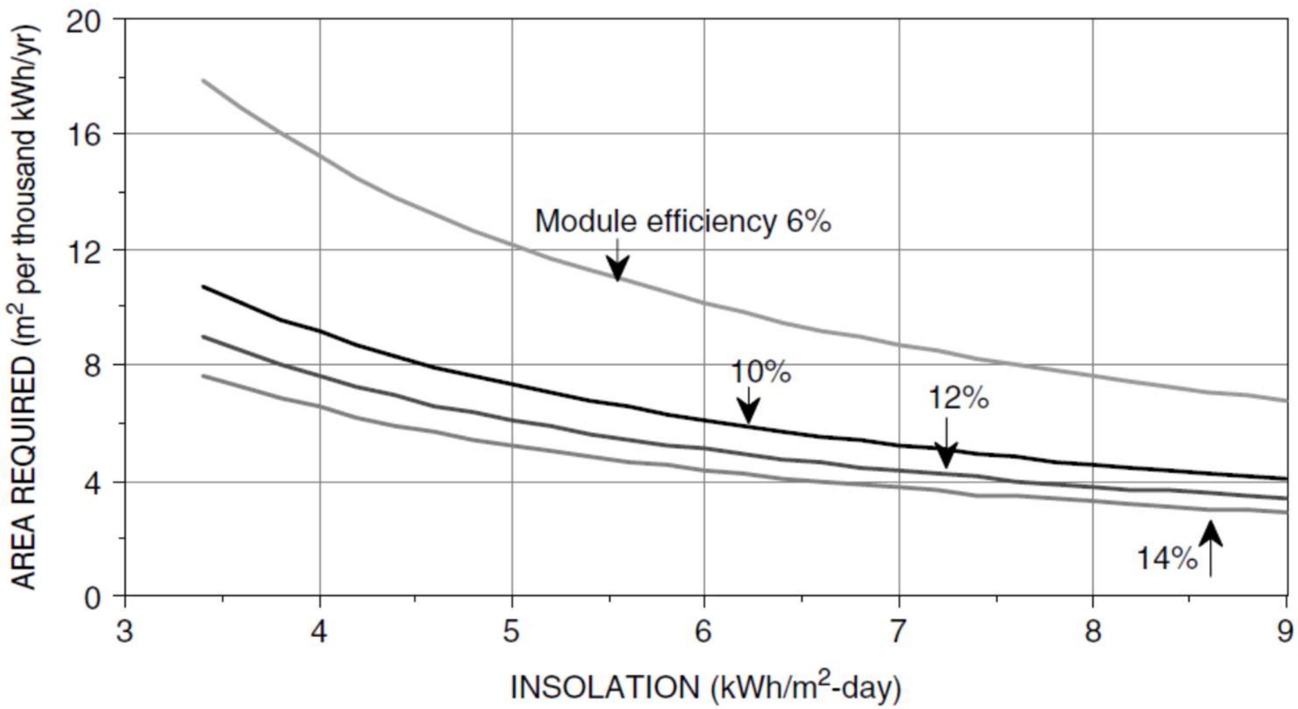
To estimate the collector efficiency, P_{dc} = 1 kW/m^2 insolation · A (m^2) · η

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%

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

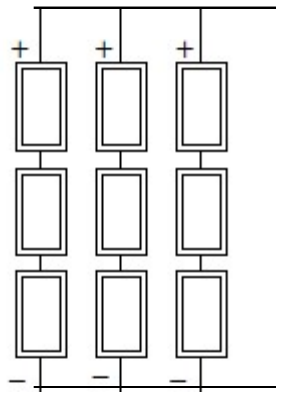
Example: System sizing (more accurate calculation)

- 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)

Example: 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

25% safety margin

Combiner fuses > 7.58 A × 1.25 = 9.475 A

- The array disconnect fuse must accommodate three such strings, so it must handle

3 strings!

Array disconnect fuse > *9.475 x 3* = 28.425 A

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
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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%

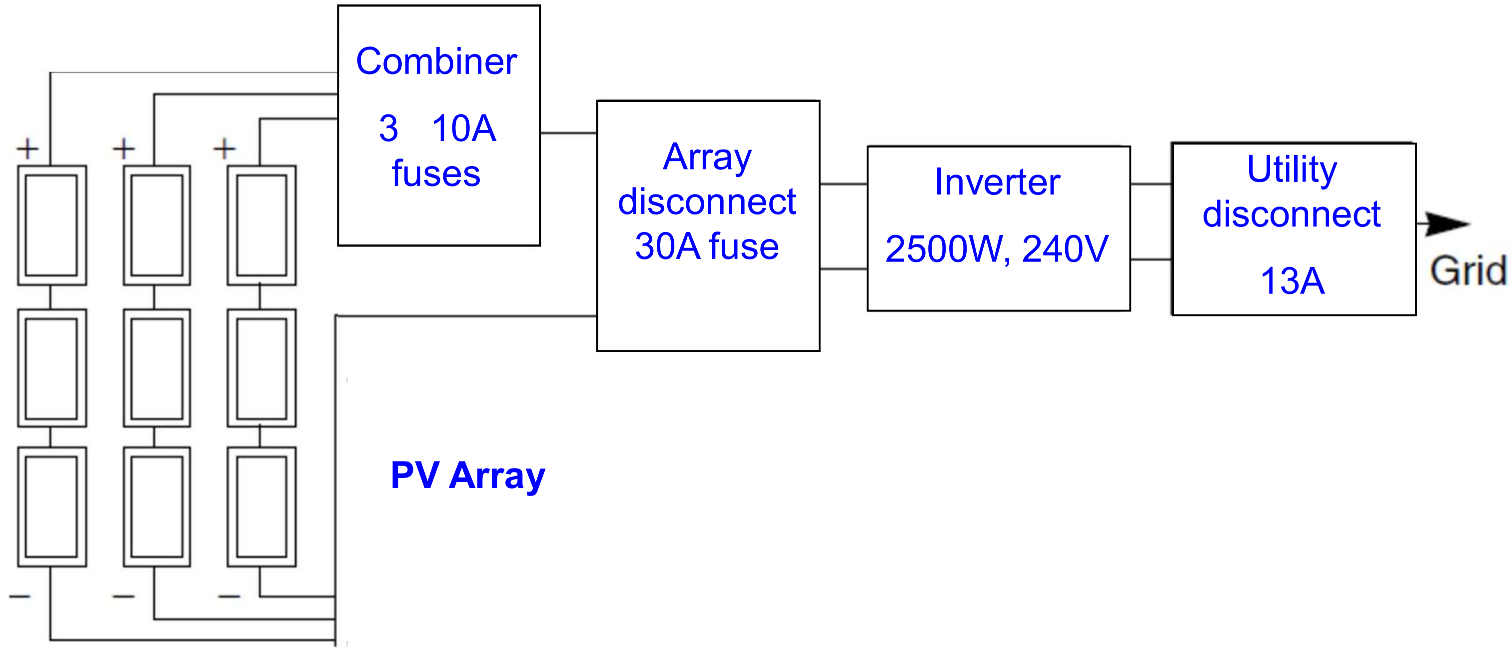
Example: System sizing

- $$\text{Inverter fuse} > 1.25 \times \frac{2500\ \text{W}}{240\ \text{V}} = 13\ \text{A}$$

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%

Example: System Design

- Complete system



System Integration

PV System Integration Parameters

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

Overall reduction in the power to be generated

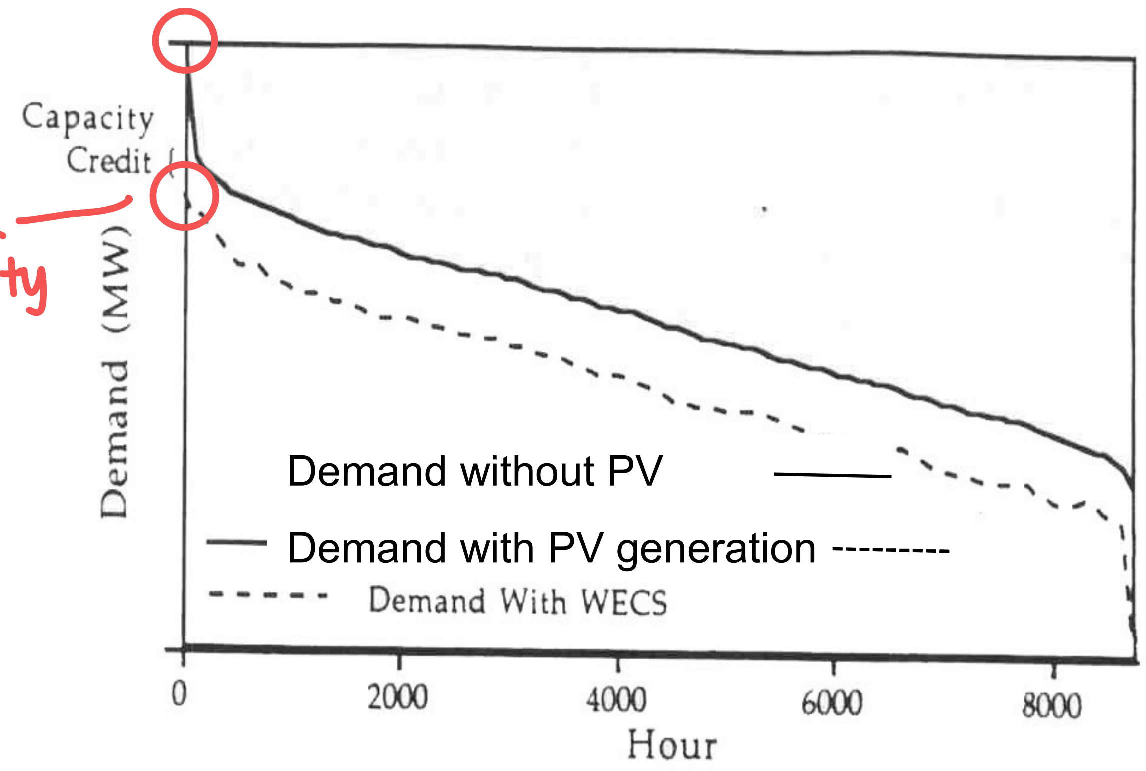
Capacity displacement

Which type of capacity does the inclusion of PVs displace

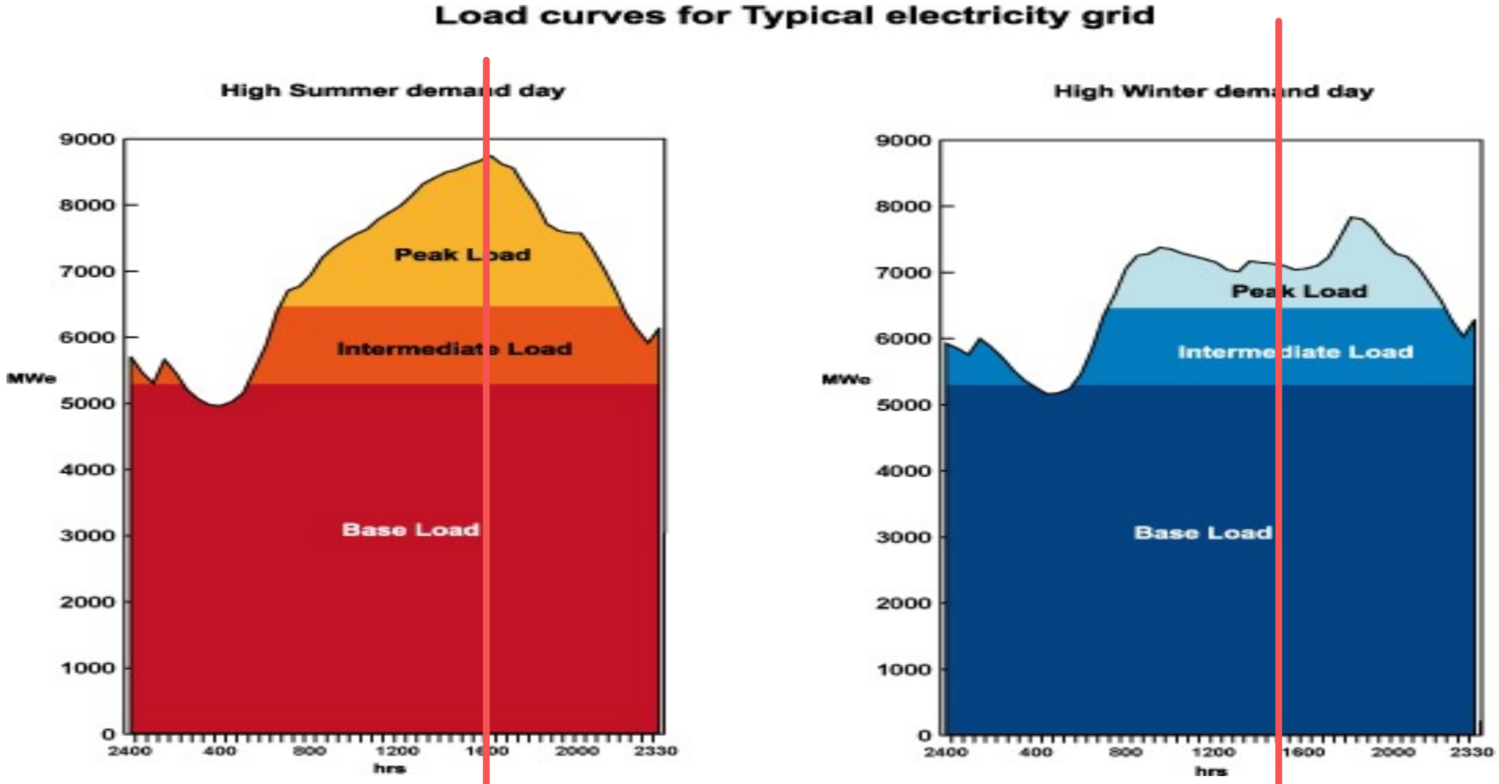
- in terms of short run operation, and
- long run construction needs

- Net load duration curve

↓ peak capacity



Overall reduction in the power to be generated



afternoon time!

afternoon time!

max. sunlight
↳ good for PV system

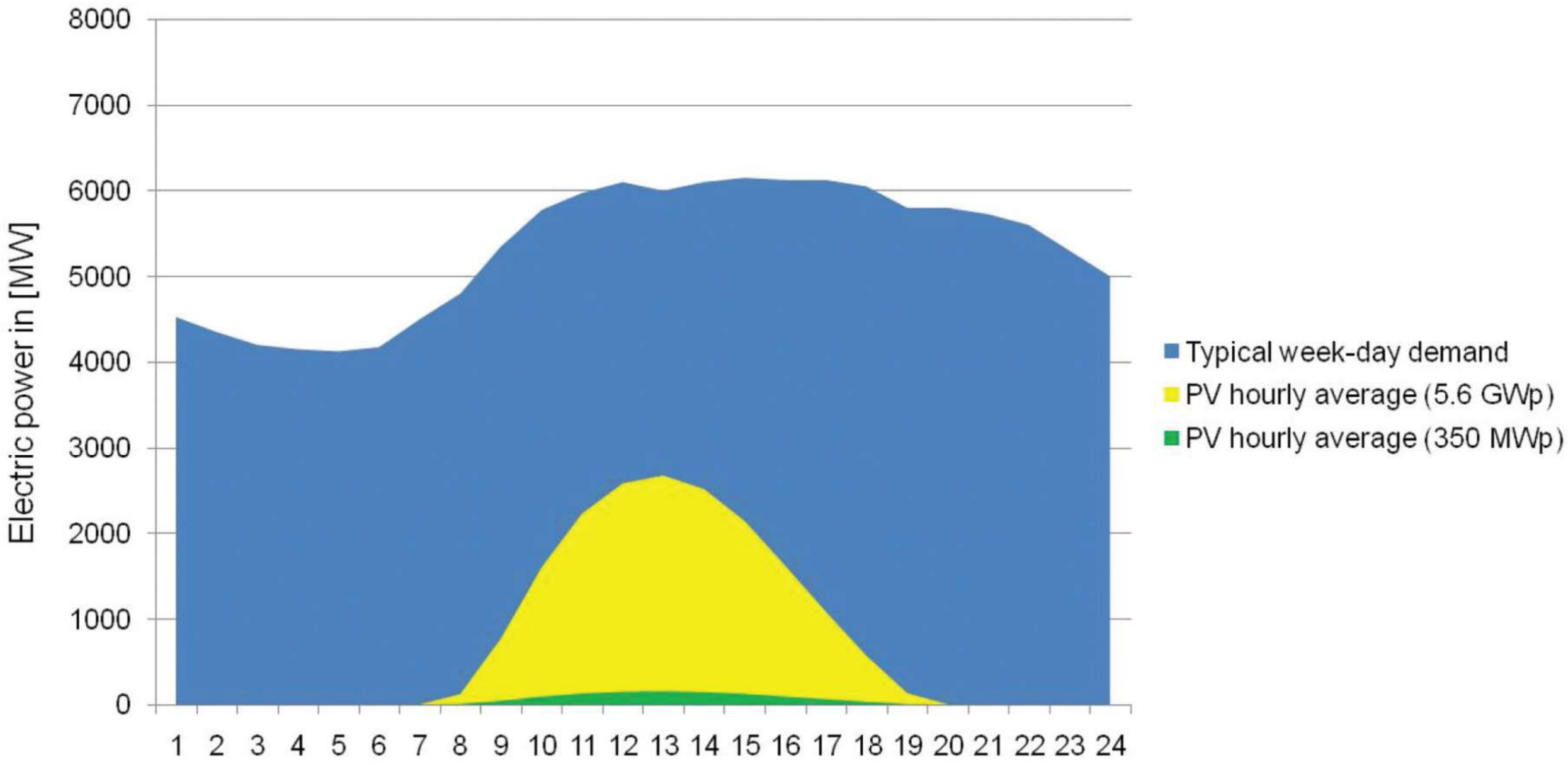
Solar generation displaces some of the demand that leads to peaking plants being activated.

Capacity displacement

- PV generation has huge potential to reduce peak load
- Capital expenditure on installation of utility generators is therefore reduced

↓peak load

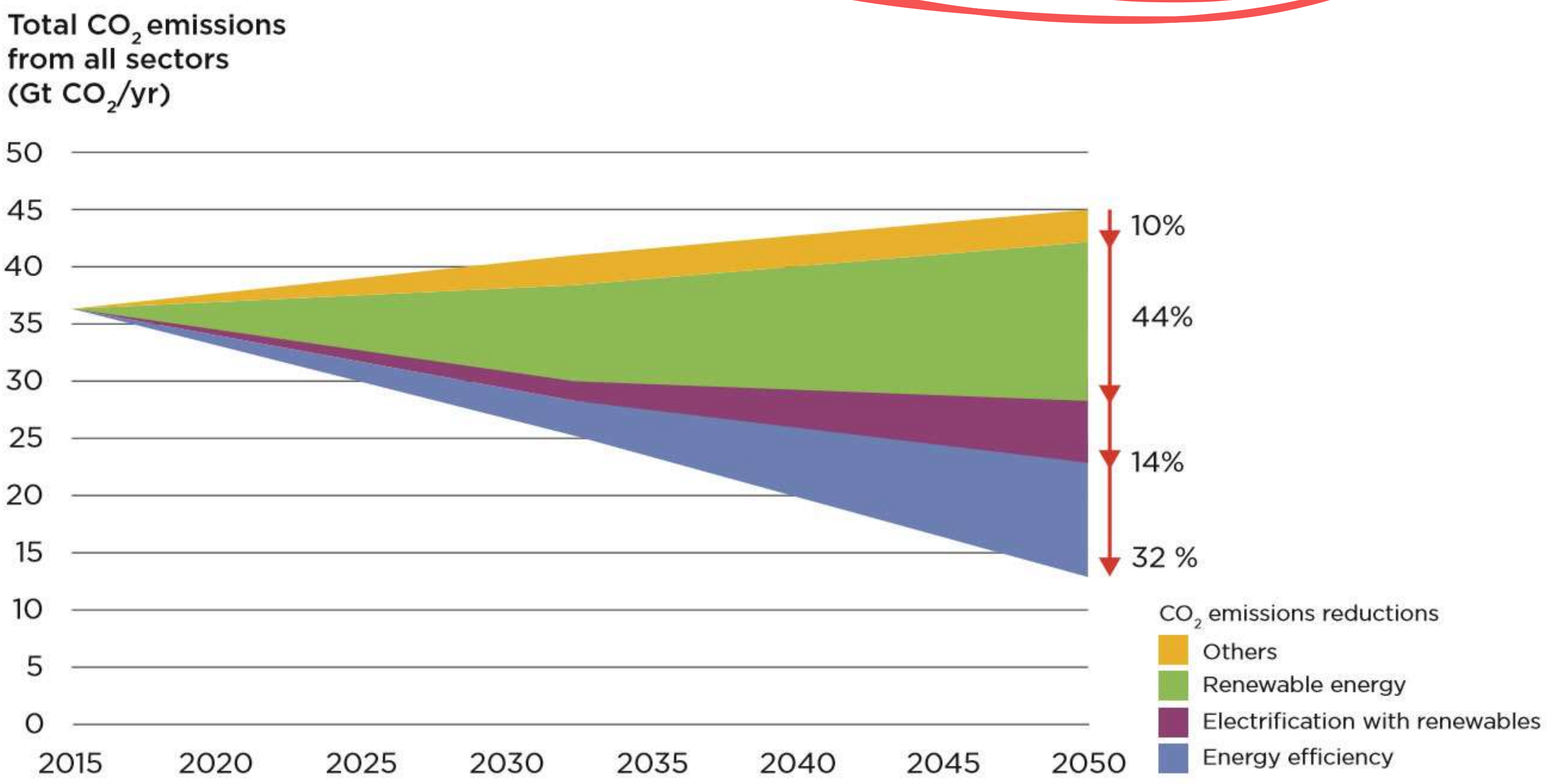
Case study in Singapore:



(Source: Phoenix Solar)

System Integration: Emission Reductions

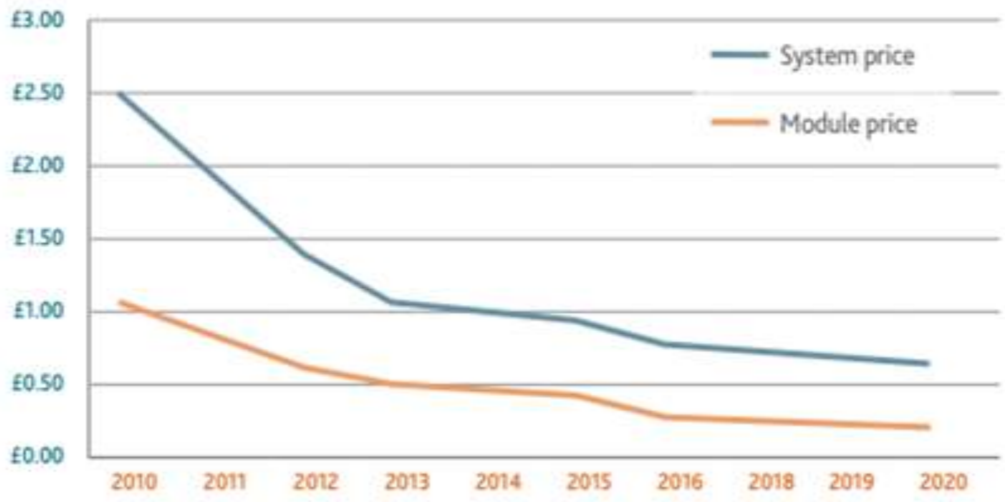
- Overall emissions decrease both from demand management/conservation and from new supply options
- **Energy Emissions Can Be Reduced 70% By 2050**



Source: IEA & IRENA Report

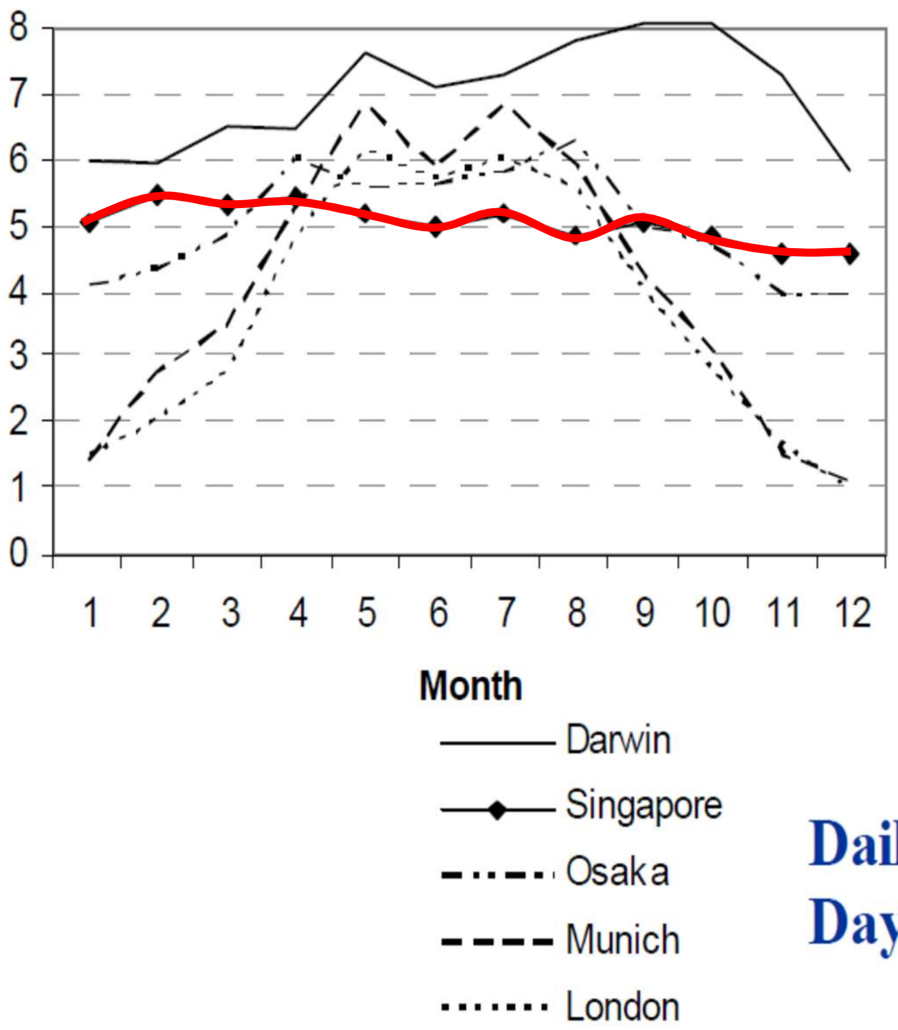
Cost of electricity

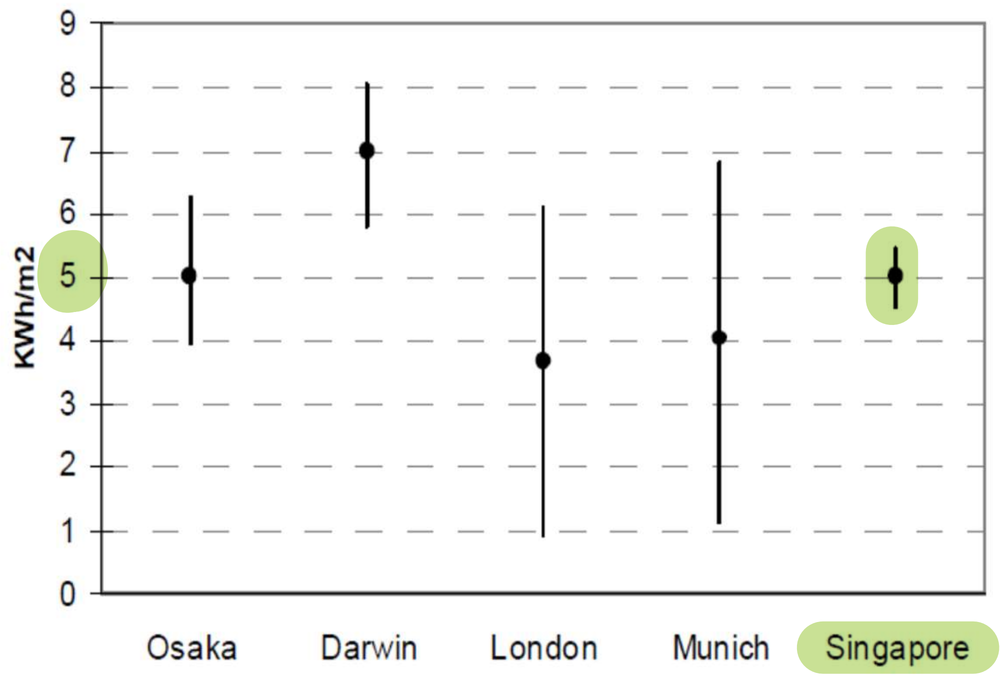
- The energy output of such PV plants reaches it's peak at midday, meeting the daily energy consumption peak, when the spot prices on energy are highest
- **Grid parity: the point at which the costs are equal to grid power**
- PV-generated electricity is usually more expensive than conventional utility-supplied electricity.
- PV power requires a high initial investment but very low running costs



Cost of electricity from PVs

Daily global solar radiation





Daily Global Solar Radiation Charts

Daylight = Sunlight + Skylight

SG: ~5 kWh/m²

Renewable Energy potential in Singapore

Source NEA

Non-existent

Non-existent

Local sources fully-utilized

Low wind speeds

Low tidal range

High and even irradiation - Greatest potential

Solar energy has the greatest potential!

Singapore rooftops could generate 20% of electricity*

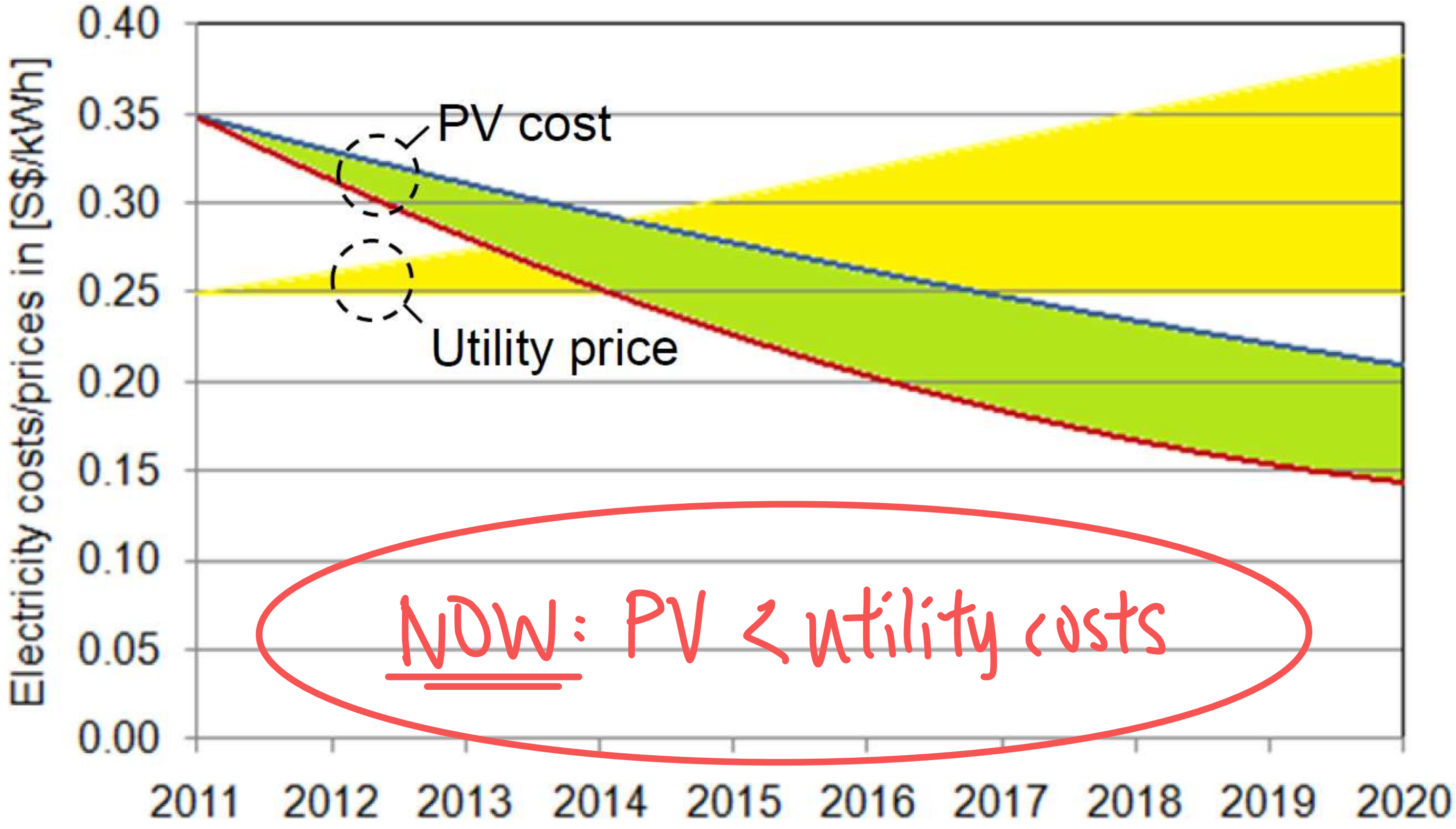
Singapore has 100km^2 of "free" real estate for PV

- Built-up land exceeds 260km^2
- Conservative estimate = 100km^2 of roof + useful facade space)
- 10GW of PV capacity can generate 20% of Singapore's electricity!

* 2016 electricity consumption = 48 TWh (source: EMA)

(Source: Phoenix Solar)

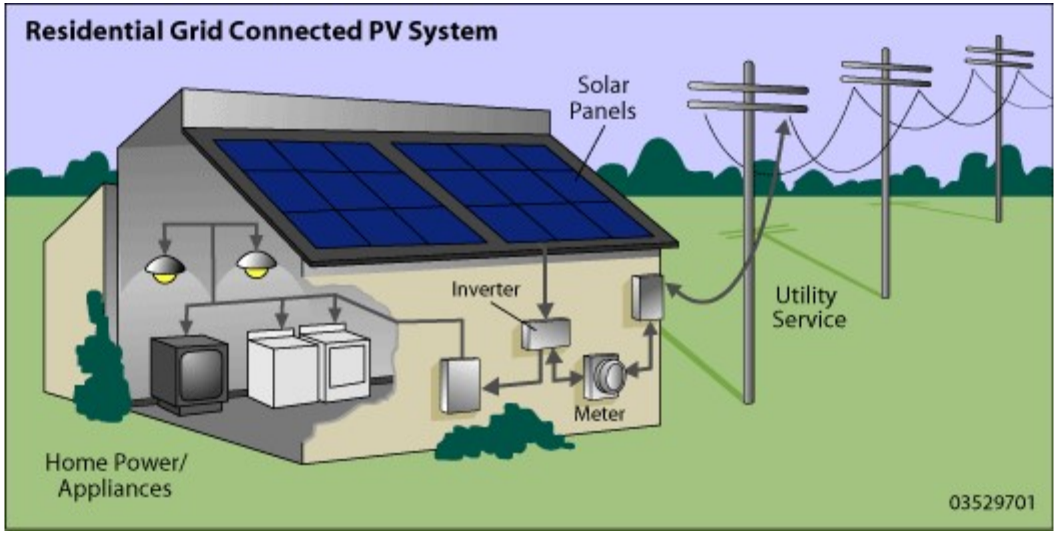
Cost of PV electricity in Singapore (Source: SERIS)



Singapore achieved grid parity in 2012 — when the cost of installing and maintaining solar photovoltaic (PV) panels became the same as that from the grid (conventional sources)

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? utility company benefits from this ↓demand, NOT owners ⇒ why would owners spend $ to benefit others???
- 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

ugly tho...

Flat Roof and Wall Installations

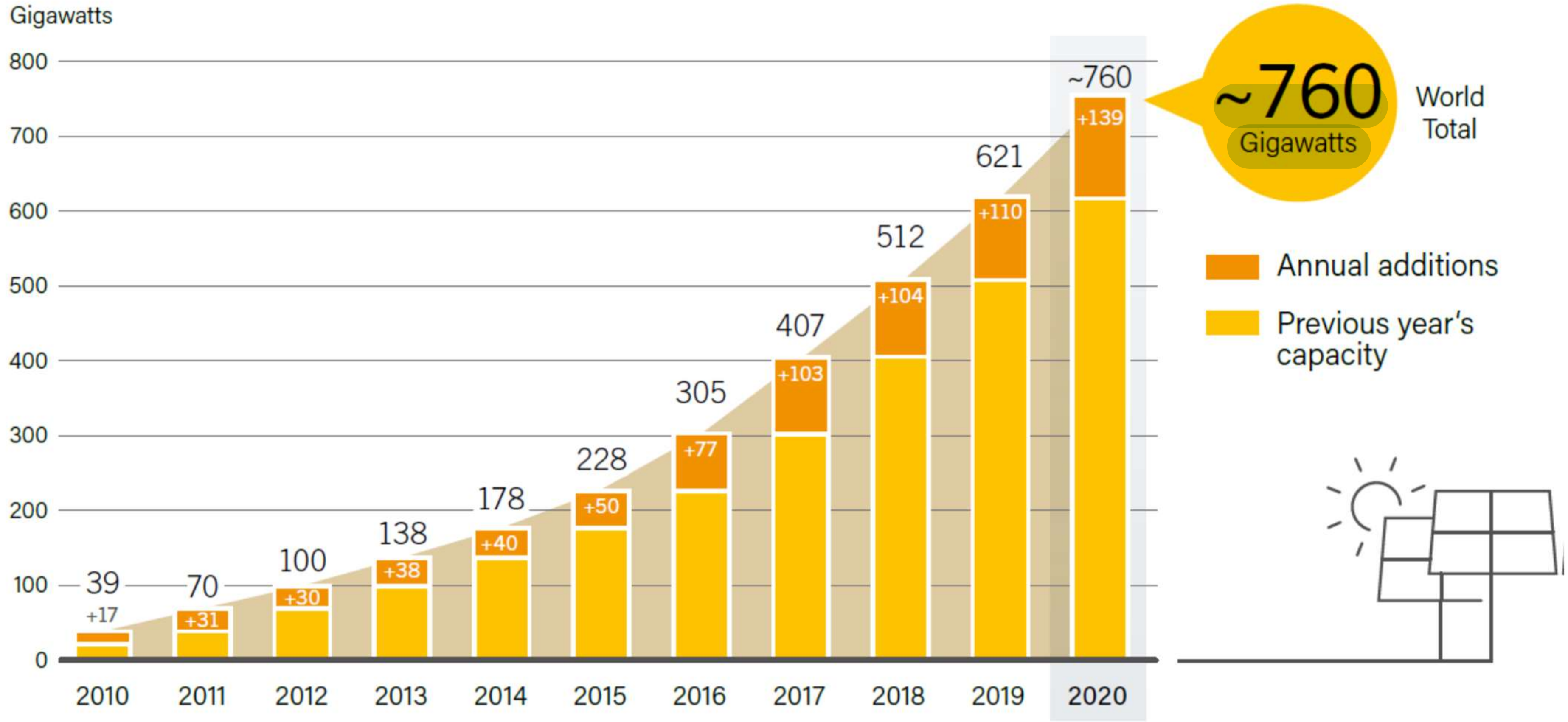
- Integrated PV may be more acceptable

Building Integrated PV in Tampines Grande project (Phoenix Solar)

Net Zero Energy Building in NUS

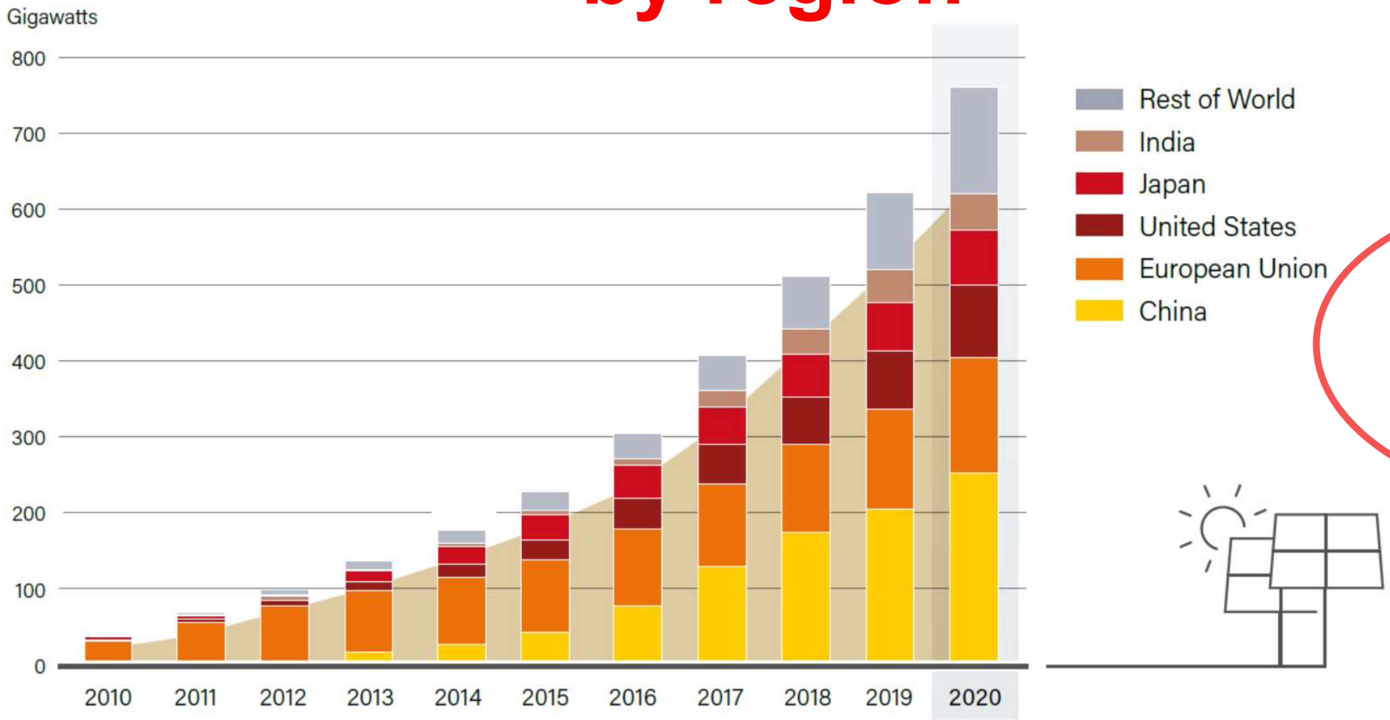
Solar PV: Current Status

Solar PV Global Capacity and Annual Additions (2010-2020)

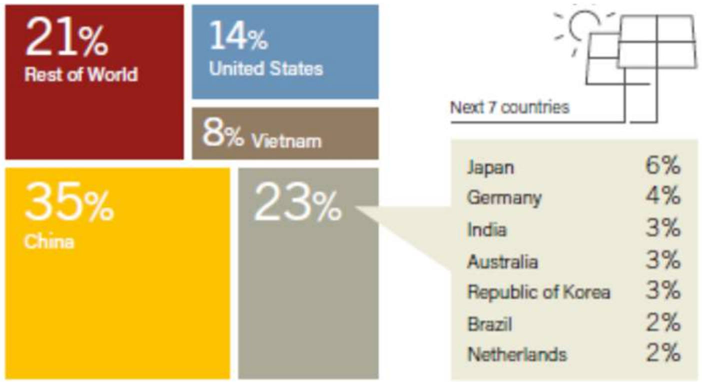


- Solar PV saw a rapid growth in 2020, driven by favourable economics and policy changes.
- About 140 GW was added in 2020 (large scale PV systems and distributed rooftop installations)

Annual Installed PV capacity (2010-2020) by region



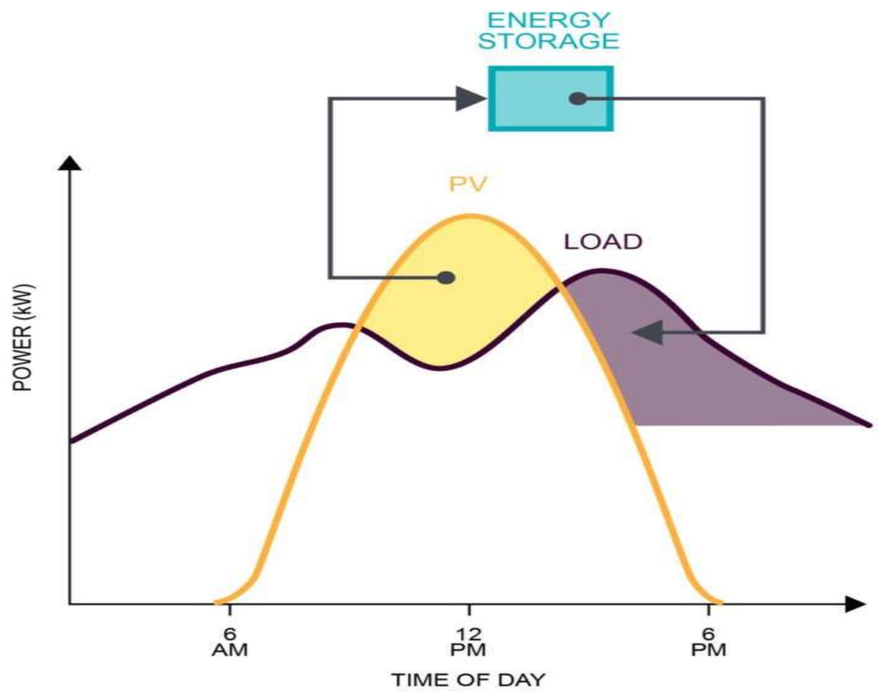
CHINA



- China is the global leader.
- Asia accounted for nearly 60% of new PV installations
- Increased interest in home improvements during the pandemic helped drive demand for residential systems around the world

Source: REN21 Renewables 2021 Global Status Report

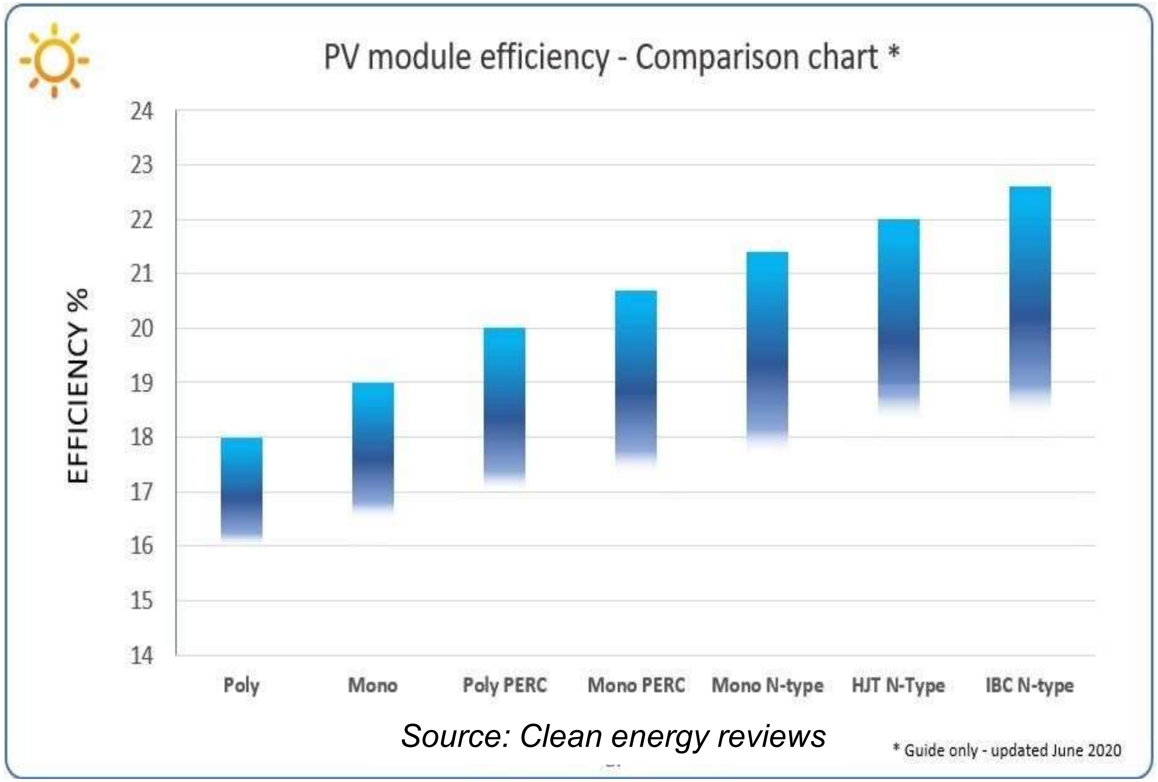
Integrated PV-Storage Systems Provide Several Benefits



Integrating PV with properly designed energy storage systems can provide a combination of financial, operational, and environmental benefits through peak shaving and reliability applications.

Efficiency of Commercial PV Modules

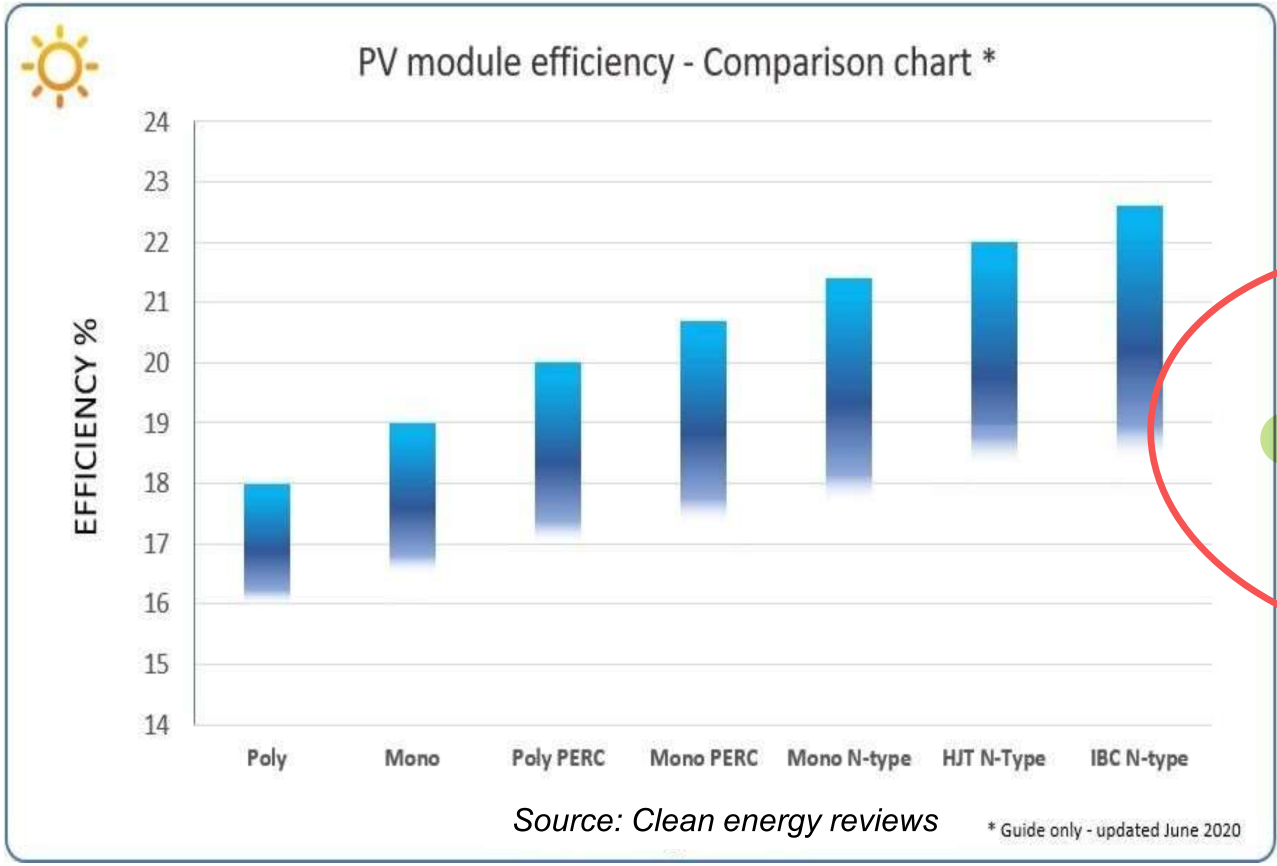
- The average panel conversion efficiency has increased from 15% ten years ago to well over 22%
- Thin Film technology (e.g. from First Solar) shows promise
- Spectrolab, a subsidiary of Boeing, has developed multi-junction solar cells with an efficiency > 40%, a new world record for solar photovoltaic cells!



Source: Clean energy reviews

Efficiency of Commercial PV Modules

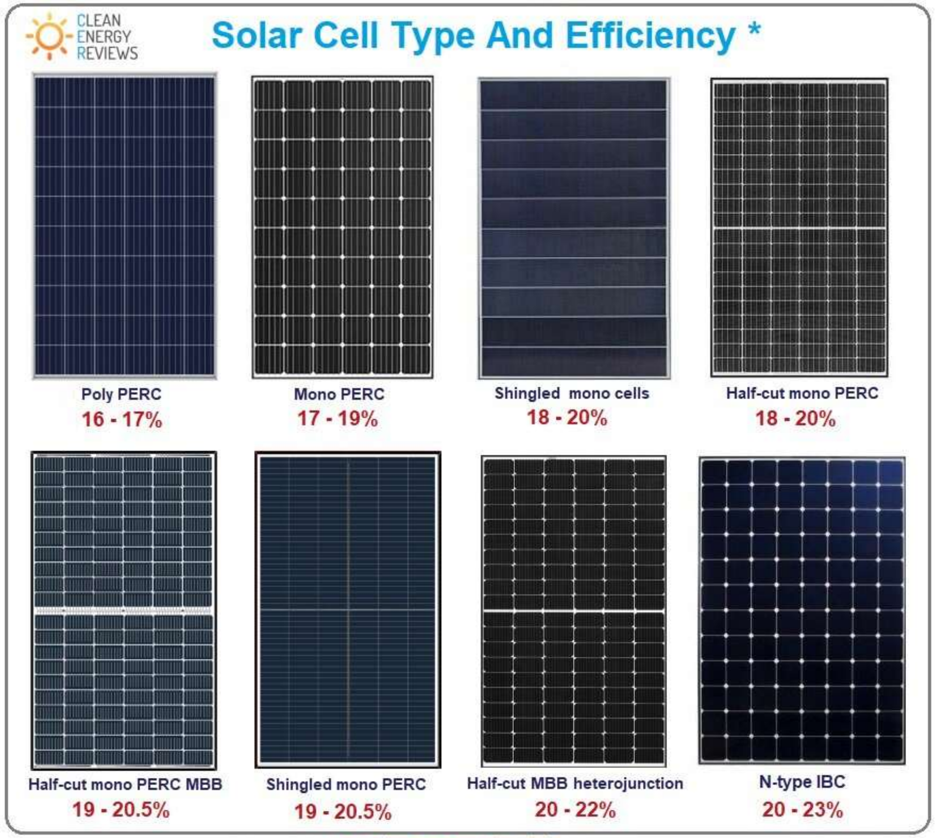
- Currently, the best achieved solar module efficiency is around 22.5%
- The average panel conversion efficiency has increased from 15% ten years ago to well over 22%



Source: Clean energy reviews

Efficiency of Commercial PV Modules

- **Cell efficiency** is determined by the cell structure and base silicon material used which is generally either P-type or N-type.
- Cell efficiency is calculated by the fill factor (FF), which is the maximum conversion efficiency of a PV cell at the optimum operating voltage and current.



Source: Clean energy reviews

- Panels built using advanced 'Interdigitated back contact' (IBC cells) are the most efficient, but also very costly
- Recent heterojunction (HJT) cells have achieved efficiency levels well above 20%.

- Thin Film technology (e.g. from First Solar) shows promise
- Spectrolab, a subsidiary of Boeing, has developed multi-junction solar cells with an efficiency > 40%, a new world record for solar photovoltaic cells!

Largest solar PV projects in recent years

Project Name	Country	Year	Capacity (MW)
Bhadla Solar Park	India	2018	2250
Huanghe Hainan Solar Park	China	2020	2200
Pavagada Solar Park	India	2020	2050
Benban Solar Park	Egypt	2019	1650
Tengger Desert Solar Park	China	2016	1547
Noor Abu Dhabi	UAE	2019	1200
Mohammed bin Rashid Al Maktoum Solar Park	UAE	2020	1013
Kurnool Ultra Mega Solar Park	India	2017	1000
Datong Solar Power Top Runner* Base	China	2016	1000
NP Kunta	India	2018	978
Villanueva Solar Park	Mexico	2018	828

- These Utility-scale solar plants generate reliable, clean electricity with a stable fuel price.
- Many utility-scale solar designs can also include energy storage capacity that provides power when the sun is not shining, and increases grid reliability and resiliency.
- In some places, solar plants are grouped together in solar parks or clusters, leading to even higher capacities.

Bhadla Solar Park, India

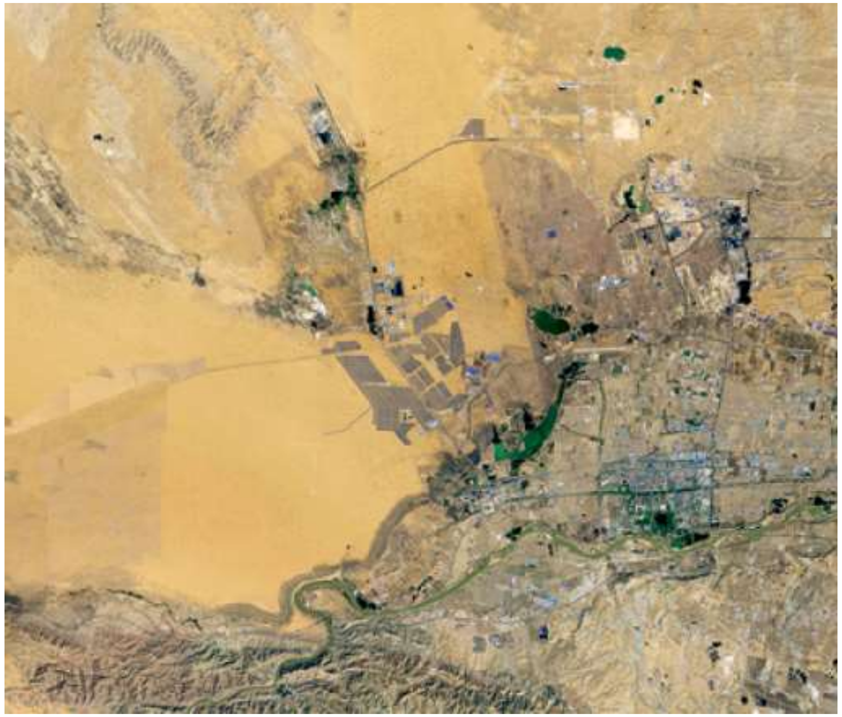
- Total capacity: 2250 MW
- World's biggest solar power plant
- Located in Jodhpur district, Rajasthan
- Comprises of 10 million solar panels, which are cleaned using robots
- Produces electricity at approx \$0.05/kWh (₹2.44/kWh), which is much lower than the utility's tariff of \$0.065/kWh

Huanghe Hydropower Hainan Solar Park, China

- World's second largest solar PV plant
- Total capacity: 2200 MW
- Located in Qinghai
- Includes an energy storage system of 202.9 MW supplied by domestic company Sungrow.
- It is part of a giant renewables project, which is planned to reach 16 GW (with 10 GW Solar PV and 1 GW Concentrated Solar Power)

Tengger Desert Solar Park, China

- Total capacity: 1547 MW
- Fully operating since: 2016
- Located in Ningxia, in the Inner Mongolia Autonomous Region in China
- Dubbed the ‘Great Wall of Solar’, it covers 1,200km of the 36,700km Tengger desert, occupying 3.2% of the arid region.



Kurnool Ultra Mega Solar Park, India

- PV capacity: 1000 MW
- In operation since 2017
- Located in Andhra Pradesh
- Over four million solar panels were installed in the park, each with a capacity of 315W or 320W.
- Produces electricity at approx $0.074/kWh

Villanueva solar park, Mexico

- Total capacity: 828MW
- In operation since 2018
- Located in the Mexican state of Coahuila, just south of the Texas border
- The facility comprises over 2.3 million solar panels across 2,400 hectares
- Largest solar PV park in the Americas

Lonyangxia Dam Solar Park, China

- Total PV capacity: 850 MW
- Fully operating since: 2015
- Integrated with the hydroelectric power station with a capacity of 1280 MW (4 hydroelectric generators, 320 MW each)
- The site sits on the Tibetan Plateau in northwestern China's Qinghai province
- Hybrid operation - automatically regulates the output to balance the variable generation from solar before dispatching power to the grid.

Solar PV current status

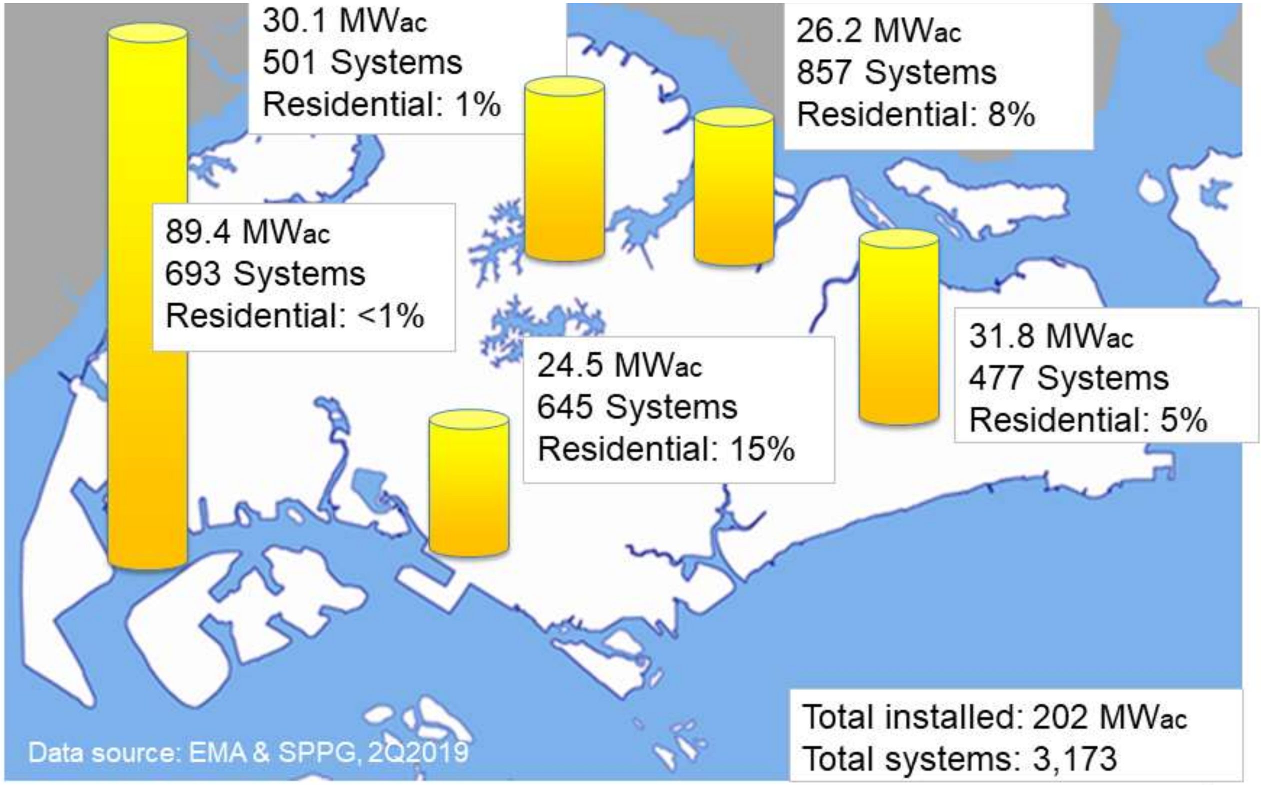
- Record efficiencies for solar cells of various materials are produced every year. Many research institutions are still exploring new materials and also tandem solar cells (multiple layers of solar cells absorbing different portions of the spectrum). Nevertheless, crystalline Silicon solar cells still dominate the market.

- China is leading the way in terms of manufacturing of components (solar cells, modules, inverters) as well as installation thanks to the government investment, but the domestic Chinese market is getting saturated with as much as 30% of the solar energy gets curtailed at some hours in the year

- Bifacial solar modules (solar modules that can capture light on both sides are gaining popularity, and so are building integrated PV (the solar modules are replacing building materials such as glass or roof)

- Solar PV, combined with batteries, can be the most economical solution to power remote areas with no grid access.

Solar PV current status
- PV Installation in Singapore



- Solar energy is the most promising renewable energy source for Singapore
- Singapore has an average annual solar irradiance of 1,580 kWh/m2/year
- Installations by end of 2020: 350 MWp
- **Singapore could be 25% solar-powered by 2025 (hoping to keep its** climate change pledge to reduce emissions intensity by 36 percent from 2005 levels by 2030)

Source: EMA and SERIS

Solar PV current status

Main challenges:

- Efficiency of single layer/material solar cells are getting closer to theoretical efficiency of 30%
- May still not be competitive in developing countries with low electricity prices (artificially low or otherwise)
- Most utilities are still wary of solar intermittency
- Batteries are still very expensive, both for remote communities, and for grid operators

Rise of Floating PV (Floatovoltaics)

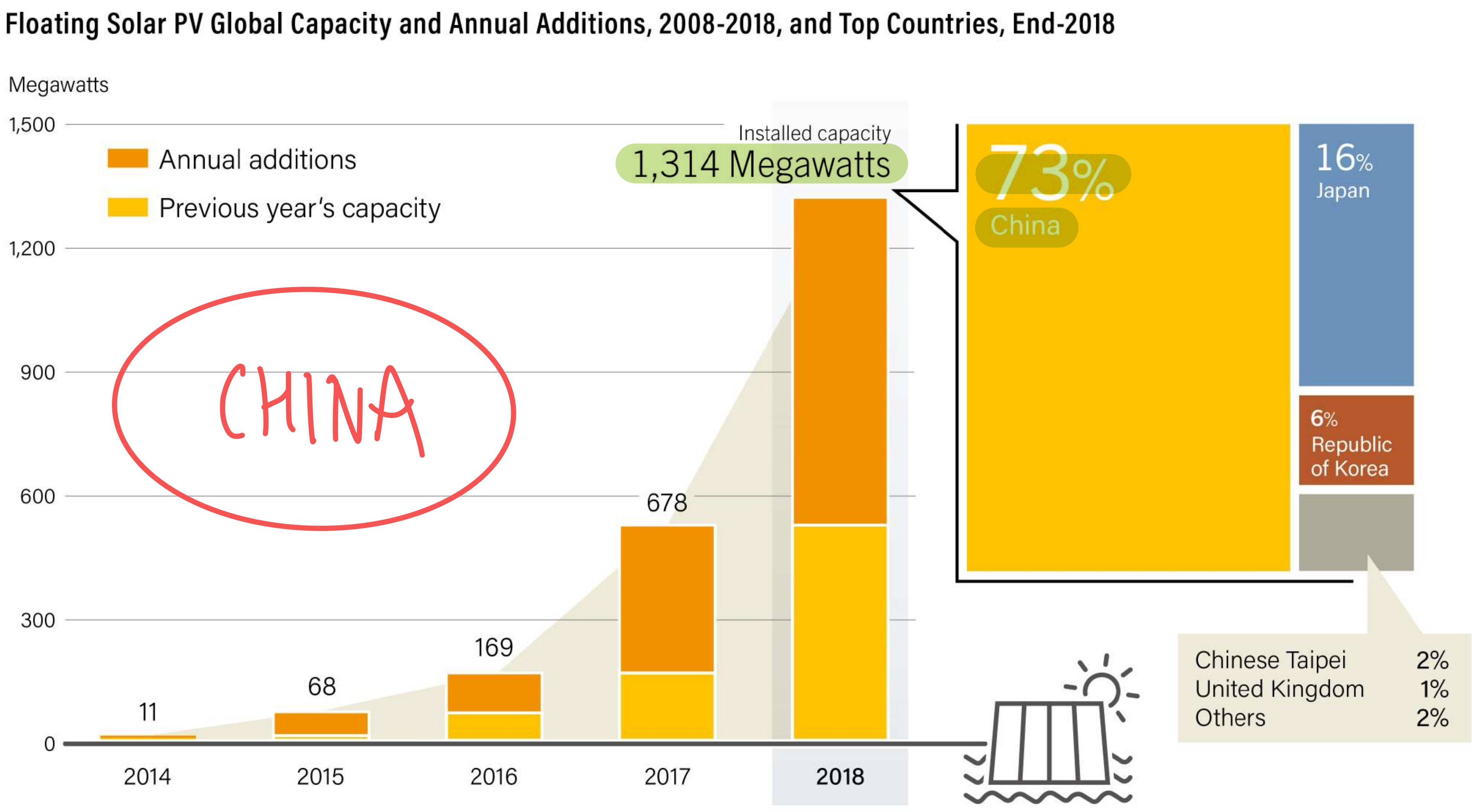
Advantages:

- cooling effect from the water body → higher efficiency
- doesn't occupy land
- No fixed structure (installation is reversible)
- Reduced water evaporation

Disadvantages:

- Higher operational and maintenance cost
- Complicated anchor and mooring for changing water level

Rise of Floating PV: Current status



Source: World Bank Group, ESMAP and SERIS.

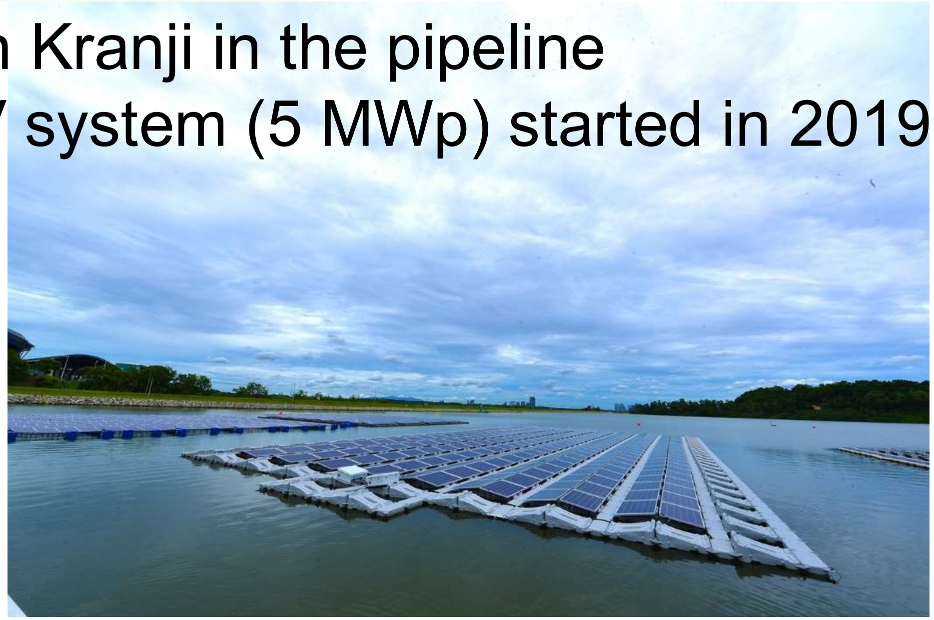
Rise of Floating PV : Current status

Global:

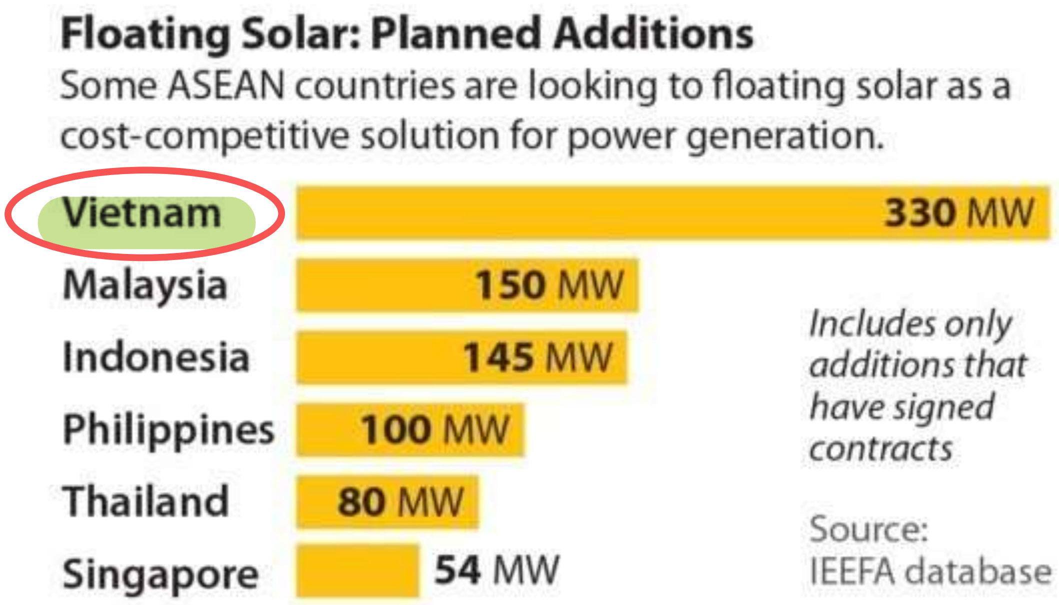
- Installed capacity now > 1 GWp
- Largest markets: China, Japan, Korea
- Largest system sizes: up to 150 MWp
- Prices from auctions <0.8 $/Wp

Singapore:

- Tengeh testbed still largest worldwide
- A new plant of 100 MWp in Kranji in the pipeline
- First Off-shore Floating PV system (5 MWp) started in 2019



Floating solar farms in Southeast Asia



- More ASEAN countries are building floating solar farms to produce electricity at prices that can compete with coal-fired power

- Floating Solar PV can help insulate coal-importing ASEAN countries from the risk of volatile fuel prices and the expensive supply logistics of the global fossil fuels market

Source: Institute for Energy Economics and Financial Analysis (IEEFA)

Advantages of solar PV

- PV generation coincides with periods of peak demand (cooling in the summer)
- No moving parts --> Very low maintenance cost
- Moderate net energy

- Moderate environmental impact
- No emissions
  (note: there are emissions during the process of manufacturing of solar PV modules)

Disadvantages of solar PV

- Unavailable at periods of high heating demand (for heating in countries with winter)
- Highly variable and intermittent
  ↳ dependent on weather etc.
- High upfront investment cost
- Require large area

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