



Solar Photovoltaic (PV) systems

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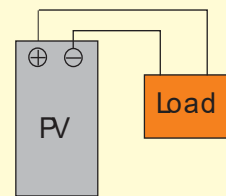
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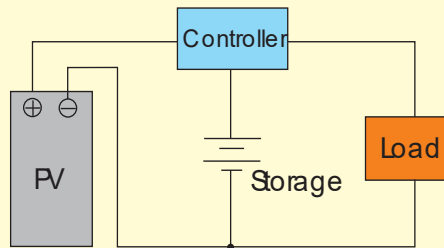
- ❑ Categories of solar PV systems
- ❑ Solar cells to solar PV arrays



a. Good for some daytime uses.

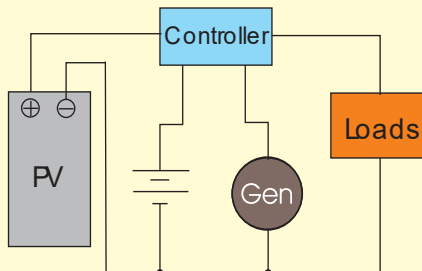


a. PV connected directly to load

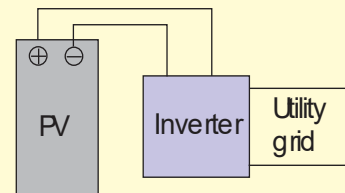


b. Controller and battery storage included

c. Fossil generators can provide backup battery charging if the sun doesn't shine



c. System with battery storage and backup generator



d. Grid-connected system

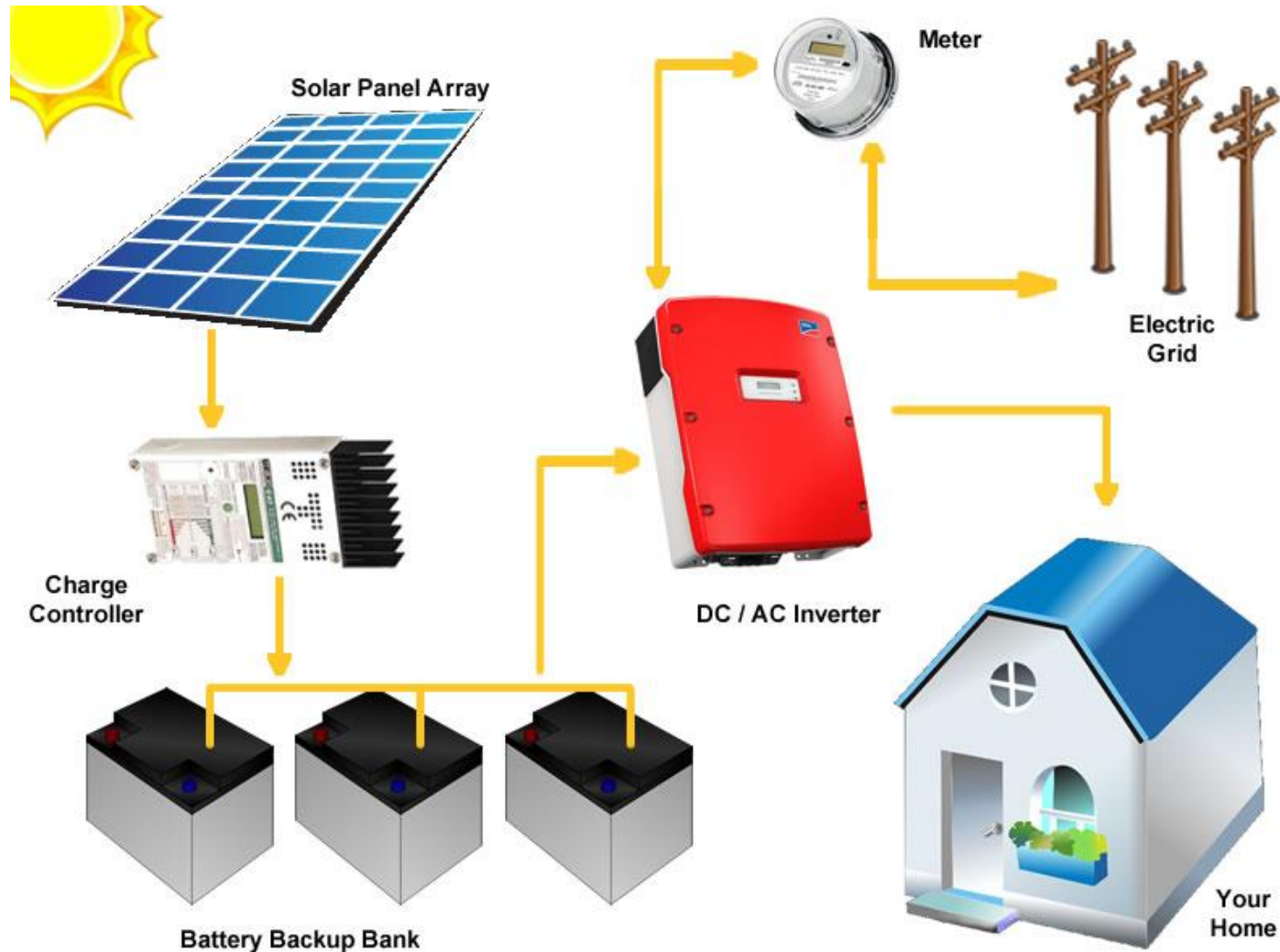
b. Storage allows for nighttime use, and some charge controllers can maximize PV energy.

d. Inverters can be used to connect PV power to the grid.

Auxiliary power sources can also be wind or hydro power

Connected to the utility directly or via the user's premises

Categories of Solar PV Systems



- ❑ PV system components depend on the type of system selected.



Types of systems	Sub-systems/configuration	Main components	Applications
Stand-alone systems (NOT connected to utility grid system)	Solar PV (direct connection to the load)	Solar PV module	- Mainly good deferrable loads, such as consumer appliances, water pumping
	Solar PV with storage system	Solar PV module; Energy storage systems (e.g., battery); Inverter (to supply AC loads)	Power for remotes houses, emergency power systems, battery charging stations, street lighting, weather stations, telephone and radio base stations, vaccine refrigeration at remote locations, etc.
	Hybrid system with/without storage	Solar PV module, Energy storage systems (e.g., battery) Generator (fossil/biofuels); Wind turbine; hydropower; Inverter (to supply AC loads)	

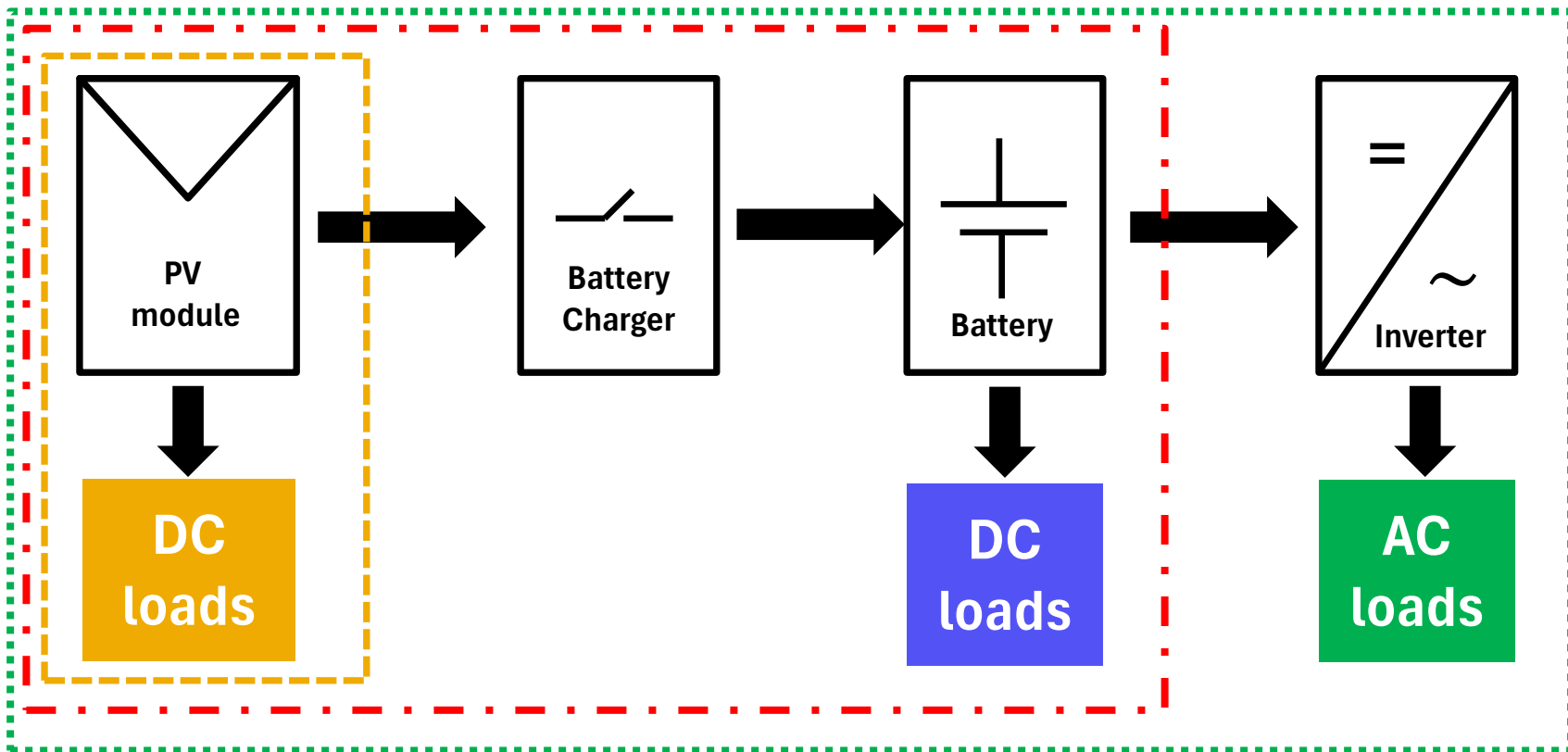
Solar PV systems – Stand-Alone



Consumer
Applications

Solar Home
System

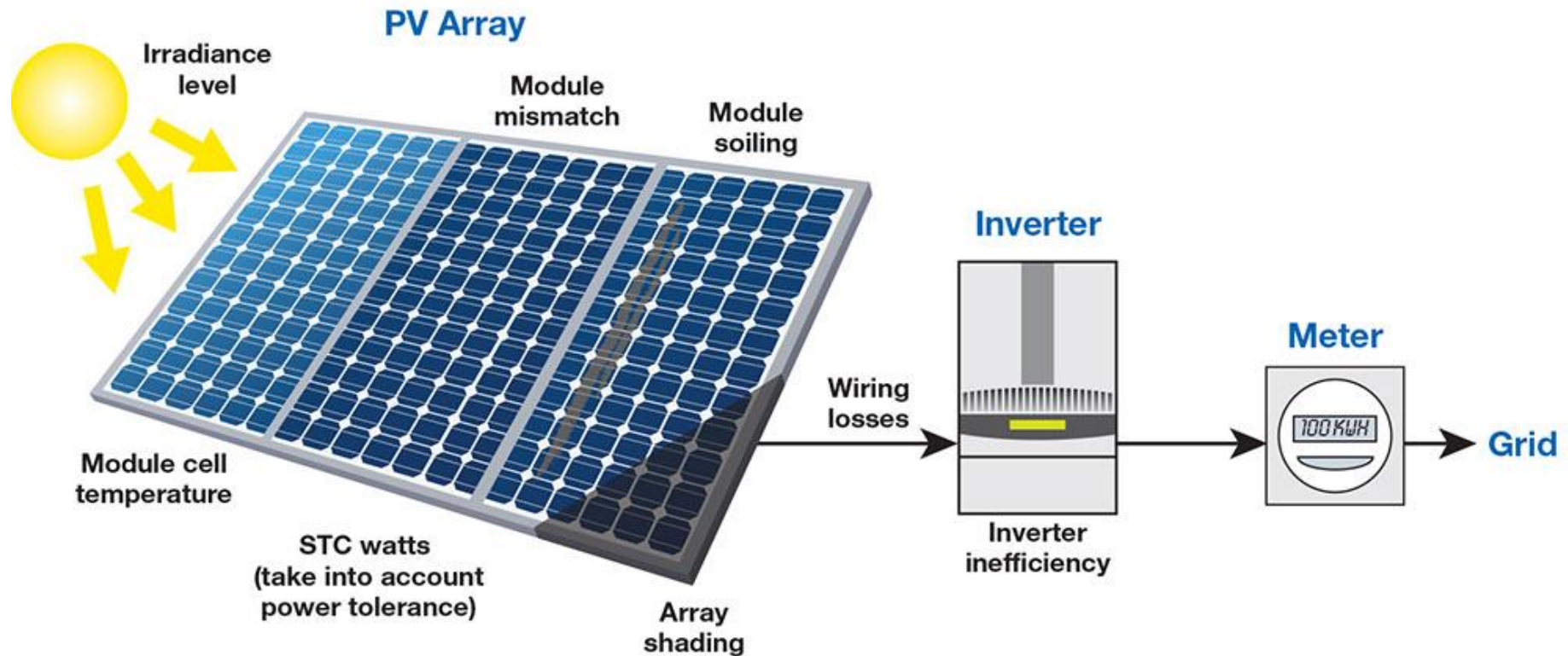
Residential
Systems



Solar PV systems – Stand-Alone

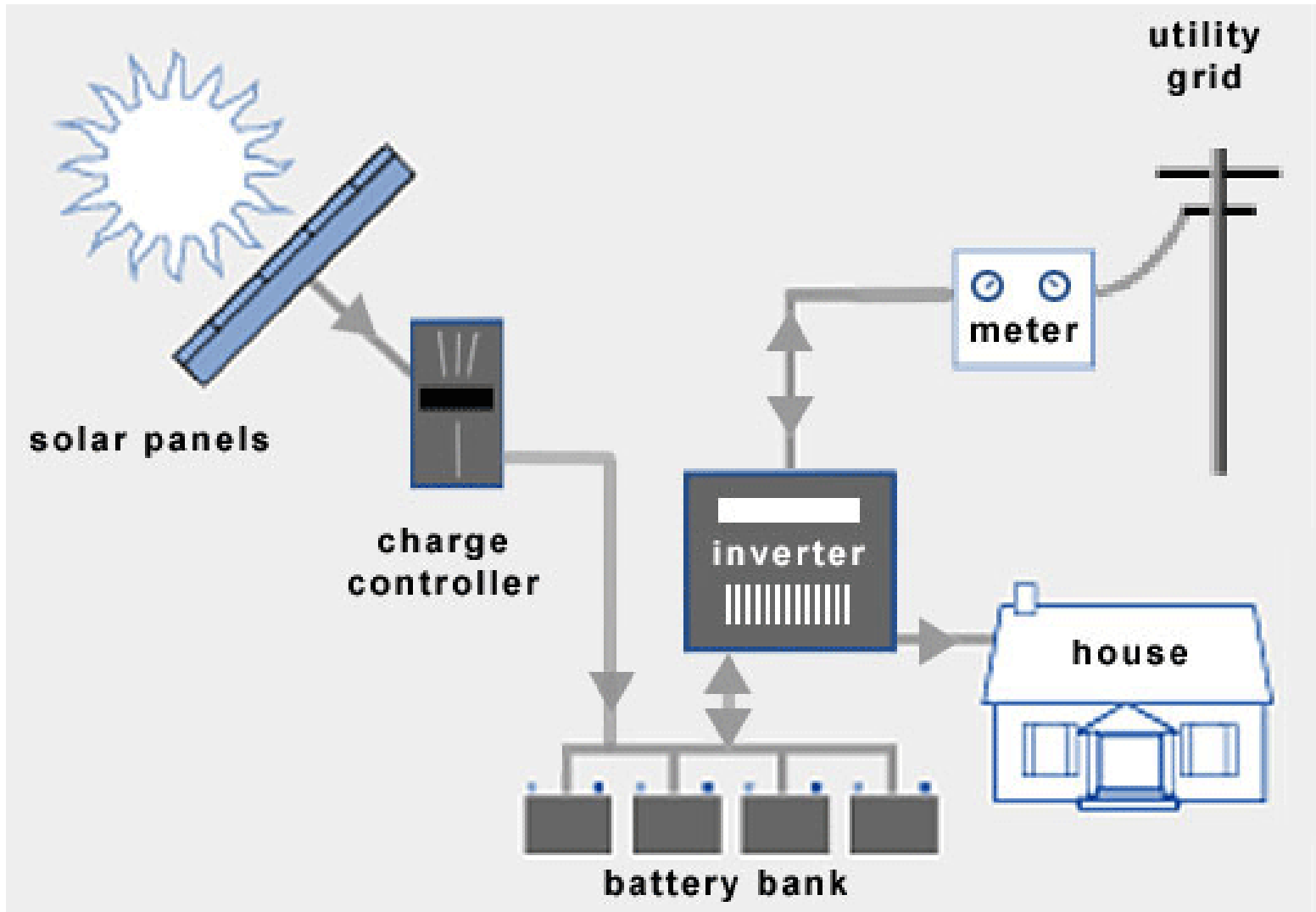


Types of systems	Sub-systems/configuration	Main components	Applications
Grid-connected systems	Decentralized • Connected at user residential premises • Grid acts as storage facility • Relatively small power range	Solar PV module; Inverter	Locations with reliable grid systems
	Centralized • Part of utility grid system • Grid acts as storage facility • Mostly ground-based large-scale system	Solar PV module; Inverter	
	Decentralized/centralized (with storage)	Solar PV module, Energy storage systems (e.g., battery); Inverter (to supply AC loads)	Locations with unreliable grid systems Areas prone to disasters (hurricanes, tropical storms, earthquakes)



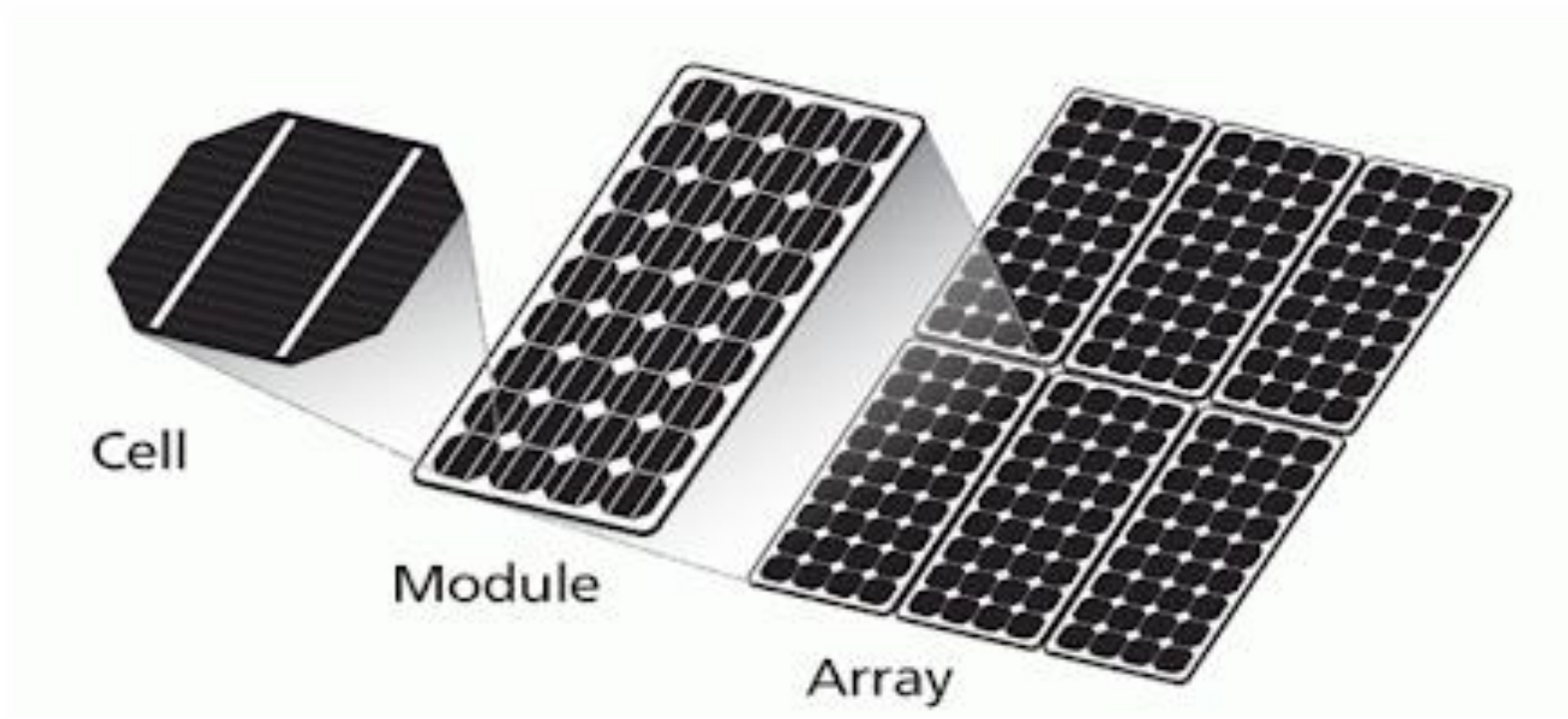
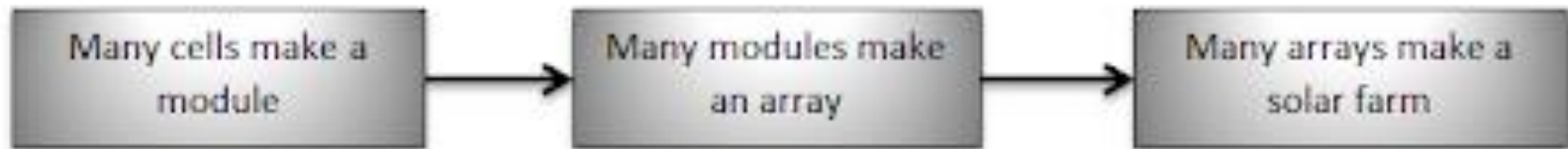
Source: <http://www.homepower.com>

Solar PV systems – Grid-Connected with no Battery



<http://www.homebrewpower.co.uk/html-articles/diy-solar-pv-articles/battery-or-batteryless-grid-tied-solar-system.html>

Solar PV systems – Grid-Connected with Battery

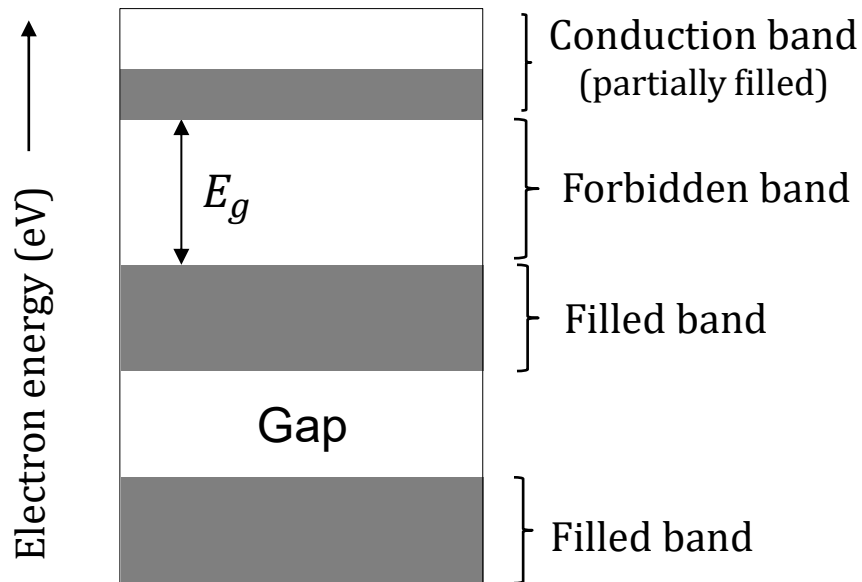


Source: <http://www.solarmango.com/scp/solar-panels-a-nice-package-to-capture-the-sun/>

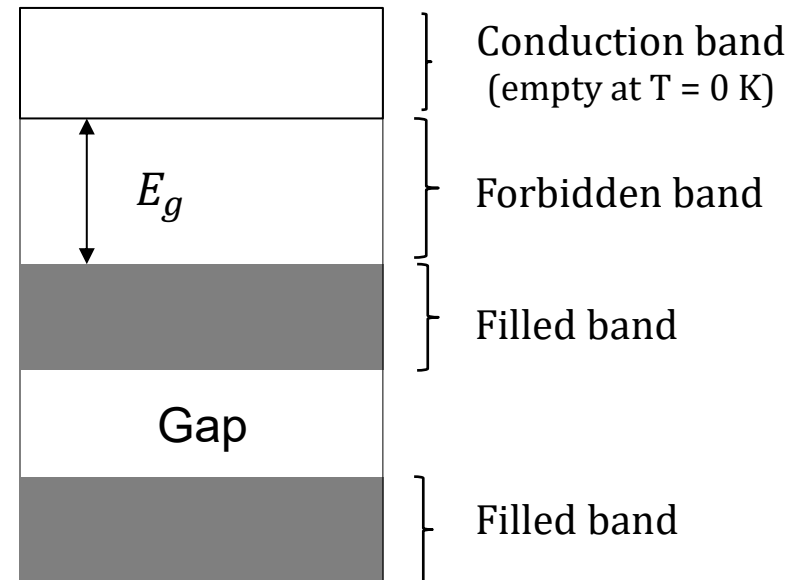
Solar Cell to PV Arrays



Metals



Semiconductors



Definition:

The energy that an electron must acquire to jump across the forbidden band into conduction band is called band-gap energy (in eV).



	Si	a – Si	CdTe	CuInSe ₂	CuGaSe ₂	GaAs
Band-gap energy (eV)	1.12	1.70	1.49	1.04	1.67	1.43
Cut-off wavelength (um)	1.11	0.73	0.83	1.19	0.74	0.87

Where:

Si: crystal silicon

a – Si: Amorphous silicon

CdTe: Cadimium telluride

CuInSe₂: Copper indium diselenide

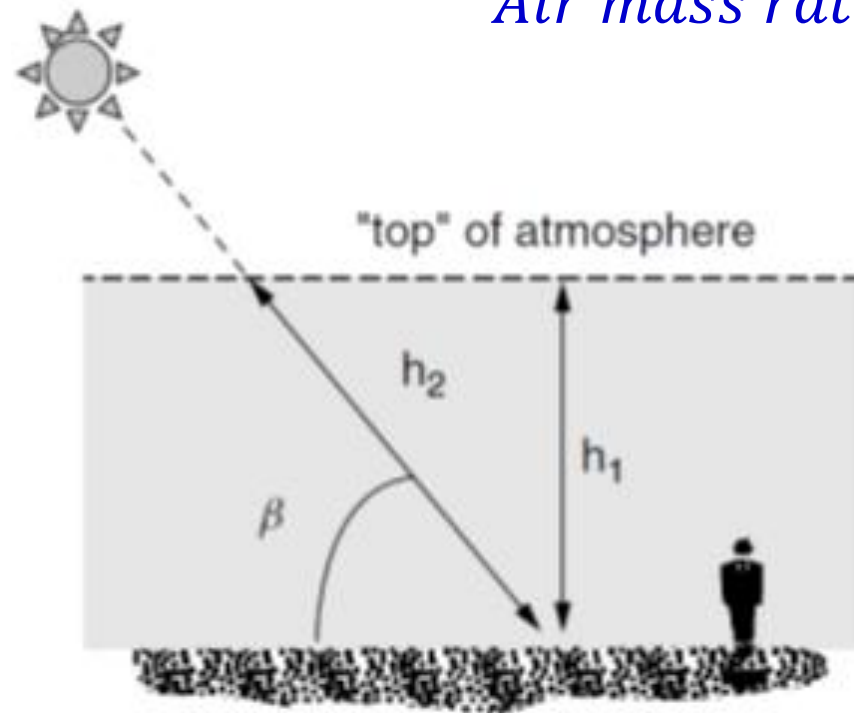
CuGaSe_s: Copper gallium diselenide

GaAs: Gallium arsenide



- The length of the path h_2 taken by the sun's rays as they pass through the atmosphere, divided by the minimum possible path length h_1 , which occurs when the sun is directly overhead, is called the *air mass ratio*, m .

$$\text{Air mass ratio, } m = \frac{h_2}{h_1} = \frac{1}{\sin \beta} \quad (1)$$

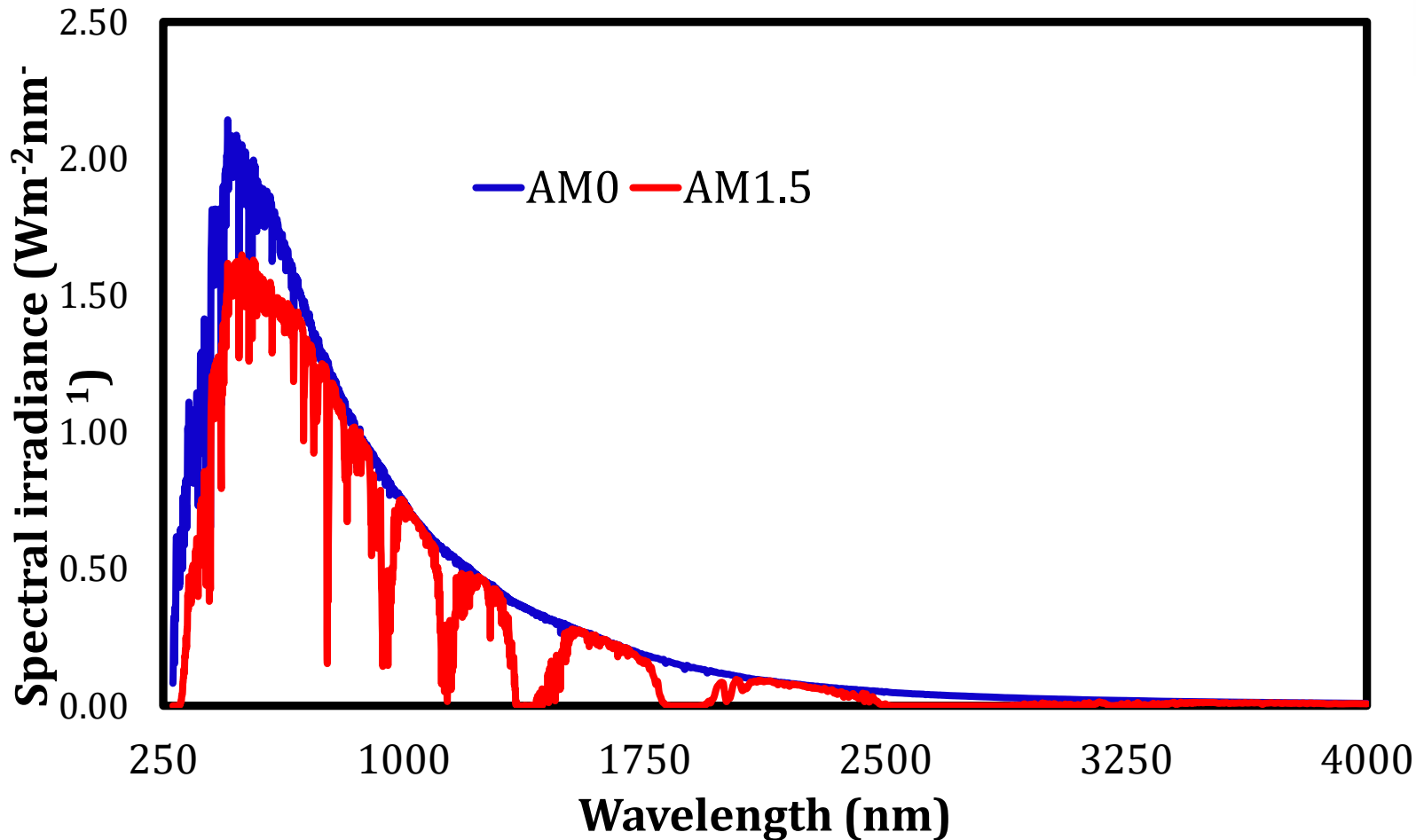


Where,

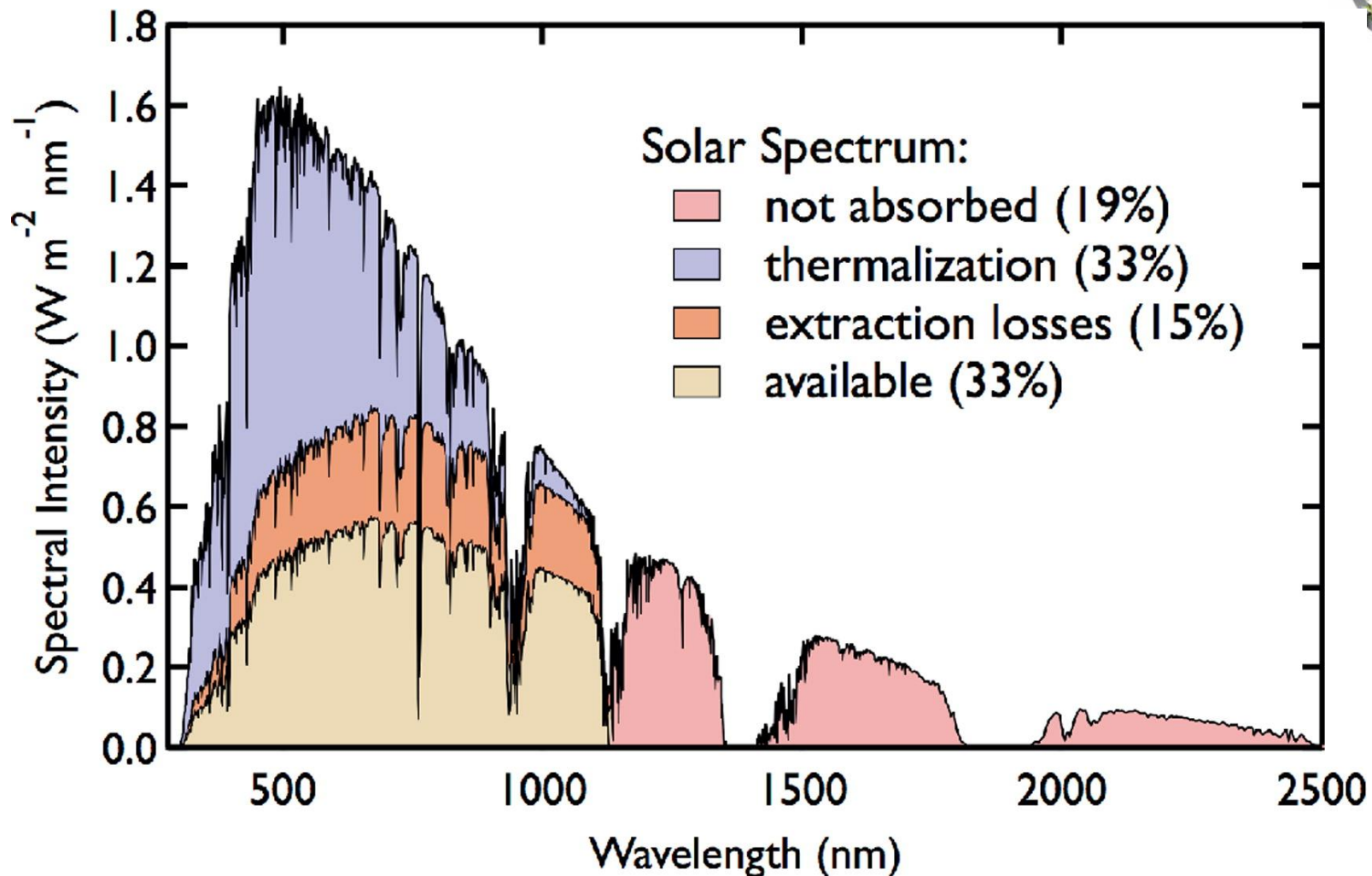
h_1 = path length through the atmosphere with the sun directly overhead

h_2 = path length through the atmosphere to reach a spot on the surface

β = the altitude angle of the sun

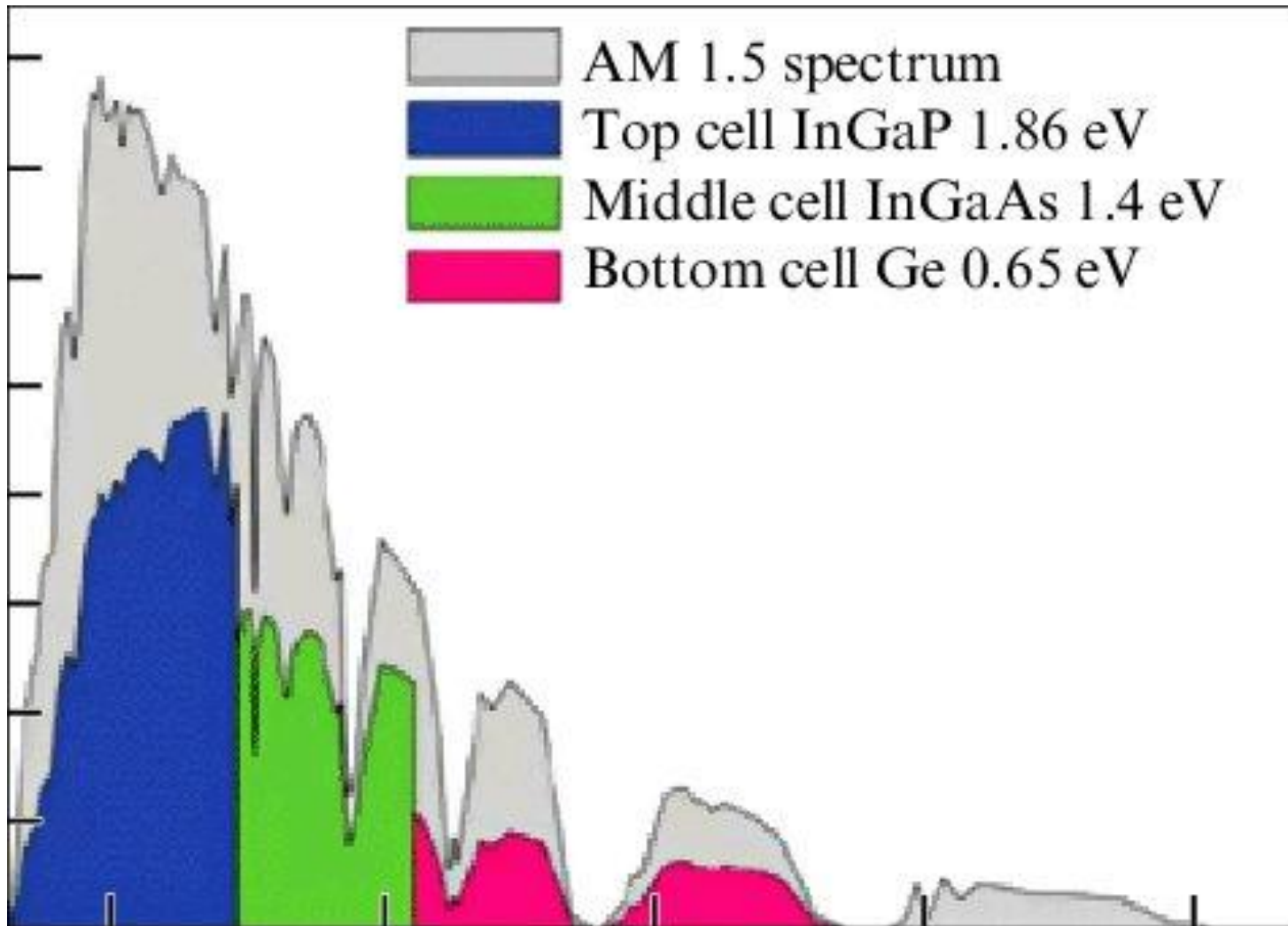


- ❑ The AM1.5 is generally assumed averaged value for an solar spectrum at the earth's surface, and it is used as the standard value for the solar radiation spectrum for photovoltaic (PV).



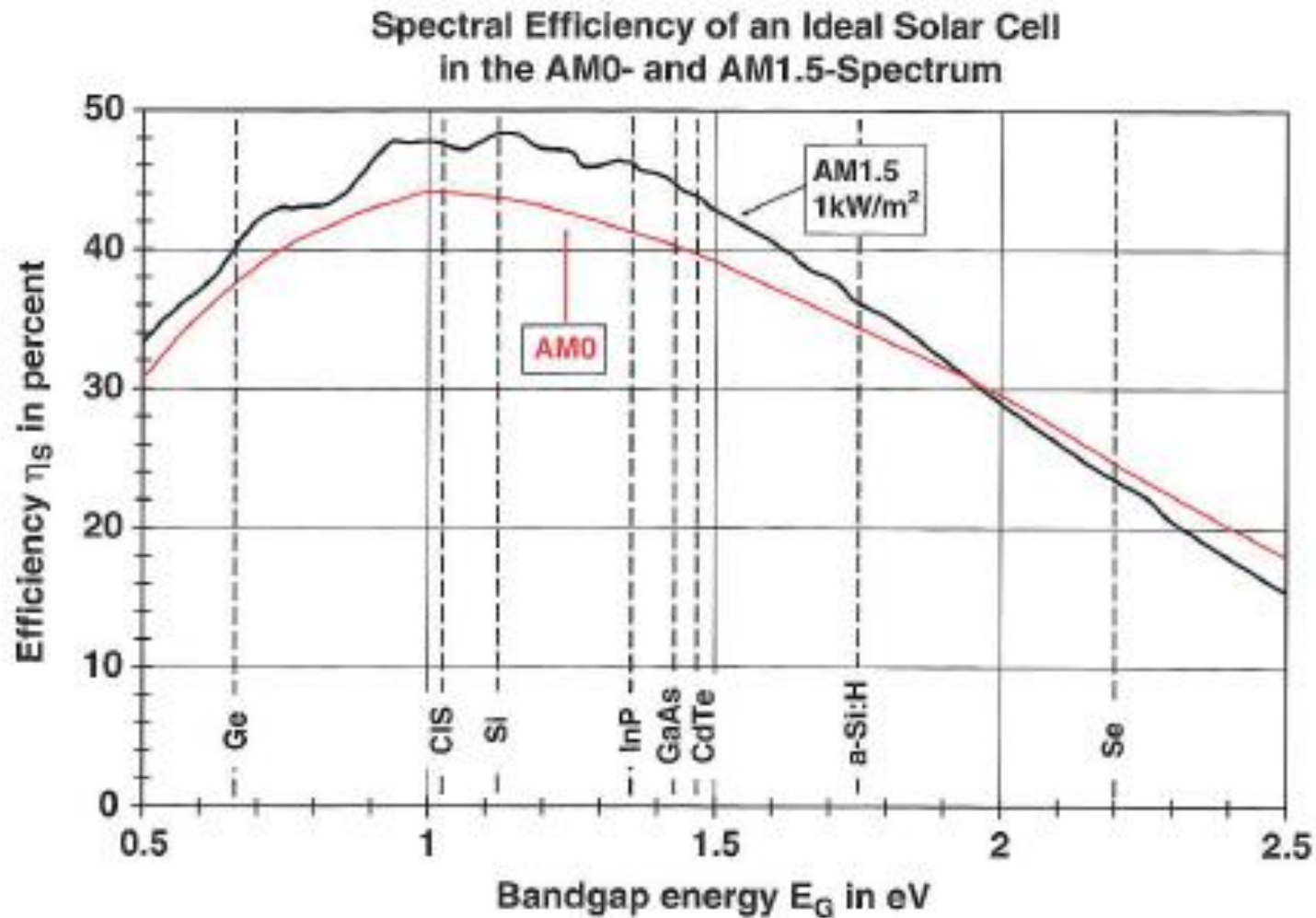
Source: [https://doi.org/10.1016/S1369-7021\(12\)70220-1](https://doi.org/10.1016/S1369-7021(12)70220-1)

Theoretical Efficiency of Solar Cells - Silicon



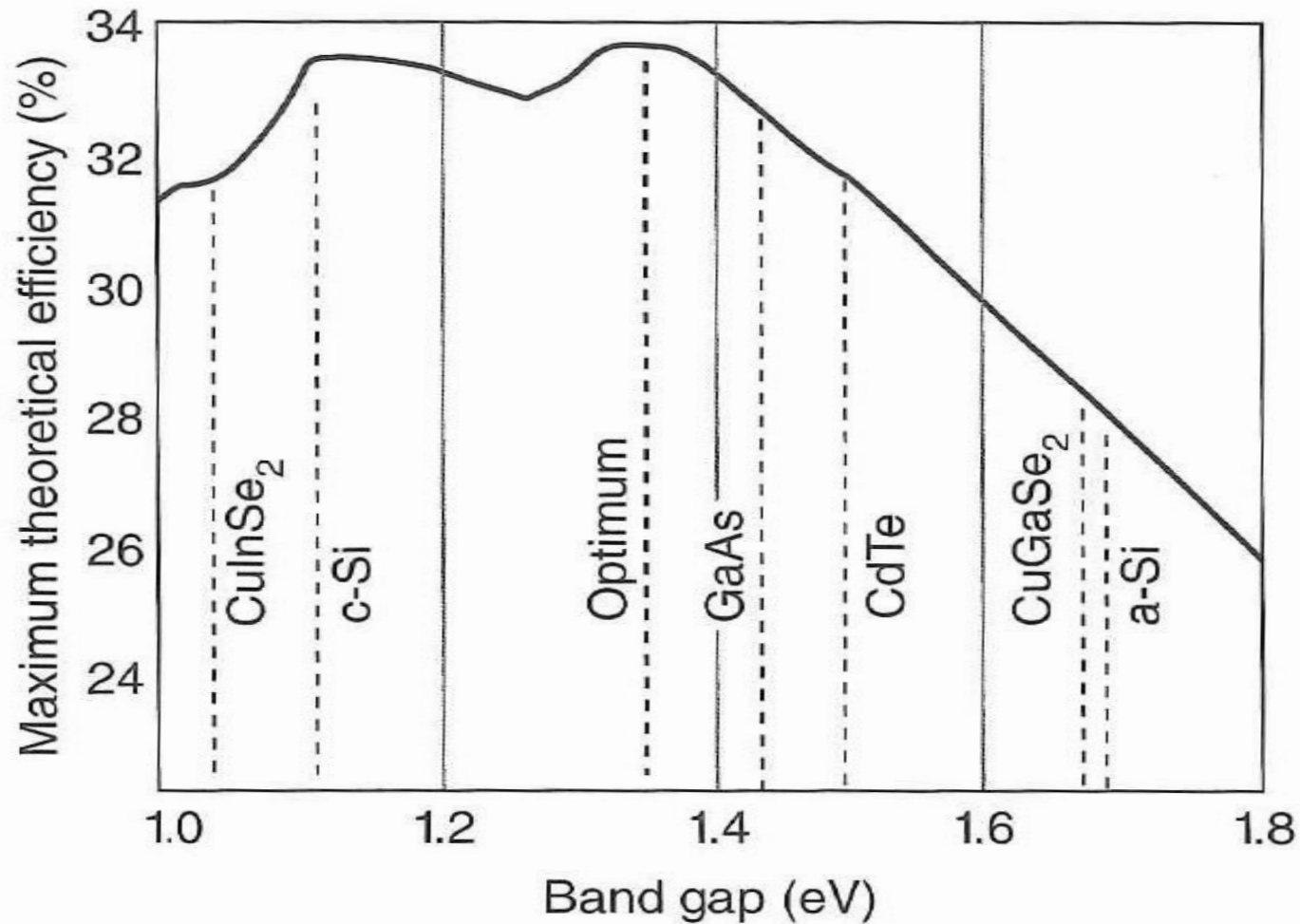
Source: [\(17\) \(PDF\) Solar photovoltaics: Current state and trends \(researchgate.net\)](#)

Solar Spectral for Multiple Layers Cell

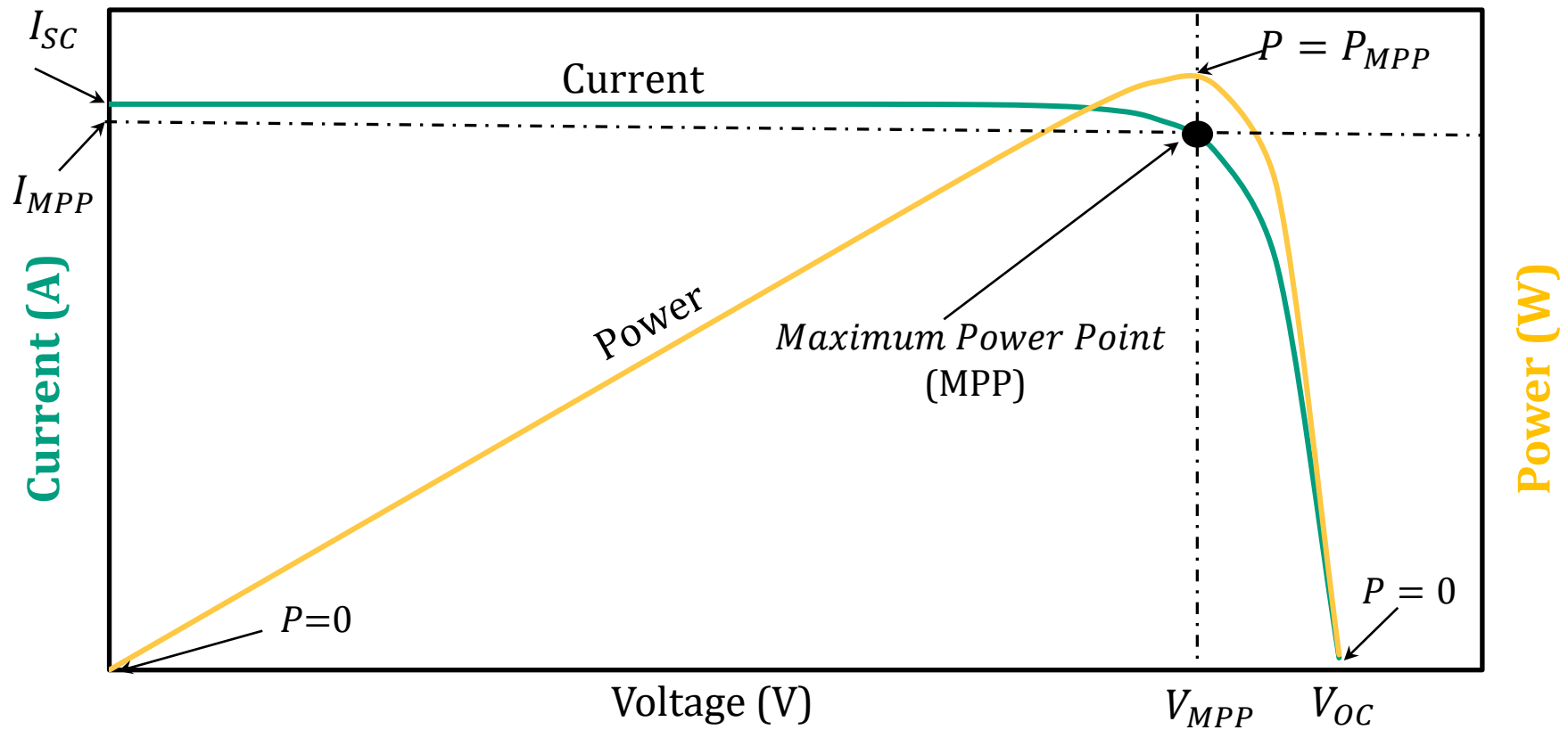


Source: Häberlin H (2012). Photovoltaics- system design and practice. John Wiley and Sons, Ltd, 1st Edition

Spectral Efficiency for an Ideal Solar Cell



- The Shockley-Queisser limit for the maximum possible solar cell efficiency (single-junction, unenhanced insolation) as a function of band-gap.



Typical Current-Voltage (I-V) Curve



- ❑ A solar cell is a key device that converts light energy into electrical energy in photovoltaic energy conversion.
- ❑ An individual solar cell produces a small voltage of about 0.5 V
- ❑ To increase this voltage, depending on applications, a certain number of solar cells are connected in series.





- ❑ The efficiency of solar cells is the relationship between the power delivered by the solar cells and the power irradiated by the sun.
- ❑ It is function of maximum power, solar irradiance ($G \text{ W}/m^2$) and the area ($A \text{ m}^2$) of the solar cell (or module).

$$\eta = \frac{P_{MPP}}{A*G} = \frac{FF*V_{OC}*I_{SC}}{A*G} \quad (2)$$

Where FF is the fill factor, V_{oc} is the open-circuit voltage and I_{sc} is the short-circuit current



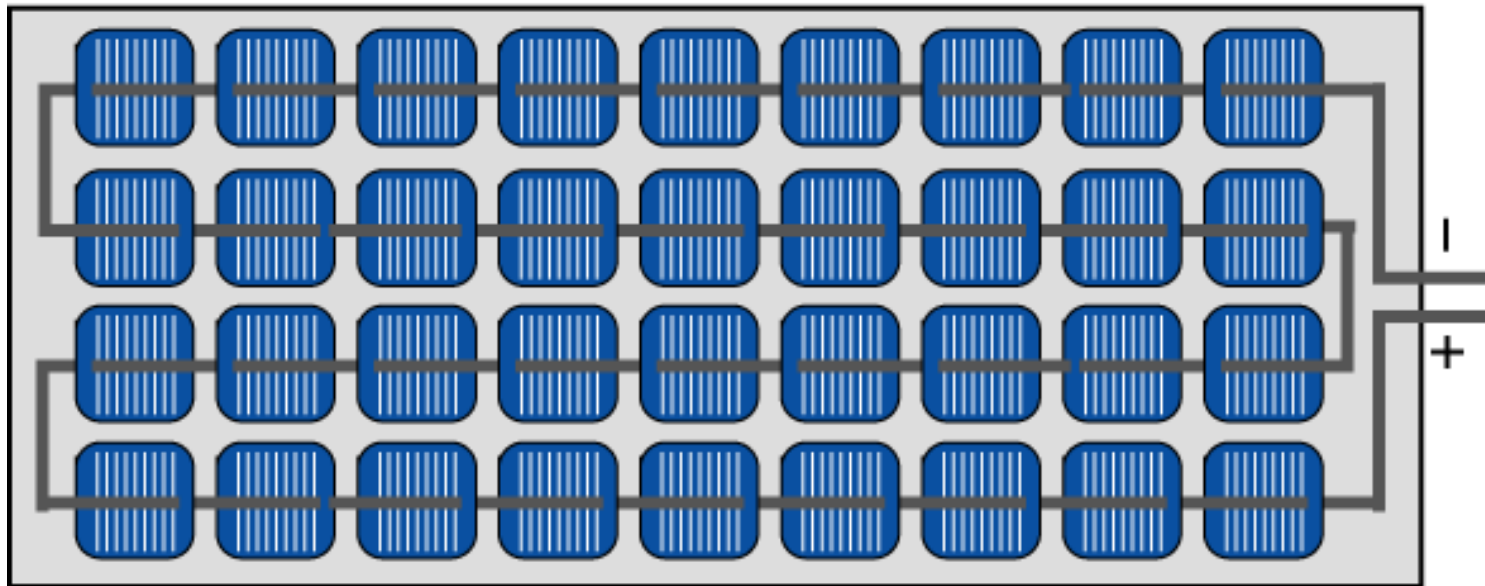
- ❑ Nominal efficiency at standard test conditions (STC) is:

$$\eta_{STC} = \frac{P_{MPP (STC)}}{A * 1000 \text{ W/m}^2} \quad (3)$$

- ❑ Solar cell efficiency depends on irradiance and temperature.

❑ The series-connected solar cells are called a module.

- For a standard standalone system (e.g., to charge a battery), about 36 cells are connected to produce a module of up to 17 V



- For grid-connected applications, between 54 and 128 cells are generally connected in series to produce a higher-voltage module.
 - 72-, 96-, and 128-cell modules are common for large modules



- ❑ The electrical characteristics for PV modules are determined by the manufacturers at STC.
 - Cell temperature = $25^{\circ}C$
 - AM1.5
 - Solar irradiance = $1000W/m^2$
- ❑ The maximum power, voltage, and current at the maximum power point are generally specified.
- ❑ *Temperature coefficients* are generally listed for:
 - Maximum power
 - Open-circuit voltage
 - Short circuit current



TABLE 5.3 Examples of PV Module Performance Data Under Standard Test Conditions (1 kW/m², AM1.5, 25°C Cell Temperature)

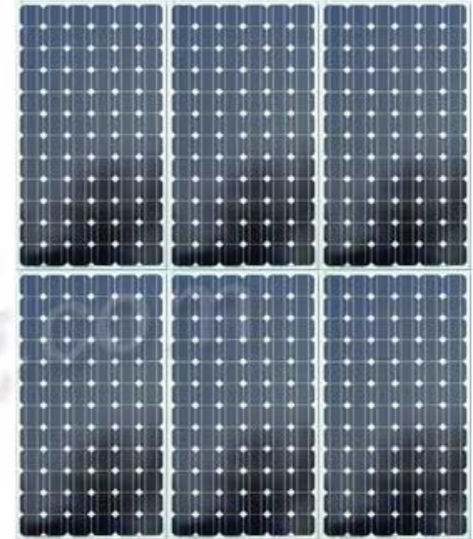
Manufacturer	SunPower	Yingli	First Solar	NanoSolar	Sharp
Model	E20/435	YGE 245	FS Series 3	Utility 230	NS-F135G5
Material	c-Si	mc-Si	CdTe	CIGS	a-Si
Panel efficiency	20.1%	15.6%	12.2%	11.6%	9.6%
Rated power P_{MPP} (W _p)	435	245	87.5	230	135
Rated voltage V_{MPP} (V)	72.9	30.2	49.2	40.2	47
Rated current I_{MPP} (A)	5.97	8.11	1.78	6	2.88
Open-circuit voltage V_{OC} (V)	85.6	37.8	61	50.7	61.3
Short-circuit current I_{SC} (A)	6.43	8.63	1.98	6.7	3.41
NOCT (°C)	45	46	45	47	45
Temp. Coeff. of P_{max} (%/K)	-0.38	-0.45	-0.25	-0.39	-0.24
Temp. Coeff. V_{OC} (%/K)	-0.27	-0.33	-0.27	-0.30	-0.30
Temp. Coeff. I_{SC} (%/K)	0.05	0.06	0.04	0.00	0.07
Dimensions (m)	2.07 × 1.05	1.65 × 0.99	1.20 × 0.60	1.93 × 1.03	1.40 × 1.00
Weight (kg)	25.4	26.8	15	34.7	26

□ Depending on the desired power of the array, modules can be arranged in:

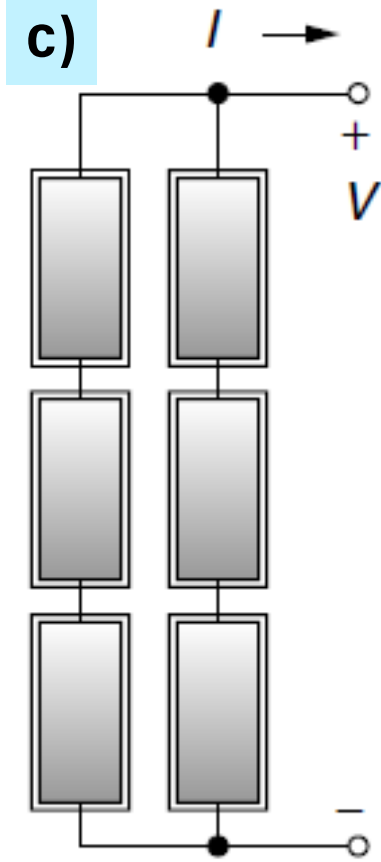
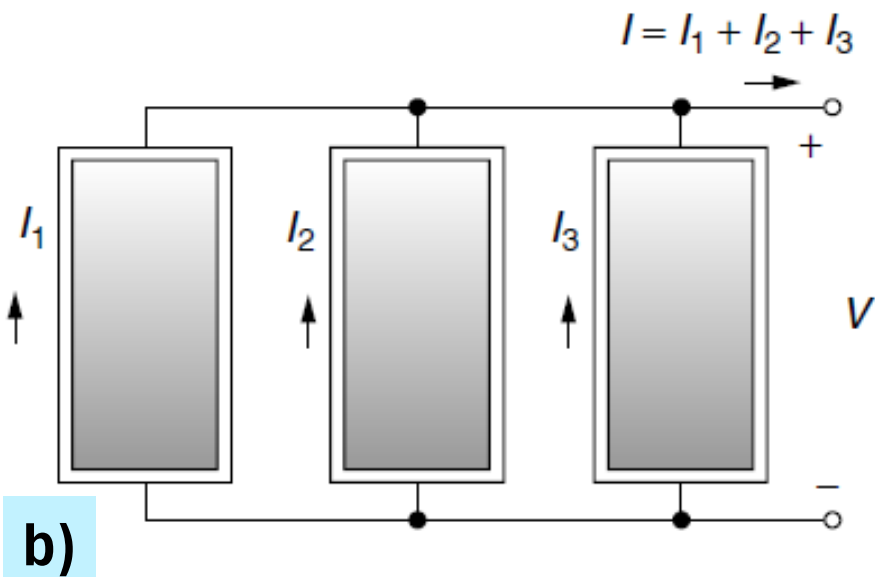
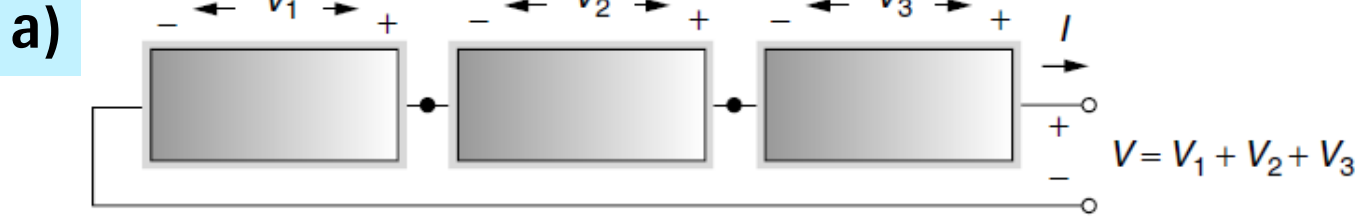
- Series
- Parallel
- Combination of series and parallel



Solar Panel
(Module)



Solar PV Array
(Multiple modules)



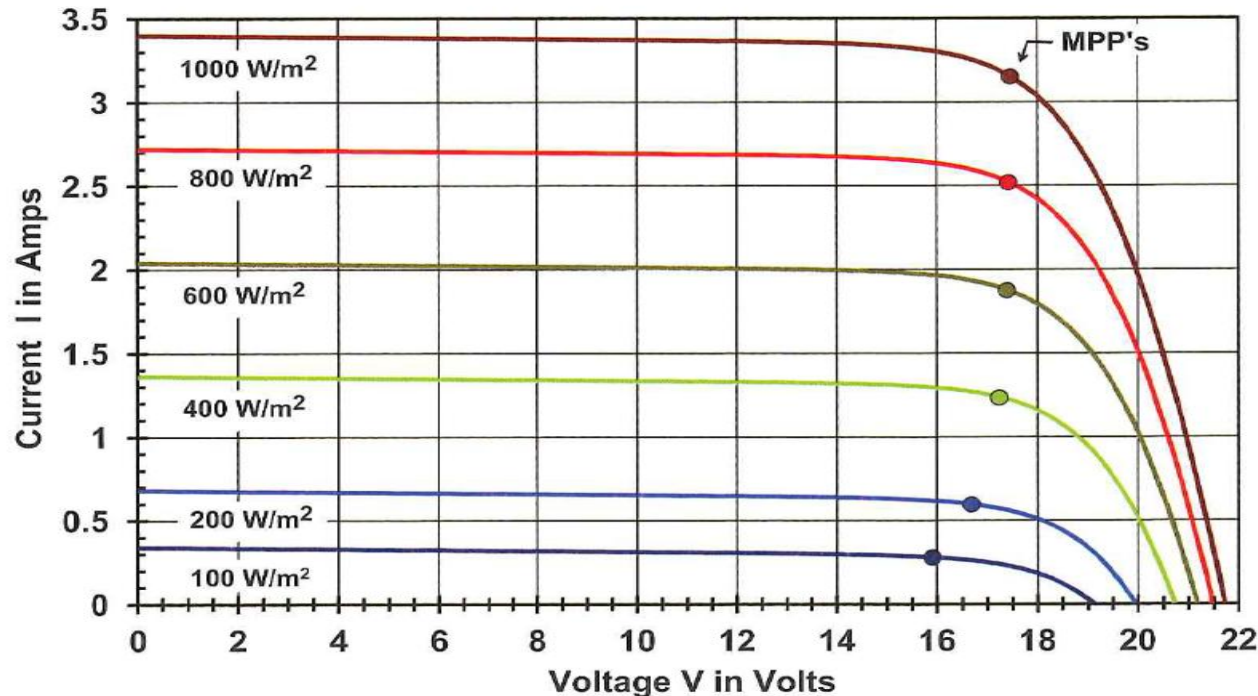
- a) Series-connected modules
- b) Parallel-connected modules
- c) Series-parallel connected modules

From Modules to Arrays – Arrangement Options



- ❑ Current is directly proportional to the solar irradiance.

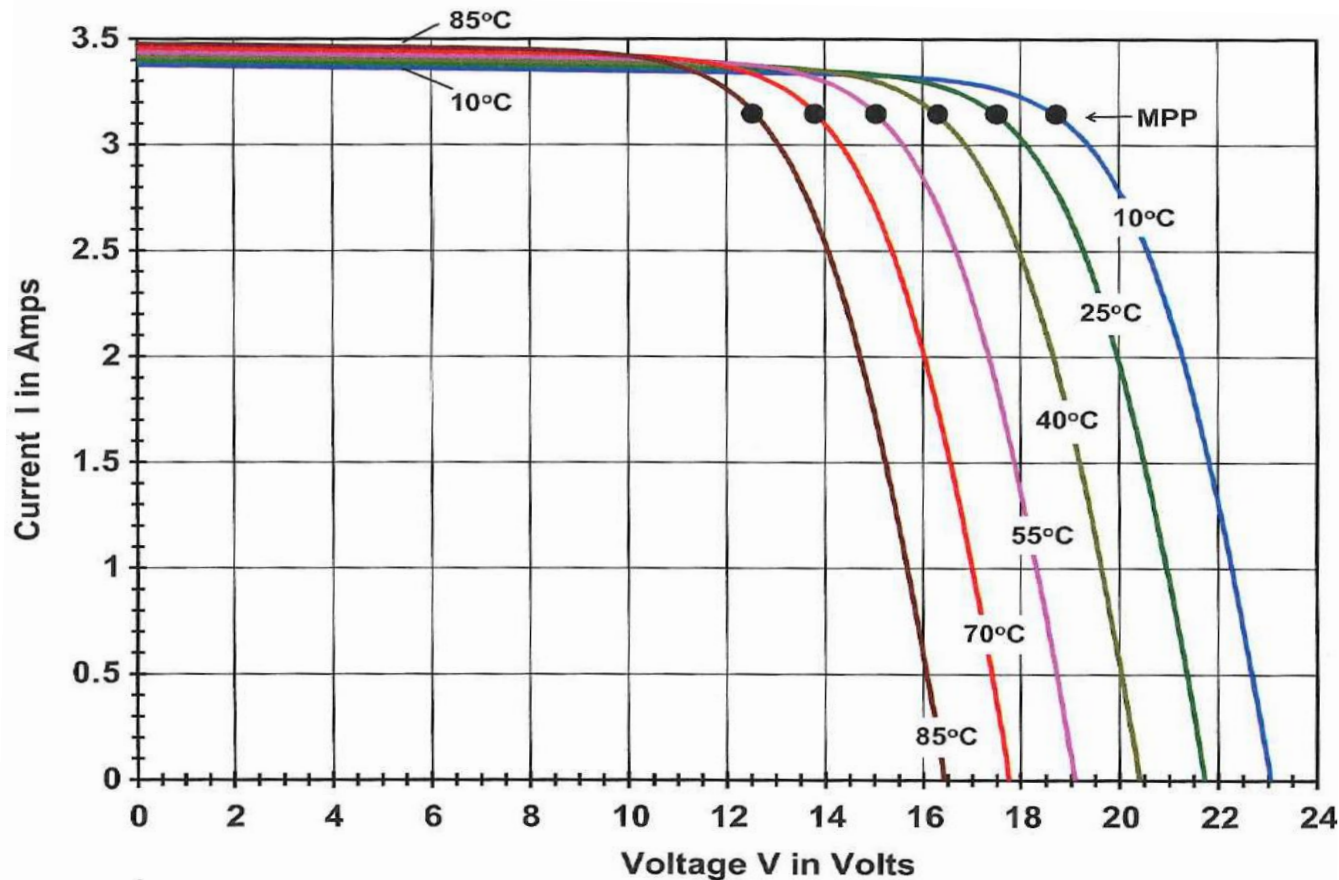
$$I_{sc} = I_{sc-STC} * \frac{G_c}{G_{STC}} \quad (4)$$



- ❑ Open-circuit voltage increases slightly with increasing solar irradiance.



- ❑ Module cell temperature affects the module's voltage and hence its power output.



I-V Curves and Ambient Conditions



□ The temperature coefficients can be expressed as:

- Percentage changed in the variable value with respect to a unit change in temperature ($\varepsilon\%/^{\circ}C$) or
- An absolute value with represent to a unit change in temperature ($\varepsilon_{ab}/^{\circ}C$).

□ For example, in terms of the temperature coefficient, the new value of open-circuit voltage due to a temperature change can be determined from:

$$X_c = X_{STC} * \left[1 + \left(\frac{\varepsilon}{100} \right) * (T_c - T_{STC}) \right] \quad (5)$$

$$X_c = X_{STC} + \varepsilon_{ab} * (T_c - T_{STC}) \quad (6)$$

Where X_c is the module temperature adjusted variable X_{STC} and represent current, voltage and power of solar module.



❑ Module (or solar cell) temperature mostly depends on:

- Solar radiation
- Ambient temperature
- Wind speed
- Installation method
- Solar cell technology (NOCT and temperature coefficients)

❑ Nominal Operating Cell temperature (NOCT) is defined as the temperature that is reached under the following conditions:

- Solar irradiance = 800 W/m^2
- Ambient temperature = 20°C
- Wind speed = 1 m/s



□ Module (or solar cell) temperature is given as:

$$T_c = T_a + \left[\left(\frac{9.5}{5.7 + 3.8 * V_f} \right) * \left(\frac{NOCT - 20^{\circ}C}{800} \right) * G_c \right] \quad (7)$$

where T_a is the ambient temperature ($^{\circ}C$), V_f is the wind speed (m/s) at the installation site, $NOCT$ is the module normal operating cell temperature ($^{\circ}C$) and G_c (W/m^2) is solar radiance on the module plane.



Questions?