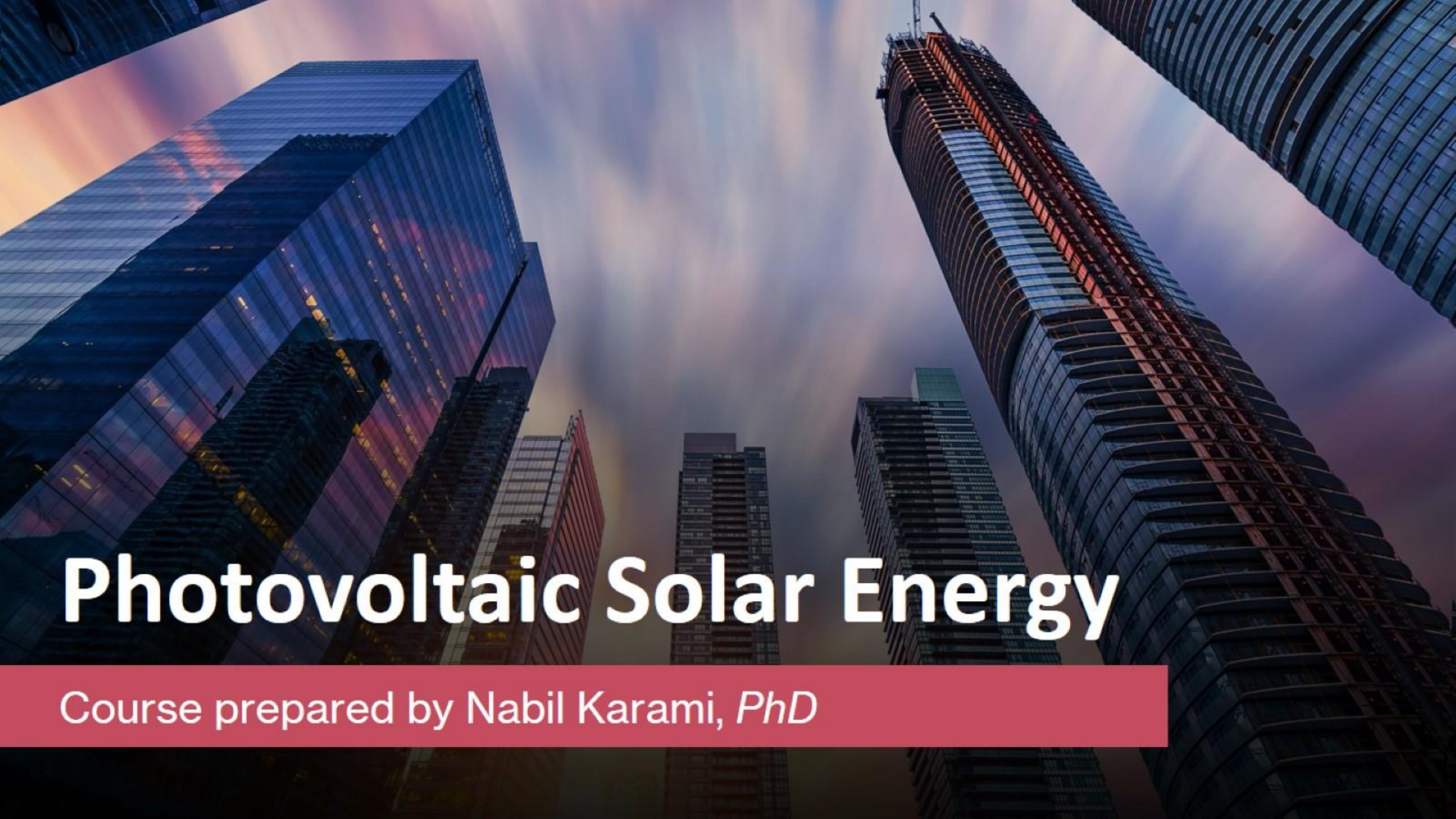


Photovoltaic Solar Energy

Course prepared by Nabil Karami, *PhD*

Course content

Section 1: Solar resources

Part 1
- Solar Characteristics
- Solar Irradiance
- Extraterrestrial Solar Irradiance
- Daily Extraterrestrial Irradiance
- Angle of Incidence

Part 2
- Solar Irradiance and Air Mass
- Type of Irradiance
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- Surface tilting effect
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- Solar coordinate

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Course content

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Part 2

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- Cables
- Energy Flow meter

Part 3

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Photovoltaic Solar Energy Training Course

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Section 1: Solar resources

Part 1

- Solar Characteristics
- Solar Irradiance
- Extraterrestrial Solar Irradiance
- Daily Extraterrestrial Irradiance
- Altitude, Incidence, and Zenith Angles

Solar Characteristics

- Solar Energy originates from the sun
- It is driven by nuclear fusion of hydrogen into helium
- The surface temperature of the sun is approximately 5500 ℃



- Heat is transferred to earth via electromagnetic radiation, also called solar radiation
- Irradiance, G, is calculated using Stefan-Boltzmann law as

$$G\left(\frac{W}{m^2}\right) = \sigma T^4$$

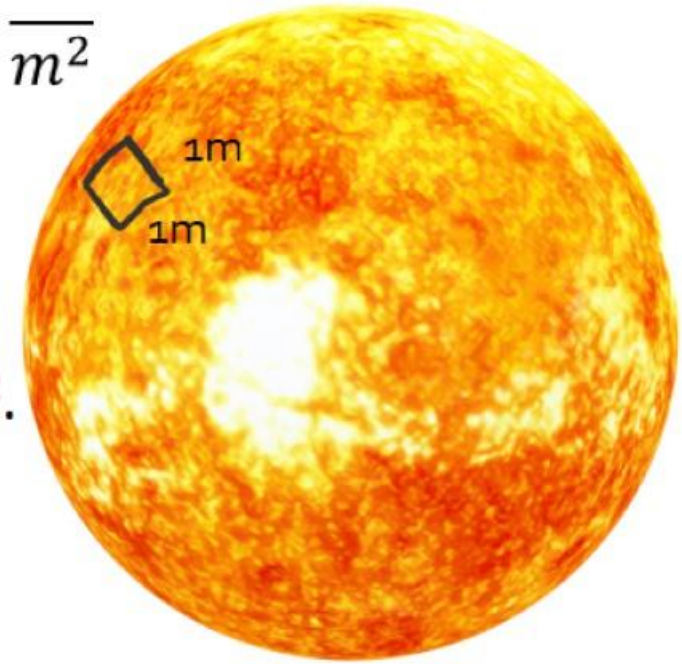
- σ: *is the Stefan-Boltzmann constant* = $5.67\times10^{-8}\ W\cdot m^{-2}\cdot K^{-4}$
- *T: Temperature in Kelvin*

Solar characteristics

- For example, the irradiance of the sun at 5500 ℃ at its surface is

$$G_{sun} = \sigma T^4 = 5.67 \times 10^{-8} \times (5500 + 273)^4 = 63 \times 10^6 \frac{W}{m^2}$$

- Or 63MW on every m^2



- **Irradiance** is an instantaneous measurement of solar power over some area. The units of irradiance are **W/m²**.

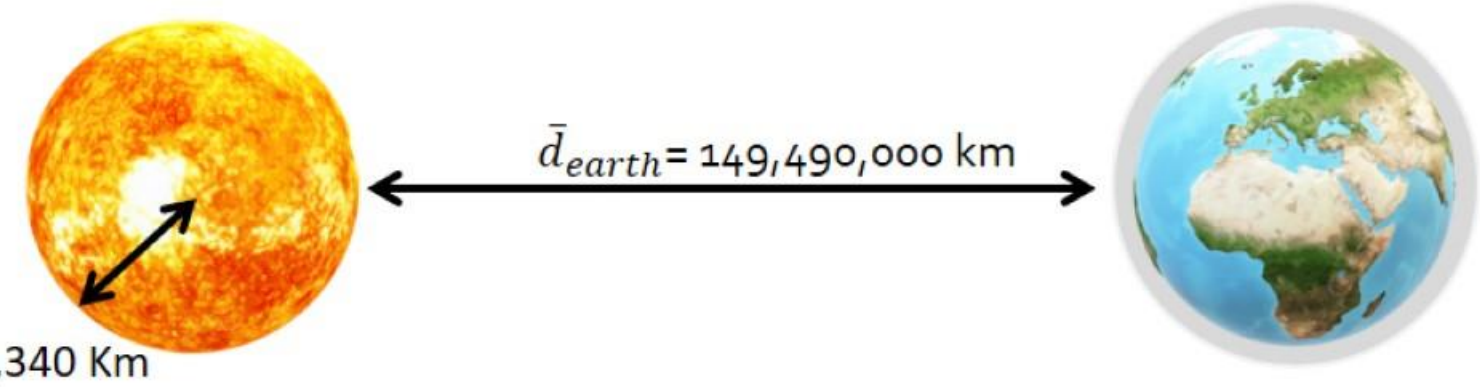
- **Insolation** is a measurement of the cumulative energy measured over some area for a defined period of time (e.g., annual, monthly, daily, etc.). The common unit of insolation is **kWh/m²**.

Solar Irradiance

- What is the irradiance that arrives at the top of the earth's atmosphere (Extraterrestrial) ?

$$G = G_{sun}\left(\frac{R_{sun}^2}{d_{earth}^2}\right)$$

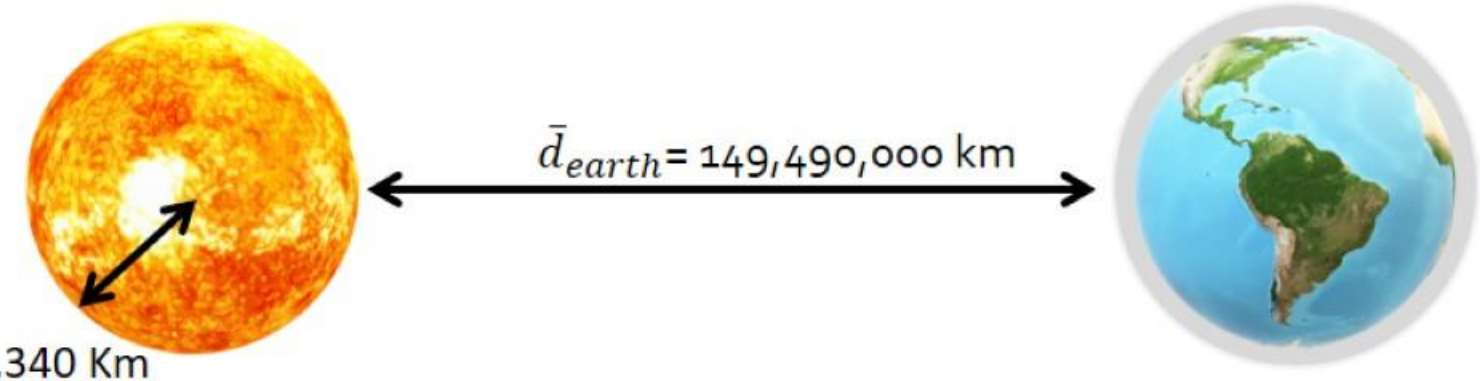
- G_{sun}: *Irradiance of the sun*
- R_{sun}: *Radius of the sun is 696,340 Km*
- d_{earth}: *Distance between sun and earth's atmosphere*



Extraterrestrial Irradiance

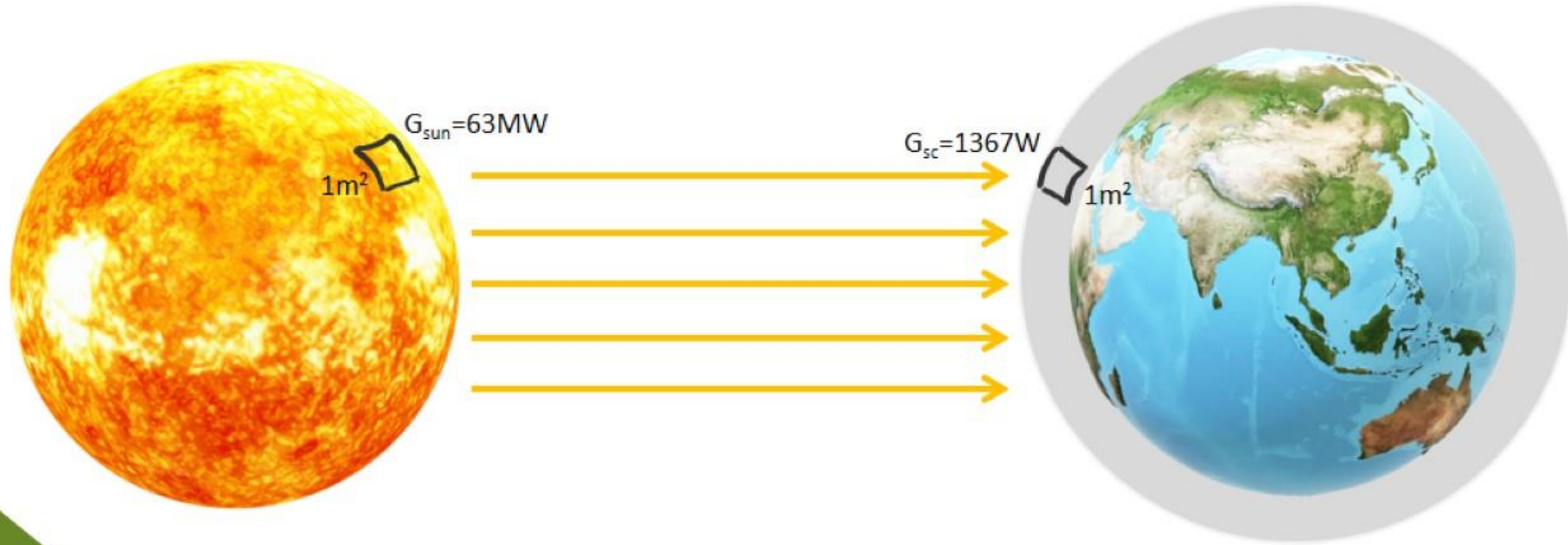
- The average extraterrestrial irradiance at the earth at $\bar{d}^2_{earth} = 149{,}490{,}000$ km from the sun (Solar Constant) is:

$$G_{sc} = G_{sun} \frac{R^2_{sun}}{\bar{d}^2_{earth}} \approx 1367\ W/m^2$$



Extraterrestrial Irradiance

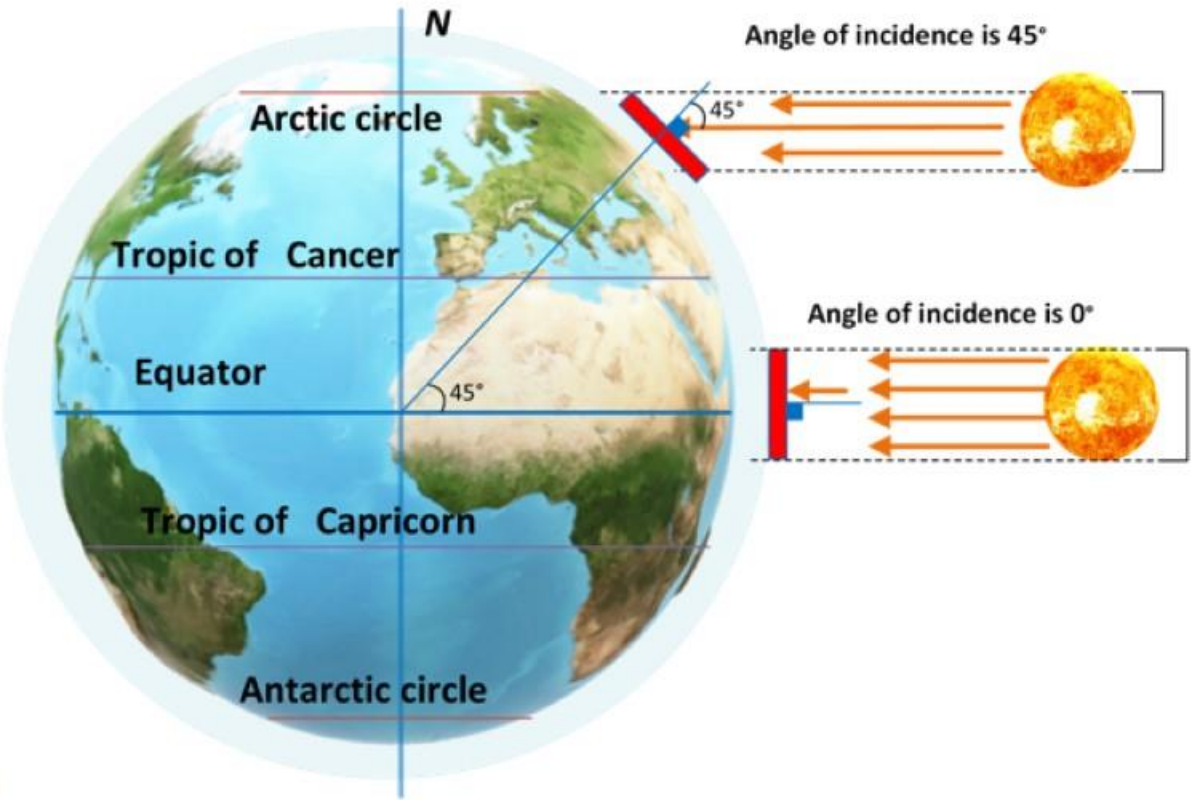
- So, the average solar irradiance on the top of the earth's atmosphere is 1367 W/m^2



Extraterrestrial Irradiance

Some Definitions

- G_{0n}: Extraterrestrial irradiance on a plane normal to the radiation (W/m^2)
- G_0: Extraterrestrial irradiance on horizontal surface (W/m^2)
- Subscript '0' means 'extraterrestrial', or top of the atmosphere

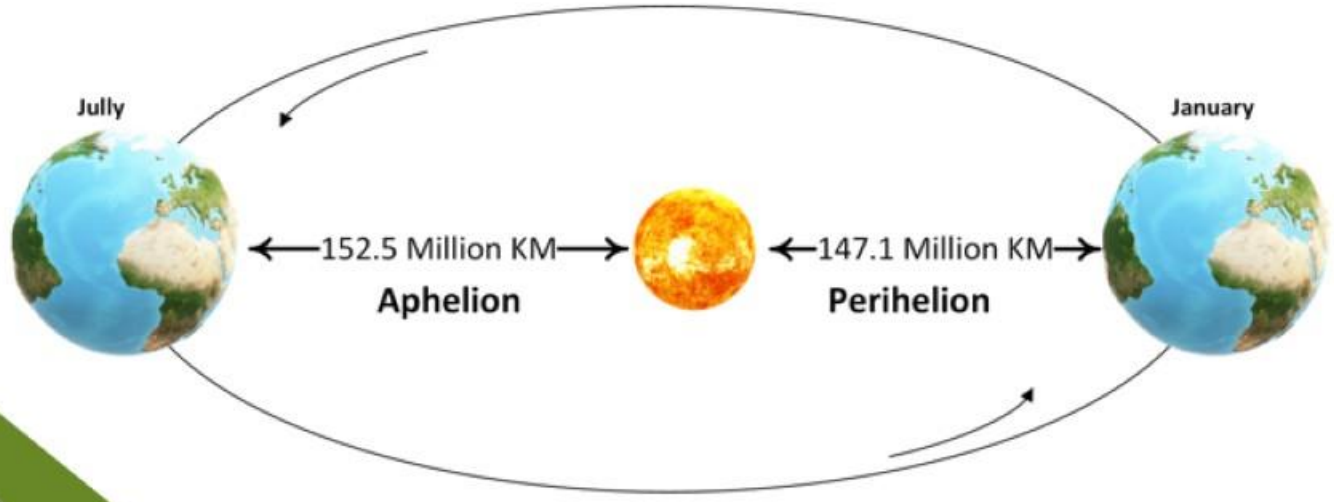


Daily Extraterrestrial Irradiance

- Since the distance between the sun and the earth is not fix, the irradiance can be calculated in function of day as:

$$G_{0n}(d) = G_{sc}\left[1 + 0.033\cos\left(\frac{2\pi d}{365}\right)\right]$$

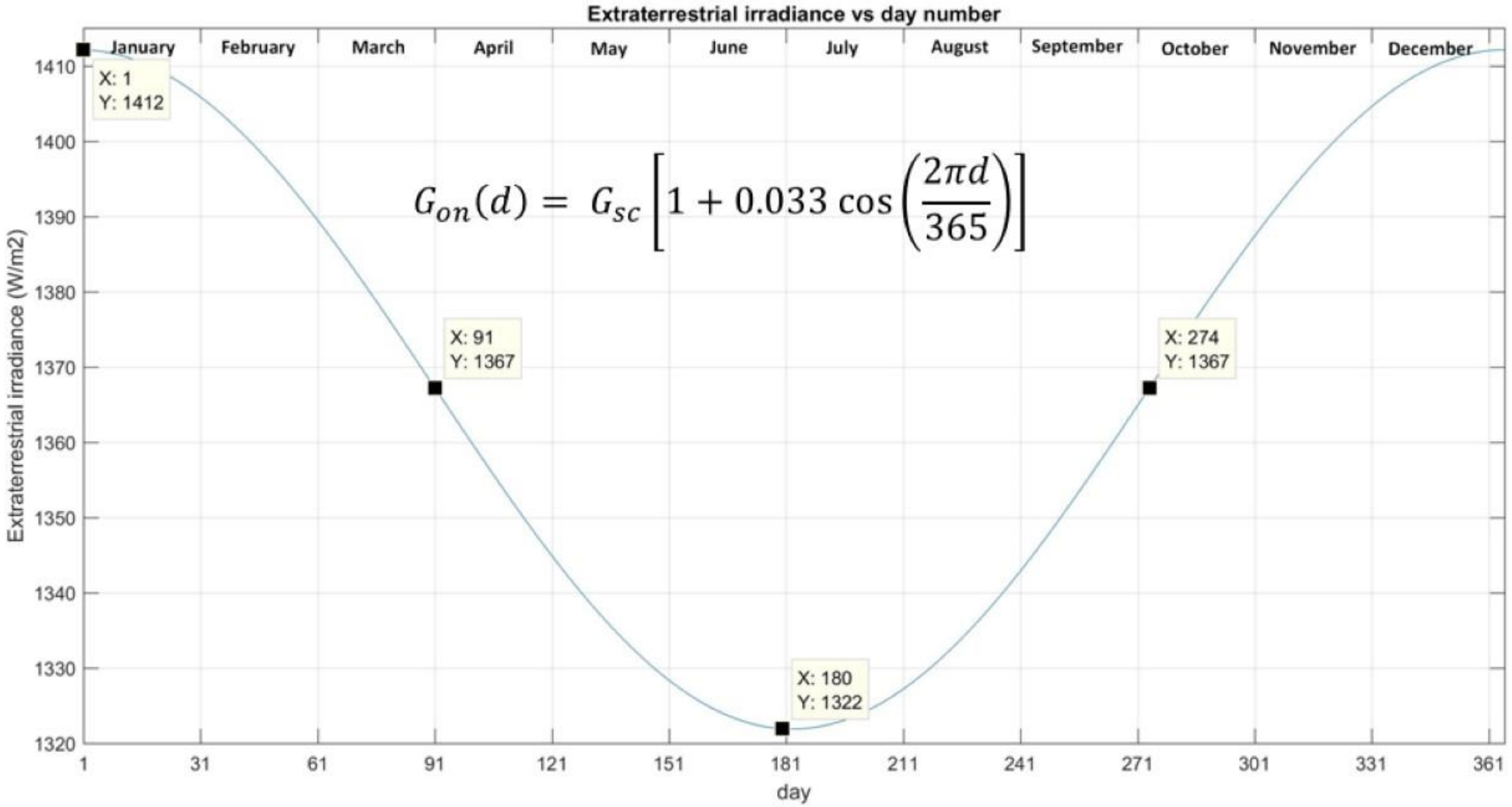
- d is the day of the year (d=1 on 1 January)



first day of:	d
January	1
February	32
March	60
April	91
May	121
June	152
July	182
August	213
September	244
October	274
November	305
December	335

Daily extraterrestrial Irradiance





Daily extraterrestrial Irradiance

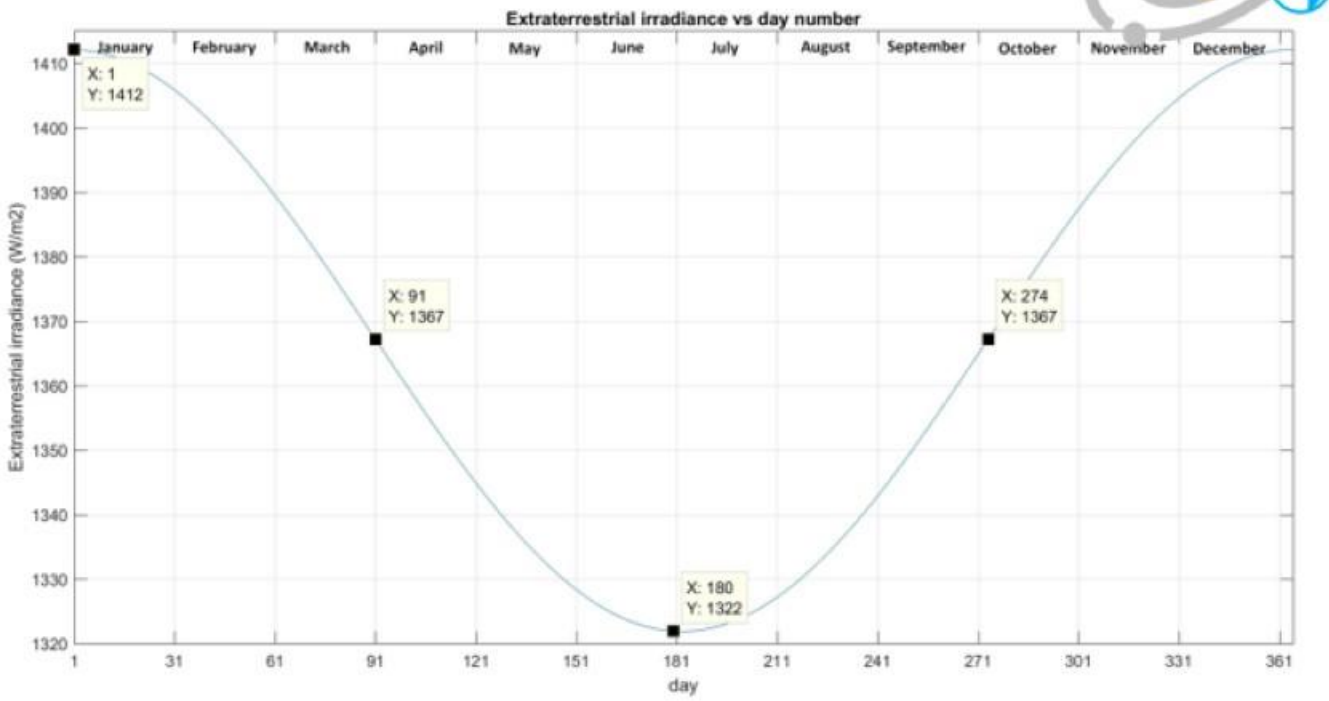


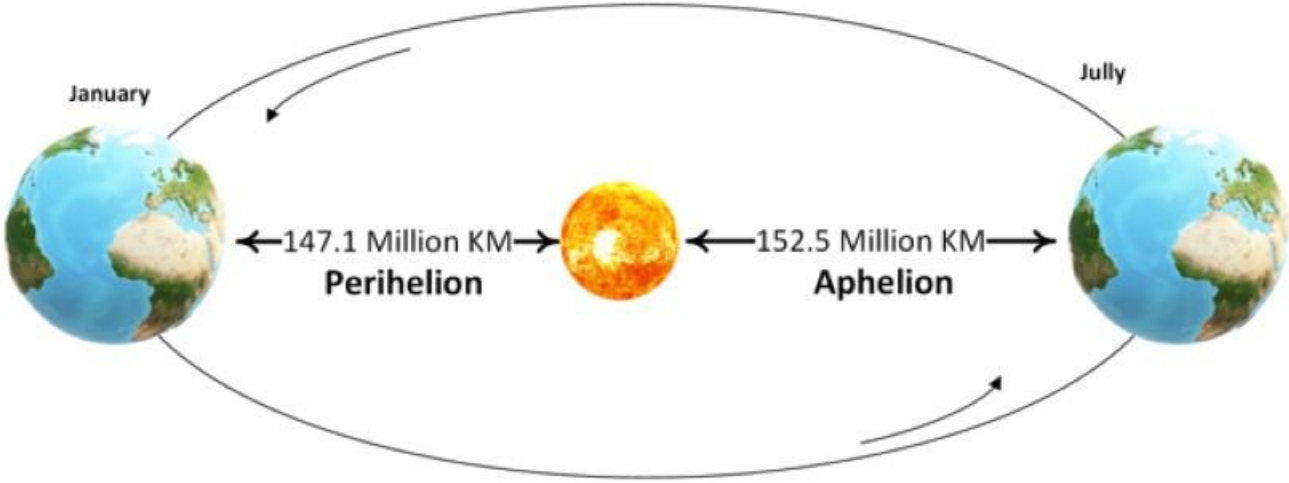
Matlab script

```
close all
Gsc = 1367;
d=1:365;
G0n = Gsc * (1 + 0.033 * cos(2*pi*d/365));
plot(n, G0n)
title('Extraterrestrial irradiance vs day number')
xlabel('day');
ylabel('Extraterrestrial irradiance (W/m2)');
axis([1, 365, 1320, 1415])
grid on
set(gca,'xtick',[1:30:365])
```

Daily extraterrestrial Irradiance

- When the sun is closest to the earth, on January 3rd, the solar heat on the outer edge of the earth's atmosphere is about 1410 W/m^2; and
- when the sun is farthest away, on July 4th, it is about 1320 W/m^2.





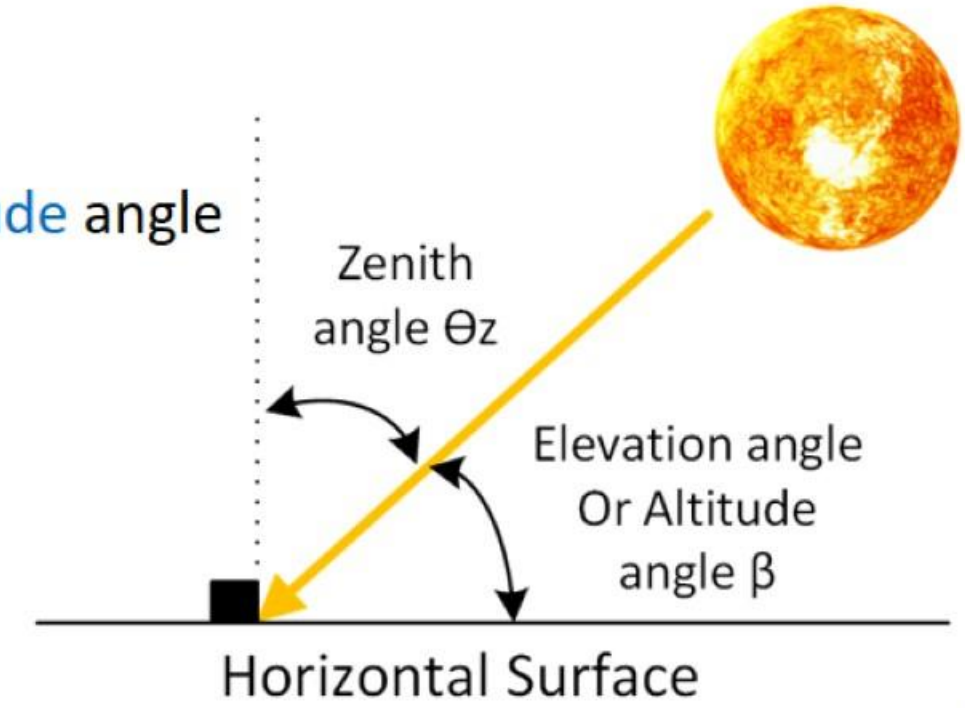
Day number

January	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
day #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
February	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28			
day #	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59			
March	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
day #	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
April	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
day #	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	
May	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
day #	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151
June	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
day #	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	
July	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
day #	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212
August	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
day #	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243
September	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
day #	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	
October	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
day #	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304
November	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
day #	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	
December	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
day #	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365

Zenith angle Θ_z and Altitude angle β

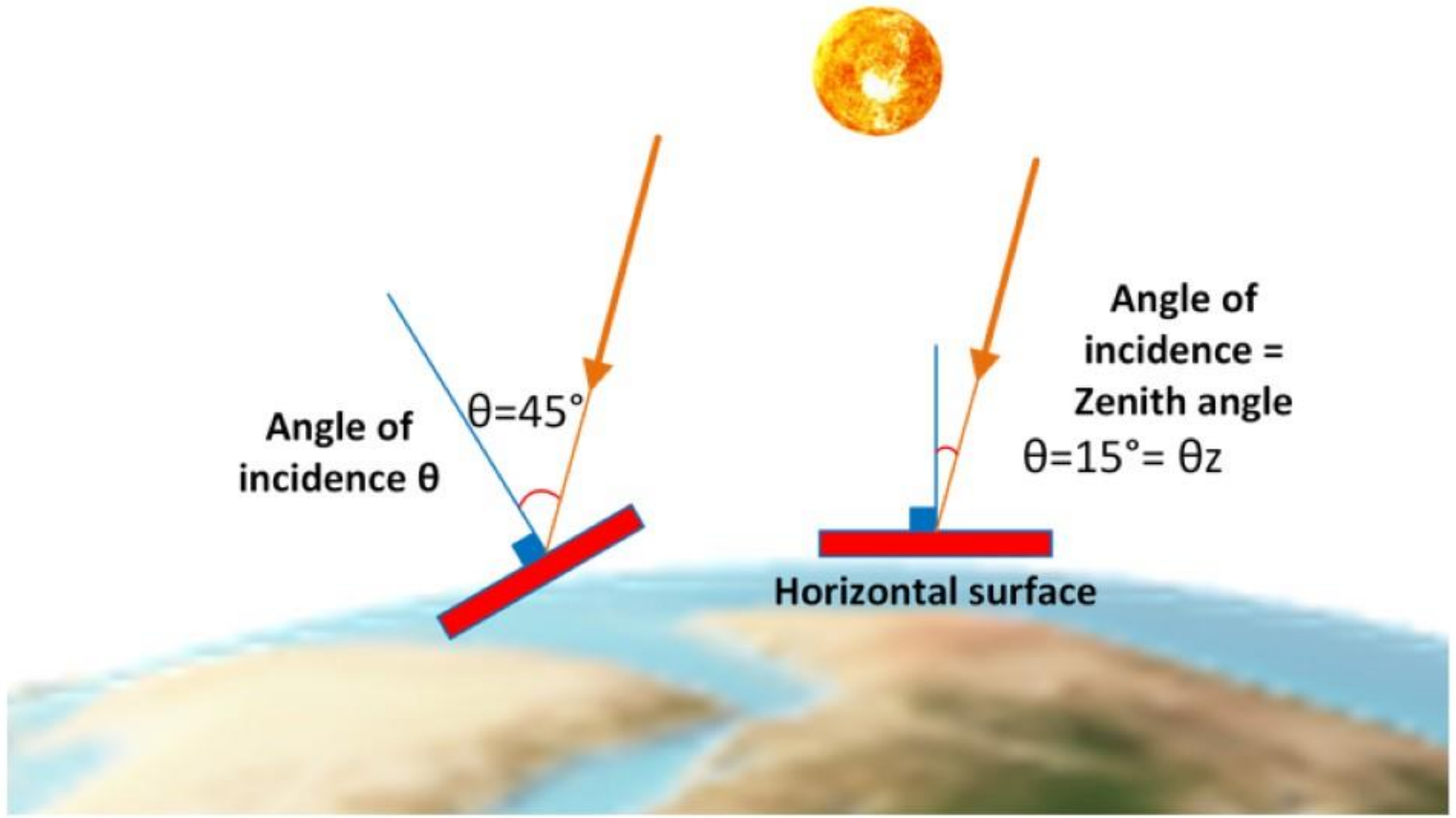
- The angle between the sun's ray and the perpendicular (normal) to horizontal plane is known as Zenith angle Θz
- The angle between sun's ray and its projection on the horizontal surface is known as the Elevation angle or Altitude angle β.

- Zenith angle is the compliment of the Altitude angle
- $\beta + \Theta z = 90$
- Θz is +90 at sunrise and -90 at sunset
- β is 0° at sunrise and sunset



Solar Incidence Angle Θ

- The solar incidence angle, θ, is the angle between the sun's rays and the normal on a surface (not necessary horizontal).
- For a horizontal plane, the incidence angle, θ, and the zenith angle θ_z are the same



- End of part 1

Photovoltaic solar energy training course

Section 1: Solar resources

Part 2

- Solar Irradiance and Air Mass
- Type of Irradiance
- Atmosphere effects
- Solar Direct and Diffuse Irradiance

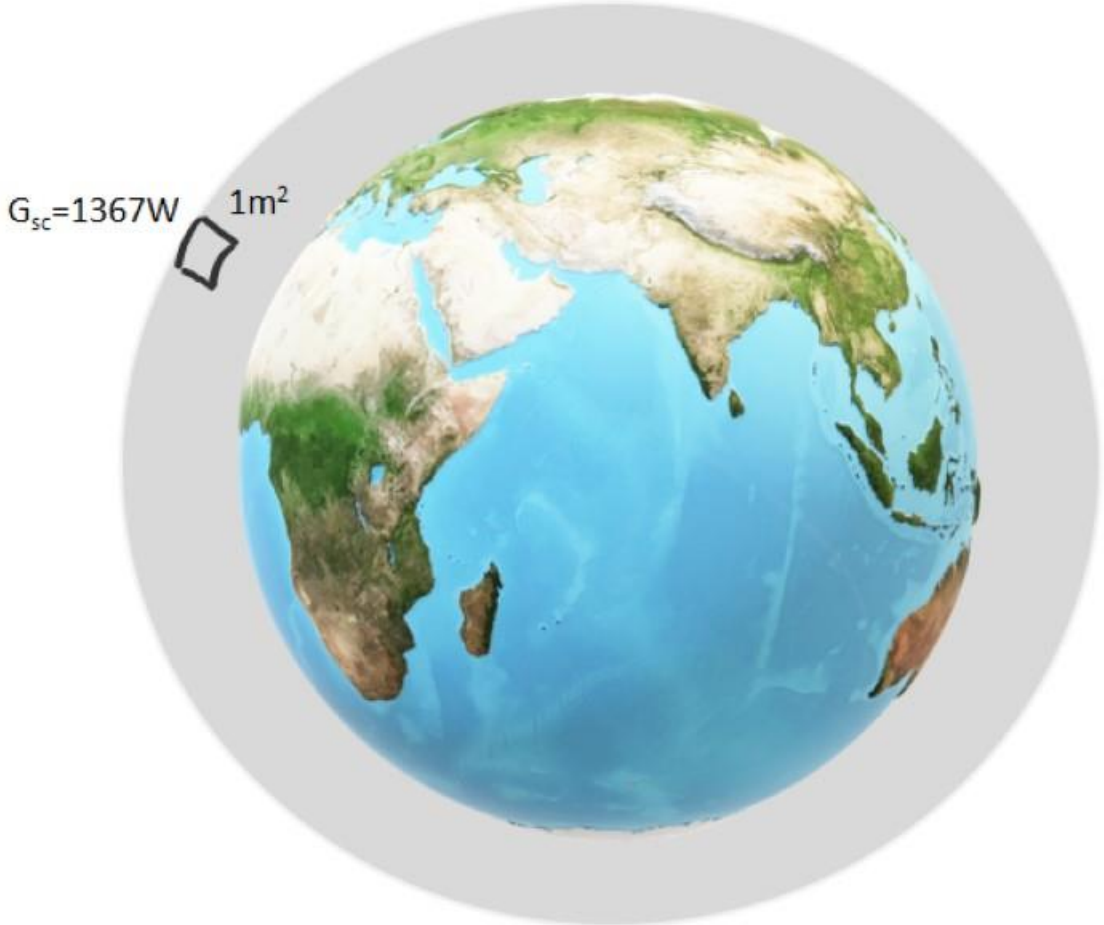
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Solar Irradiation at the Earth's Surface (Inside the Atmosphere)

- The extraterrestrial irradiance, as calculated, is about 1367W/m^2

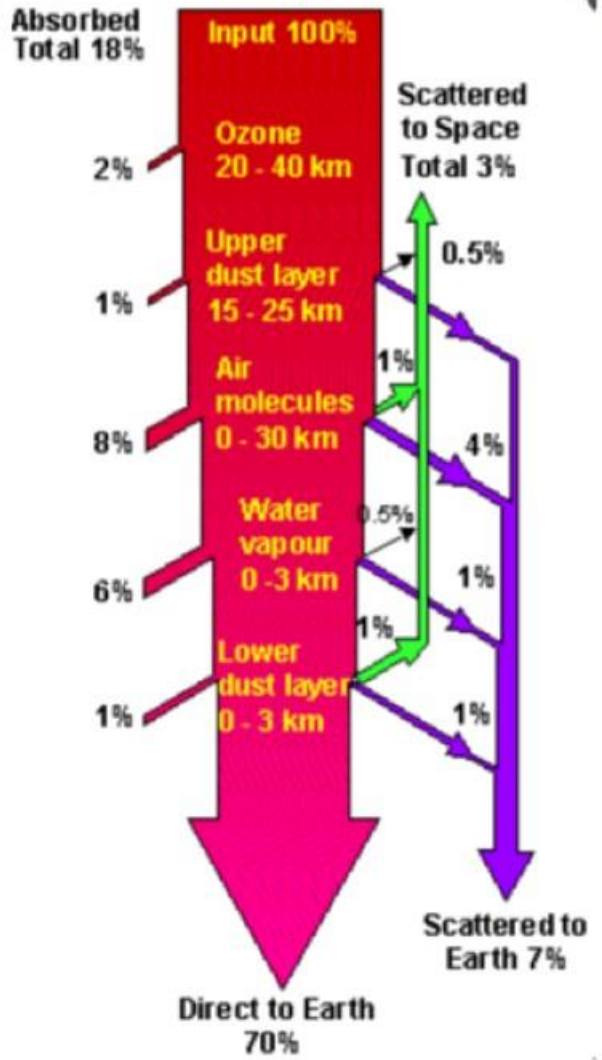
BUT

- What is the irradiance on the earth surface ?!
- Earth's atmosphere is **about 480 kilometers thick**
- and is not 100% transparent



Solar Irradiation at the Earth's Surface (Inside the Atmosphere)

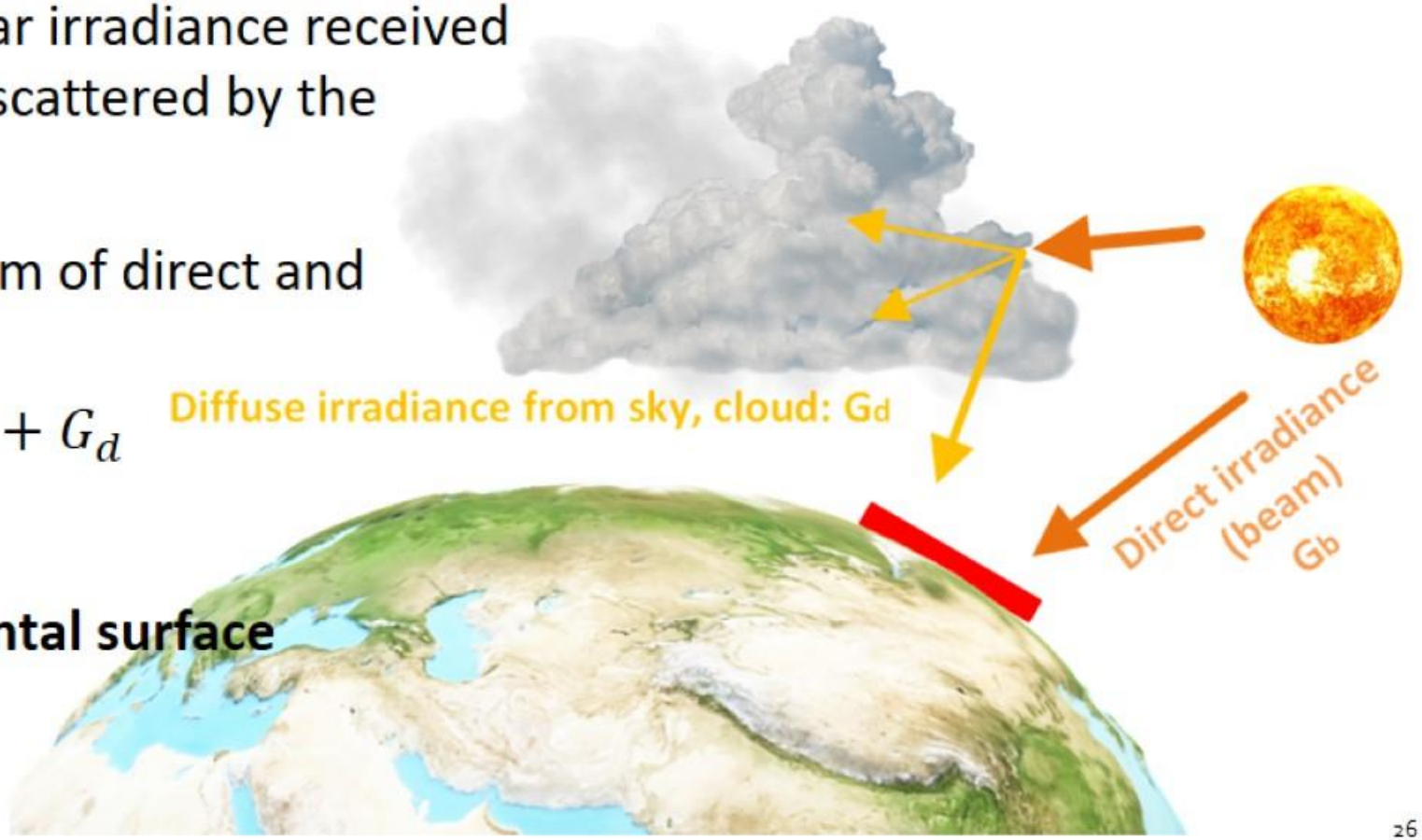
- Solar irradiance G at the Earth's surface varies from the solar irradiance G_D incident on the Earth's atmosphere due to:
  - atmospheric effects, including absorption and scattering (due to particles).
  - local variations in the atmosphere, such as water vapor, clouds, and pollutions
  - latitude of the location
  - season of the year and the time of the day.



Solar Direct and Diffuse Irradiation

- Direct irradiance (beam) G_b: Solar irradiance received from the sun directly. It has not been scattered by the atmosphere
- Diffuse irradiance G_d: Solar irradiance received from the sun after being scattered by the atmosphere
- Global Irradiance G_{GHI}: Sum of direct and diffuse

$$G_{GHI} = G_d + G_d$$

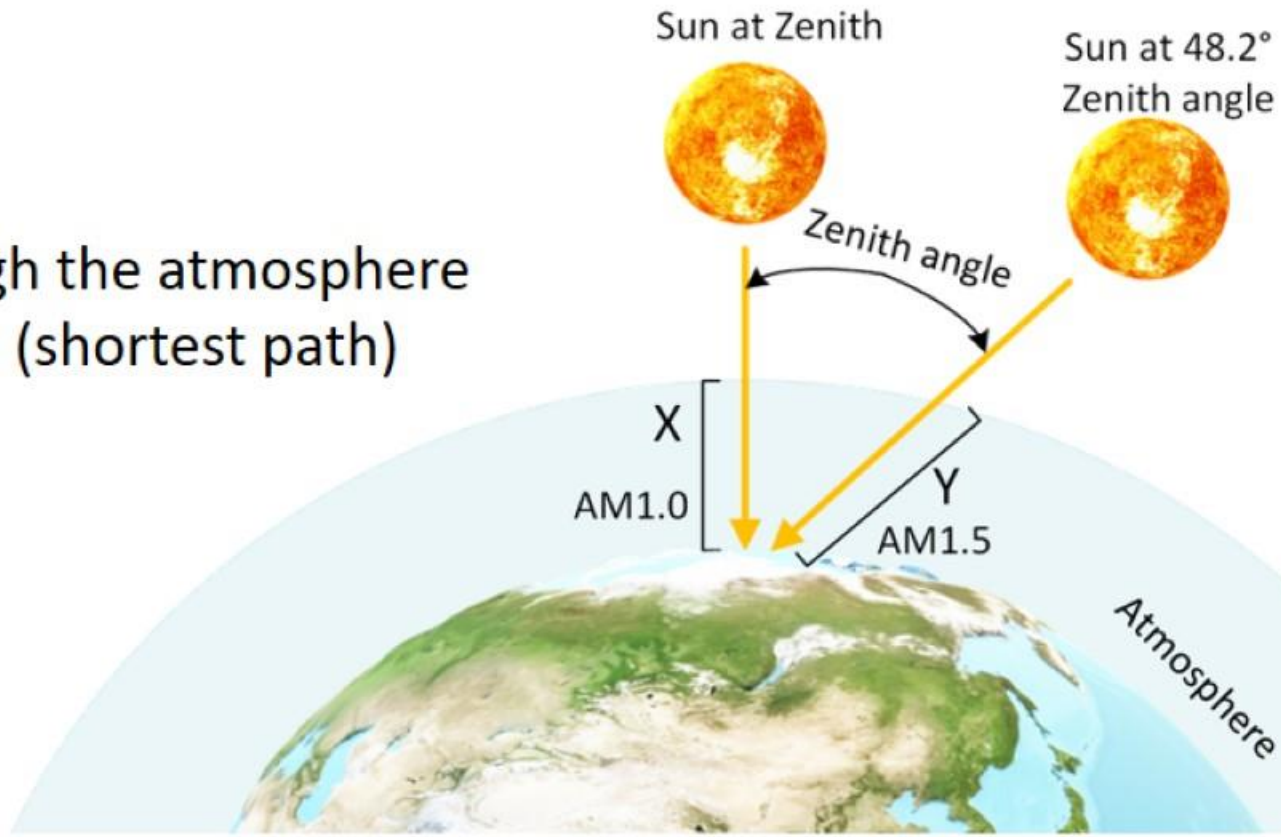


All G are referred to horizontal surface

Solar irradiation and Air mass

- The Air Mass represents how much atmosphere, sunlight must pass through to reach the surface of Earth (it is also defined as the path length which light takes through the atmosphere normalized to the shortest possible path length).
- Air mass is a number compared to the vertical path
- $AM = \frac{Y}{X} = \frac{1}{\cos \theta_z}$

  - Y: is the path length through the atmosphere
  - X: is the zenith path length (shortest path)
  - θz : is the Zenith angle

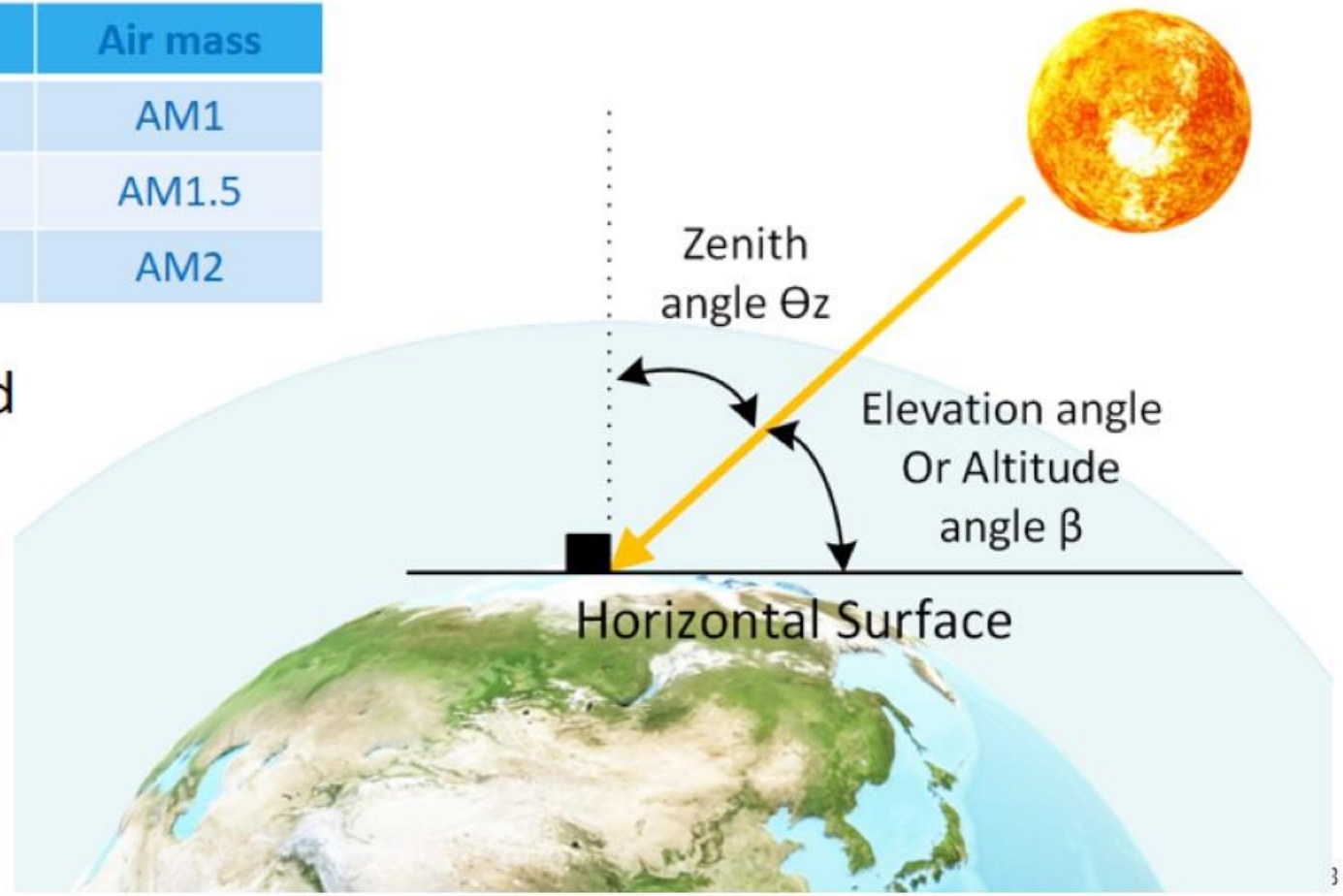


Solar irradiation and Air mass

- $AM = \frac{Y}{X} = \frac{1}{\cos \theta_z} = \frac{1}{\sin \beta}$

β	θz	$1/cos\ \theta z$	Air mass
90	0	1	AM1
41.8	48.2	1.5	AM1.5
30	60	2	AM2

AM1.5 is used as testing standard



Solar irradiation at the Earth's surface (inside the atmosphere)

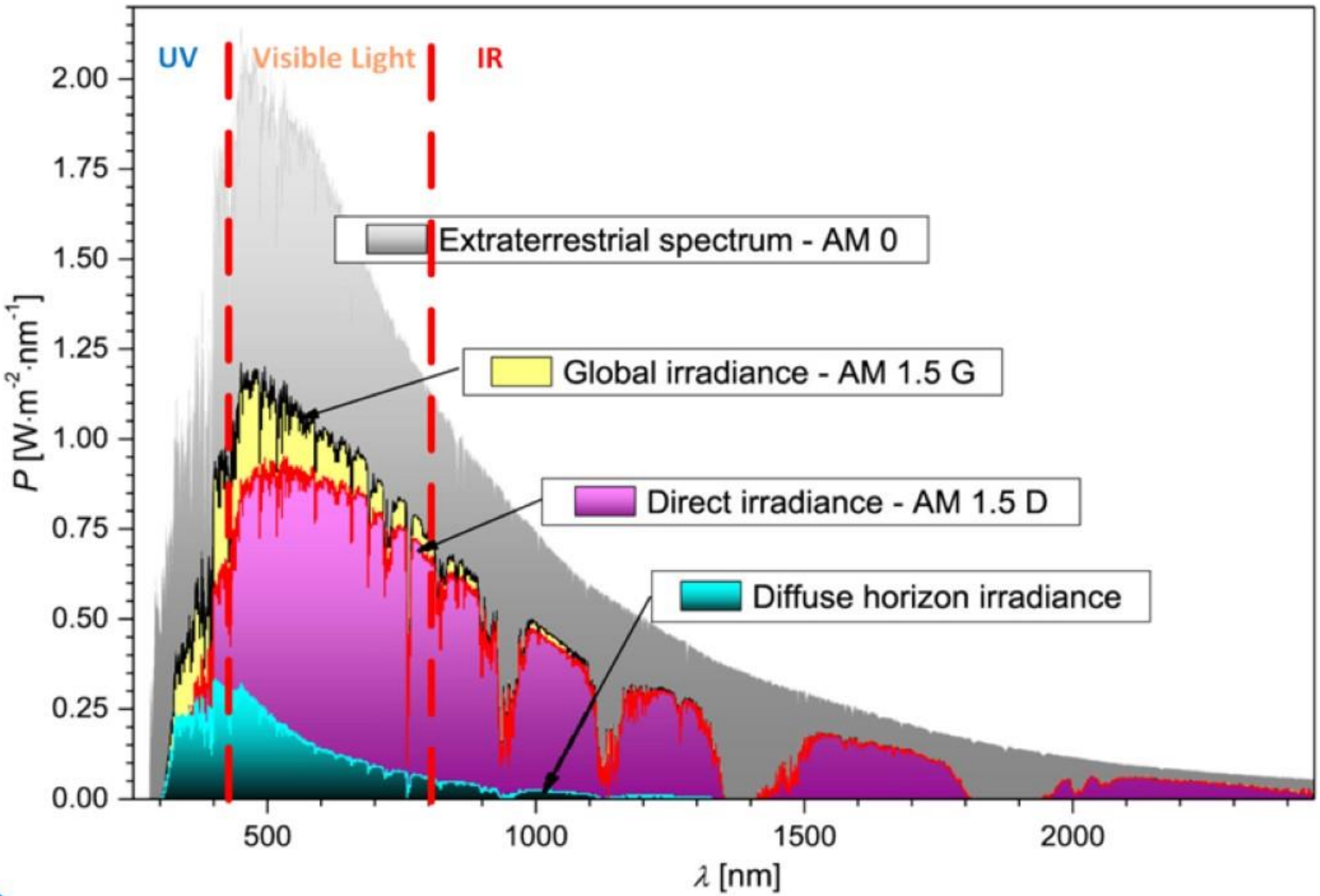


Table below shows the dependency of irradiance on the Zenith/Elevation angle.

- Absorption and Rayleigh scattering increase at lower solar altitudes.
- Scattering of pollution in the air (Mie scattering) is strongly location dependent. It is greatest in industrialized areas.
- Local weather effects such as clouds, rain and snowfall cause further weakening of irradiance.

Zenith angle (degree)	Elevation angle (degree)	AM	Absorption %	Rayleigh scattering %	Mie scattering %	Overall reduction %
0	90	1	8.7	9.4	0 - 25.6	17.3 - 38.5
30	60	1.15	9.2	10.5	07 - 29.5	19.4 - 42.8
60	30	2	11.2	16.3	4.1 - 44.9	28.8 - 59.1
80	10	5.76	16.2	31.9	15.4 - 74.3	51.8 - 85.4
85	5	11.5	19.5	42.5	24.6 - 86.5	65.1 - 93.8

Solar irradiation at the Earth's surface (inside the atmosphere)



Solar irradiation at the Earth's surface (inside the atmosphere)



- The intensity of the direct component (beam irradiance) of sunlight throughout each day can be determined as a function of air mass from the experimentally determined equation:

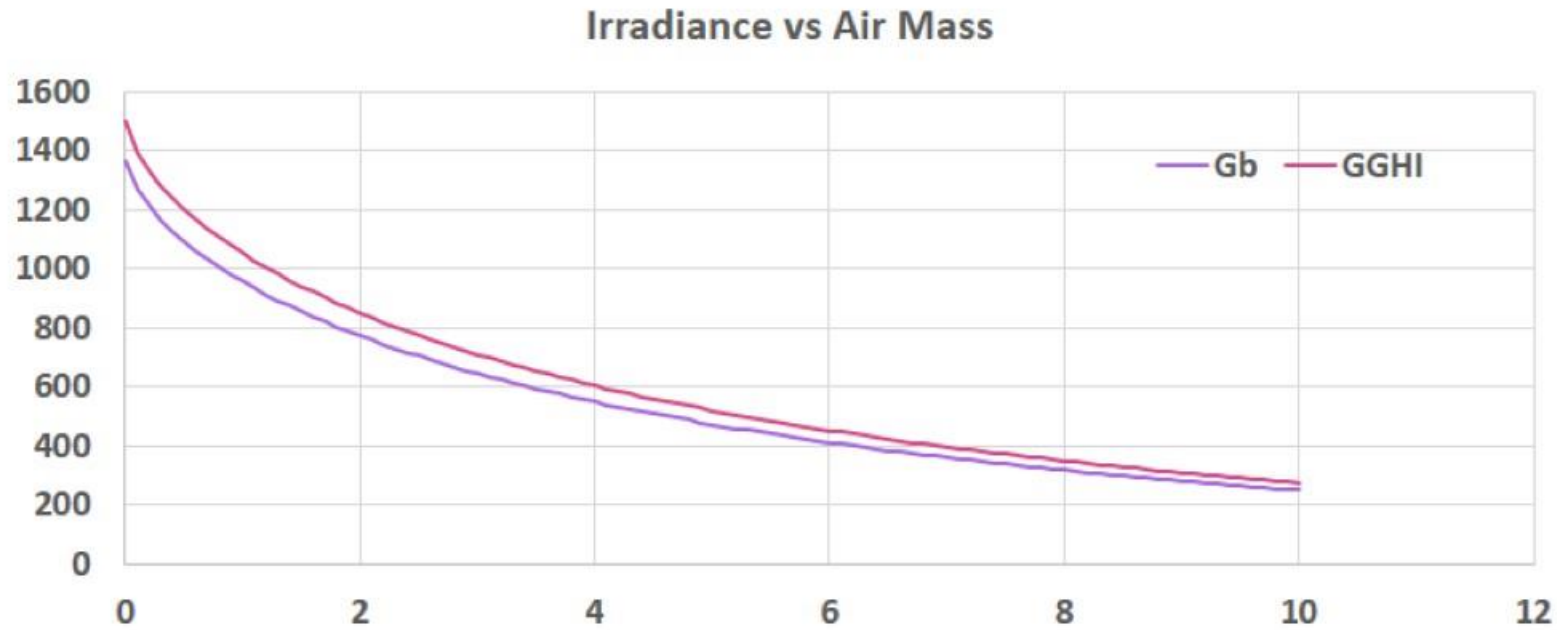
$$G_b = 1367 \times 0.7^{AM^{0.678}}$$

  - G_b is the intensity on a plane perpendicular to the sun's rays in units of W/m^2
  - *AM* is the air mass.
  - The value of 1367 W/m^2 is the solar constant (depending on the ref)
  - and the number 0.7 arises from the fact that about 70% of the radiation incident on the atmosphere is transmitted to the Earth.
  - The extra power term of 0.678 is an empirical fit to the observed data and takes into account the non-uniformities in the atmospheric layers.

Solar irradiation at the Earth's surface (inside the atmosphere)

- Even on a clear day, the diffuse radiation is still about 10% of the direct component. Thus on a clear day the global irradiance on a module perpendicular to the sun's rays is:

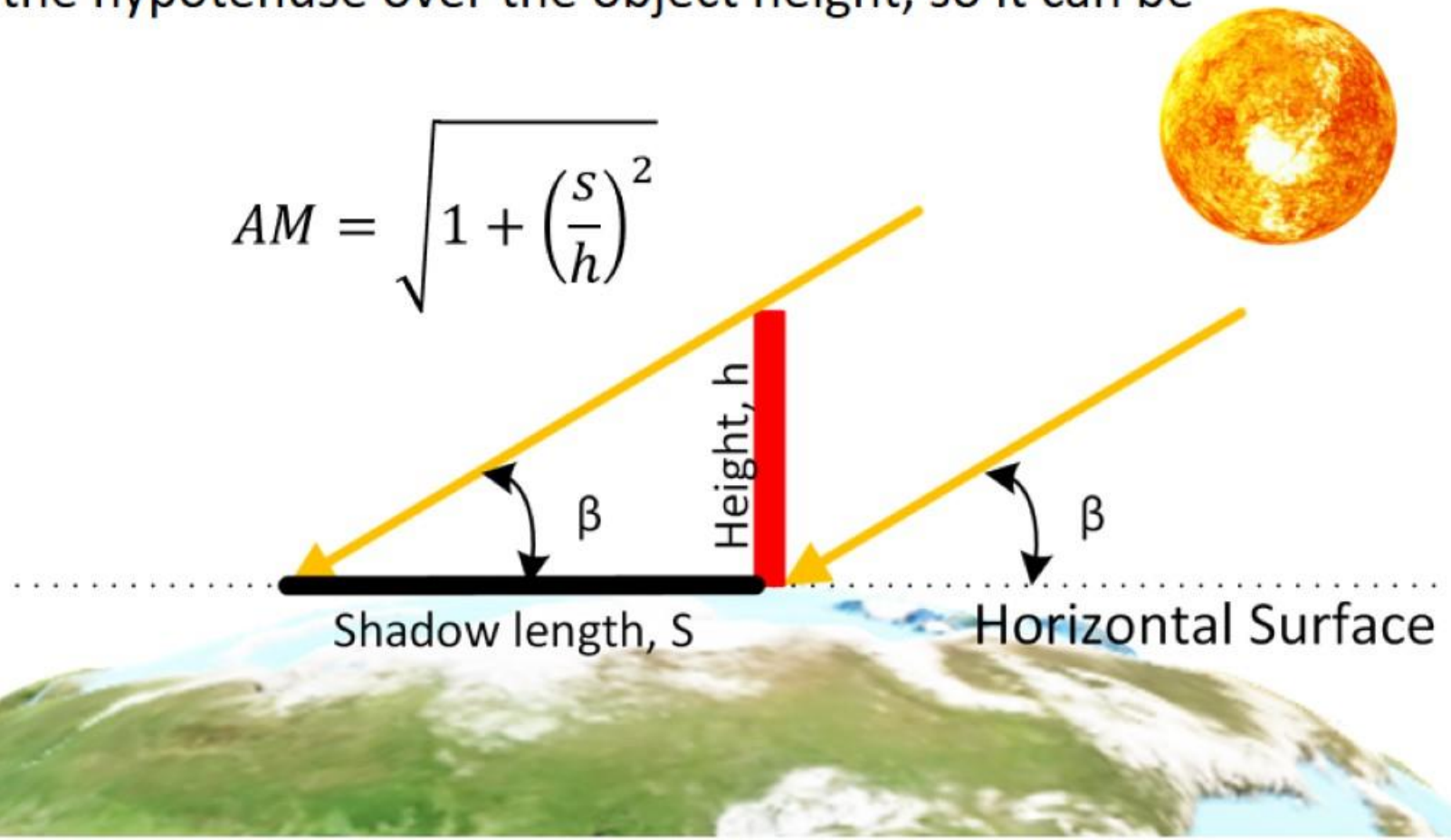
$$G_{GHI} = 1.1 \times G_b$$



Solar irradiation and Air mass

- An easy way to determine the AM is from the shadow of a vertical object.
- AM is the length of the hypotenuse over the object height, so it can be modeled as

$$AM = \sqrt{1 + \left(\frac{S}{h}\right)^2}$$



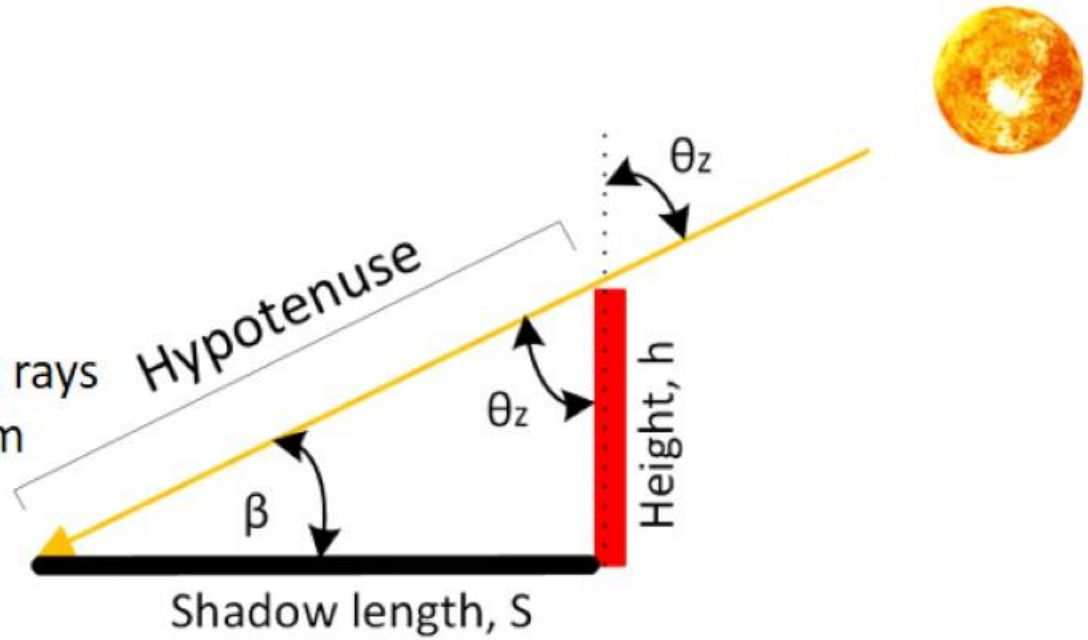
Solar irradiation and Air mass

Example:

- Assume that the shadow of a 1m pole is 2m.

  Calculate the

  1. Air Mass
  2. Elevation angle
  3. Zenith angle
  4. Thickness of the atmosphere in which sun rays are passing through (Assume the minimum thickness is 480km)
  5. Direct irradiance
  6. Global irradiance



Solar irradiation and Air mass

Solution:

The AM can be calculated using

$$AM = \sqrt{1 + \left(\frac{s}{h}\right)^2} = \sqrt{1 + \left(\frac{2}{1}\right)^2} = 2.23$$

The elevation angle can be calculated by

$$\beta = \sin^{-1}\frac{1}{AM} = \sin^{-1}\frac{1}{2.23} = 26.6°$$

The zenith angle can be calculated as

$$\theta_z = \cos^{-1}\frac{1}{AM} = 63.3° \text{ or } \theta_z = 90 - \beta$$

Solution:

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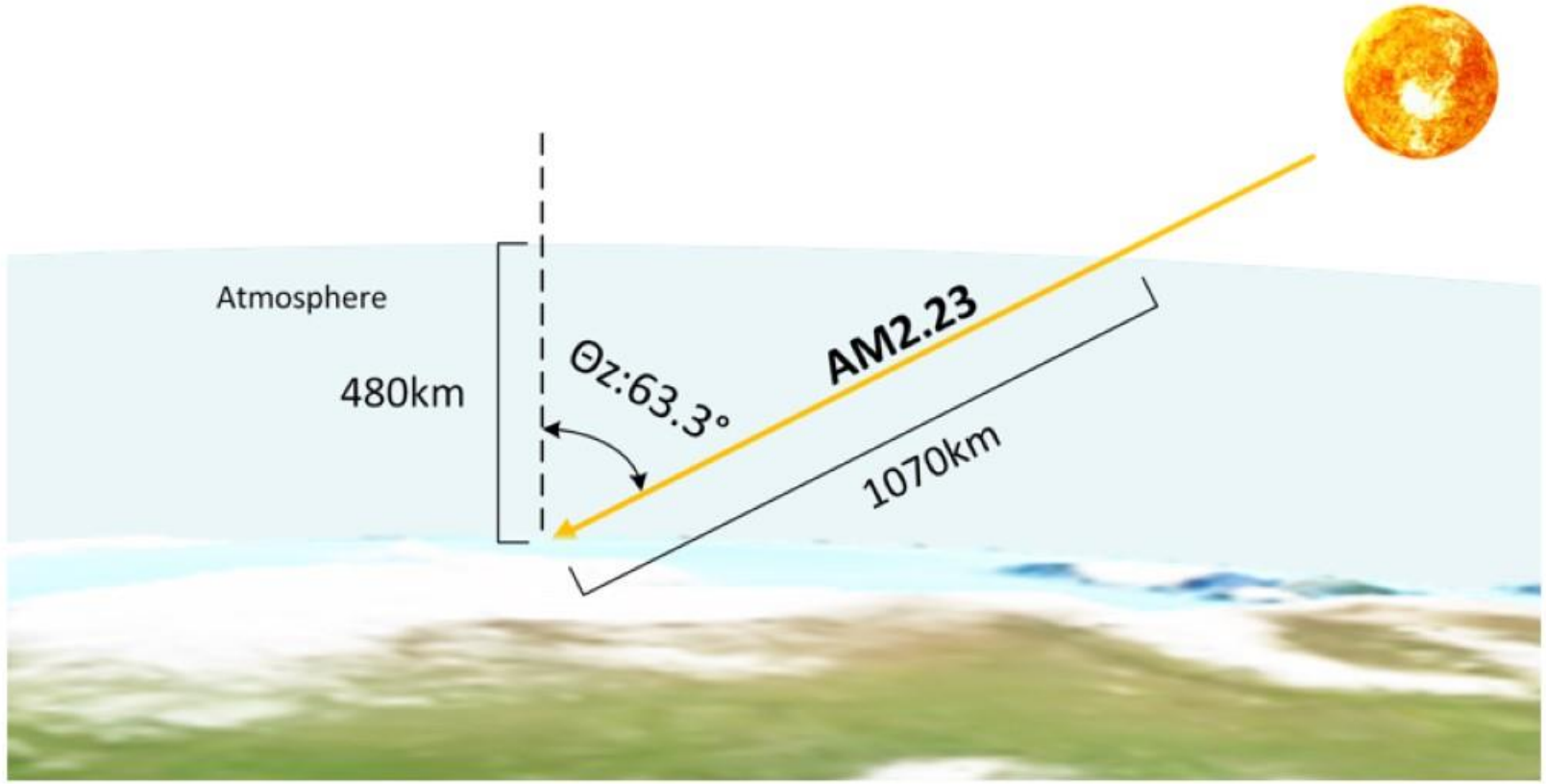
$$\theta_z = \cos^{-1}\frac{1}{AM} = 63.3° \text{ or } \theta_z = 90 - \beta$$

Solar irradiation and Air mass

Solution:

The thickness of the Atmosphere in which ray passes through is calculated as

$$Y = X \times AM = 480 \times 2.23 = 1070km$$



Solar irradiation and Air mass



Solution:

The direct irradiance can be calculated using

$$G_b = 1367 \times 0.7^{AM^{0.678}} = 1367 \times 0.7^{2.23^{0.678}} = 740 W/m^2$$

The Global Horizontal Irradiance is calculated as

$$G_{GHI} = 1.1 \times G_b = 1.1 \times 740 = 814 W/m^2$$

Observation:

- Irradiance drops from 1367W/m^2 at the top of the atmosphere to 814W/m^2 because light penetrates in 1070km of atmosphere thickness
- Only 60% received

  Power loss of 553W/m^2 (40% loss)

Solar irradiation and Air mass



- The standard spectrum at the Earth's surface is called AM1.5G,
- The G stands for global and includes both direct and diffuse radiation or
- AM1.5D (which includes direct radiation only).
- The intensity of AM1.5D radiation can be approximated by reducing the AM0 spectrum by 28% (18% due to absorption and 10% to scattering).
- The global spectrum is 10% higher than the direct spectrum.
- These calculations give approximately 970 W/m^2 for AM1.5G. However, the standard AM1.5G spectrum has been normalized to give $1kW/m^2$

- End of part 2

Photovoltaic solar energy training course

Section 1: Solar resources

Part 3

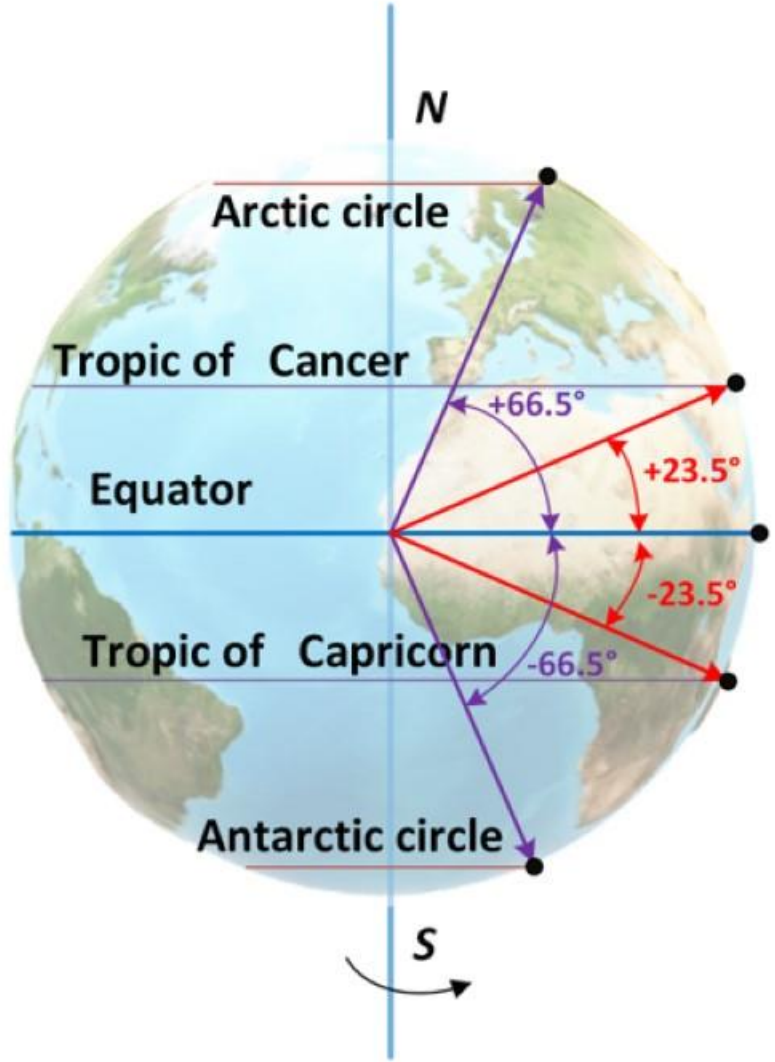
- Earth Angle and Geometry
- Declination/Latitude Angle Over Year
- Extraterrestrial Irradiance Calculation
- Irradiance Calculation

Nabil Karami, PhD

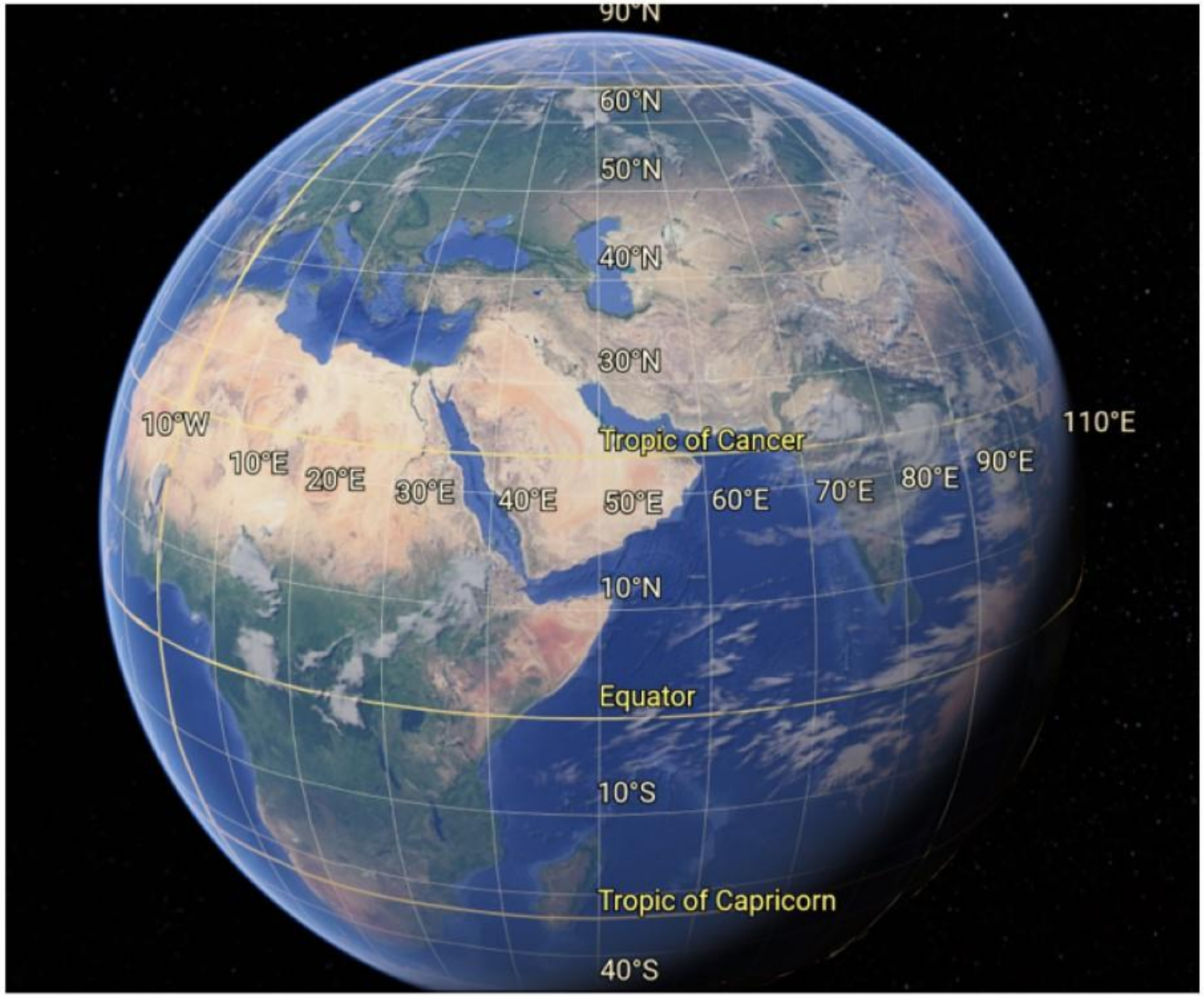
Earth angles and geometry

We can consider 5 imaginary circles (angles) on the earth surface:

1: Equator: located at 0° latitude
2: Tropic of Cancer: located at 23.5 °N latitude
3: Tropic of Capricorn: located at 23.5 °S latitude
4: Arctic circle: located at 66.5 °N latitude
5: Antarctic circle: located at 66.5 °S latitude

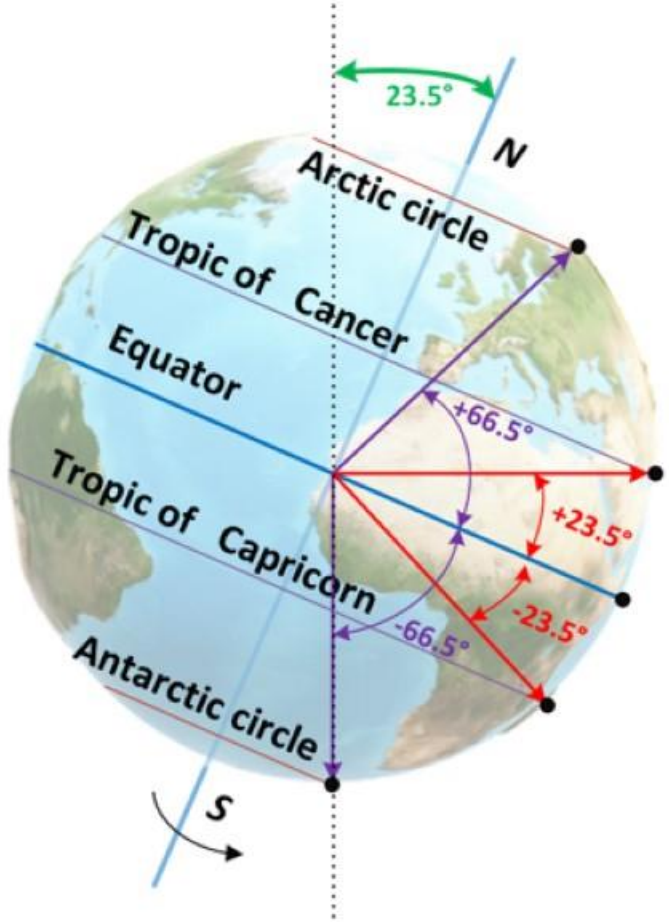


Earth angles and geometry



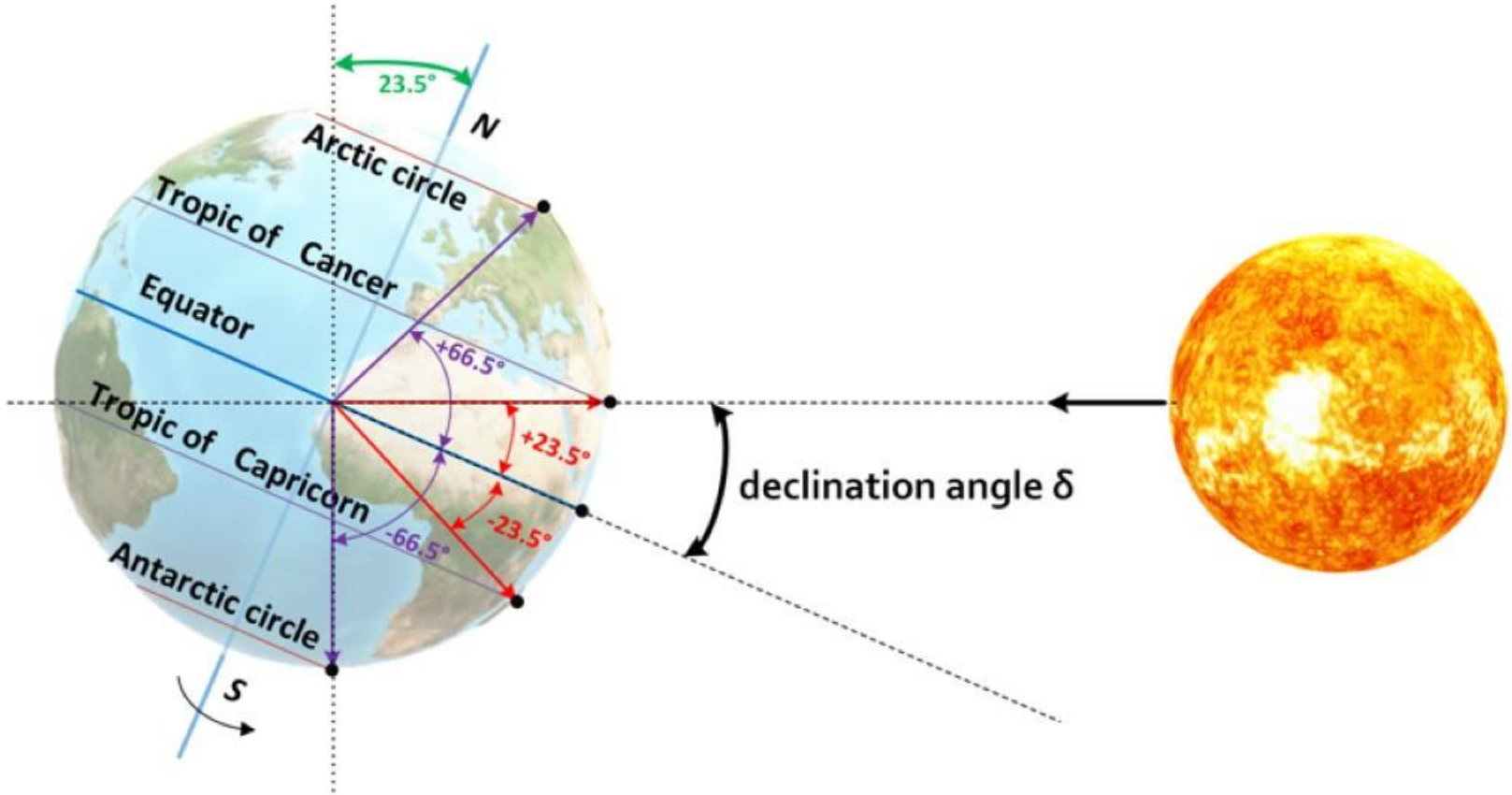
Earth angles and geometry

- The Earth's axis is tilted by 23.5° from the plane of its orbit around the sun.
- Because this tilt changes, the seasons as we know them can become exaggerated.
- More tilt means more severe seasons: warmer summers and colder winters;
- Less tilt means less severe seasons: cooler summers and milder winters.



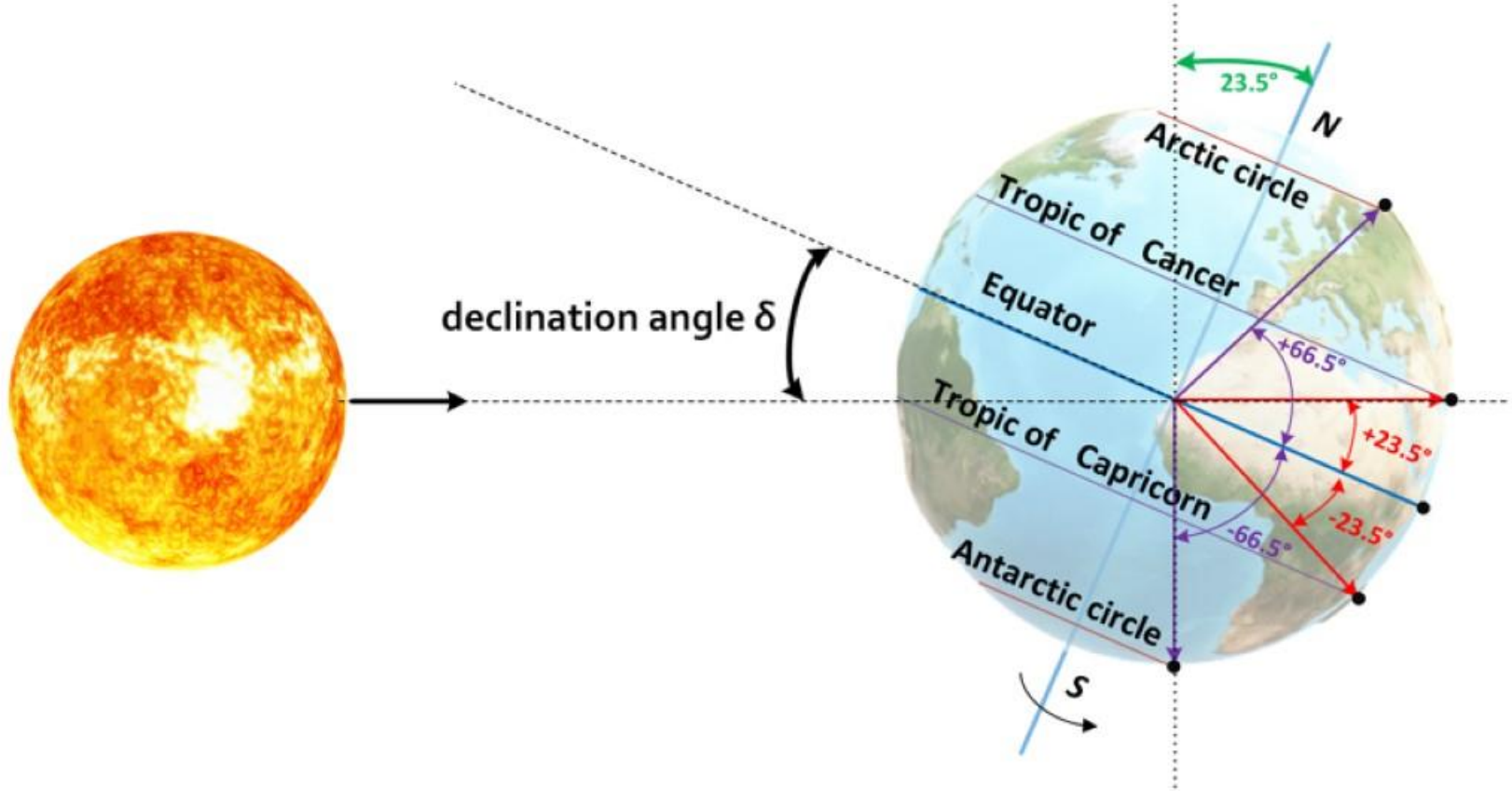
Earth-Sun angles and geometry

- The solar declination δ is the angle between the Earth–Sun line and the Equatorial plane
- δ is a function of the time of the year
- Therefore, δ varies from +23.5° on June 21 to −23.5° on December 21

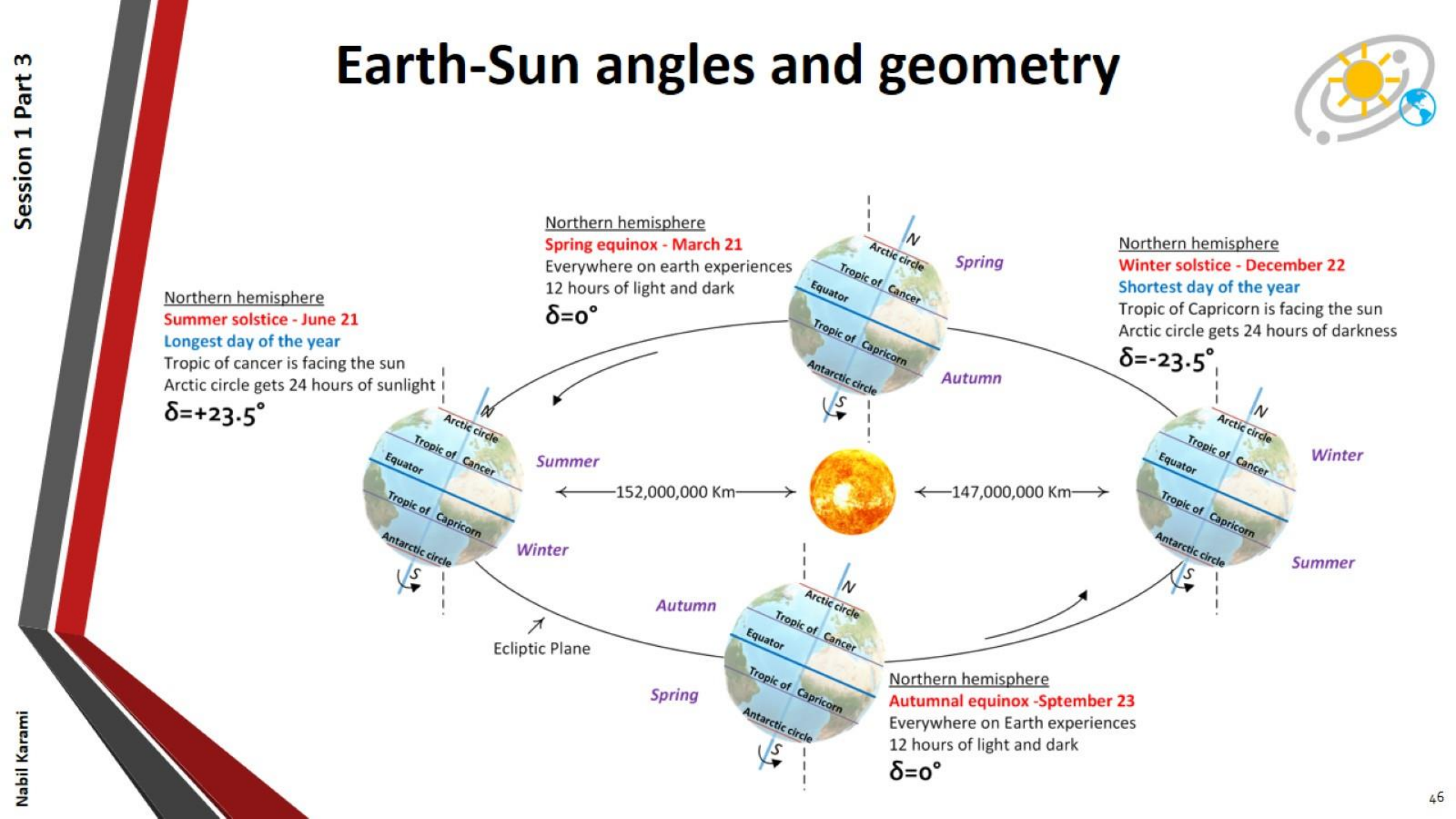


Earth-Sun angles and geometry

- The minimum declination value is $\delta_0 = -23.5°$

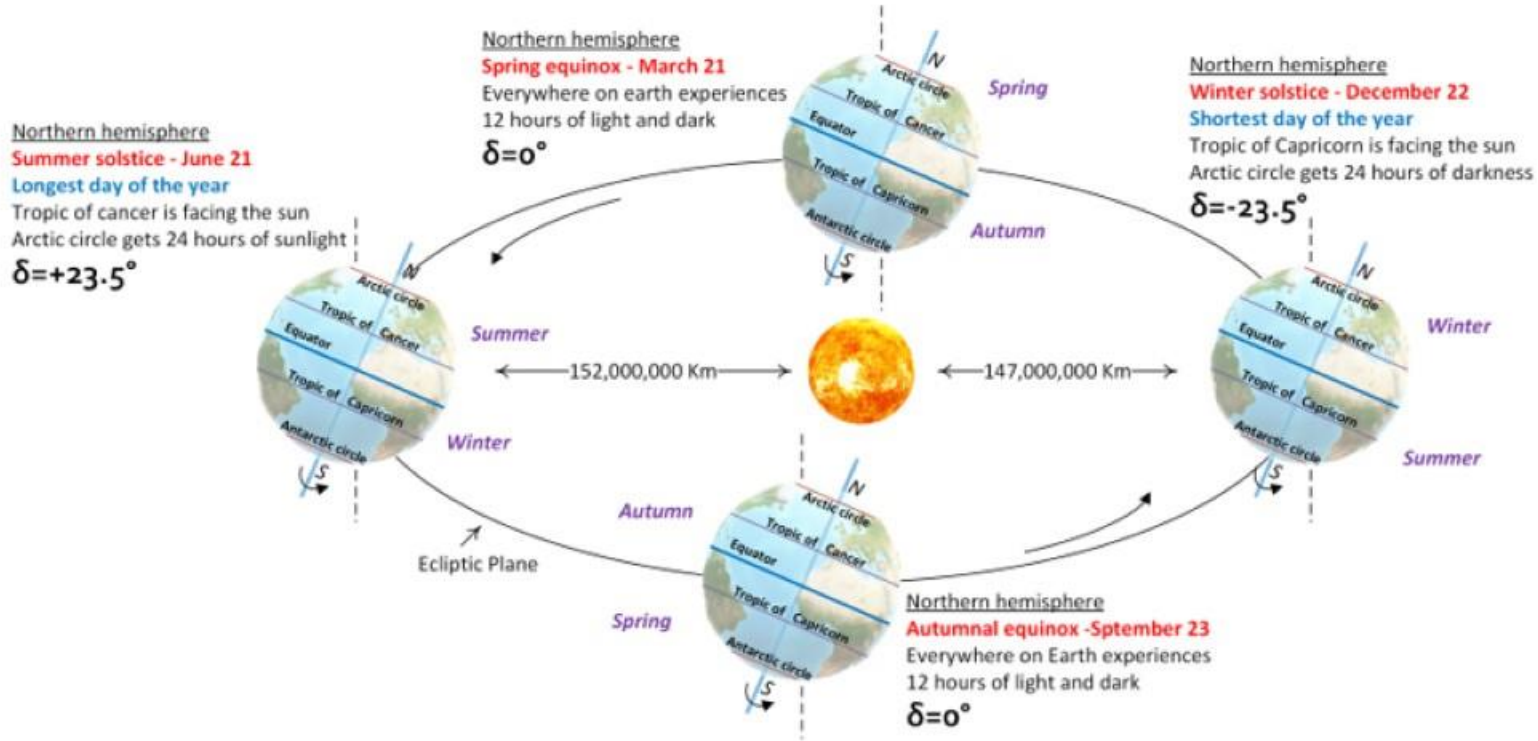


Earth-Sun angles and geometry



Earth-Sun angles and geometry

	δ	Day	Day number
Summer solstice	δ_0= 23.5°	21 June	172
Winter solstice	δ_0= -23.5°	22 December	355
Spring equinox	0°	22 March	81
Autumn equinox	0°	22 September	265

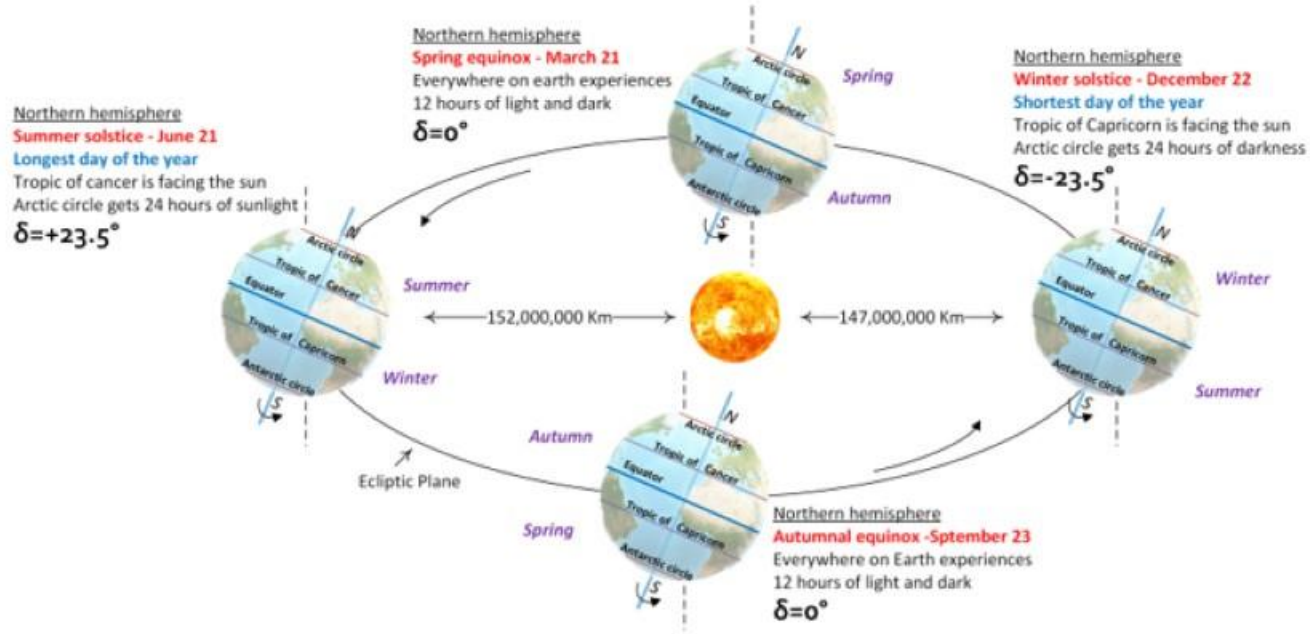


Declination angle over year

- The declination angle can be calculated for every day as:

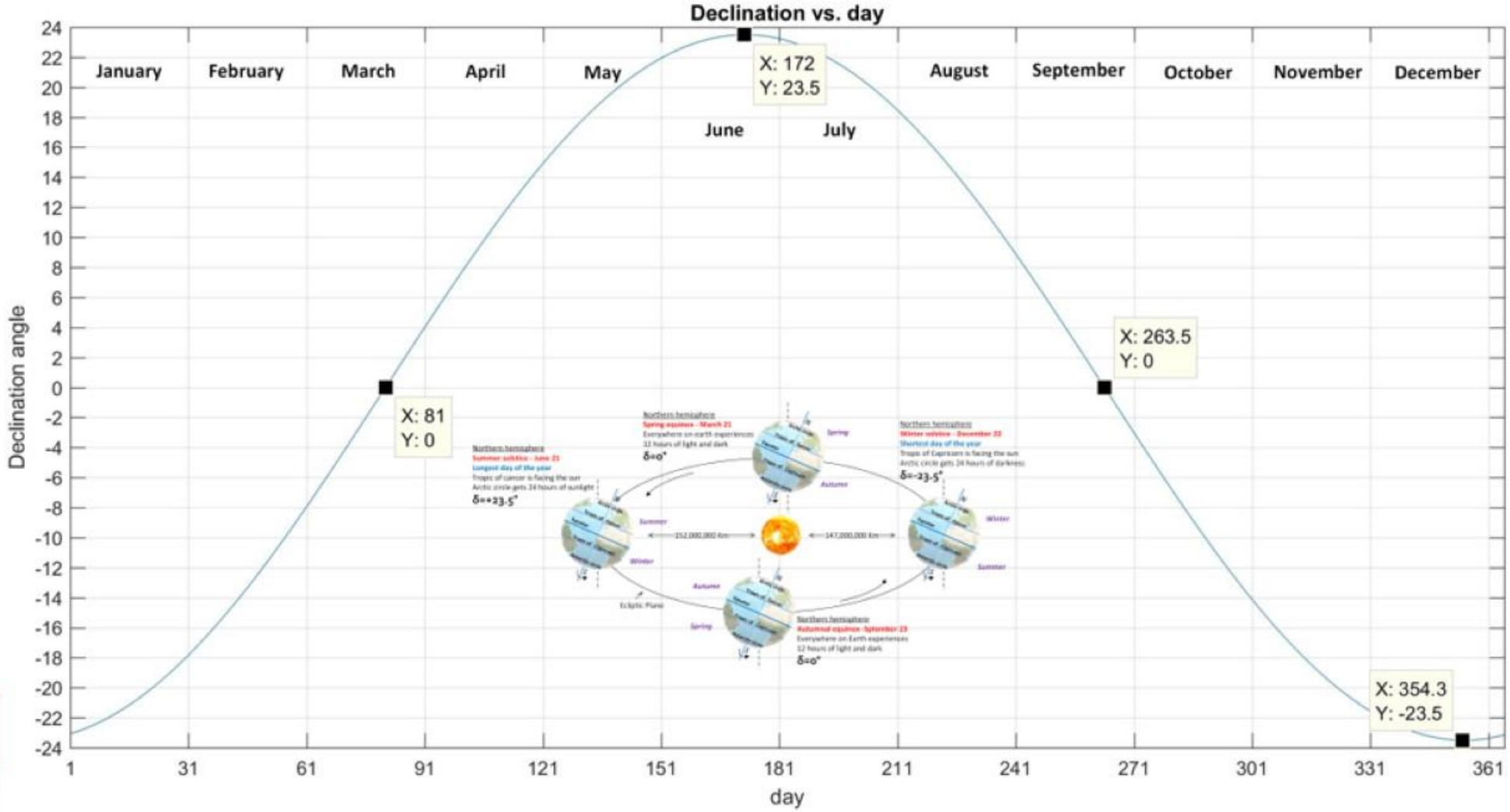
$$\delta = \delta_0 \sin\left(\frac{360 \times (284 + d)}{365}\right)$$

  - δ_0 = 23.5° and
  - d is the day number from 1 to 365



Declination angle over year

$$\delta = \delta_0 \sin\left(\frac{360 \times (284 + d)}{365}\right)$$

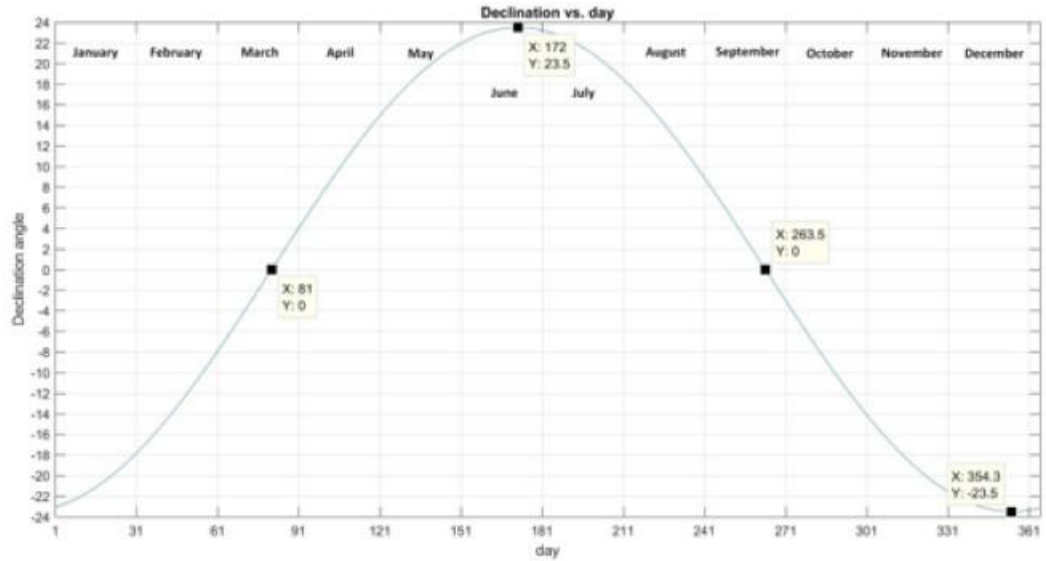


Declination angle over year

Matlab script

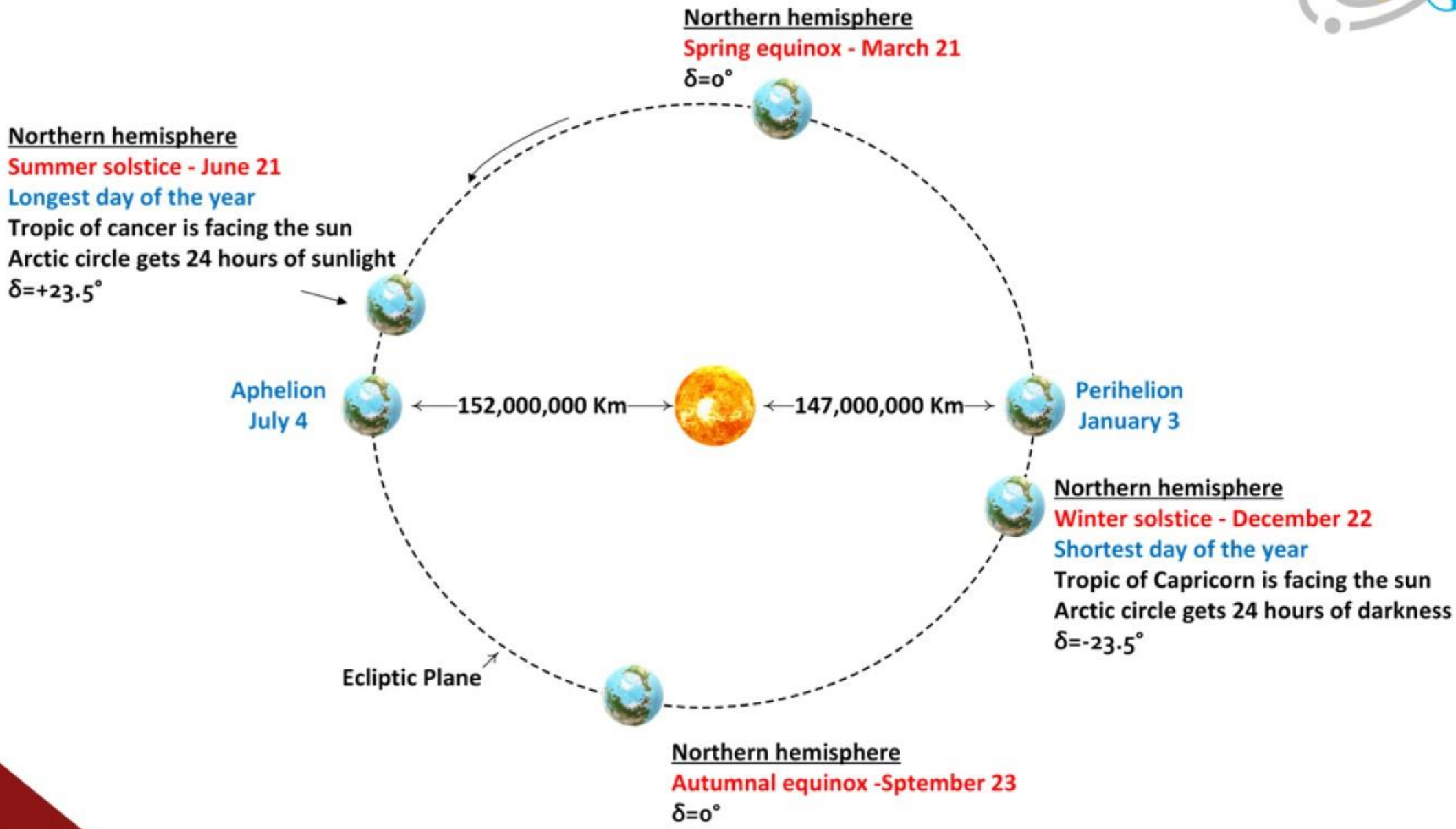
```
close all
S0 = 23.5;
d= 1:0.1:365;
S = S0 * sind(360 *(d+284)/365);


plot(d, S)
title('Declination vs. day')
xlabel('day');
ylabel('Declination angle');
axis([1, 365, -24, +24])
grid on
set(gca,'xtick',[1:30:365])
set(gca,'ytick',[-24:2:+24])
```



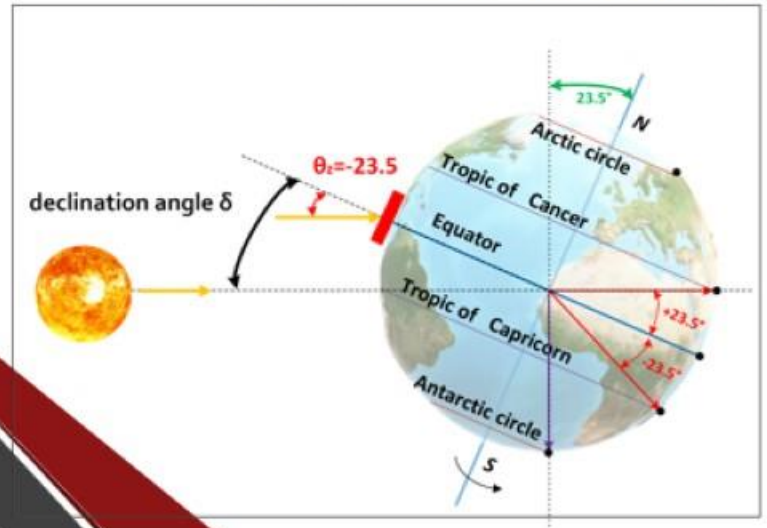
Earth-Sun angles and geometry

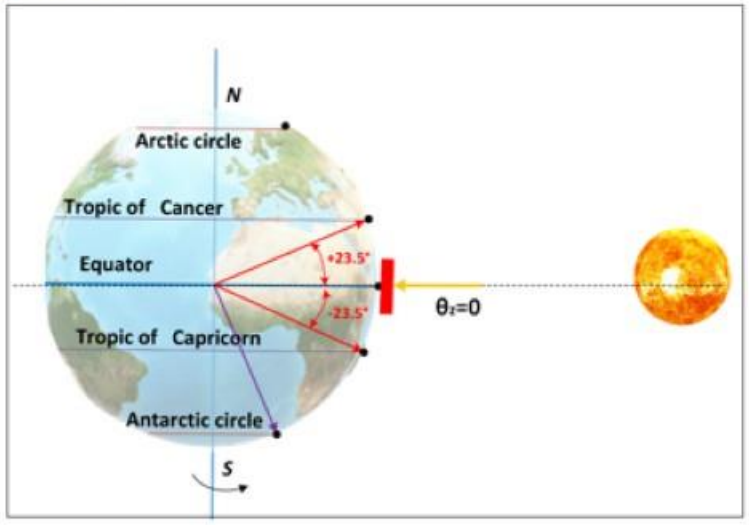


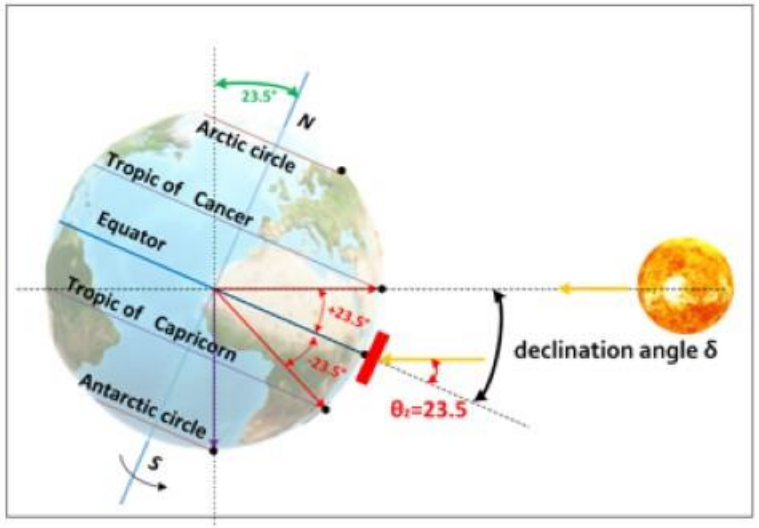


Effects of Declination and Latitude angles on irradiance

- Declination affects zenith angle
- For solar noon (sun directly overhead) and assume the surface is at equator (latitude=0)
- The zenith angle will be:
  - θz = 0° in spring and autumn equinox
  - θz = 23.5° in summer solstice
  - θz = = -23.5° in winder solstice

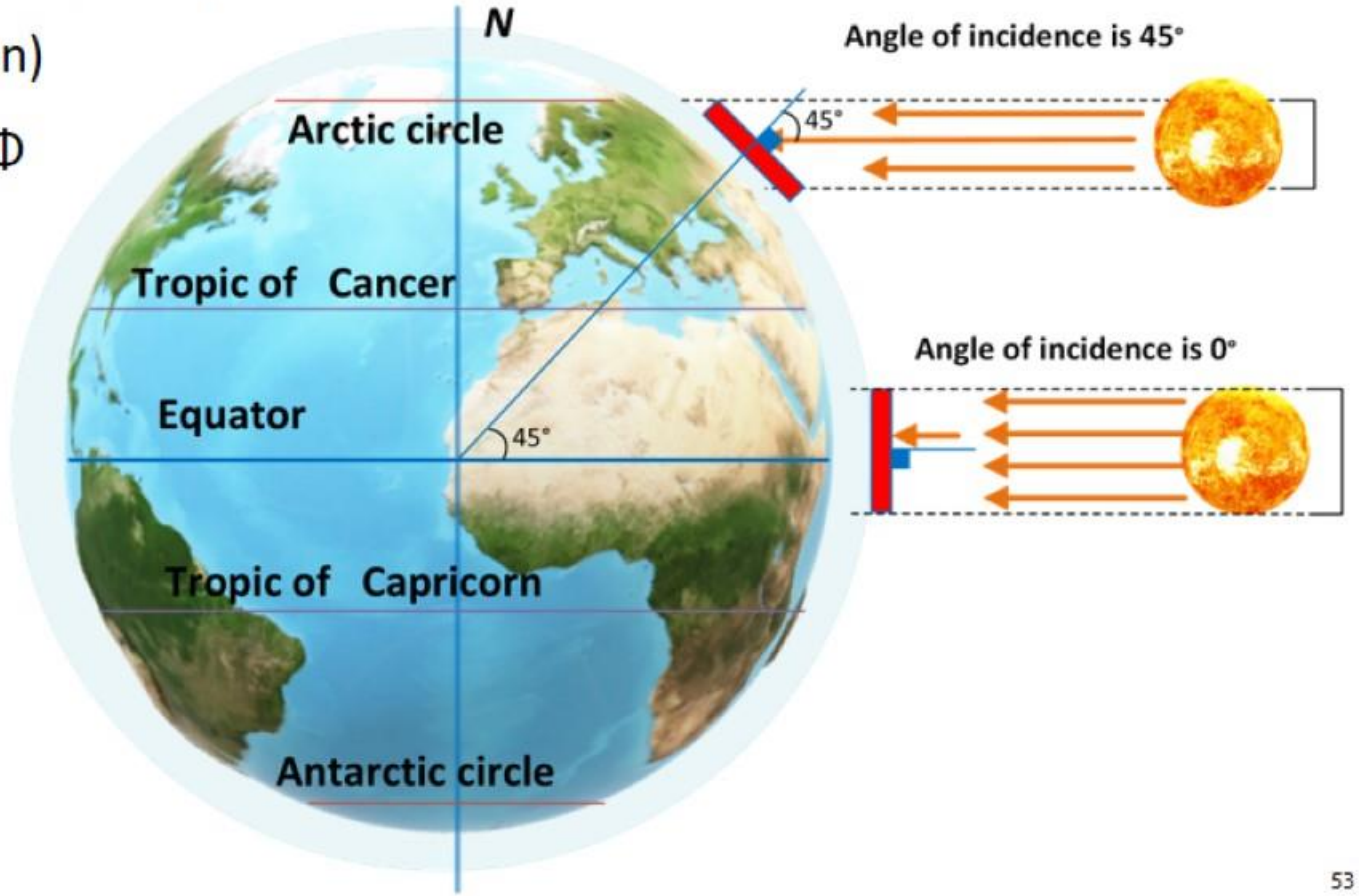






Effects of Declination and Latitude angles on irradiance

- Assume
  - Declination δ= 0° (spring/Autumn equinox)
  - Sun directly overhead (solar noon)
  - Horizontal surface is at latitude Φ
- It follows that θ = θz = Φ
- And $G_0 = G_{0n} Cos(\Phi)$



Effects of Declination and Latitude angles on irradiance

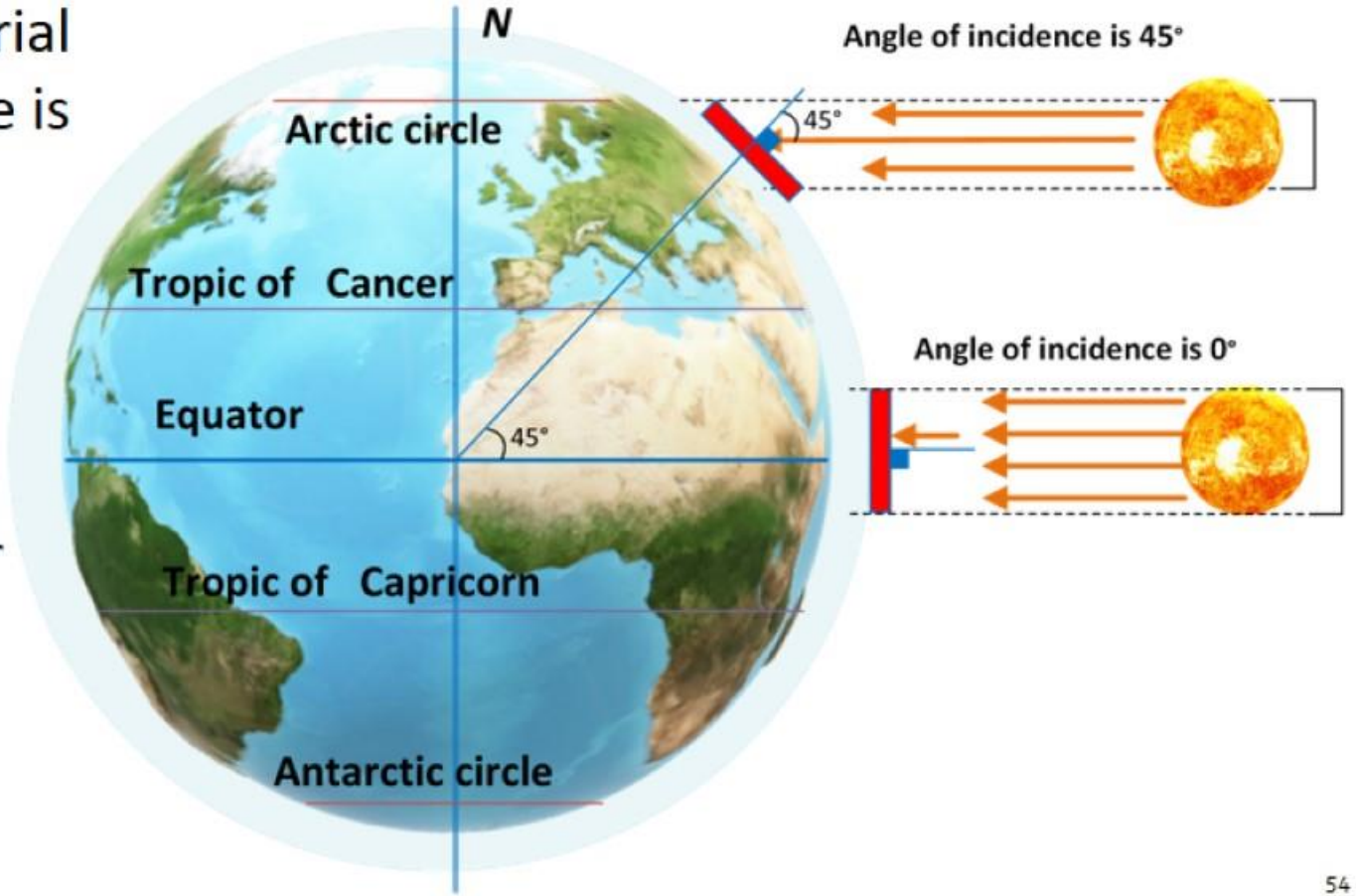
- **Example**

For the horizontal surface located at latitude of 45° N, the extraterrestrial irradiance received on this surface is calculated as:

$$G_0 = G_{0n}\, Cos(\Phi)$$

$$= 1367\ Cos(45) = 966 W/m^2$$

Which is, for sure, less than the object located directly on Equator



Effects of Declination and Latitude angles on irradiance

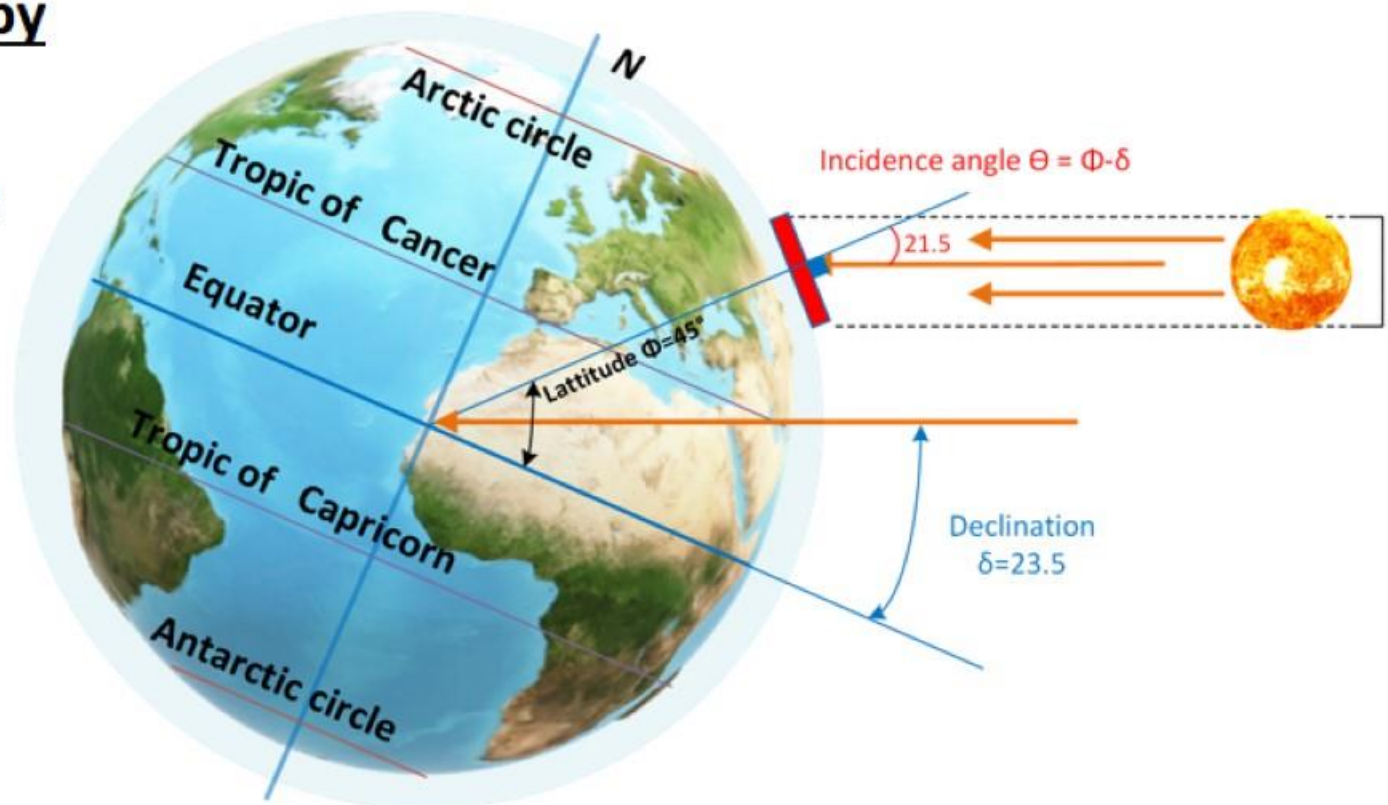
- **Now assume earth is declined by δ=23.5° (summer solstice)**

The same horizontal object will be facing the sun by 21.5 degrees.

The incidence angle is

calculated as:

$$\theta = \theta_z = \Phi - \delta$$



Effects of Declination and Latitude angles on irradiance

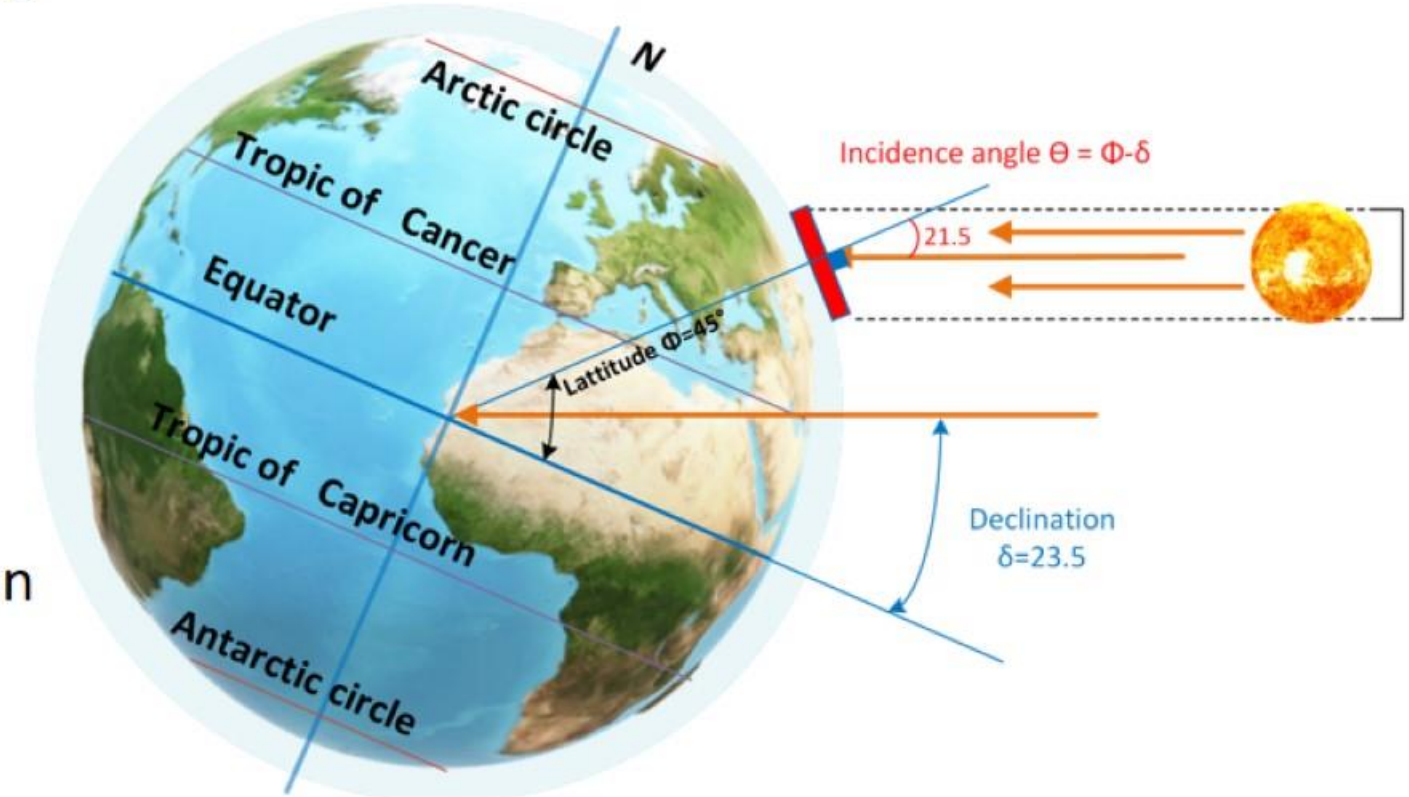
- **Therefore**

The horizontal surface facing the sun now at 21.5°, the extraterrestrial irradiance received is:

$$G_0 = G_{0n} \cos\theta$$

$$= 1367 \cos(21.5) = 1272 W/m^2$$

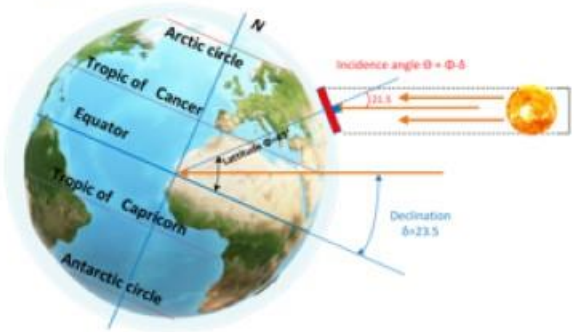
Which, in this case, this object will receive more energy than an object on equator



Extraterrestrial Irradiance calculation anywhere any day

- **To find the extraterrestrial irradiance, on horizontal surface, over any country at any time we need to calculate:**

1. The extraterrestrial irradiance using $G_{0n}(d) = G_{sc}\left[1 + 0.033\ cos\left(\frac{2\pi d}{365}\right)\right]$
2. The declination angle using $\delta = \delta_0 sin\left(\frac{360 \times (284+d)}{365}\right)$
3. The Zenith angle using $\theta = \theta_z = \Phi - \delta$
4. The extraterrestrial irradiance using $G_0 = G_{0n}\ cos\ \theta$



- NB: we are calculating the irradiance at solar noon (12PM). i.e, the maximum irradiance value at this particular day

Extraterrestrial Irradiance calculation anywhere any day

Example:

- Find the maximum extraterrestrial irradiance (at 12PM) on a horizontal surface over Genoa on October 3rd!



Extraterrestrial Irradiance calculation anywhere any day



Solution

- Step 1: Find the extraterrestrial irradiance on October 3rd

  From the table, October 3rd is the day 276

$$G_{0n} = G_{sc}\left[1 + 0.033\, cos\left(\frac{2\pi \times 276}{365}\right)\right] \approx 1368\, W/m^2$$

- Step 2: the declination at day 276 is calculated as

$$\delta = \delta_0\, sin\left(\frac{360 \times (284+276)}{365}\right) = -5\,^\circ\, or\, 5\,^\circ S$$

- Step3: The Zenith angle $\theta = \theta_z = \Phi - \delta = 44.5 - (-5) = 49.5^\circ$
- Step4: The extraterrestrial irradiance $G_0 = G_{0n}\, cos\, \theta = 888\, W/m^2$

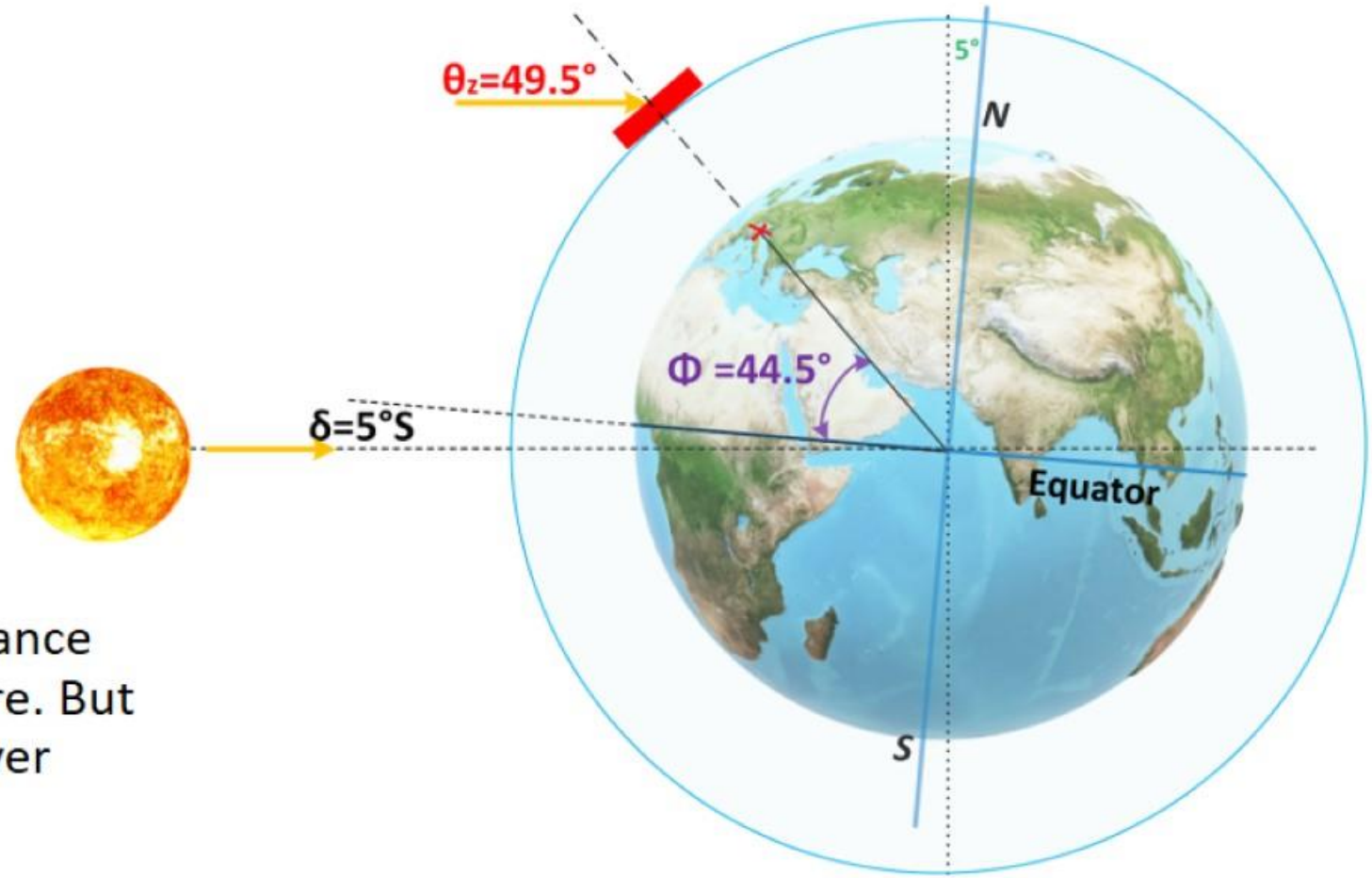
Extraterrestrial Irradiance calculation anywhere any day



- **MATLAB script**

```
%extraterrestrial irradiance calculation
phi = 44.5;                                  % latitude
d = 276;                                     % day number
G0n =1367*(1+0.033*cos(2*pi*(d/365)))        % normal extra irradiance
Sig = 23.5*sind(360*(284+d)/365)             % declination angle
Theta = phi - Sig                            % Zenith angle
G0 = G0n *cosd(Theta)                        % Extraterrestrial irradiance
```

Irradiance calculation anywhere any day



We calculated the irradiance on the top of atmosphere. But what is the irradiance over Genoa surface ?

Irradiance calculation anywhere any day

- To calculate the irradiance on Genoa's surface, we need to know more about Air mass
- Air mass can be calculated knowing the Zenith Angle as

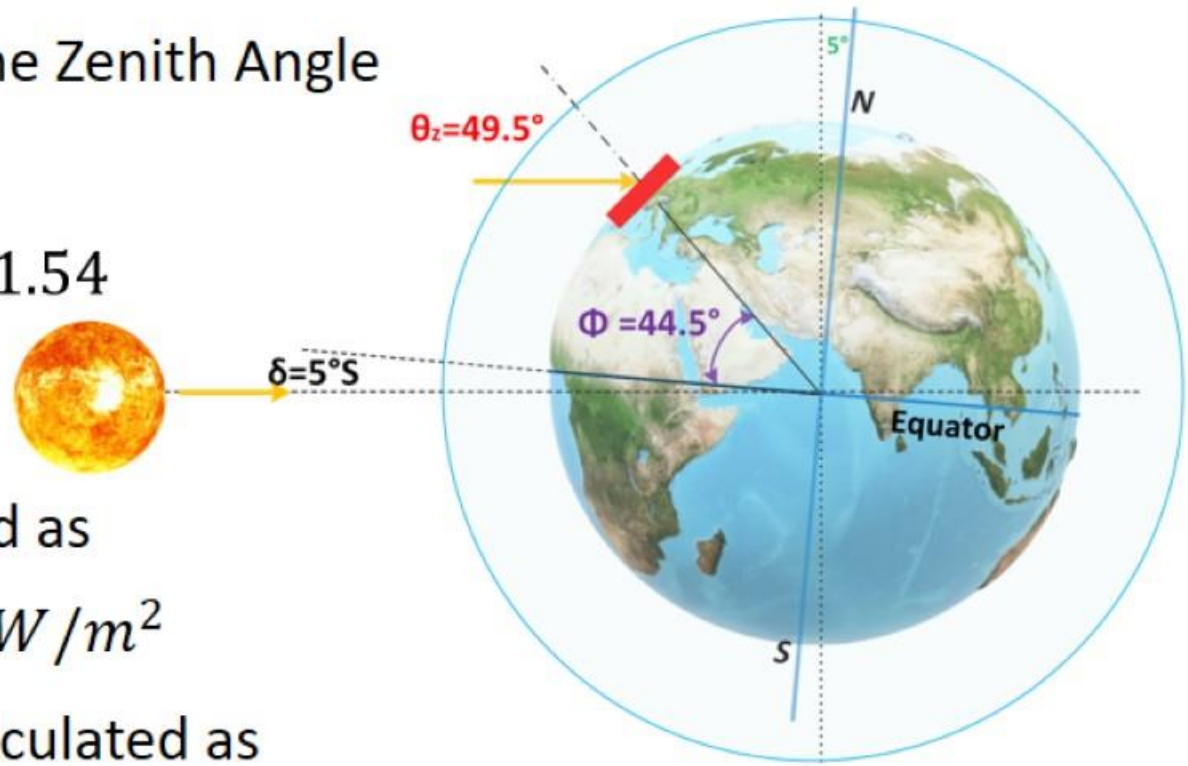
$$AM = \frac{1}{\cos\theta_z} = \frac{1}{\cos 49.5} = 1.54$$

- This Air Mass is at solar noon
- The direct irradiance can be calculated as

$$G_b = 888 \times 0.7^{1.54^{0.678}} = 612 W/m^2$$

- The Global Horizontal Irradiance is calculated as

$$G_{GHI} = 1.1 \times G_b = 1.1 \times 612 = 673 W/m^2$$

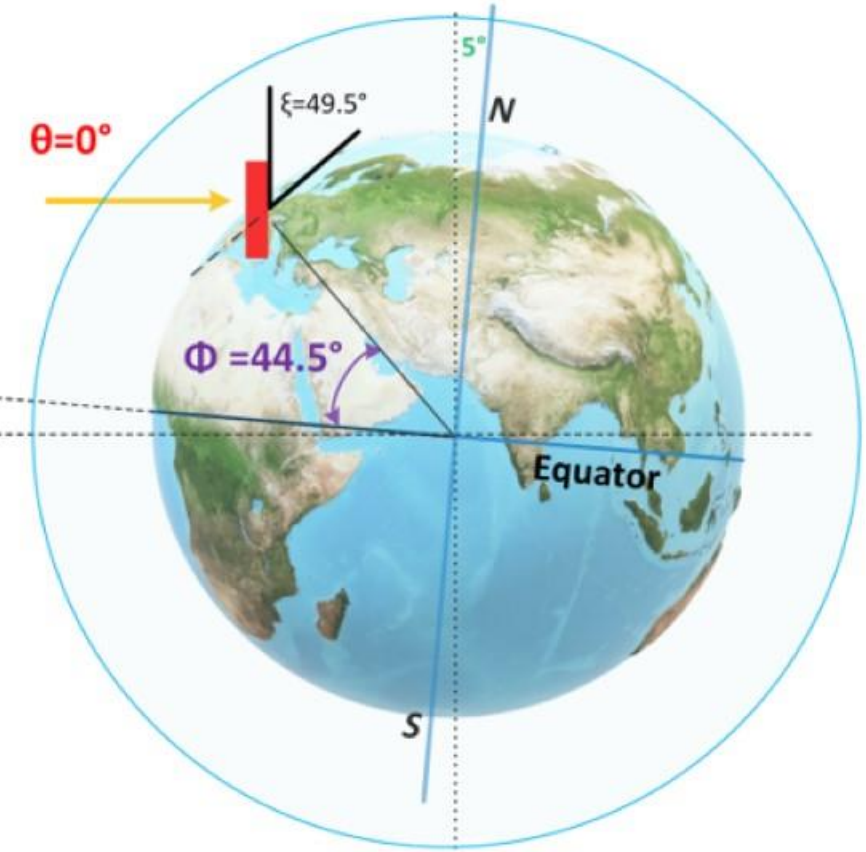


Irradiance calculation anywhere any day

Remark

- The maximum irradiance Genoa can get on 3rd of October is 673W/m^2 at solar noon.
- This is due to:
  - Latitude angle of Genoa
  - Declination angle of the earth
  - Thickness of the Atmosphere (Air Mass)
- Proposed solution to get more irradiance:
  - Tilt the surface by 49.5° to face the sun





- End of Part 3

Photovoltaic solar energy training course

Section 1: Solar resources

Part 4

- Surface tilting effect
- Altitude angle at solar noon
- Surface tilting rules
- Solar position
- Hour angle
- Solar coordinate

Nabil Karami, PhD

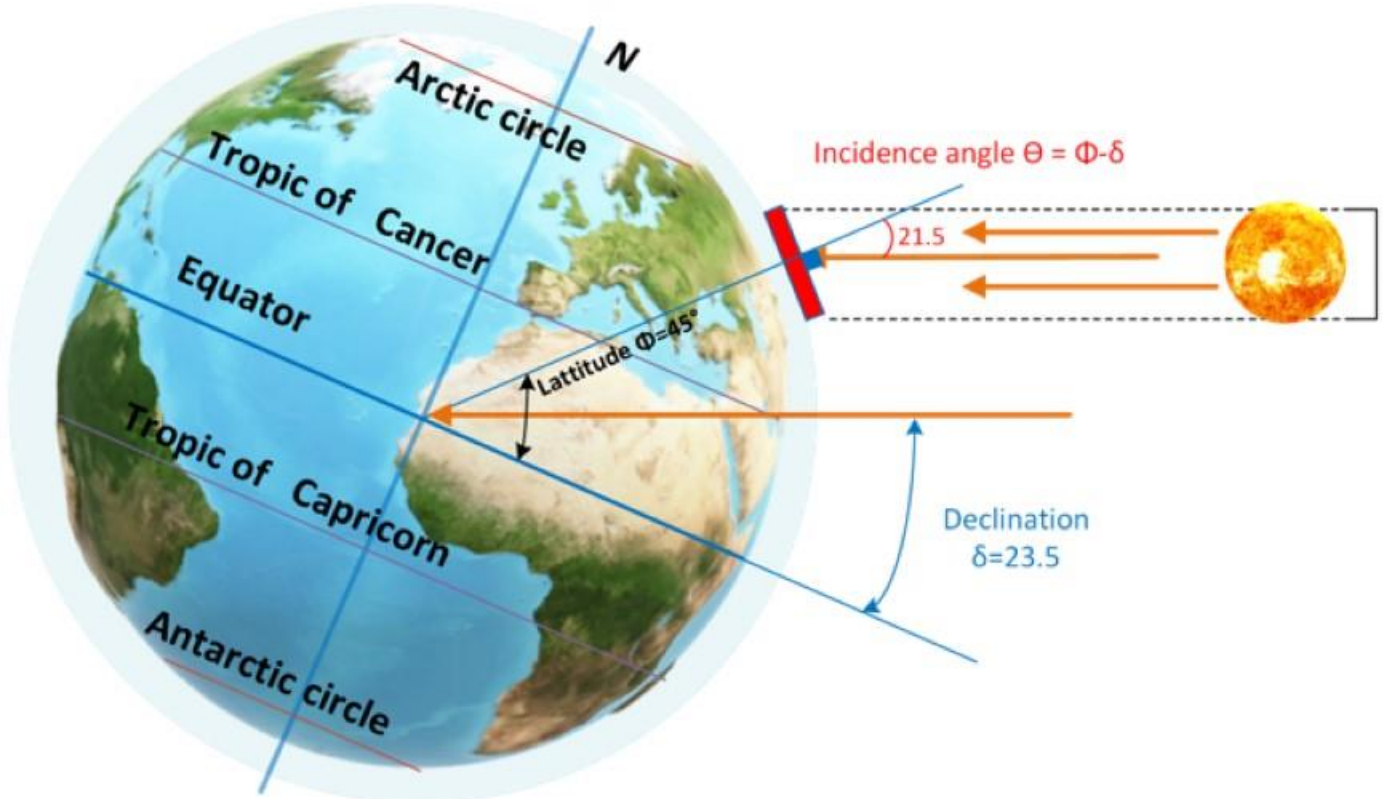
Surface tilting effect

- As seen before, the amount of irradiance received over Genoa at solar noon was 673W/m^2
- And we can increase it by tilting the surface!

- In this section, we will be interested in finding the irradiance at any hour at this day, not necessary at solar noon

Surface tilting effect

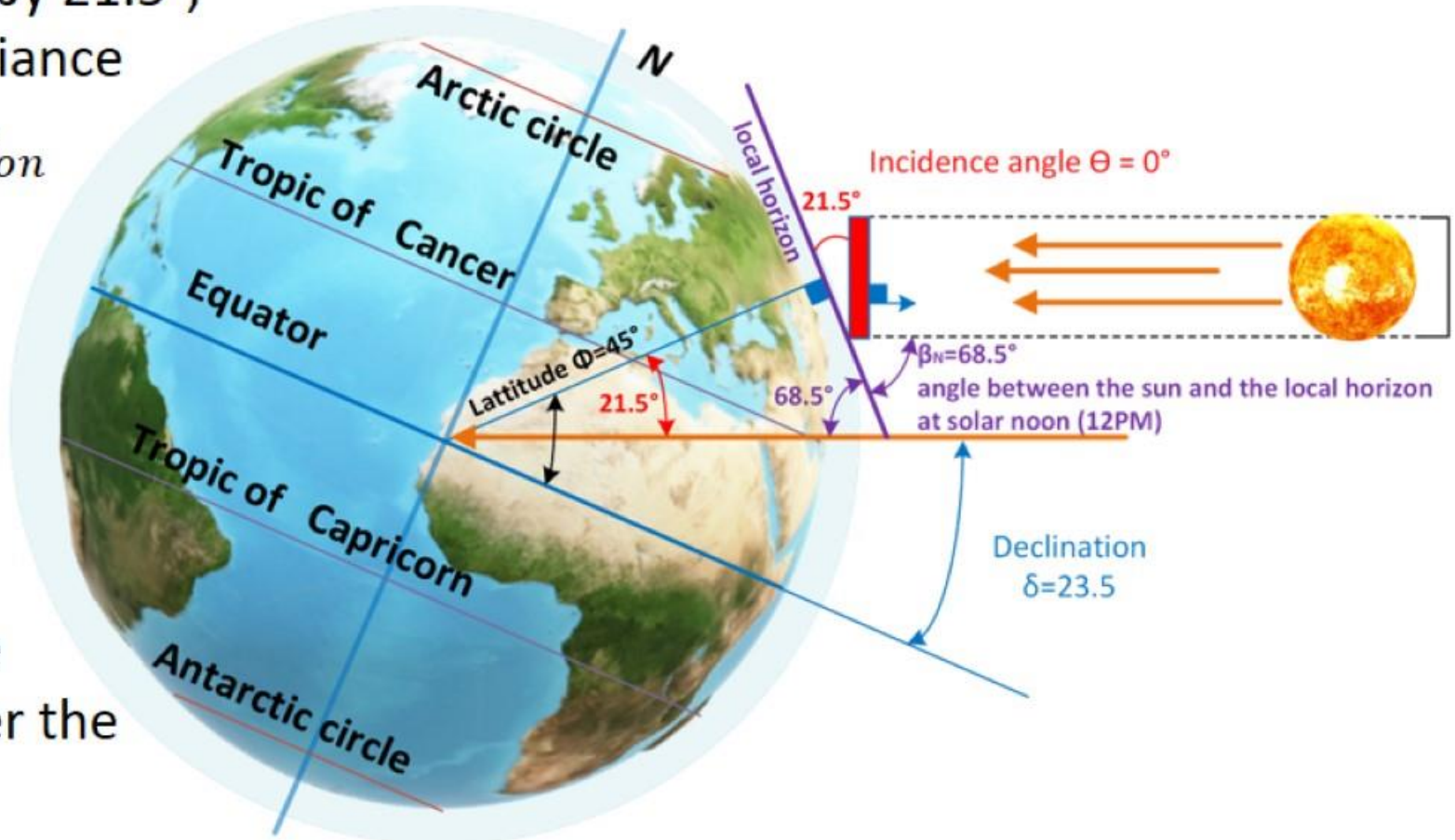
- From the previous example, the horizontal surface facing the sun was at 21.5°and the extraterrestrial irradiance received was 1272W/m^2



Surface tilting angle ξ

- If we tilt the red surface by 21.5°, the extraterrestrial irradiance

$$G_0 = G_{on} \cos 0 = G_{on}$$



- i.e. we are increasing the irradiance projection over the surface

Altitude angle β_N at solar noon

- The altitude angle β_N at solar noon (index N) is the angle between the sun ray and the horizontal
- It is calculated as:

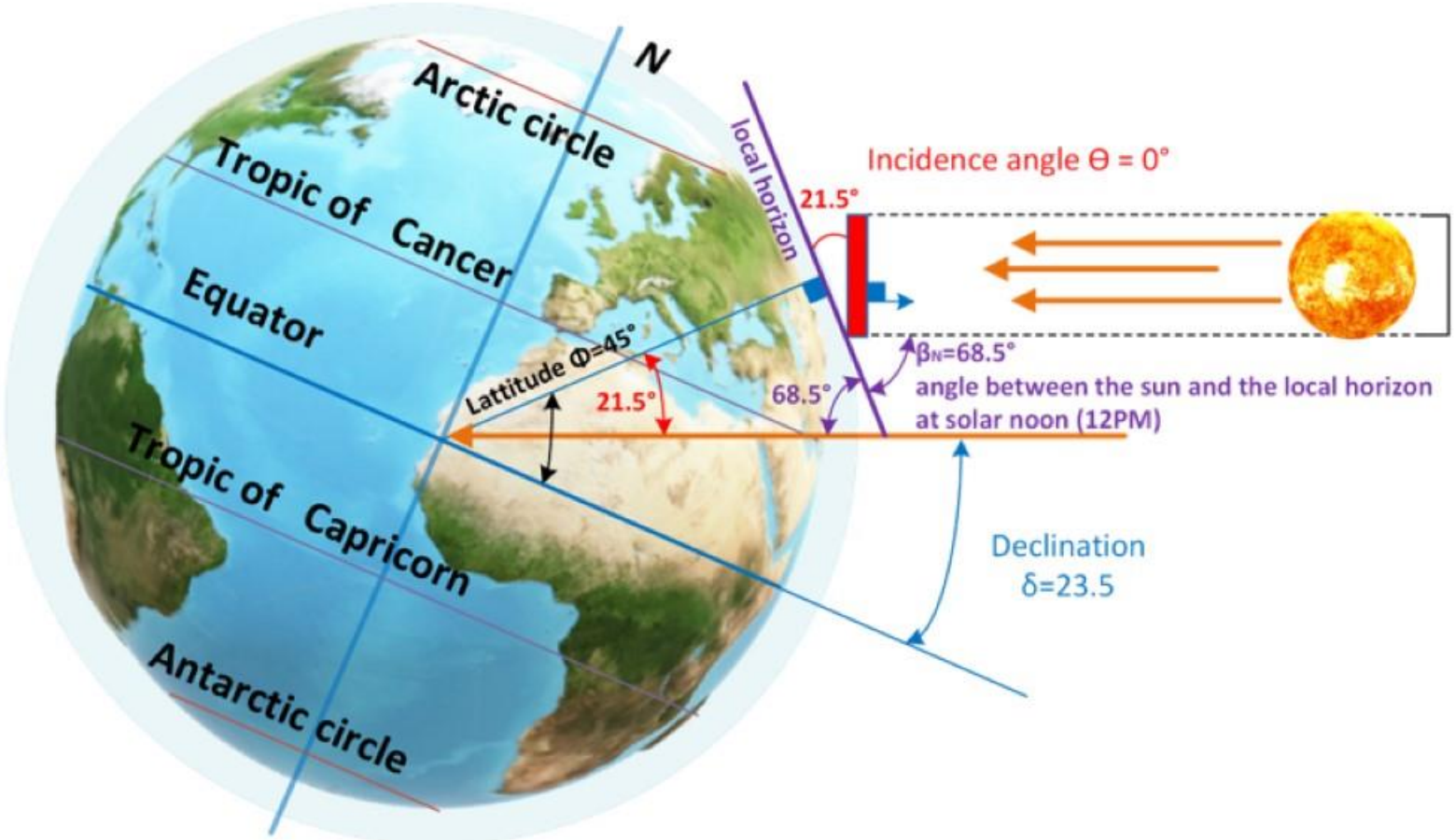
$$\beta_N = 90° - \Phi + \delta$$

We can also observe that the surface inclination ξ is:

$$\xi = \Phi - \delta$$

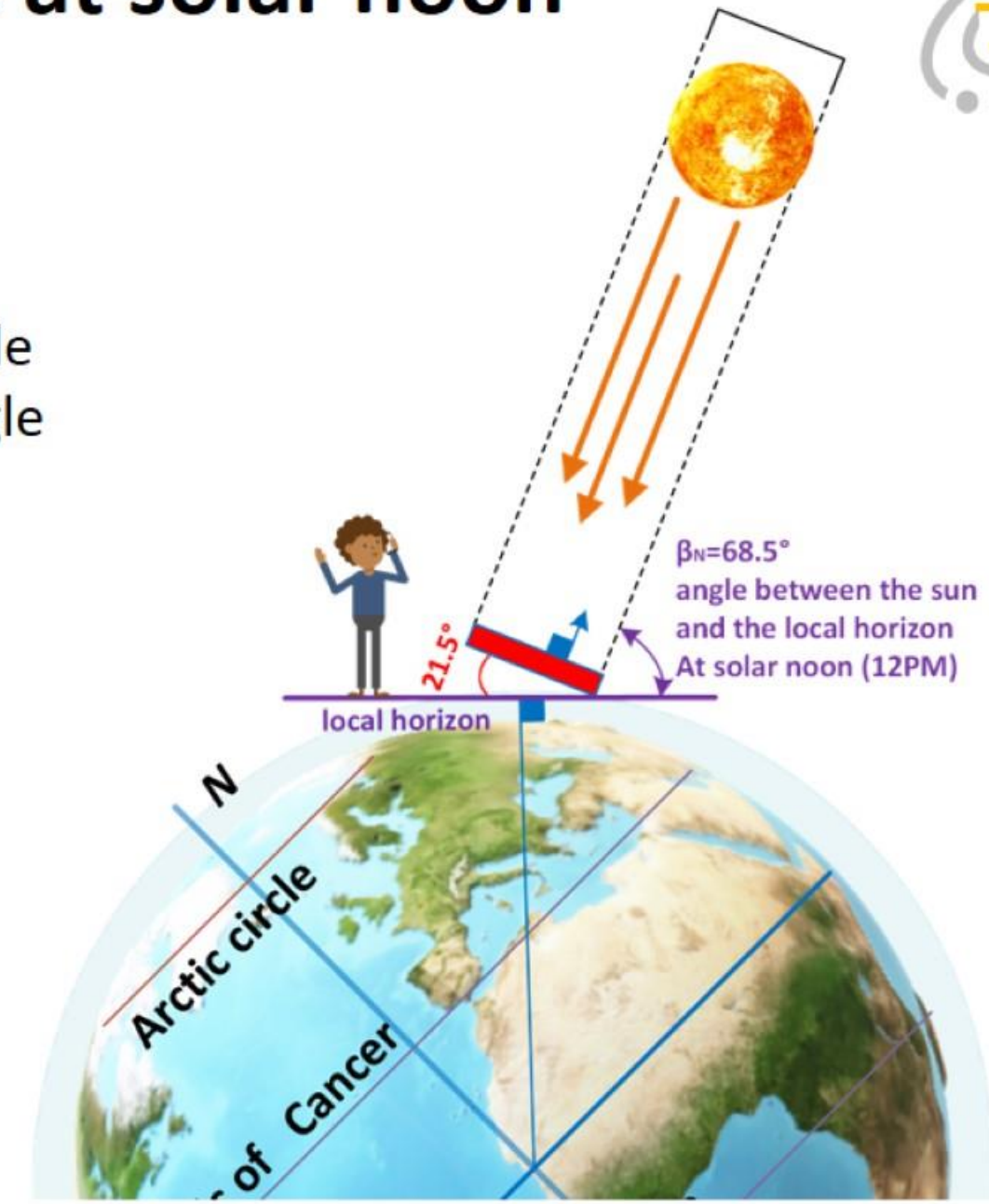
So,

$$\beta_N + \xi = 90°$$



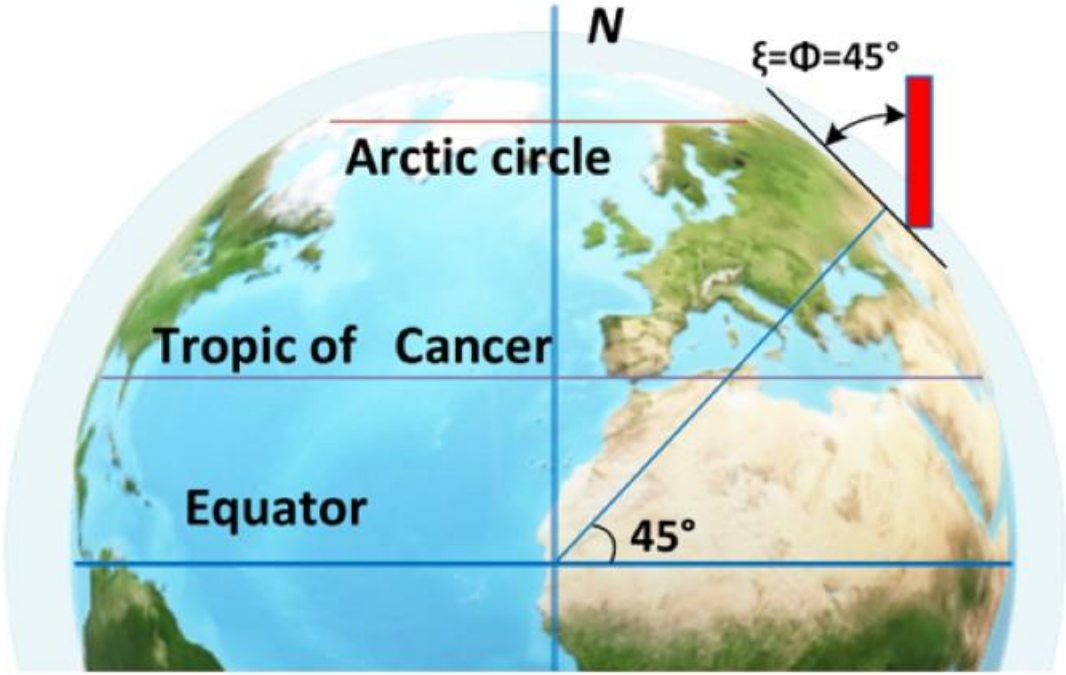
Altitude angle at solar noon

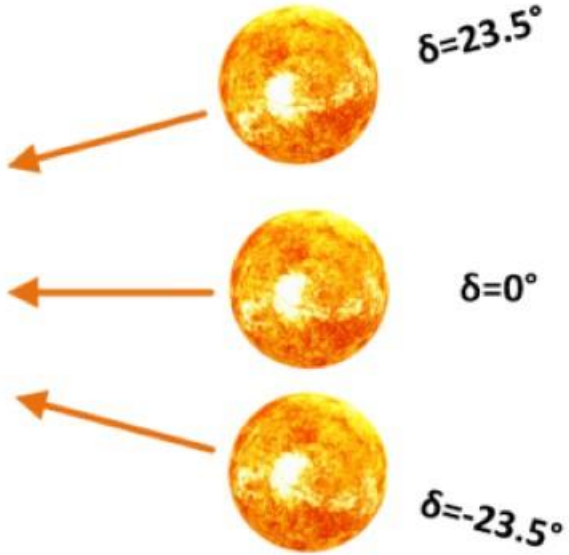
- Usually, the altitude angle is the angle we use to describe the elevation angle of the sun.
- Sun is low at sunrise and sunset
- Sun is high at noon
- During the day, the altitude angles follow a parabolic shape having a maximum value at 12 PM.



Rule of thumb: Surface tilting angle ξ

- Rule of thumb for the Northern Hemisphere:
- A South-facing collector tilted at an angle equal to the local latitude so that on an equinox, during solar noon, the sun's rays are perpendicular to the collector face

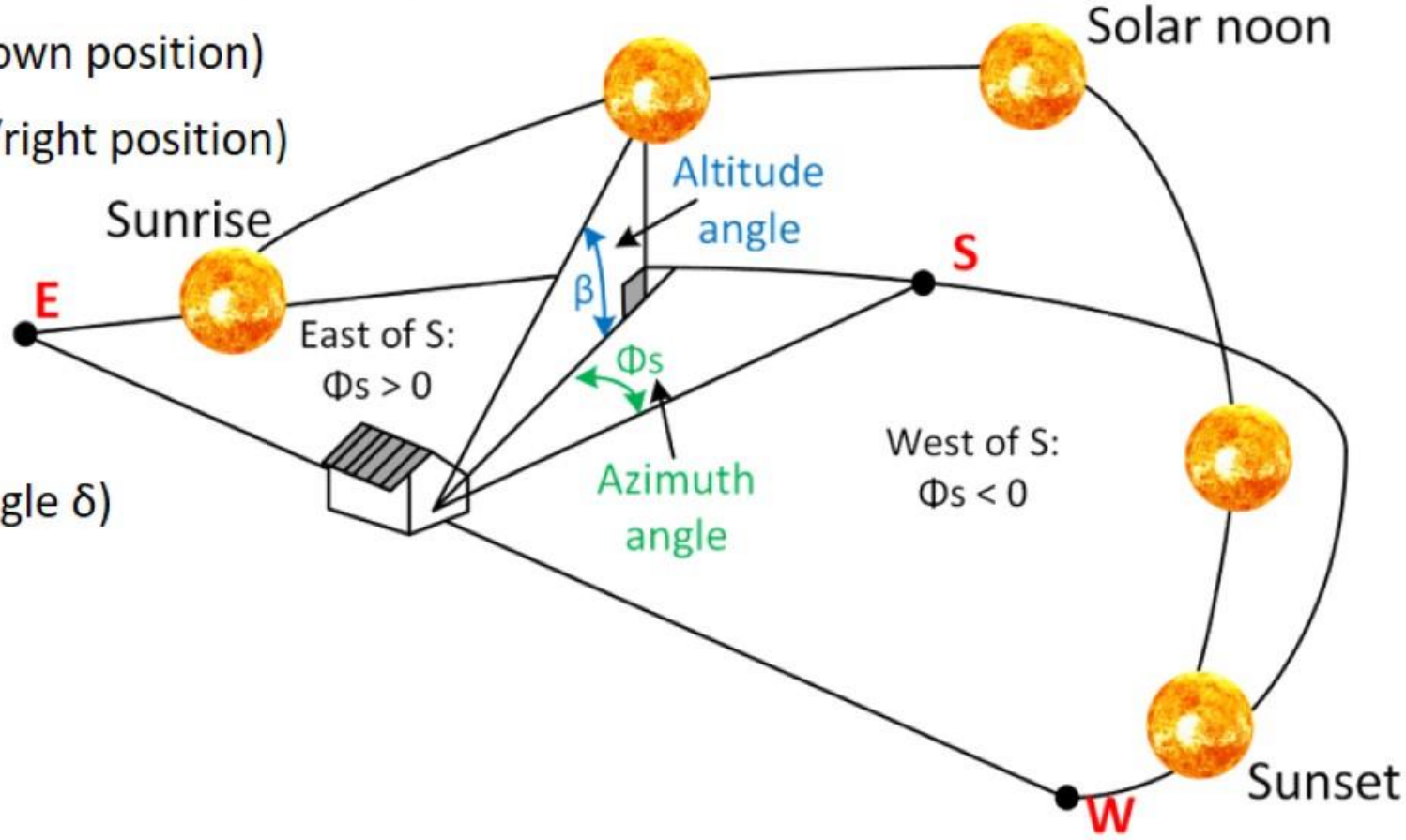




Solar position at any time of the day

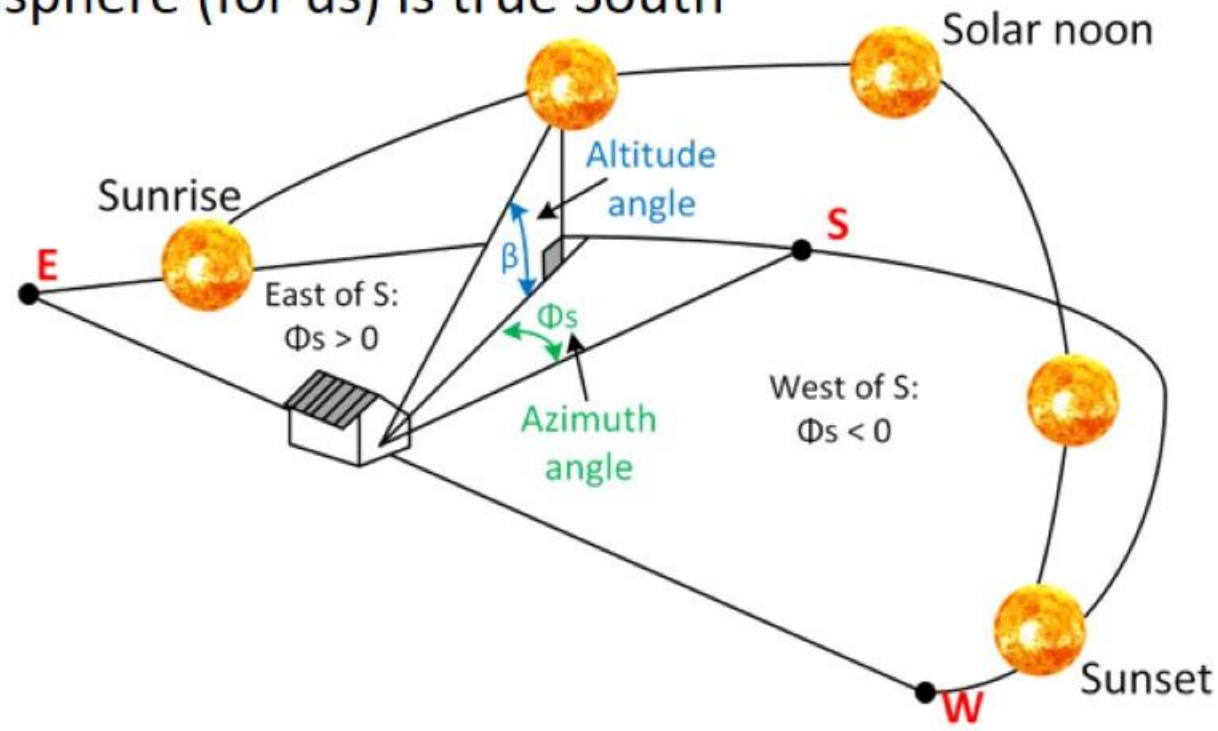
- The sun position can be determined using:
  1. Altitude angle β (up/down position)
  2. Azimuth angle Φ_s (left/right position)

- β and Φ_s depend on
  1. Latitude Φ
  2. Day number (zenith angle δ)
  3. Time



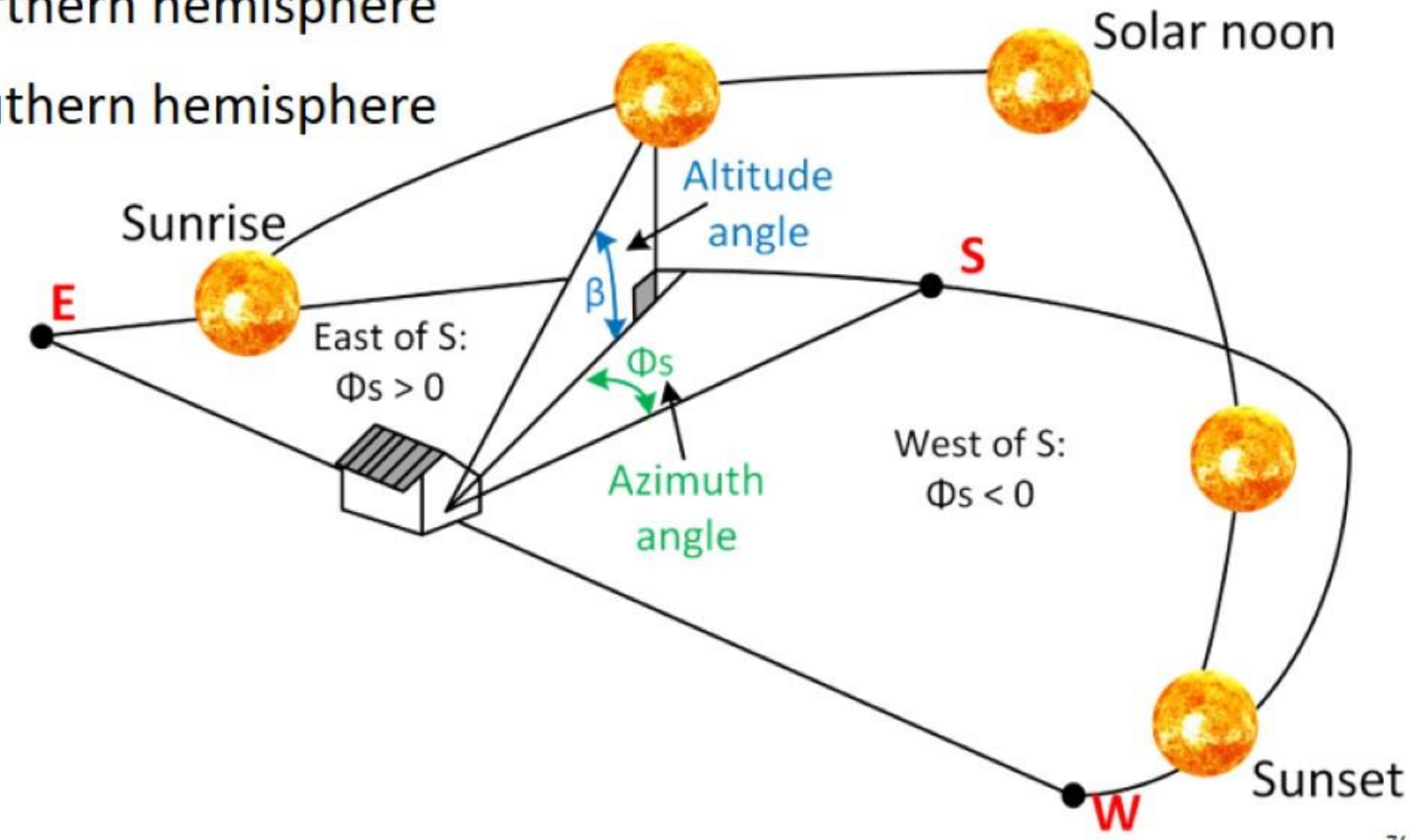
Solar position at any time of the day

- Azimuth angle Φ_s convention
  - Positive in the morning when Sun is in the East
  - Negative in the evening when Sun is in the West
  - Reference in the Northern Hemisphere (for us) is true South
- Hours are referenced to solar noon



Solar position at any time of the day

- Solar time Noon occurs when the sun is over the local meridian
  - due south for the northern hemisphere
  - due north for the southern hemisphere



Hour angle *H*

- The **Hour angle** *H* is the number of degrees the earth must rotate before sun will be over the local line of longitude
- The earth rotates 360˚/24hr or 15˚/hr, then

$$H = \frac{15°}{hour} \times (hours\ before\ solar\ noon)$$

- For Examples:
  - At 11 AM **solar time**, *H*= +15˚ (the earth needs to rotate 1 more hour to reach solar noon)
  - At 2 PM **solar time**, *H*= -30˚

Solar coordinates

- Calculate the position of the sun at any time of day on any day of the year:

$$\sin\beta = \cos\Phi\cos\delta\cos H + \sin\Phi\sin\delta$$

$$\sin\Phi_s = \frac{\cos\delta\sin H}{\cos\beta}$$

- So

$$\beta = \sin^{-1}(\cos\Phi\cos\delta\cos H + \sin\Phi\sin\delta)$$

$$\Phi_s = \sin^{-1}\left(\frac{\cos\delta\sin H}{\cos\beta}\right)$$

Solar coordinates



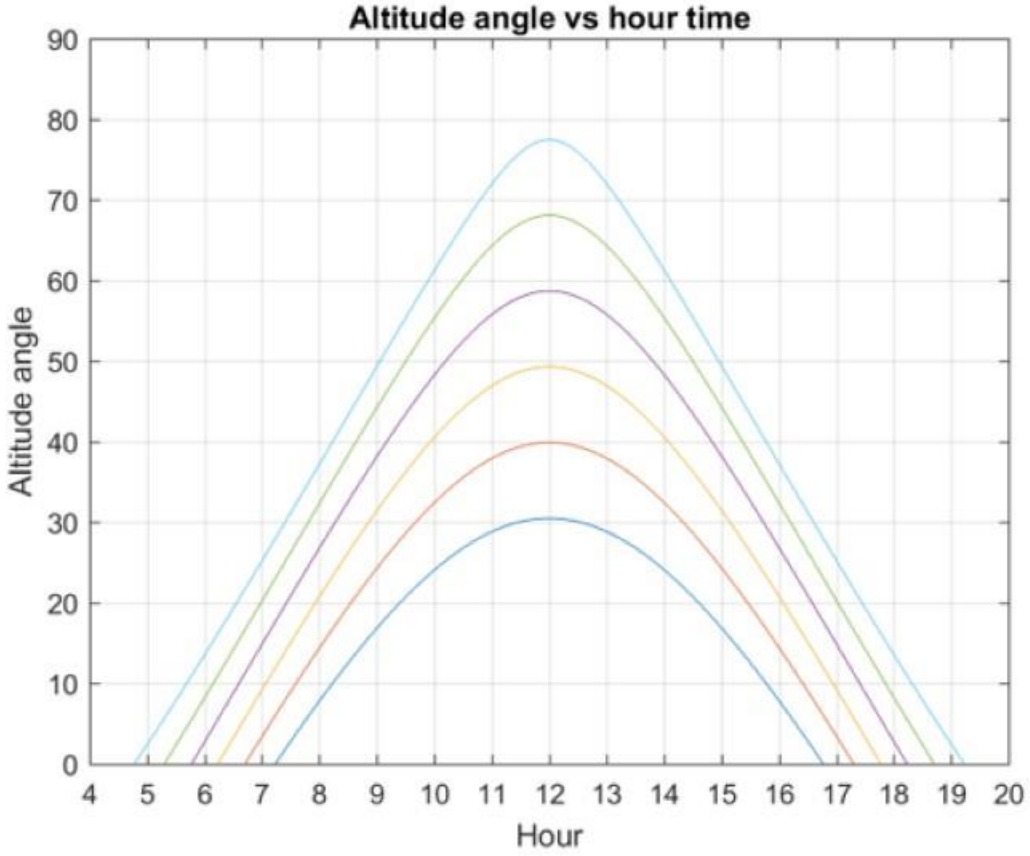
MATLAB script

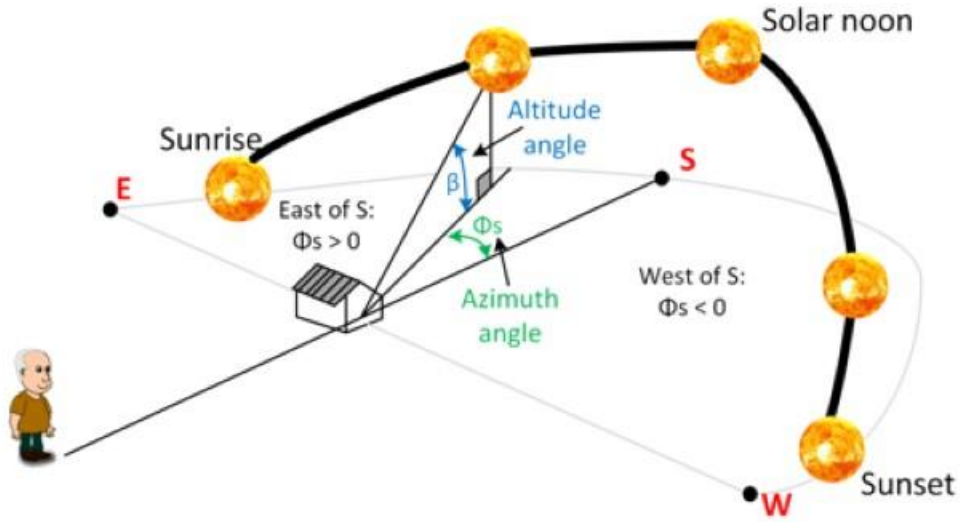
```
% Altitude and Azimuth calculation
clear all
Phi = 28            % input Latitude
Sig = -23.5         % input declination angle
BetaN =90-Phi+Sig % Maximum Altitude at 12Pm
% range of hours from 4AM to 8PM
Hours = 4:0.01:20;
H = 15 * (Hours-12) % hour angle
sinB =cosd(Phi)*cosd(Sig).*cosd(H) +
sind(Phi)*sind(Sig)
Beta = asind(sinB)    % Altitude angle
SinPhis = cosd(Sig)*sind(H)./cosd(Beta)
Phis = asind(SinPhis) % Azimuth angle
```

```
subplot(2,1,1)
plot(Hours, Beta)
title('Altitude angle vs hour time')
xlabel('Hour');
ylabel('Altitude angle');
axis([4, 20, 0, 90])
grid on

subplot(2,1,2)
plot(Hours, Phis)
title('Azimuth angle vs hour time')
xlabel('Hour');
ylabel('Azimuth angle');
axis([4, 20, -120, 120])
grid on
```

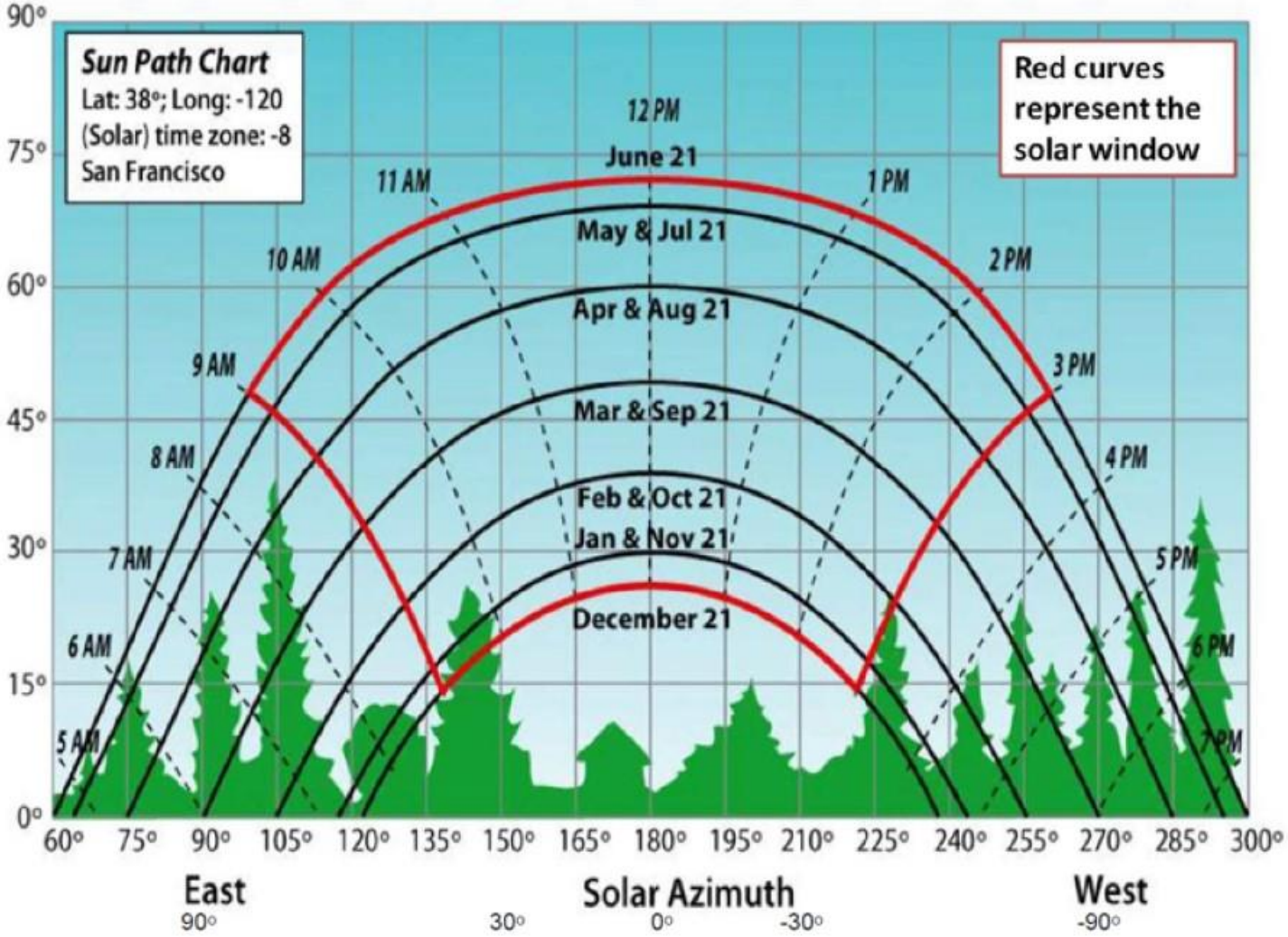
Solar coordinates





Solar coordinates

Solar Window 9am – 3pm "Strong Sun"



References

- Pulkit singh Rana (2021). Sun's Path Simulation In MATLAB (https://www.mathworks.com/matlabcentral/fileexchange/75506-sun-s-path-simulation-in-matlab), MATLAB Central File Exchange. Retrieved August 3, 2021.
- Tadeusz Rodziewicz, Małgorzata Rajfur, Janusz Teneta, Paweł Świsłowski, Maria Wacławek,"Modelling and analysis of the influence of solar spectrum on the efficiency of photovoltaic modules", Energy Reports, 2021
- F. Kasten and Young, A. T., "Revised optical air mass tables and approximation formula", Applied Optics, vol. 28, pp. 4735–4738, 1989.
- A. B. Meinel and Meinel, M. P., Applied Solar Energy. Addison Wesley Publishing Co., 1976.
- E. G. Laue, "The measurement of solar spectral irradiance at different terrestrial elevations", Solar Energy, vol. 13, pp. 43 - 50, IN1-IN4, 51-57, 1970.

End of Session 1

Photovoltaic Solar Energy Training Course

Section 2: Photovoltaics

Part 1
- Photovoltaics
- Solar Cells
- Advantage of Photovoltaics
- Raw Material
- Mono vs Polycrystalline
- Cell voltage, current and Power
- Cell, Module, Panel and Array
- Some Important Rule of Thumbs

Part 2
- PV circuit and Mathematical model
- Open Circuit Voltage, Short Circuit Current, Max Power
- Fill Factor, Efficiency, Packing Factor
- PV Standards
- Application Classes

Part 3
- PV Specification
- Standard Test Condition 'STC'
- Irradiance/ Temperature Effects
- Temperature Coefficients (Absolute and relative)
- Normal Operating Cell Temperature 'NOCT'

Part 4
- Effect of Irradiance on Cell Temperature
- Discussion
- Examples

Nabil Karami, PhD

Photovoltaic solar energy training course

Section 2: Photovoltaics

Part 1

- Photovoltaics
- Solar Cells
- Advantage of Photovoltaics
- Raw Material
- Mono vs Polycrystalline
- Cell voltage, current and Power
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Photovoltaic

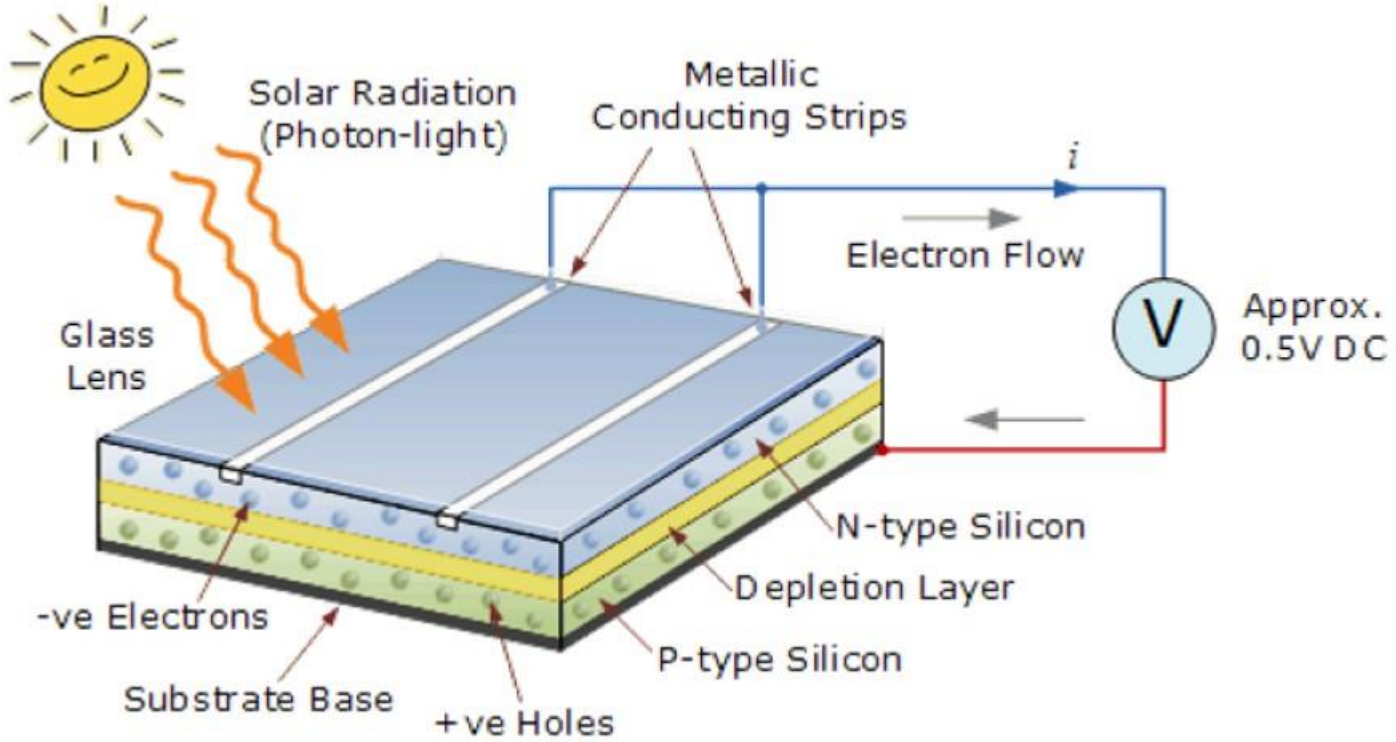
- The word “photovoltaic” comes from the Greek word “photo”, meaning light, and “voltaic”, meaning electricity.
- Photovoltaic technology therefore describes the technology involved in the generation of electricity from light and photovoltaic is the process of converting sunlight directly into electricity using PV cells.
- This technology makes use of semi-conductor material (usually silicon) which can be adapted to release electrons, under solar radiation.





Solar cell

- All PV cells have at least two layers of such semiconductors, one positively charged and one negatively charged.
- When light shines on the semi conductor, the electric field across the junction between these two layers causes electricity to flow generating DC current.
- The greater the intensity of the light the greater the flow of electricity.



Advantage of Photovoltaics

- The fuel is free.
- No moving parts.
- Minimal maintenance
- Modular systems can be quickly installed anywhere.
- Produces no noise, harmful emissions or polluting gases.
- Life expectancy of 25 to 30 years.



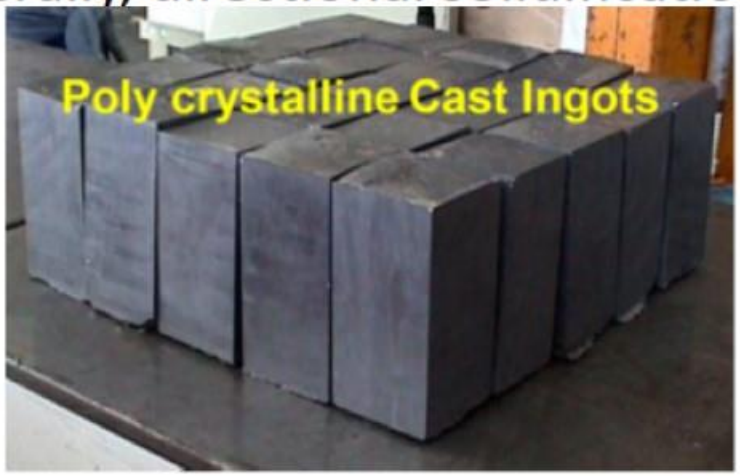
Raw Materials of Photovoltaics

- PV energy is extremely **clean** and environmentally friendly, and engenders no noise pollution, waste-gas emissions or toxic waste.
- **Silicon**, the main raw material used for solar cells, is one of the most abundant substances on earth (**Sand**)
- Thus electricity from **solar cells** can in a sense be thought of as "**power from sand and Sun**"



Silicon Mono and Polycrystalline

- There are two types of crystalline silicon depending on its purity and crystals orientation obtained during the crystal growth process:
  - **Poly-crystalline**: Non-uniform crystals orientation
  - **Mono-crystalline**: Uniform crystals orientation (purer and more expensive and efficient)
- The mono-crystalline silicon ingots are prepared by the exacting Czochralski (CZ) crystal growth process (crystal pulling).
- While the poly-crystalline silicon ingots are prepared by a simpler casting (or, more generally, directional solidification).





Visual difference between polycrystalline and monocrystalline silicon solar cells

Mono-Crystalline Solar cell

- Uniform appearance
- Semi-square shape







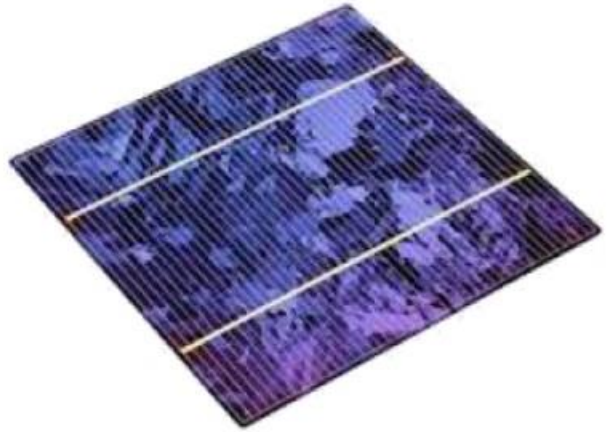


Poly-Crystalline Solar cell

- Non-uniform appearance
- Complete square shape

Polycrystalline vs. Monocrystalline

Parameters	Polycrystalline	Monocrystalline
Cost	Low	High
Efficiency	Low	High
Appearance	Bluish color panels	Black color panels
Lifespan	Up to 25 years	Minimum 25 years
Temperature Coeff.	Low	High





Solar Absorption

- Energy of the photon must be > 1.1eV (Wavelengths less than 1.1 x10^{-6}m)

- ~ 23% of the solar radiation (AM1.5) does not meet this requirement
- ~ 33% of solar radiation (AM1.5) is wasted by having too much energy

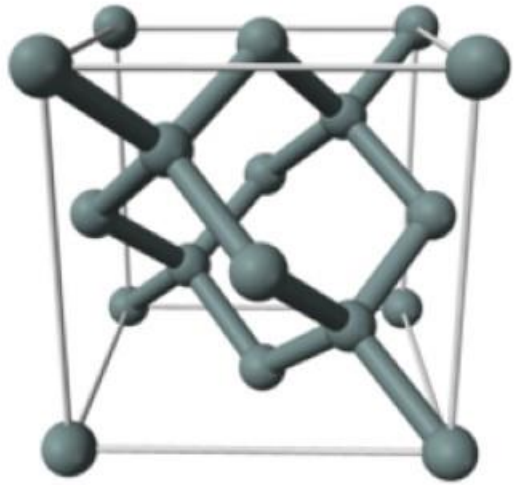
- At most, < 50% of energy radiated on a solar panel can be used

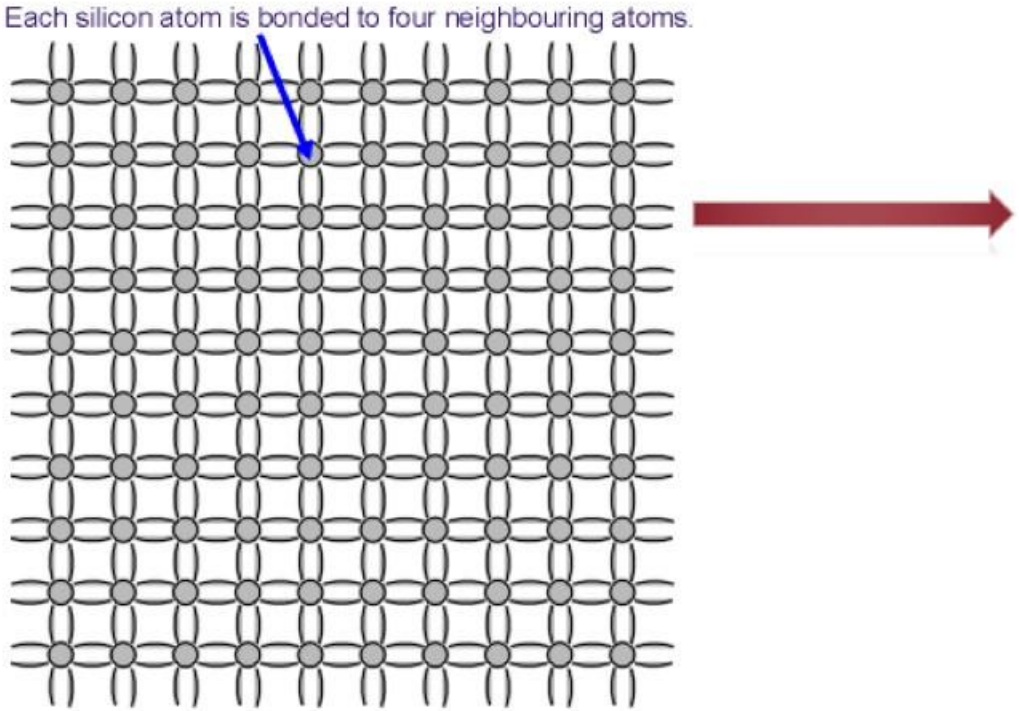
- Actual efficiency is closer to 16%



Monocrystalline Solar Panel

- Silicon that has been solidified into a single large crystal
- **Efficiency:** Up to 24.5 %

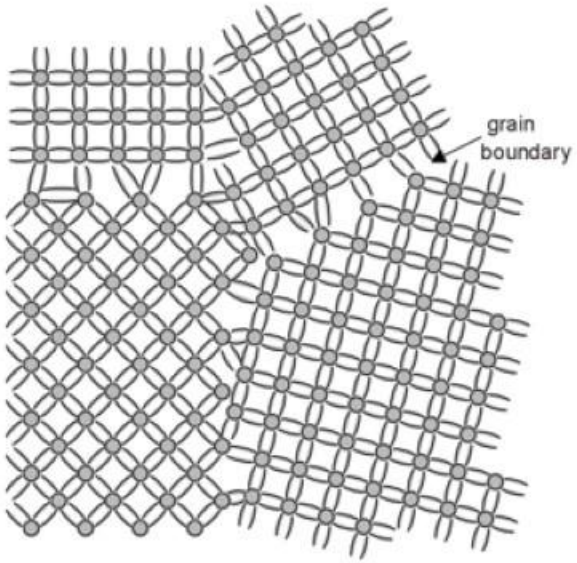


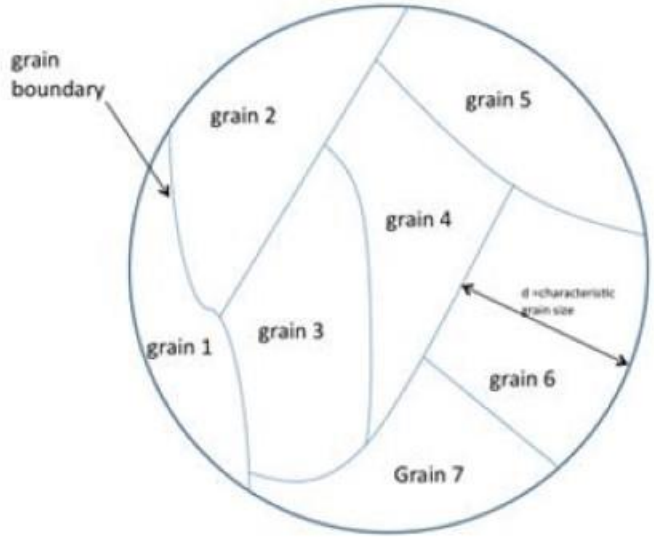




Polycrystalline silicon (Poly c-Si):

- Silicon that has been solidified into a many small crystals (crystallites) in any orientation.
- **Efficiency**: up to 19.1%.







One cell voltage and current

- Solar cell is a semiconductor diode with large barrier layer exposed to light, which generates electrical energy directly when sunlight strike it.
- Laboratory silicon cells have open-circuit voltage of up to 720mV and a short-circuit current of up to 10A under one Sun (1000W/m2) and AM1.5 conditions.
- Commercial devices typically have open-circuit voltages of less than 600mV and a short circuit current of 9A.



One cell voltage and current

- The voltage of individual PV cells reach values of 0.5 to 0.6V. Therefore for the standard ‘low voltage range’ of 6 -24V many cells are connected together in series.
- By doing this one has a PV module that can consist of 12, 42, 54, 60 or 72 PV cells.
- In technical literature the PV module is sometimes also referred to as a PV panel.



Solar Module

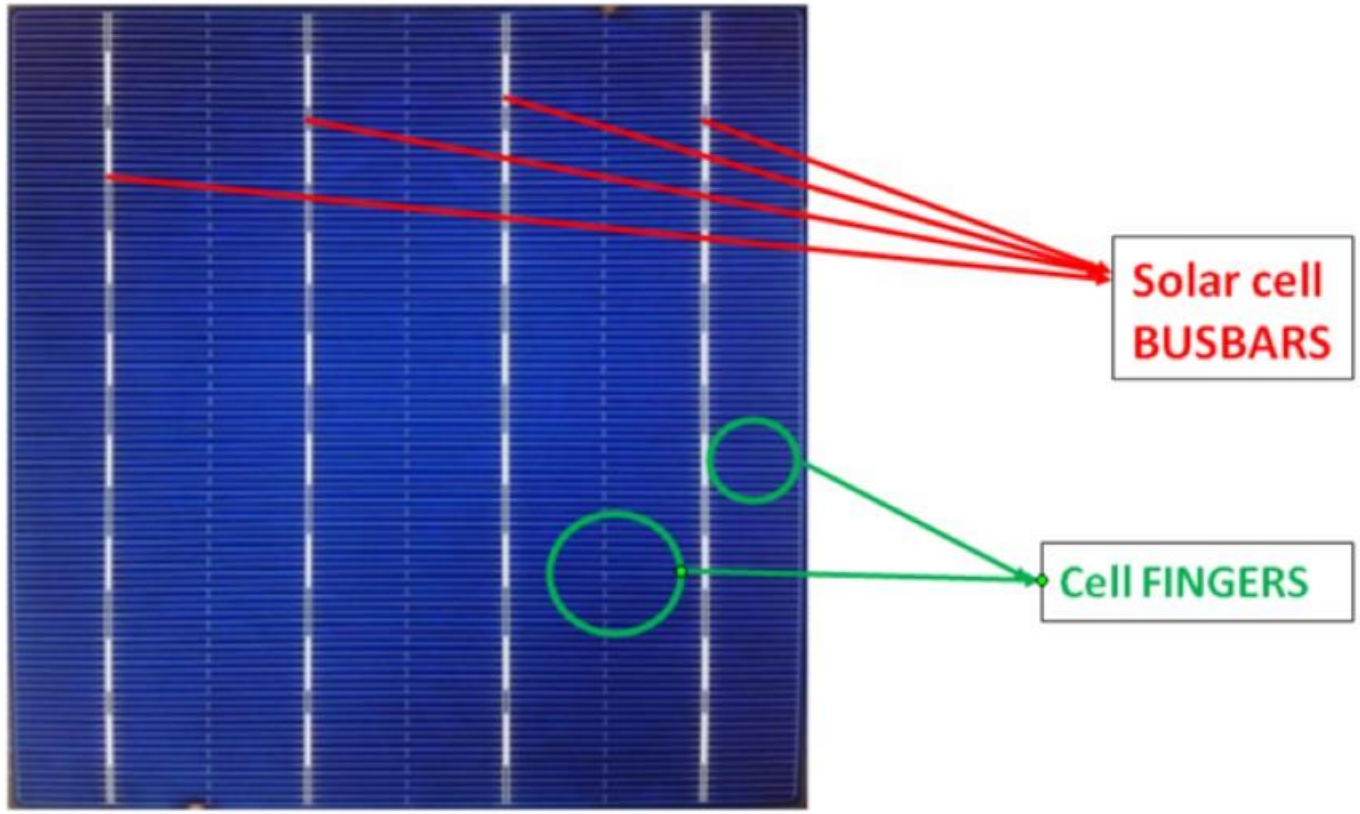
A number of connected solar cells (usually connected in series) arranged in casing to protect against environmental influences.





PV cell Bus-Bar

In a solar panel, there's a thin strip of copper or aluminum between cells that conducts electricity called a busbar. It separates solar cells and conducts the direct current the cells collect from solar photons.



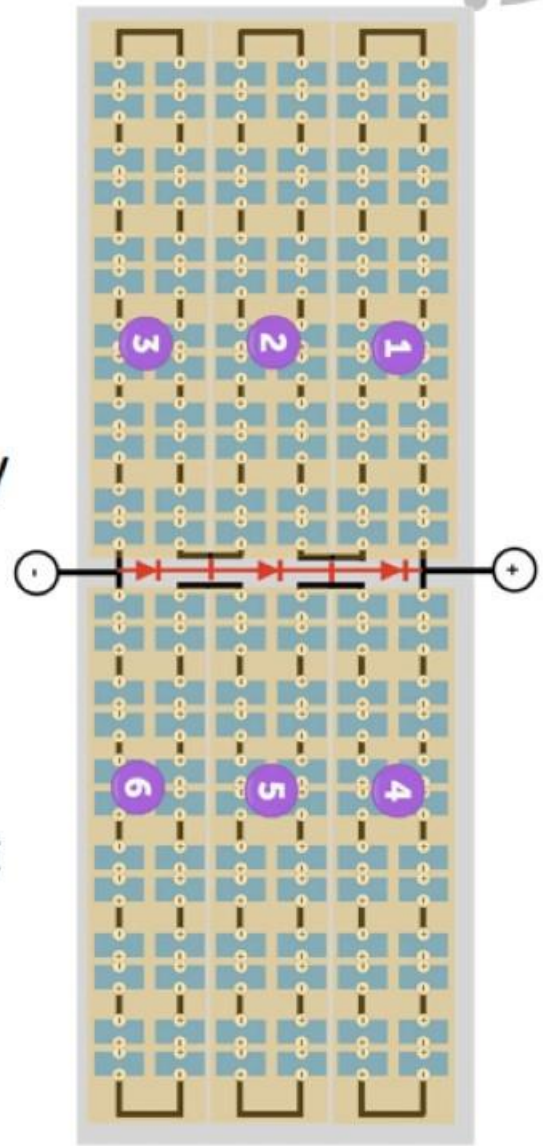
Half Cut Solar Module

- Half-cut cell solar panels are exactly what their name suggests – they are traditional silicon solar cells that have been cut in half using a laser cutter.
- Half-cut solar panels provide several benefits over traditional solar panels. Most importantly, **half-cut cell solar panels offer improved performance and durability**.



Half Cut Solar Module

1. Cell Efficiency ≈ 22%, anti LID, anti PID, 1st year degradation is less than 2%
2. Half cut Cell Technology Enables higher power and lower hot spot temperature because of low working current
3. Cells with more BB have better current collection ability
4. High Bifaciality, optional white ceramic glass on rear side
5. Spilt junction box, cable length 300mm (can be customized)
6. Unique parallel connection design, more energy output under shading or non-uniform radiation



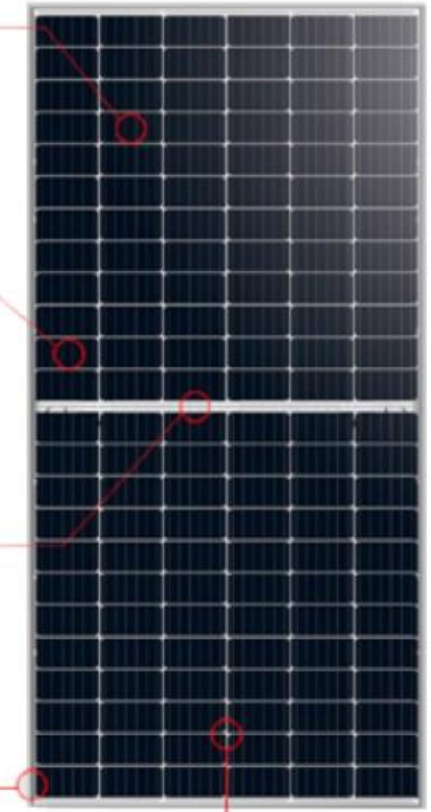
Half Cut Solar Module

Half-cut cell technology enables higher power and lower hot spot temperature because of low working current

Cells with 6BB have better current collection ability

Unique parallel connection design, more energy output under shading or non-uniform radiation

Front/back side maximum static loading 5400/2400Pa, suitable for tracker





The 33mm gap width coordinate with single axis tracker (such as NEXTracker) can reduce the shading

Split junction box, Cable Length 300mm (can be Customized)

Mounting holes with 400mm distance are added to match the horizontal single axis tracker

Glass and junction box supporting 1500V system

High bifaciality, optional white ceramic glass on rear side

Cell efficiency >22%, anti-LID, anti-PID, 1st year degradation ≤2%

Design of short frame without C side can reduce the shading caused by frame

PV cell Bus-Bar

- Large cells dimension will increase the area of the cells on the panels. That will help 9BB PV module to be more efficient (up to 450W) and to increase the module efficiency (up to 20.58%)



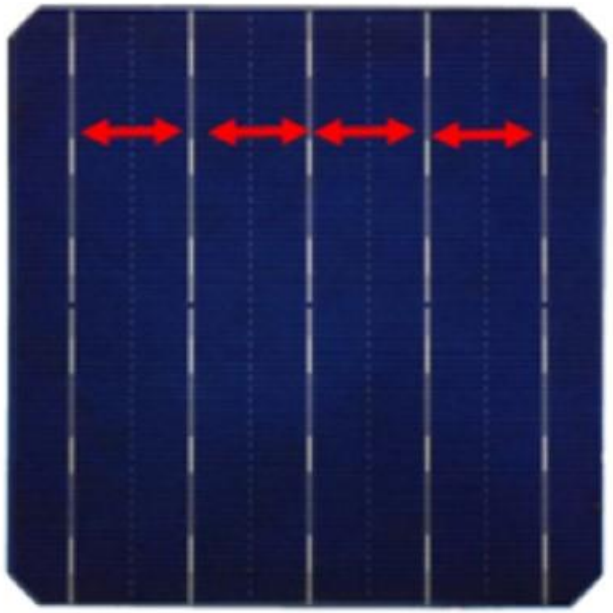
5BB Mono PERC Cells
156,75 * 156.75 mm
158 * 158 mm



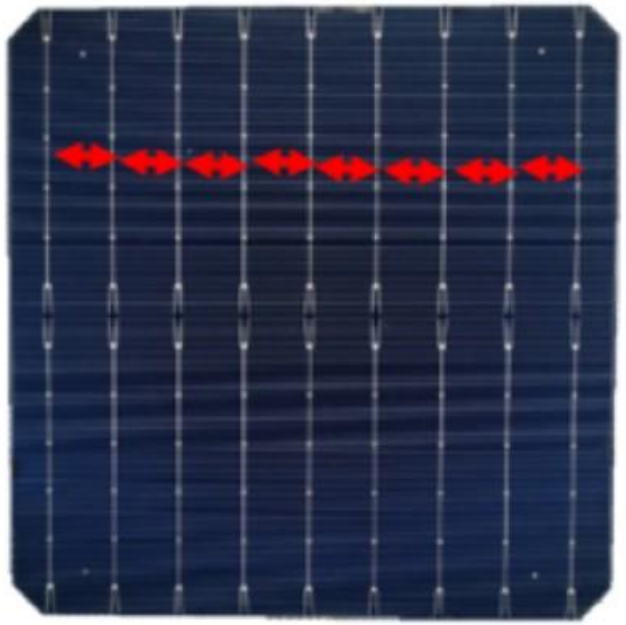
9BB Mono PERC Cells
158*158 mm
166*166 mm

PV cell Bus-Bar

- The surface area of the busbar is 22% lower on 9BB than 5BB cells, that will increase the cells receiving surface, and the output of the PV module.



Space between each cells: 31.2 mm
Busbar thickness: 0.4 mm

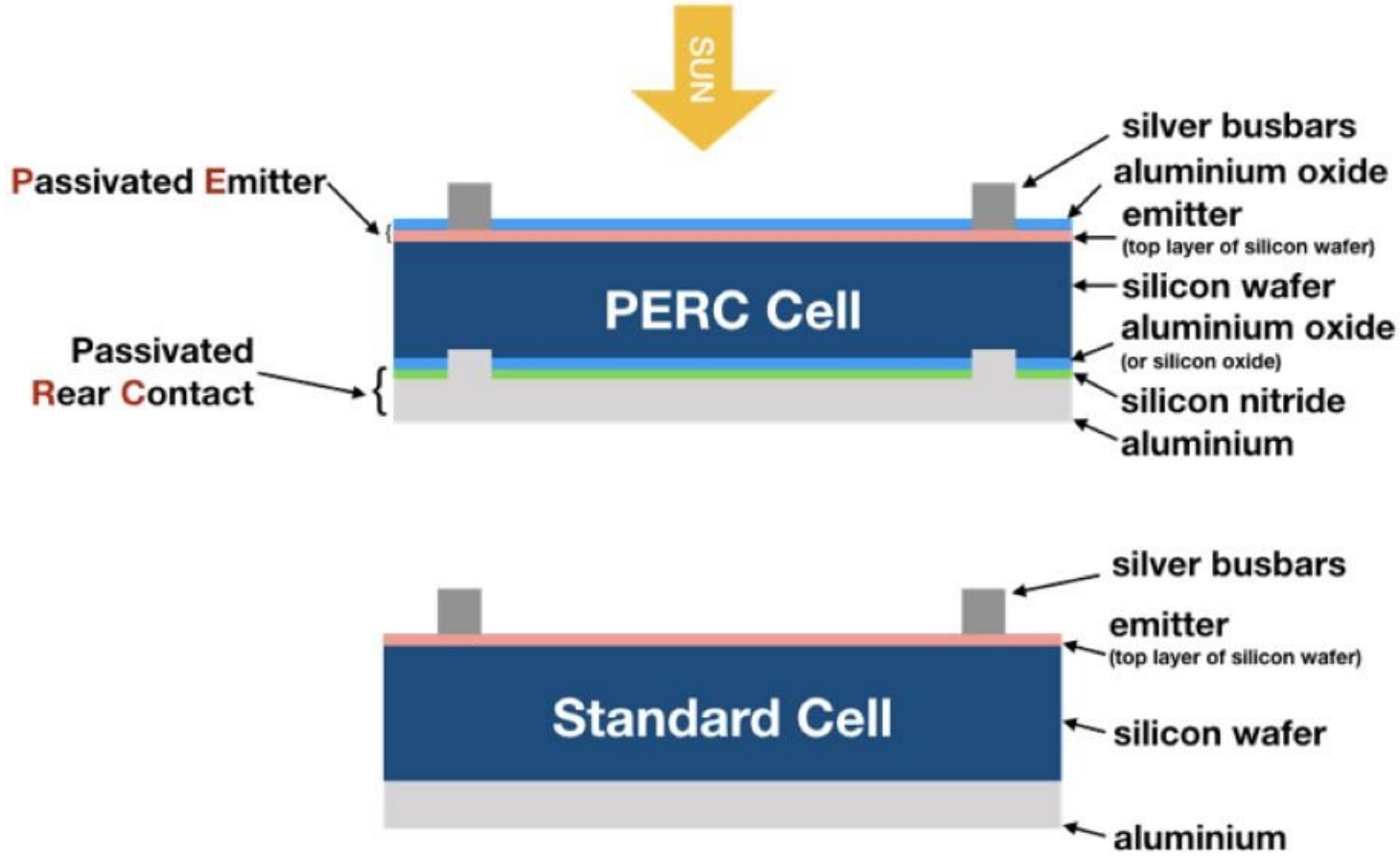


Space between each cells: 18 mm
Busbar thickness: 0.1 mm

PV PERC Cells

PERC stands for "**passivated emitter and rear contact**" or "rear cell".

Solar panels built with PERC cells have an additional layer on the back of the traditional solar cells.



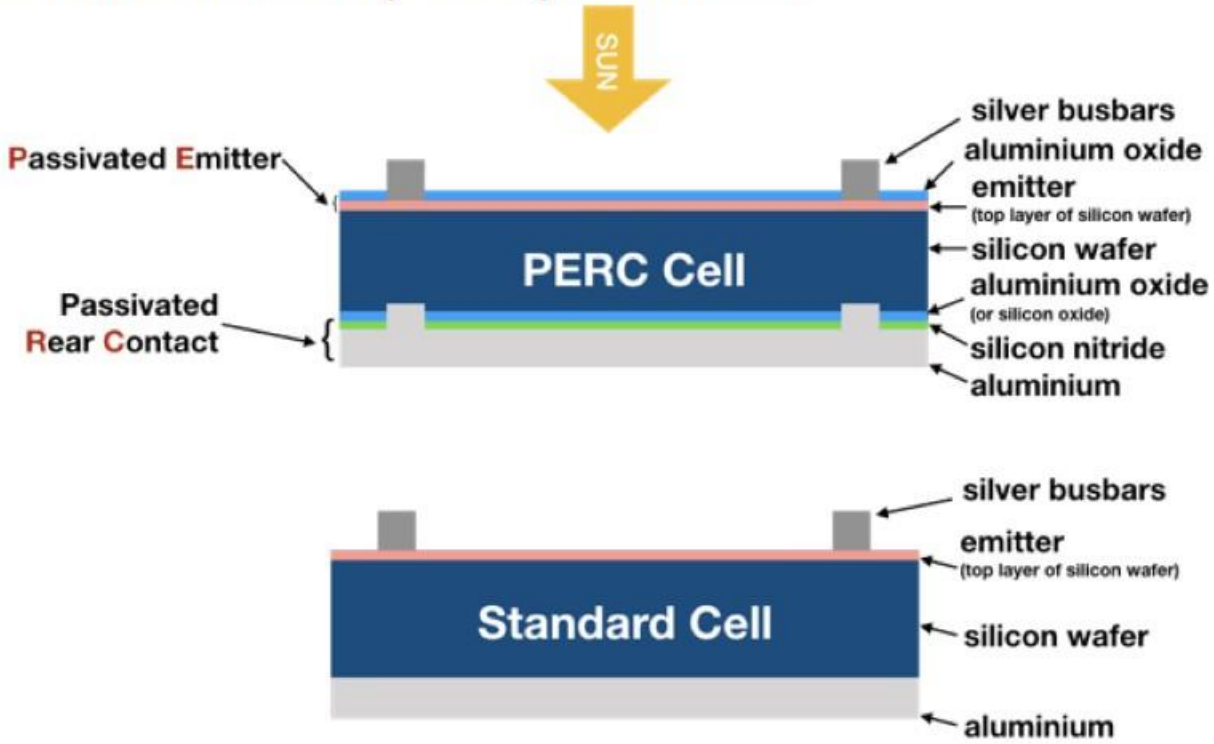
PV PERC Cells

This additional layer allows more sunlight to be captured and turned into electricity, making **PERC cells more efficient than traditional cells**

1.) Electron recombination is significantly reduced

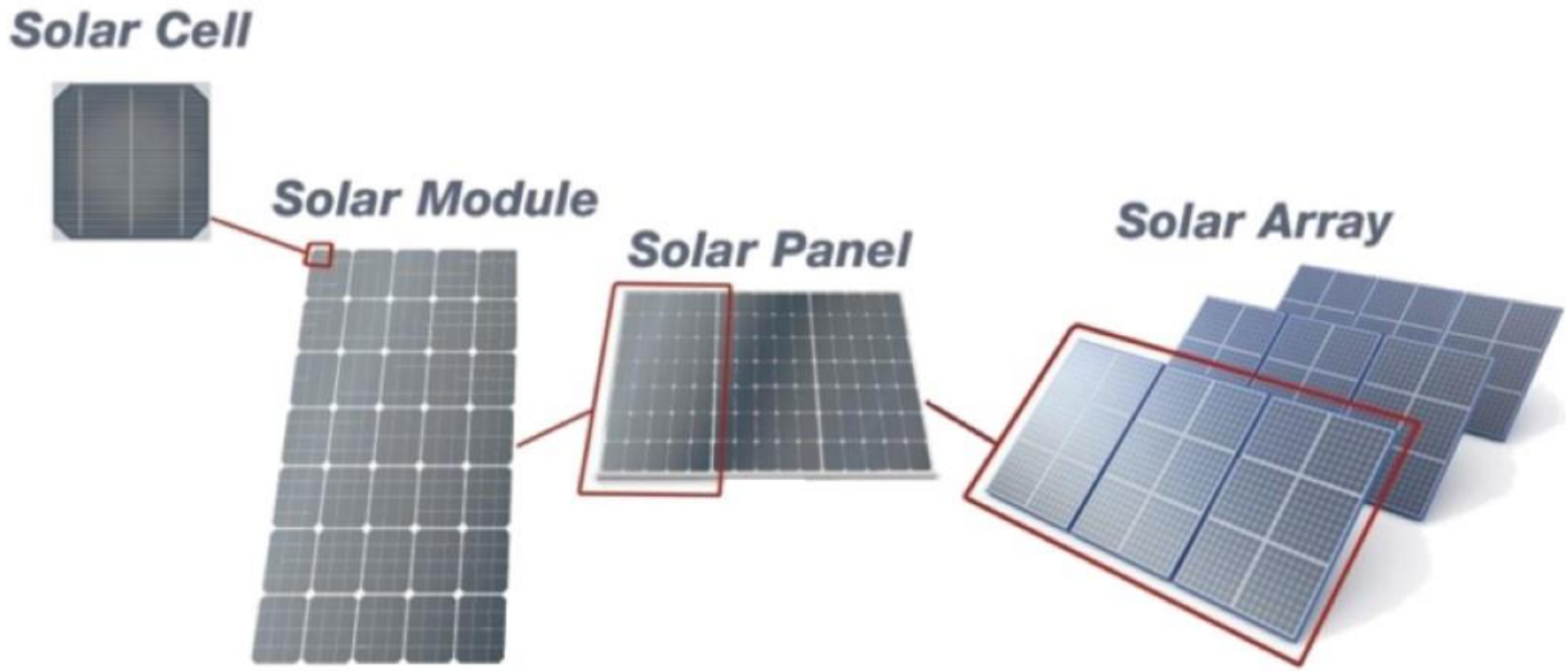
2.) More light is absorbed

3.) Higher internal reflectivity is experienced.



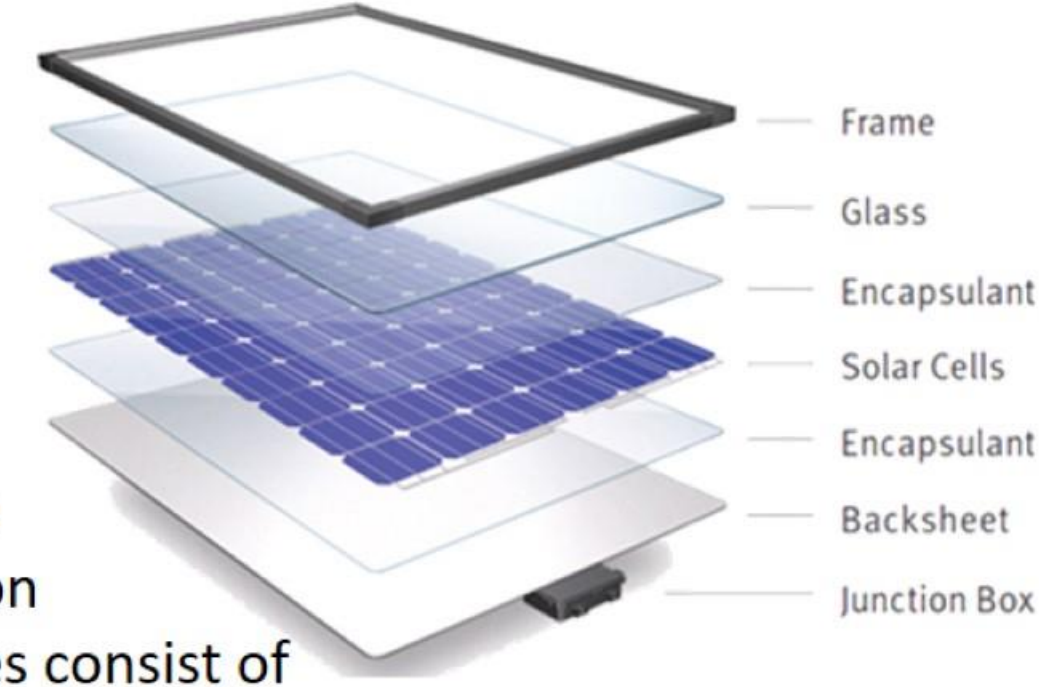
Solar Panel and Array

Panels and arrays are units consisting of several mechanically joined solar modules (often pre-wired) that are delivered pre-assembled and are used for configuring larger solar generators.



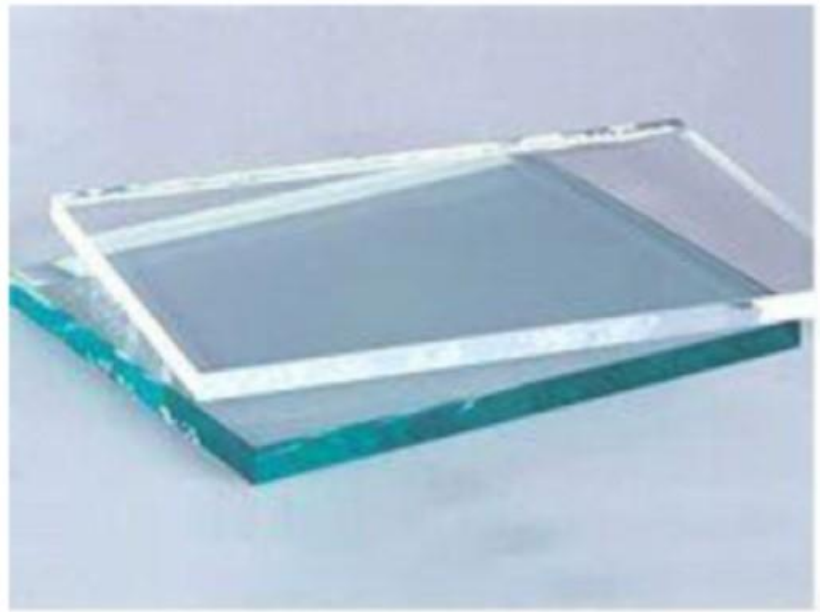
Solar Cell Fabrication Layers

- The module must be able to withstand environmental conditions such as:
  - dust
  - salinity
  - wind
  - snow
  - humidity
  - rain
  - hail
  - atmospheric gases and pollutants
  - the seasonal temperature variation
- Most PV crystalline-silicon PV modules consist of
  - a transparent top surface
  - an encapsulant
  - a rear layer
  - a frame around the outer edge



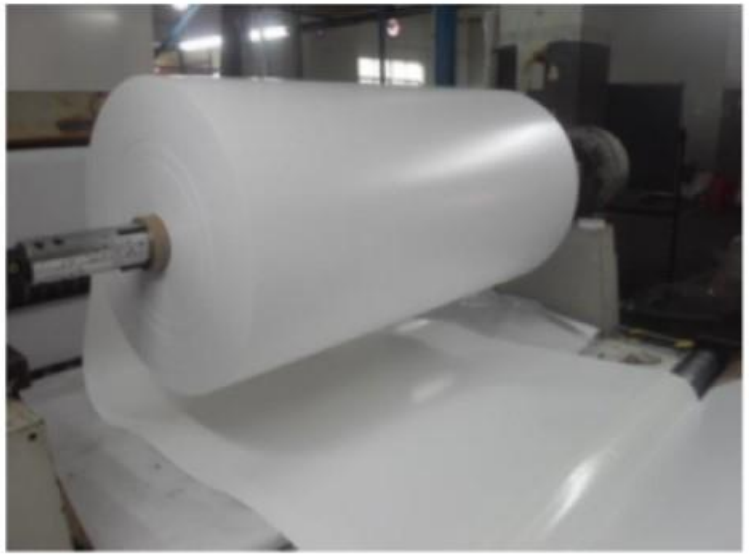
Glass Cover

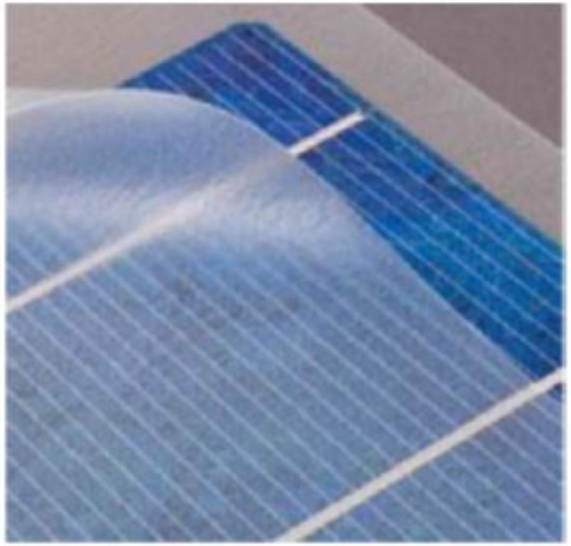
- The front surface of a PV module must have a high transmission in the wavelengths which can be used by the cells in the PV module.
- Top surface must have high transmission of light in the wavelength range of 350nm to 1200nm.
- The reflection from the front surface should be low.
- The top surface material should be
  - impervious to water,
  - good impact resistance,
  - stable under prolonged UV exposure
  - low thermal resistivity.



Encapsulant Material

- The encapsulant is used to provide adhesion between the cells, the top surface and the rear surface of the PV module.
- The encapsulant should be stable at elevated temperatures and high UV exposure.
- It should also be optically transparent and should have a low thermal resistance.
- EVA (ethyl vinyl acetate) is the most commonly used encapsulant material.





Frame

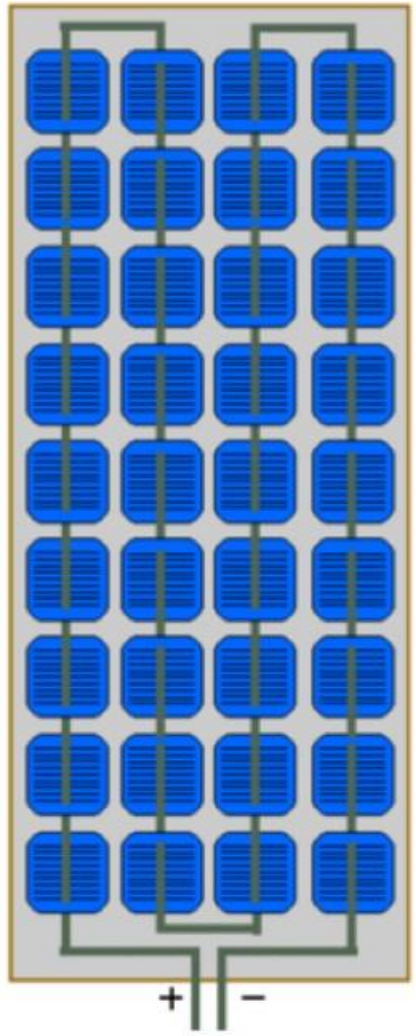
- A final structural component of the module is the edging or framing of the module.
- A conventional PV module frame is typically made of aluminum.
- The frame structure should be free of projections which could result in the lodgment of water, dust or other matter.



Rule of Thumb About Cells

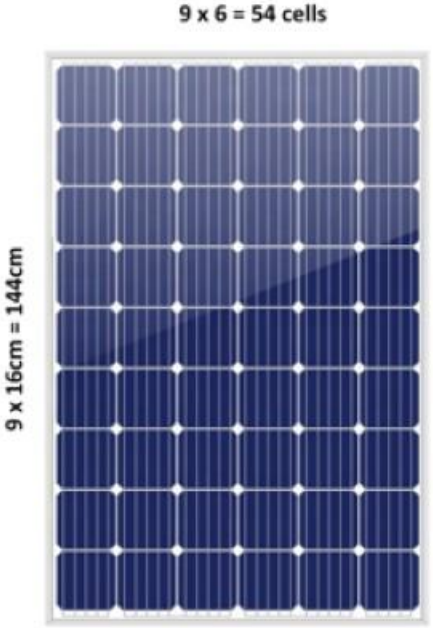
- The standard size of 1 PV Cell is **16 x 16cm** = 256 cm^2
- The current density from a commercial cell is approximately between 30mA/cm^2 to 36mA/cm^2.
- A cell can generate around **9A** under **0.6V**, i.e. **4.5 to 5.5Watt/Cell**
- **Efficiency 15%**





Rule of Thumb About Modules

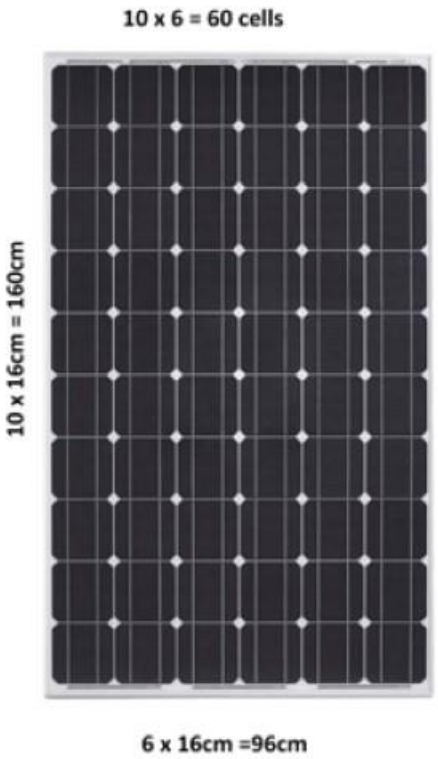




54 cells x 0.6V/cell = 32.4 volt

≈ 1.4m²

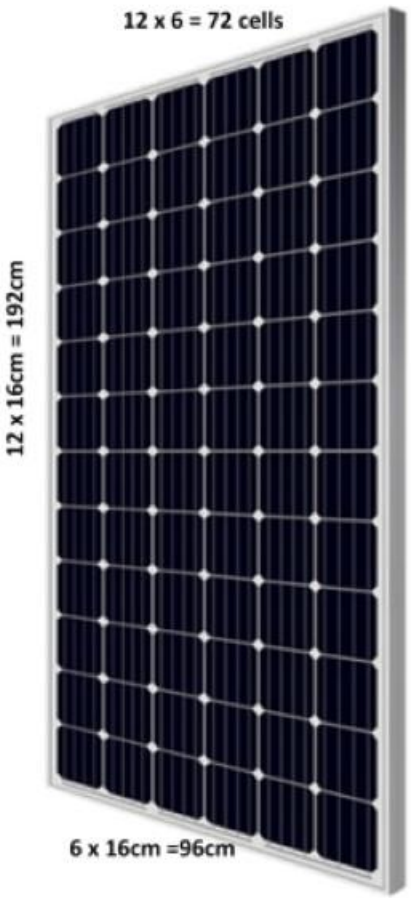
About 250 Watt module



60 cells x 0.6V/cell = 36 volt

≈ 1.6m²

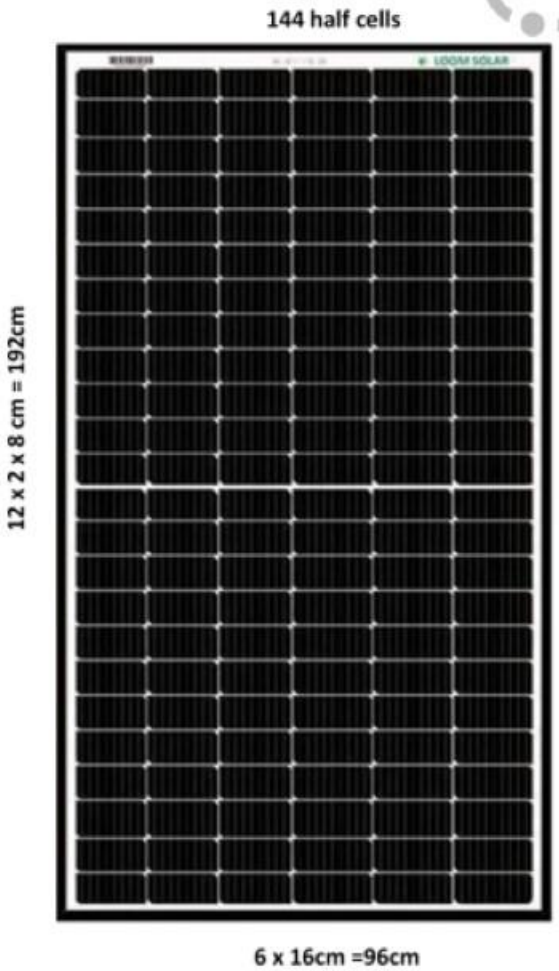
About 320 Watt module



72 cells x 0.6V/cell = 43.2 volt

≈ 1.8m²

About 380 Watt module



72 (144 half cells) x 0.6V/cell = 43.2 volt

≈ 2m²

About 440 Watt module

- End of part 1

Photovoltaic solar energy training course

Section 2: Photovoltaics

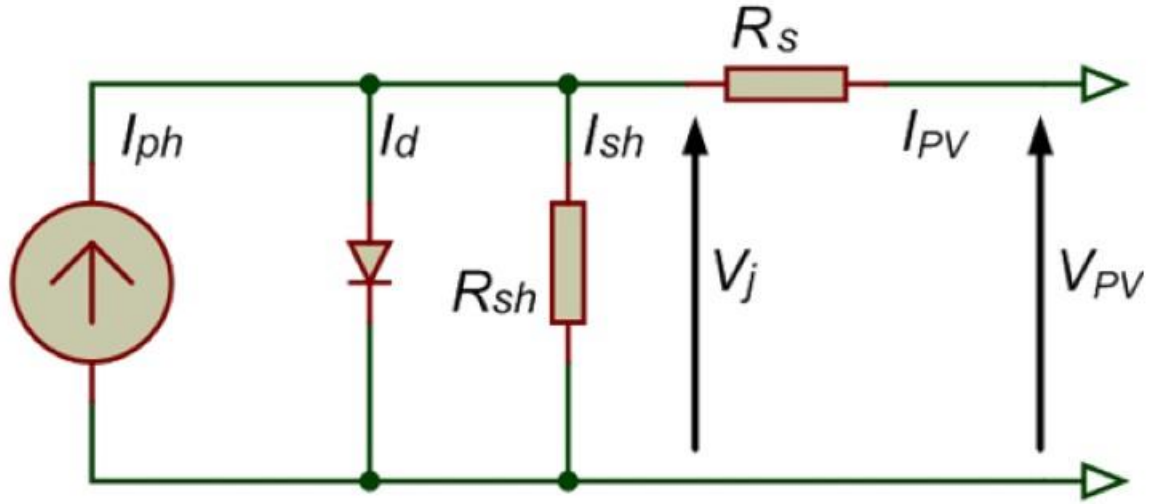
Part 2

- PV circuit and Mathematical model
- Open Circuit Voltage, Short Circuit Current, Max Power
- Fill Factor, Efficiency, Packing Factor
- PV Standards
- Application Classes

Nabil Karami, PhD

PV Circuit Model

- It consists of a
  - light generated current source
  - parallel diode
  - shunt resistor
  - series resistors.
- The model is developed describing the PV cell equivalent circuit as:



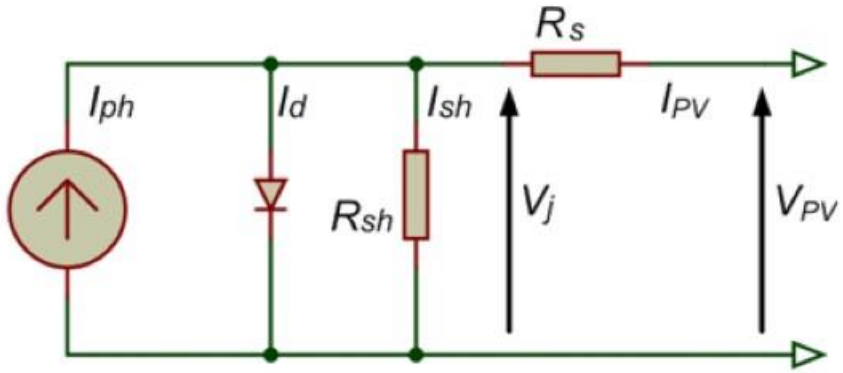
$$I_{PV} = I_{ph} - I_d - I_{sh}$$

PV Mathematical Model

$$I_{PV} = I_{ph} - I_d - I_{sh}$$

$$\begin{cases} I_{ph} = \dfrac{G}{G_{ref}}[I_{sc,ref} + \mu_{I_{sc}}(T - T_{ref})] \\ I_d = I_s\left(exp\left(\dfrac{V_d}{AV_t}\right) - 1\right) \\ I_{sh} = \dfrac{V_{PV} + I_{PV}R_s}{R_{sh}} \end{cases}$$

$$\begin{cases} I_s = I_{s,ref}\left(\dfrac{T}{T_{ref}}\right)^3 exp\left[\dfrac{qV_g(\frac{1}{T_{ref}} - \frac{1}{T})}{kA}\right] \\ I_{s,ref} = \dfrac{I_{sc,ref}}{exp\left(\dfrac{V_{oc,ref}}{AV_t}\right) - 1} \\ V_t = \dfrac{kT}{q} \end{cases}$$



- *Iph*(*A*) is the generated photo-current,
- *G*(*W/m²*) is the solar irradiation,
- *T*(*K*) is the temperature of the cell,
- *Gref* (*W/m²*) is the illumination reference,
- *Tref* (*K*) is the reference temperature,
- *Isc,ref* (*A*) is the PV module short-circuit current,
- *μIsc*(*A/K*) is the short-circuit current temperature coefficient,
- *Is*(*A*) is the cell reverse saturation current,
- *Vd*(*V*) is the voltage across the diode,
- *A* is the ideality factor,
- *Vg*(*eV*) is the band gap for silicon (1.1*eV*),
- *k*(*J/K*) is the Boltzmann constant ($1.3805 \times 10^{-23} J/K$),
- *q*(*C*) is the Electron charge ($1.6 \times 10^{-19} C$),
- *Isc,ref* (*A*) is the reference short-circuit current,
- *Voc,ref* (*V*) is the reference open-circuit voltage,
- *VPV* (*V*) is the PV voltage,
- *Rs*() is the PV series resistor,
- *Rsh*() is the PV shunt resistors.

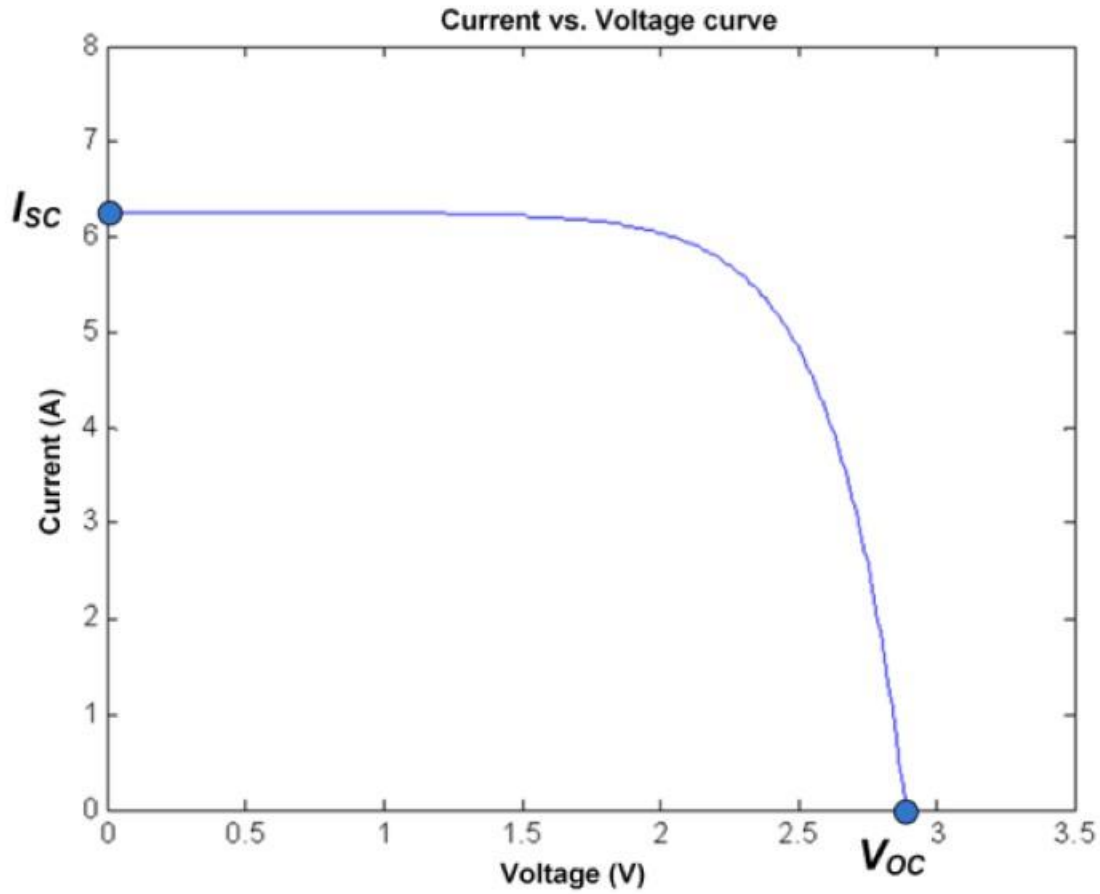
PV Mathematical Model

Straightforward computation shows that

$$I_{PV} = I_{ph} - I_s \ \ (exp[\lambda(V_{PV} + I_{PV}R_s)] - 1) - \frac{V_{PV} + I_{PV}R_s}{R_{sh}}$$

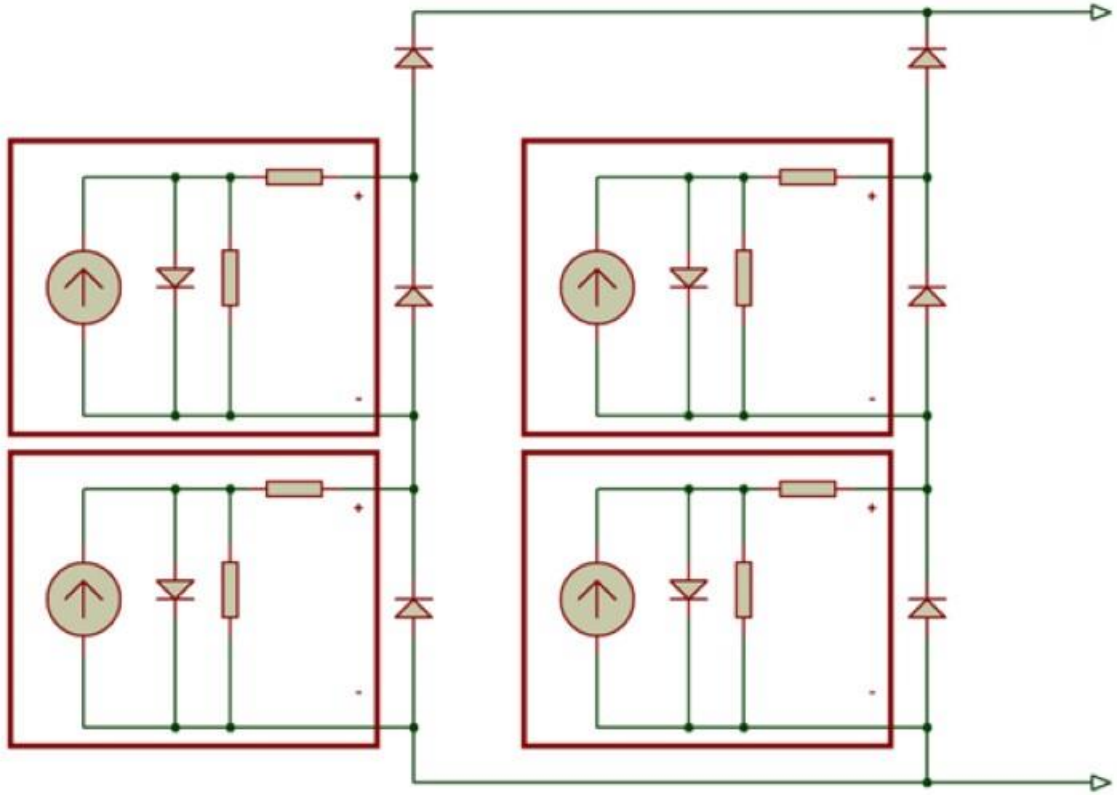
$$\lambda = \frac{1}{AV_t} = \frac{q}{AkT}$$

This is the complete equation to be solved by any iterative technique.



PV Mathematical Model

- PV cells are grouped together in order to form PV modules, which are combined in series and in parallel to provide the desired output power.
- The number of cells in series is N_S and the number of cells in parallel is N_P .

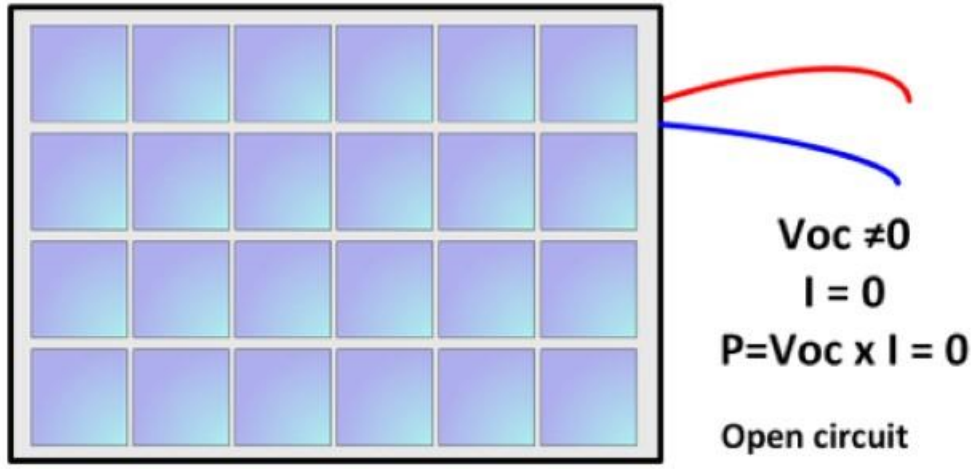


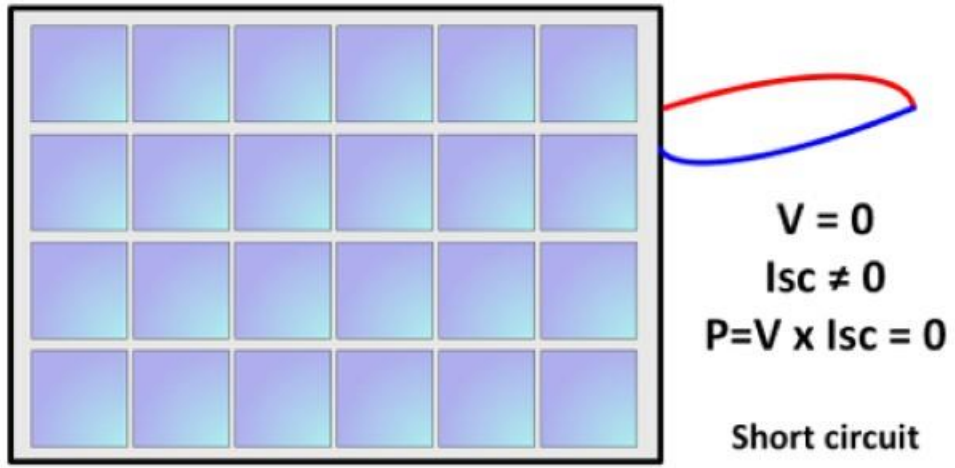
$$I_{PV} = N_P I_{ph} - N_P I_s \left(exp\left[\lambda\left(\frac{V_{PV}}{N_S} + \frac{I_{PV} R_s}{N_P}\right)\right] - 1\right) - \frac{\frac{N_P}{N_S} V_{PV} + I_{PV} R_s}{R_{sh}}$$

This is the complete equation to be solved by any iterative technique.

Open-Circuit Voltage, Short-Circuit Current

- The open circuit voltage V_{OC} and the short circuit current I_{SC} are two important points of the current-voltage characteristic.
- At both points, the power generated is zero.

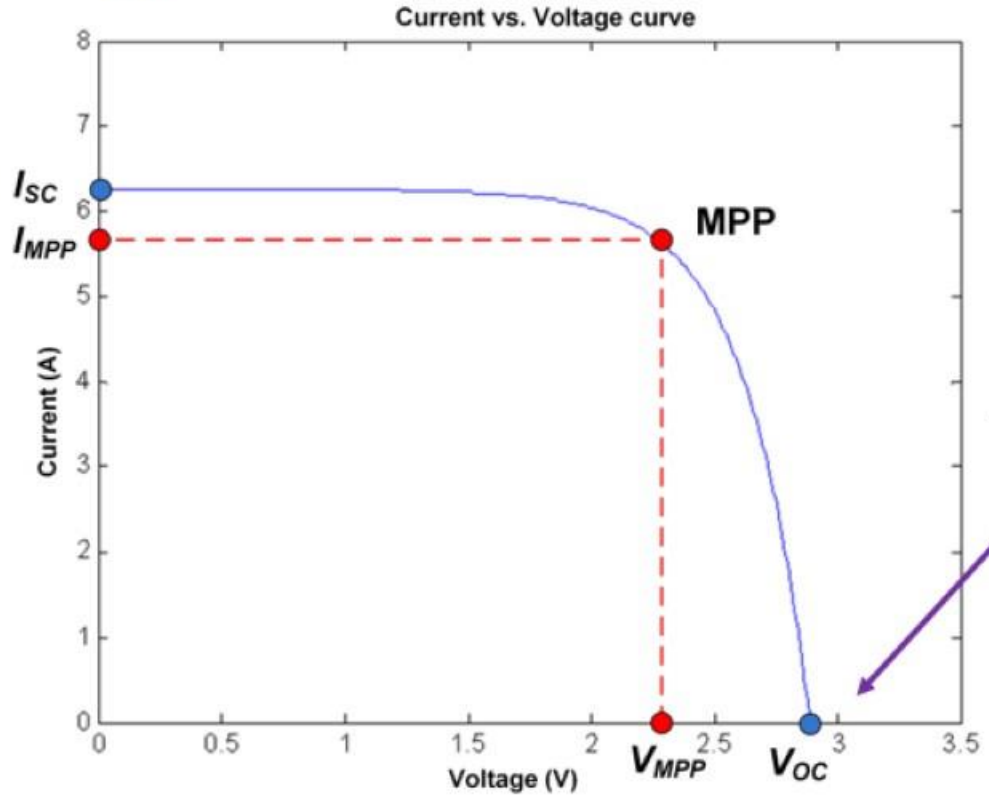




Open-Circuit Voltage, Short-Circuit Current

- V_{OC} can be approximated when the output current of the cell is zero, i.e. $I_{PV} = 0$ and the shunt resistance R_{sh} is neglected.
- The short circuit current I_{SC} is the current at $V_{PV} = 0$ and is approximated to the light generated current I_{ph}

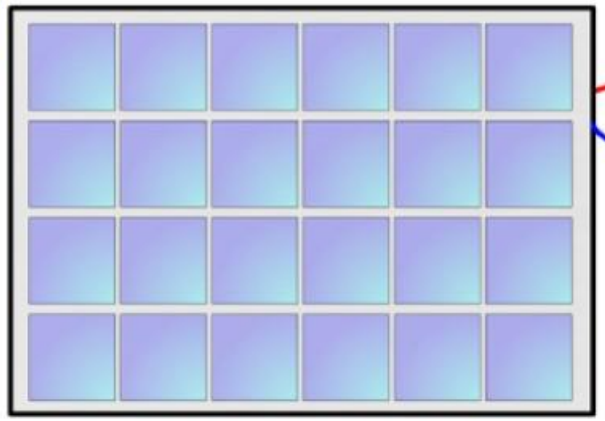
$$I_{SC} \approx I_{ph}$$



$$V_{OC} \approx \frac{1}{\lambda} ln\left(\frac{I_{ph}}{I_s} + 1\right)$$

Open-Circuit Voltage, Short-Circuit Current And Maximum Power Point 'MPP'

- The maximum PV power is generated when the product $V_{PV}\, I_{PV}$ is maximized. This point, called MPP is unique



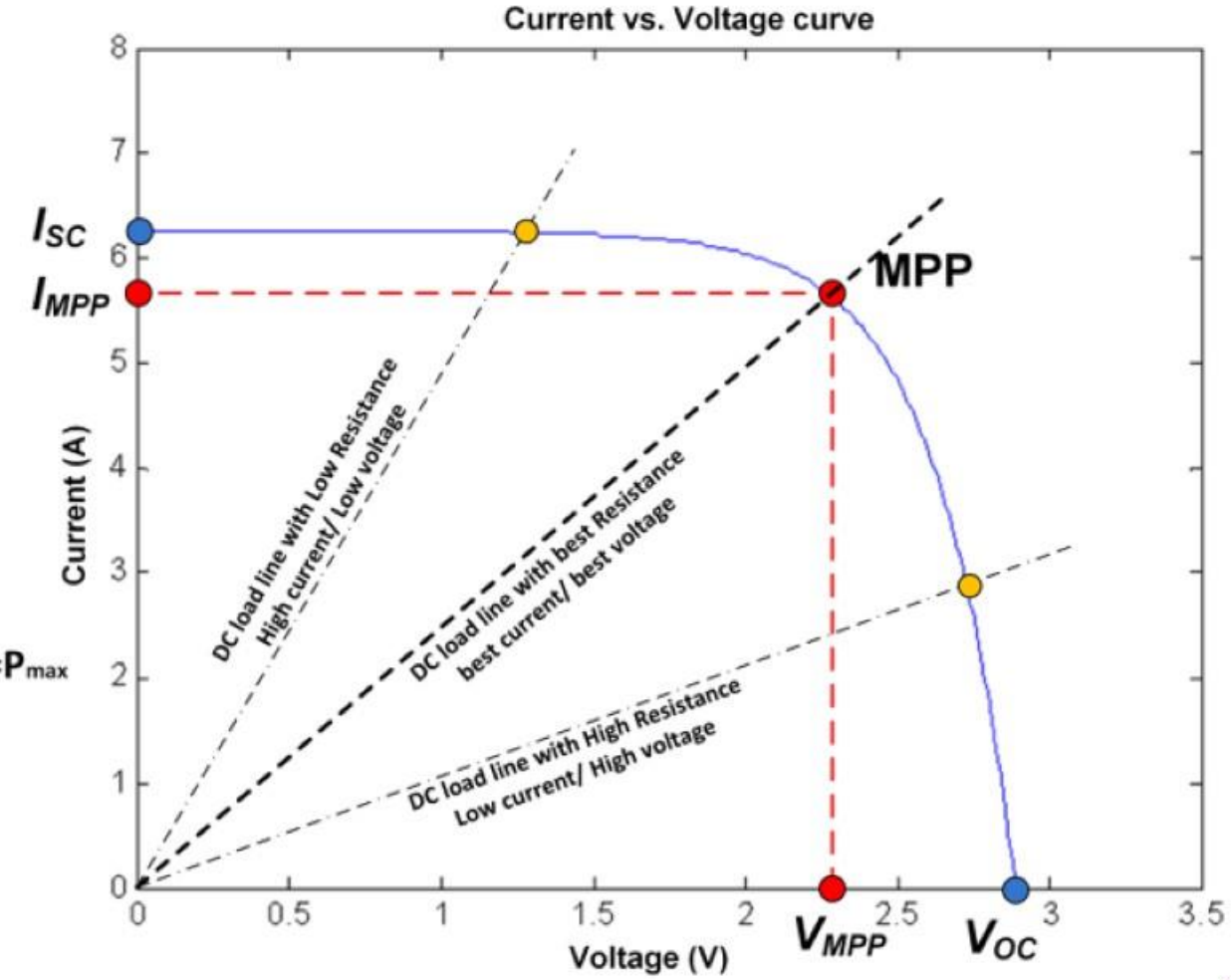


$0 \le R \le \infty$

$R=0,\ V=0,\ I=I_{sc}$

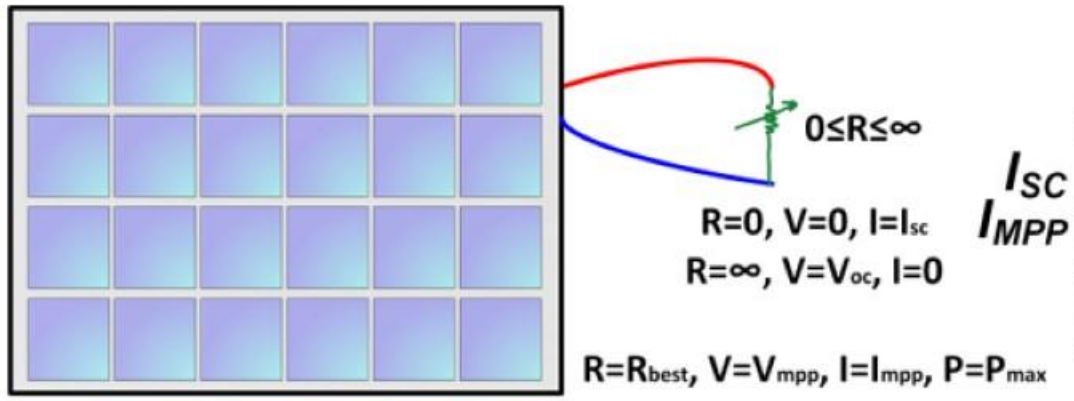
$R=\infty,\ V=V_{oc},\ I=0$

$R=R_{best},\ V=V_{mpp},\ I=I_{mpp},\ P=P_{max}$



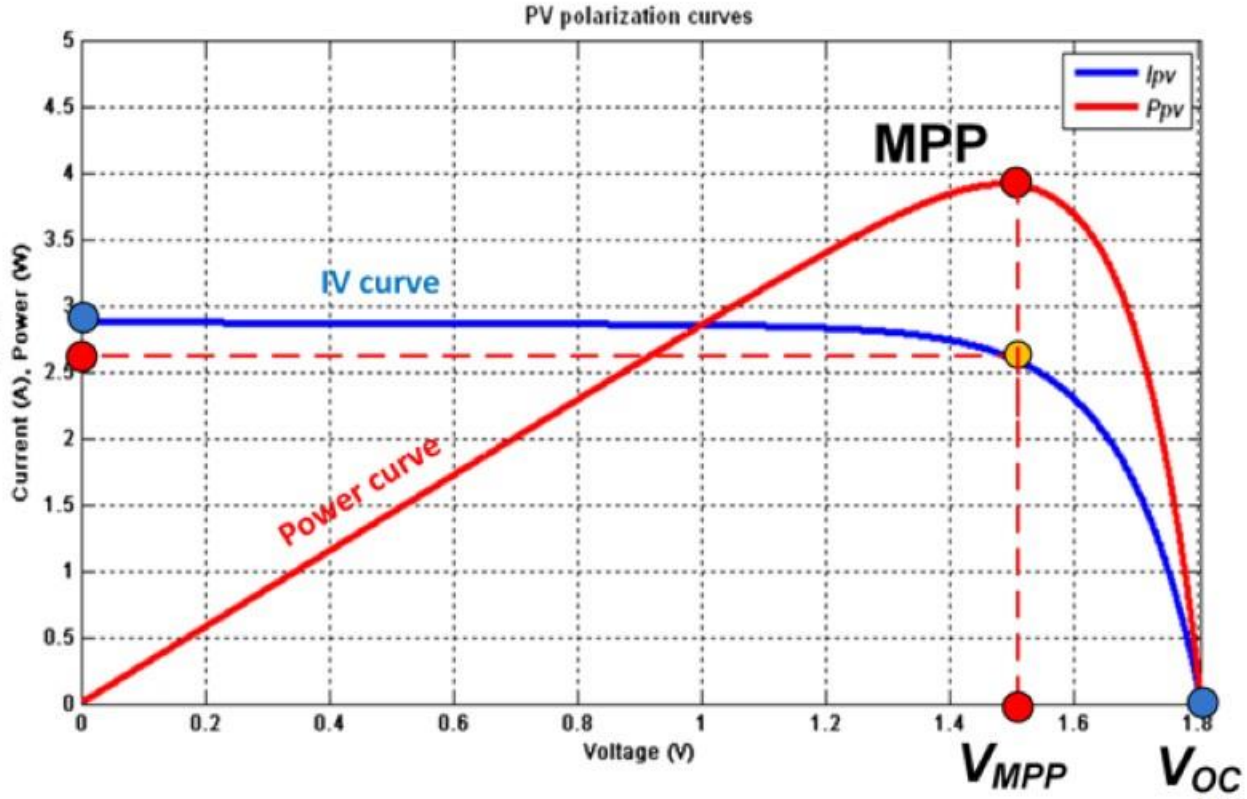
Open-Circuit Voltage, Short-Circuit Current And Maximum Power Point 'MPP'

- The maximum PV power is generated when the product $V_{PV}\, I_{PV}$ is maximized. This point, called MPP is unique



I_{SC}

I_{MPP}

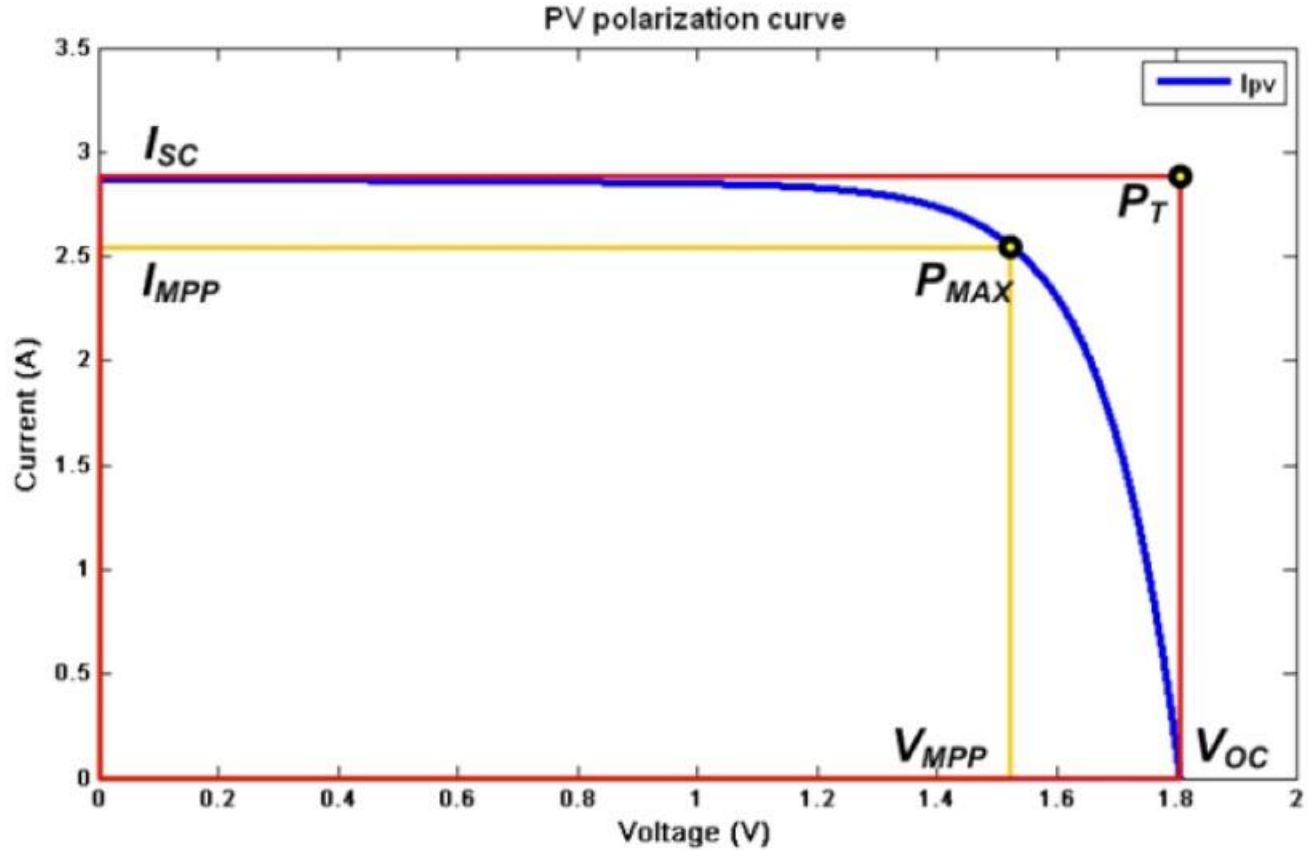


Fill Factor

- The Fill Factor (FF) can be defined as:

$$FF = \frac{P_{MAX}}{P_T} = \frac{V_{MPP} I_{MPP}}{V_{oc} I_{sc}}$$

- FF is used to measure the solar cell overall quality.
- Typical FF for commercial solar cells is usually over 0.70
- FF is unitless

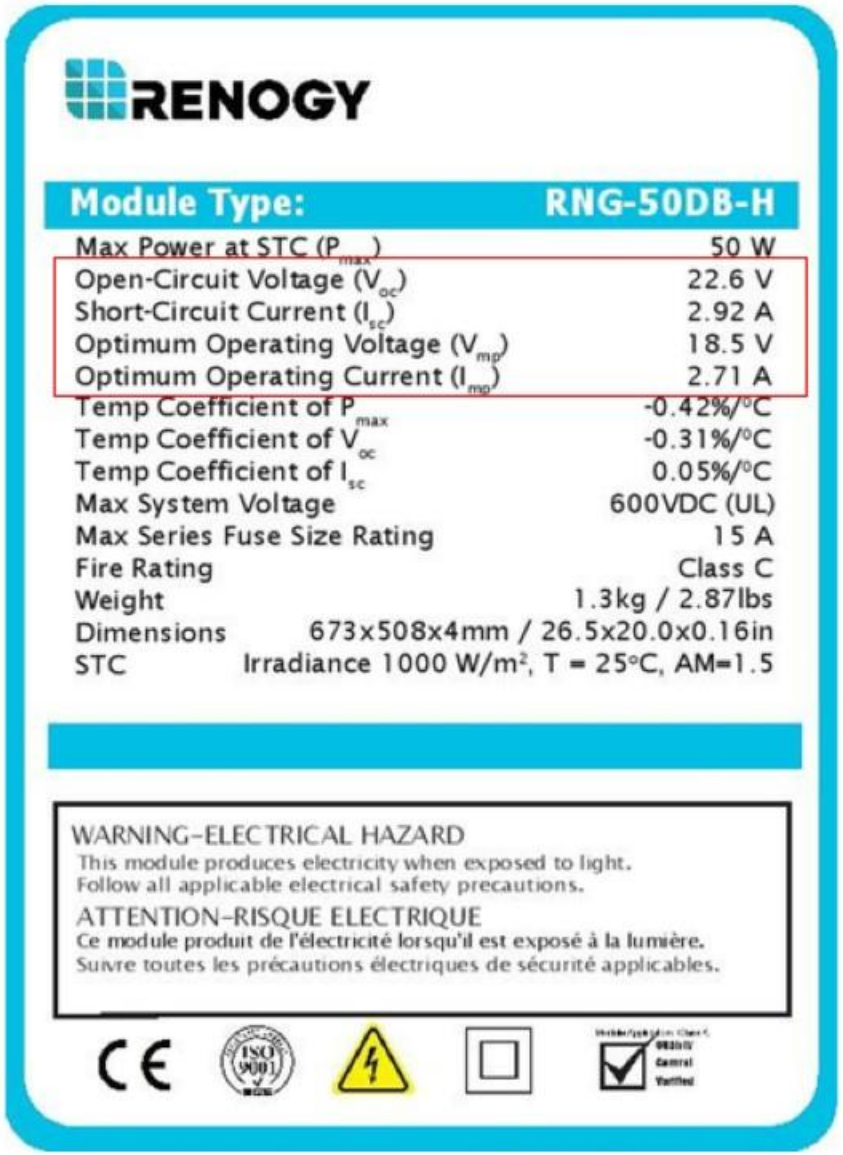


Fill Factor

Example

$$FF = \frac{P_{MAX}}{P_T} = \frac{V_{MPP} I_{MPP}}{V_{oc} I_{sc}}$$

$$FF = \frac{18.5 \times 2.71}{22.6 \times 2.92} = 0.76$$



RENOGY

Module Type:	RNG-50DB-H
Max Power at STC (P_{max})	50 W
Open-Circuit Voltage (V_{oc})	22.6 V
Short-Circuit Current (I_{sc})	2.92 A
Optimum Operating Voltage (V_{mp})	18.5 V
Optimum Operating Current (I_{mp})	2.71 A
Temp Coefficient of P_{max}	-0.42%/°C
Temp Coefficient of V_{oc}	-0.31%/°C
Temp Coefficient of I_{sc}	0.05%/°C
Max System Voltage	600VDC (UL)
Max Series Fuse Size Rating	15 A
Fire Rating	Class C
Weight	1.3kg / 2.87lbs
Dimensions	673x508x4mm / 26.5x20.0x0.16in
STC	Irradiance 1000 W/m², T = 25°C, AM=1.5

WARNING–ELECTRICAL HAZARD
This module produces electricity when exposed to light.
Follow all applicable electrical safety precautions.

ATTENTION–RISQUE ELECTRIQUE
Ce module produit de l'électricité lorsqu'il est exposé à la lumière.
Suivre toutes les précautions électriques de sécurité applicables.

PV efficiency

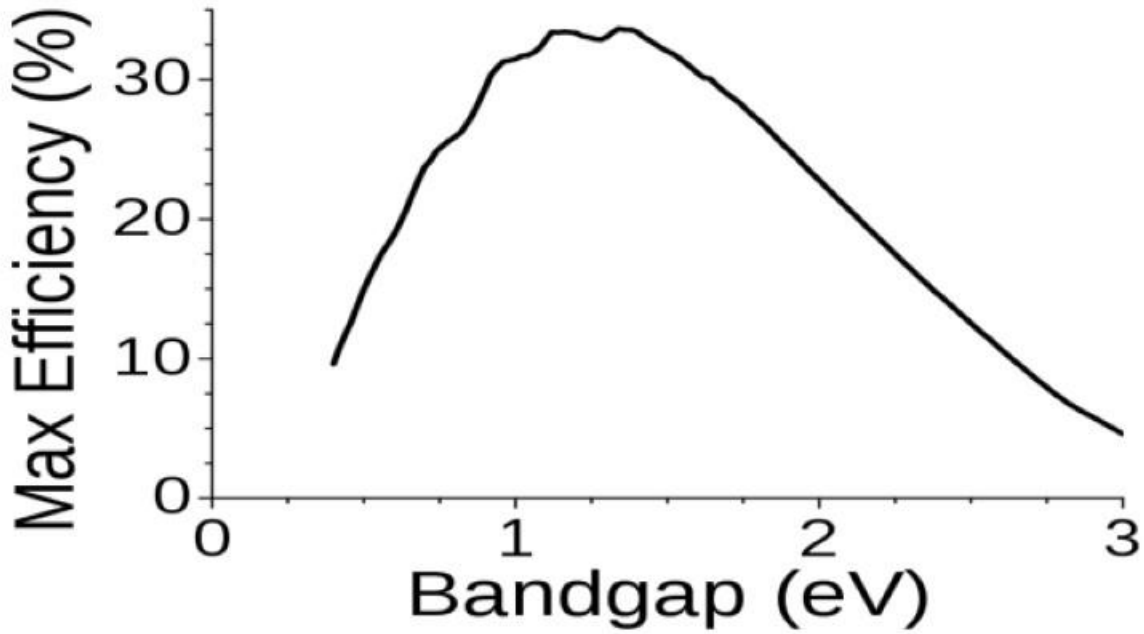
- The PV efficiency of today's **commercially** available solar cells for terrestrial applications ranges **up to 23%**.
- Although this figure is likely to rise in the coming years, the efficiency of PV installations is limited by the laws of physics.

$$\eta_{PV} = \frac{Pout}{Pin} = \frac{p_{\max}}{G.A}$$

P_{max} *(W)= peak power*

G *(W/m^2) = radiation power arriving at the solar cell*

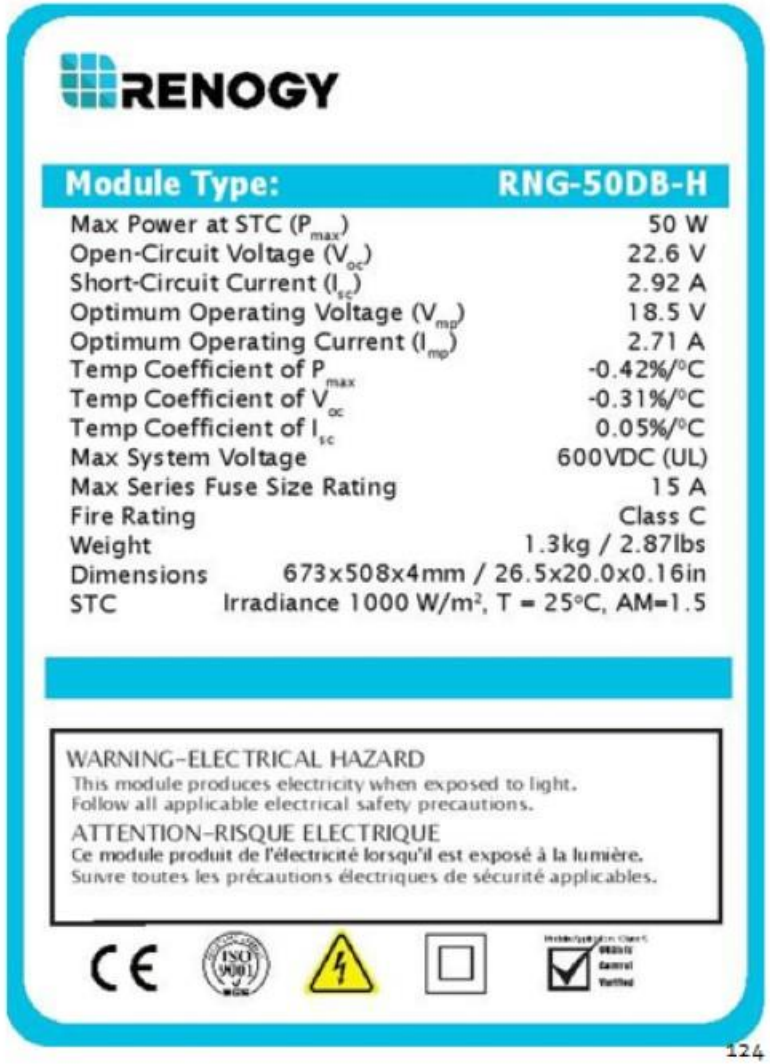
A *(m^2)= solar cell area*



PV efficiency: Rule of Thumb

- As a rule of thumb, the efficiency of:
  - Polycrystalline PV: **15%**
  - Monocrystalline PV: **20%**
- **A panel with 1m² over 1000W/m² irradiance can deliver 150W**
- For example, from the PV label, the dimension is 673 x 508 mm => Area is 0.34 m²
- The peak power indicated is 50W, so

$$\eta_{PV} = \frac{p_{\max}}{G.A} = \frac{50}{1000 \times 0.34} = 14.7\% \approx 15\%$$



PV Packing Factor PF

- Ratio of total solar cell area to total module area (including the frame).
- PF is always less than 1.

$$PF = \frac{A_c}{A}$$

A_c = Total solar cells area

A = solar module area



Example

Example (polycrystalline module)

At 1 kW/m^2 and a cell temperature of 25°C, a kyocera KC120 polycrystalline module exhibits the following characteristics:

Peak power = 120 W_p;

V_{oc} = 21.5V;

I_{sc} = 7.45A.

The module is composed of 36 (15cm X 15cm) solar cells and its outer dimensions are 96.7cm X 96.2cm.

Determine the following:

(a) Solar cell efficiency η_{PV}

(b) Packing factor PF

(c) Solar module efficiency η_M

(d) Fill factor FF

Example

Solution 1 (polycrystalline module)

(a) Solar cell efficiency η_{PV}

$$\eta_{PV} = \frac{P_{\max}}{G_0.A} = \frac{P_{max,cell}/36}{G_0.A} = \frac{120/36}{1000 \times 15 \times 15 \times 10^{-4}} = 14.8\%$$

(b) Packing factor PF

$$PF = 36 \times A_c/A = 36 \times (15 \times 15 \times 10^{-4})/(96.7 \times 96.2 \times 10^{-4}) = 0.8707$$

(c) Solar module efficiency η_M

$$\eta_M = \eta_{PV} \times PF = 14.8\% \times 0.8707 = 12.9\%$$

(d) Fill factor FF

$$FF = \frac{P_{M0}}{(V_{OC} \times I_{SC})} = \frac{120}{(21.5 \times 7.45)} = 0.749$$

PV standards

- Modules must comply with the following international standards:
  - IEC 61215 in the case of crystalline types / IEC 61646 in the case of thin film types
  - IEC 61730 -Photovoltaic (PV) module safety qualification
- •Modules must also carry a CE mark

CERTIFIED IEC 61730 Ed.1

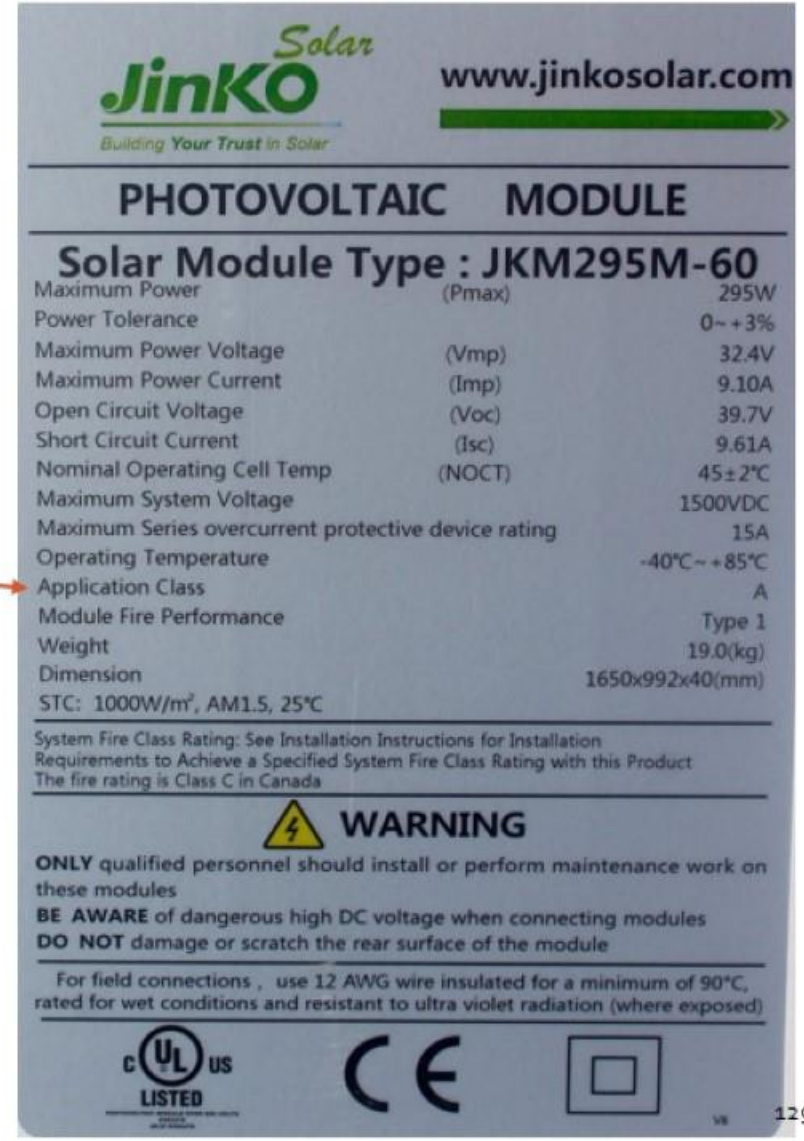
CERTIFIED IEC 61215 Ed.2

CE

PV Application Classes

Electrical Shock Hazard Tests

- **Application Class A**: for modules operating at greater than 50 VDC or 240 W and in an area where the module can be contacted by the public. This PV panel class has the most stringent testing program.
- **Application Class B**: for modules installed in locations not accessible by the public. It has a slightly less stringent test program than the Class A modules, but the differences in testing programs are not significant.
- **Application Class C**: for modules operating at less than 50 VDC and 240 W. These less powerful PV panels have a significantly reduced test program.



- End of part 2

Photovoltaic solar energy training course

Section 2: Solar resources

Part 3

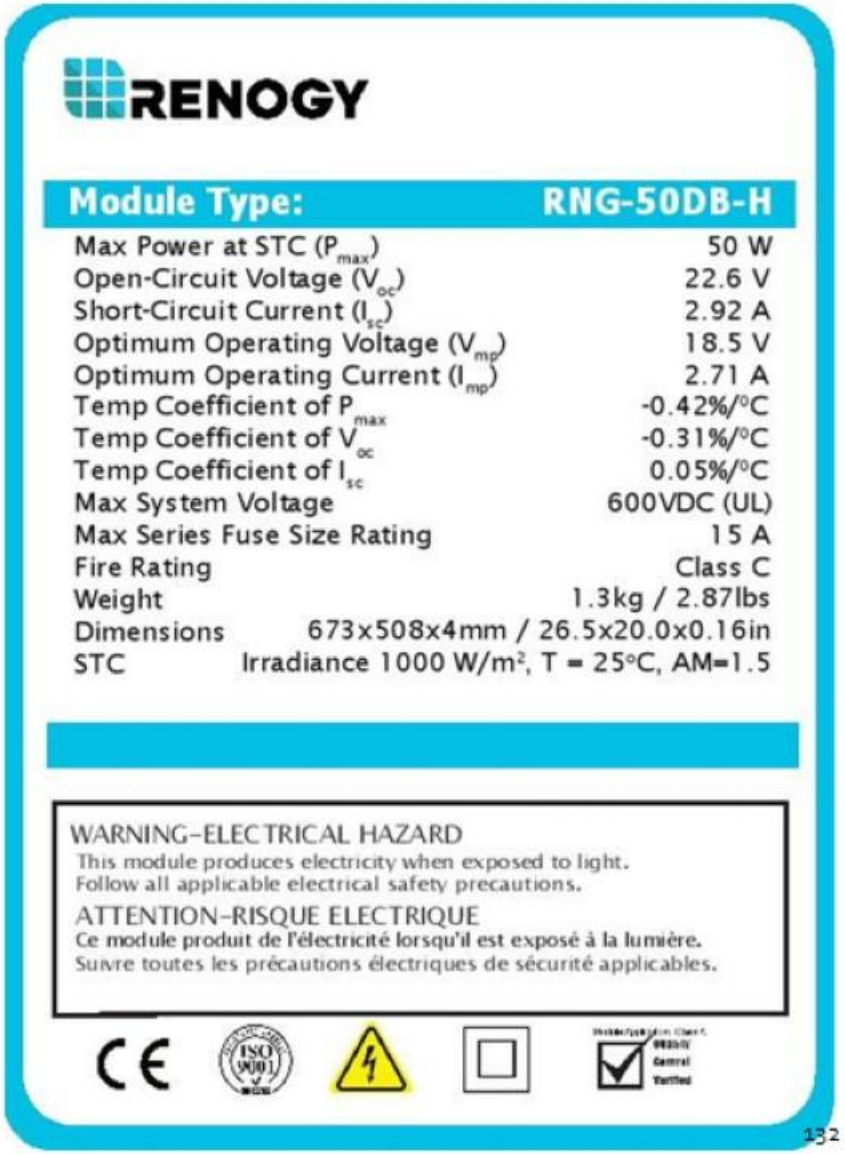
- PV Specification
- Standard Test Condition ‘STC’
- Irradiance/ Temperature Effects
- Temperature Coefficients (Absolute and relative)
- Normal Operating Cell Temperature ‘NOCT’

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PV Specification

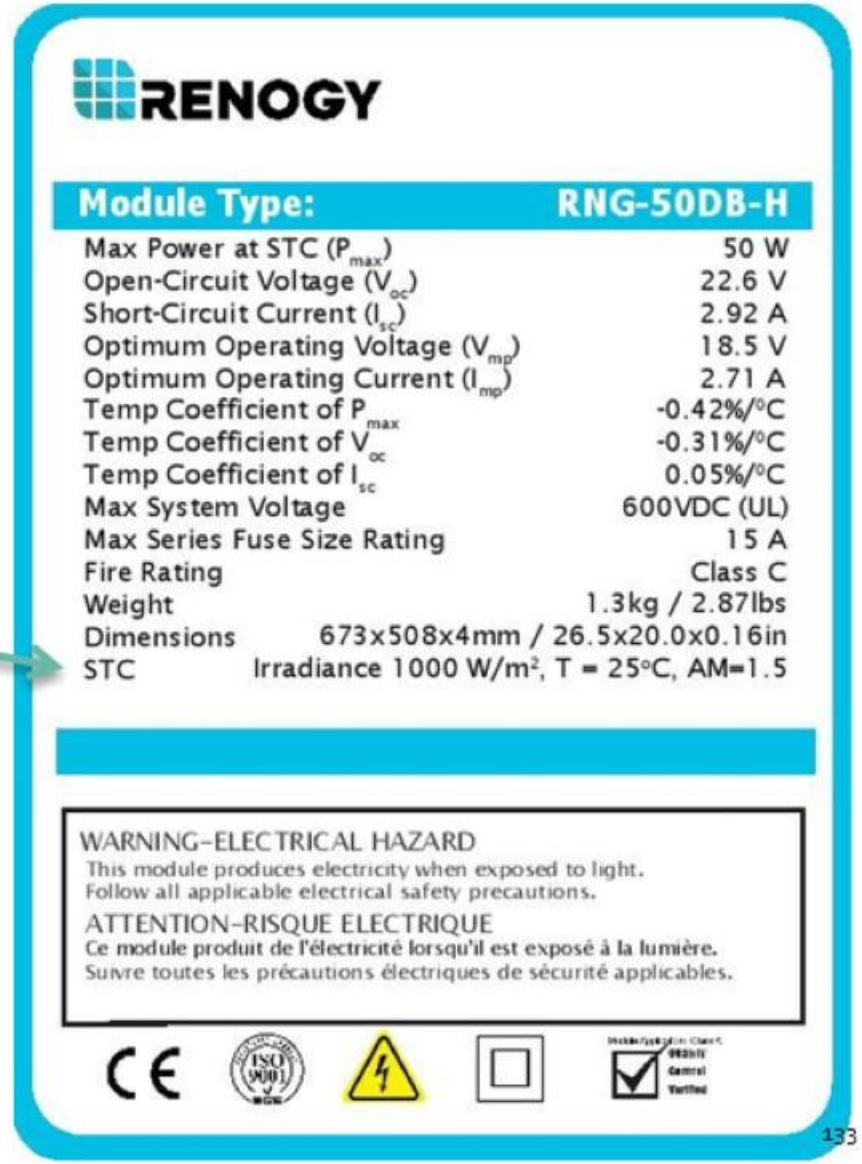
PV manufacturer mention the following at the back of the PV panel

- Maximum power P_{max} (Watt)
- Open circuit voltage V_{oc} (Volt)
- Short circuit current I_{sc} (Amp)
- Voltage at MPP, V_{mpp} (Volt)
- Current at MPP, I_{mpp} (Amp)
- Temperature coefficients for:
  - V_{oc} (%/°C) or (mV/°C)
  - I_{sc} (%/°C) or (mA/°C)
  - P_{max} (%/°C) or (W/°C)



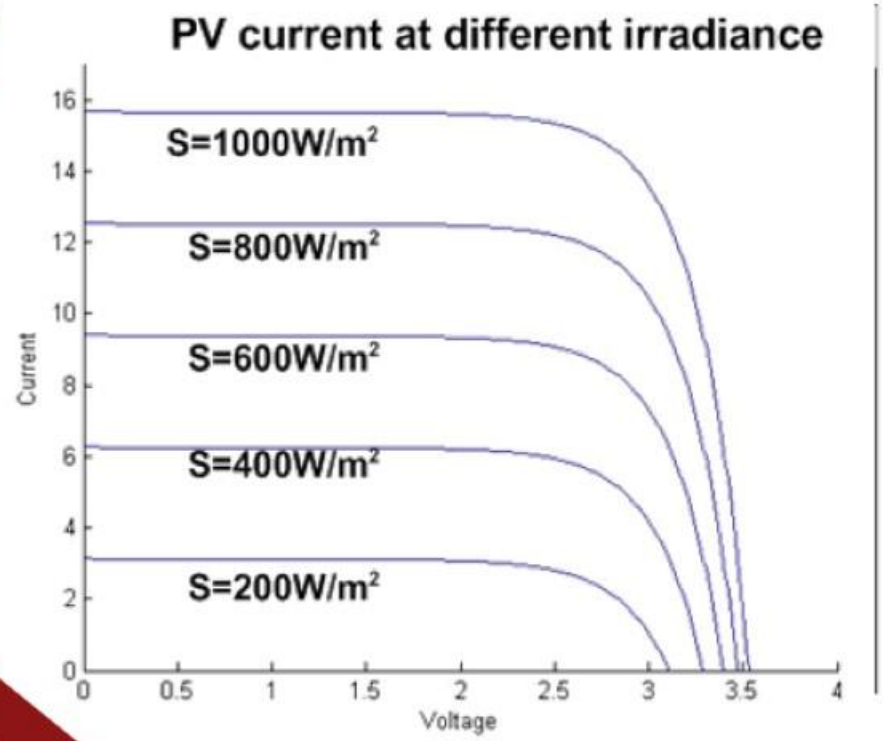
Standard Test Condition 'STC'

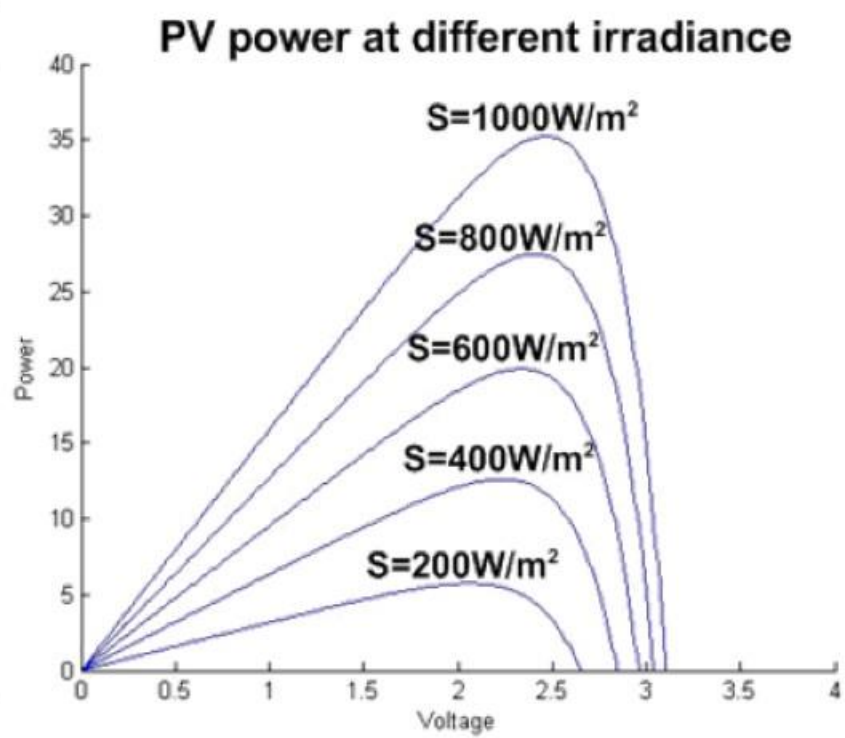
- Usual test conditions, as follows, for the purpose of specifying solar cell and solar module guide values:
- **Irradiance $G_0 = G_{STC} = 1000W/m^2$,**
- **AM1.5 spectrum,**
- **Cell temperature 25^0C.**



Irradiance effect

$$I_{PV} = I_{ph} - I_s \ \ (exp[\lambda(V_{PV} + I_{PV}R_s)] - 1) - \frac{V_{PV} + I_{PV}R_s}{R_{sh}}$$



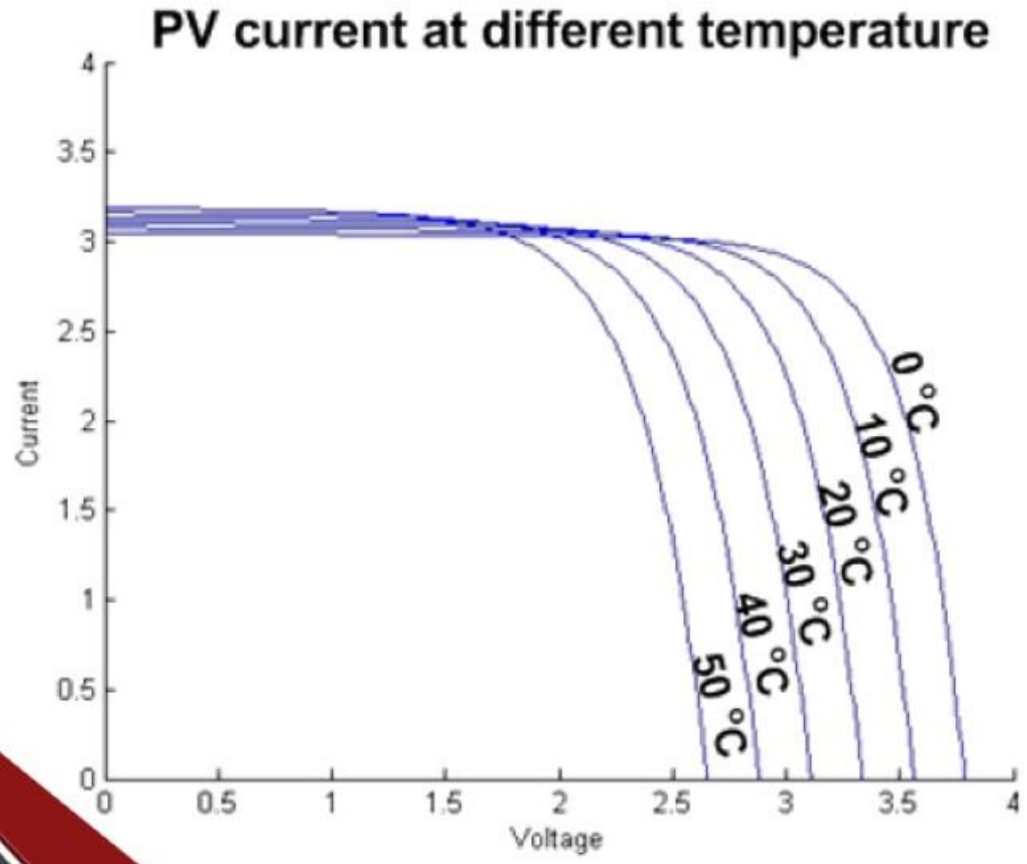


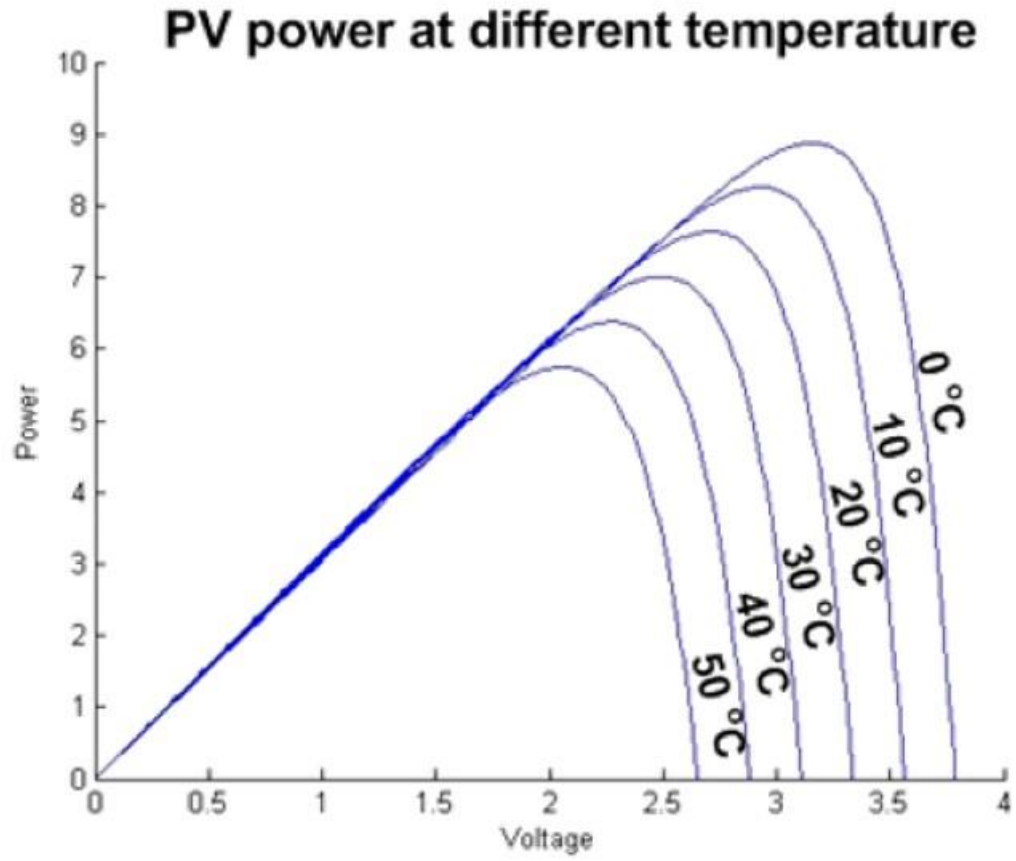


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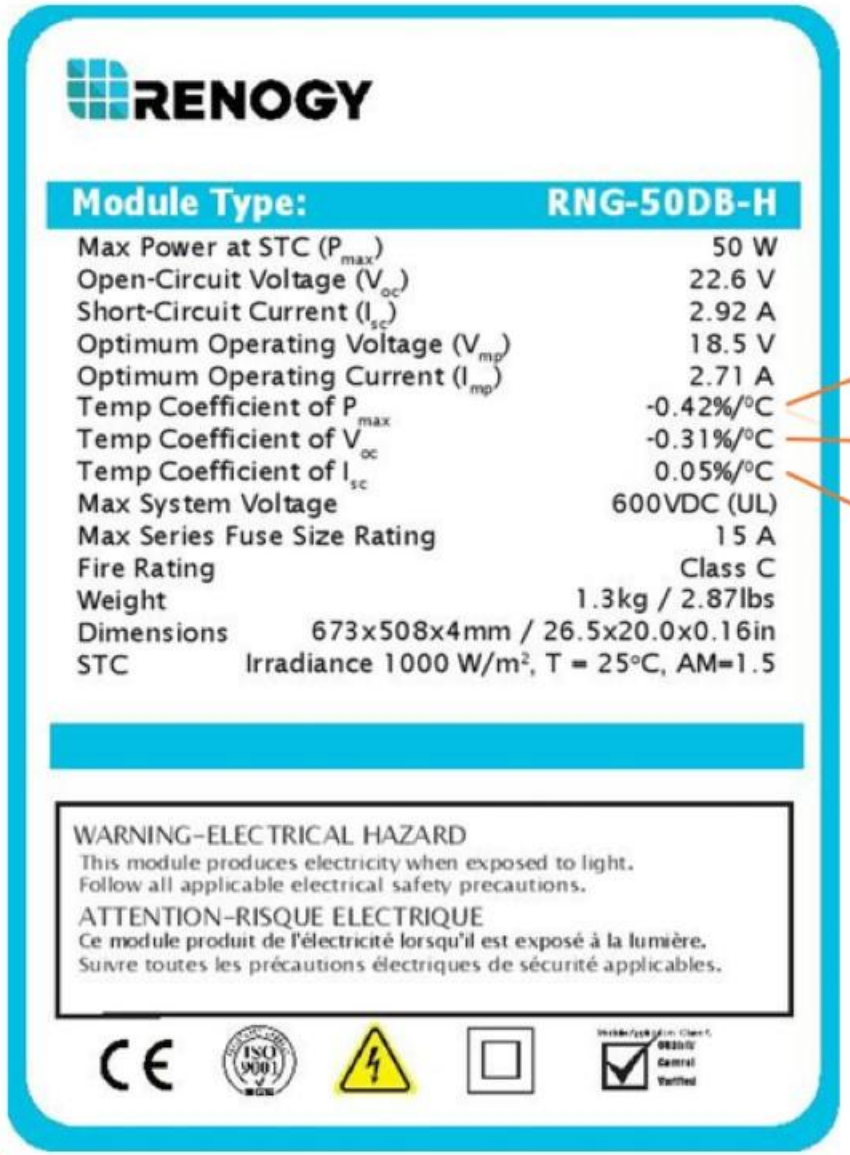
Temperature effect

- Raise in temperature has negative effect on voltage and power, but positive effect on current.





Temperature Coefficients



Negative effect on power by 0.42%/°C

Negative effect on voltage by 0.31%/°C

Positive effect on current by 0.05%/°C

- These are the **relative** Temperature Coefficients [**%/°C**]
- Called a_r, b_r, and c_r
- *r is for relative indication*

Temperature effect

- As cell temperature increases, the open-circuit voltage decreases largely while the short-circuit current increases only slightly:

$$V_{oc}(T) = V_{oc}(T_r)[1 + a_r(T - T_r)]$$

T_r is the reference temperature = 25°C and T is the cell temperature

- For crystalline silicon cells, V_{OC} drops by about 0.37% ($a_r = -3.7 \times 10^{-3}\ ^{o}C^{-1}$) for each degree Celsius increase in temperature and I_{SC} increases by approximately 0.05%.

$$I_{sc}(T) = I_{sc}(T_r)[1 + b_r(T - T_r)]$$

where $b_r = 0.5 \times 10^{-3}\ ^{o}C^{-1}$

Temperature effect



- The net result when cells heat up is the MPP slides slightly upward and toward the left with a decrease in maximum power available of about 0.5%/◦C.

$$P_{mpp}(T) = P_{mpp}(T_r)[1 + c_r(T - T_r)]$$

where $c_r = -5 \times 10^{-3}\ ^oC^{-1}$

- Photovoltaics, perhaps surprisingly, therefore perform better on cold, clear days than hot ones.

- Cells vary in temperature not only because ambient temperatures change, but since only a small fraction of the insolation hitting a module is converted to electricity. Most of that incident energy is absorbed and converted to heat.

Absolute & Relative Temperature Coefficients



- Some manufacturer provide coefficient in term of Absolute values of voltage, current and power, not in term of percentage:
  - 'a' is in mV/°C and not like a_r [%/°C]
  - 'b' is in mA/°C and not like b_r [%/°C]
  - 'c' is in mW/°C and not like c_r [%/°C]

Equations with Absolute Temperature Coefficients	Equations with Relative Temperature Coefficients
$V_{oc}(T) = V_{oc}(T_r) + a(T - T_r)$	$V_{oc}(T) = V_{oc}(T_r)[1 + a_r(T - T_r)]$
$V_{mpp}(T) = V_{mpp}(T_r) + a(T - T_r)$	$V_{mpp}(T) = V_{mpp}(T_r)[1 + a_r(T - T_r)]$
$I_{sc}(T) = I_{sc}(T_r) + b(T - T_r)$	$I_{sc}(T) = I_{sc}(T_r)[1 + b_r(T - T_r)]$
$I_{mpp}(T) = I_{mpp}(T_r) + b(T - T_r)$	$I_{mpp}(T) = I_{mpp}(T_r)[1 + b_r(T - T_r)]$
$P_{mpp}(T) = P_{mpp}(T_r) + c(T - T_r)$	$P_{mpp}(T) = P_{mpp}(T_r)[1 + c_r(T - T_r)]$

Normal Operating Cell Temperature 'NOCT'



- To help system designers account for changes in cell performance with temperature, manufacturers often provide an indicator called the NOCT, which stands for Nominal Operating Cell Temperature.

- The NOCT is cell temperature in a module when ambient is 20°C, solar irradiation is 0.8 kW/m^2, and winds speed is 1m/s. To account for other ambient conditions, the following expression may be used

$$T_{cell} = T_{amb} + G\left(\frac{NOCT - 20°}{0.8}\right)$$

Where: T_{cell} is the cell temperature (◦C),
T_{amb} is the ambient temperature,
G is the solar insolation (kW/m^2).

Normal Operating Cell Temperature 'NOCT'

- **For example**

- To estimate the cell temperature, open-circuit, and maximum power output of the 150-W BP2150S module under conditions of 1-sun insolation and ambient temperature 30°C.

- The module has an NOCT of 47°C.

$$T_{cell} = 30 + 1\left(\frac{47 - 20°}{0.8}\right) = 64°C$$



- **Observation:**
  The PV module under 800W/m^2 and at 30°C will be heated to reach 64°C

Normal Operating Cell Temperature 'NOCT'

For example

$$T_{cell} = 30 + 1\left(\frac{47 - 20°}{0.8}\right) = 64°C$$



- From the datasheet, V_{OC} = 42.8 @ T_r=25°C and a=-0.0037 °C^{-1}

$$V_{oc}(T) = V_{oc}(T_r)[1 + a(T - T_r)] = 42.8(1 - 0.0037(64 - 25)) = 36.62V$$

- **Observation:**
  Due to irradiance, the temperature increases and the voltage drops from 42.8V to 36.62V (≈15% drop)

Normal Operating Cell Temperature 'NOCT'

For example

$$T_{cell} = 30 + 1\left(\frac{47 - 20°}{0.8}\right) = 64°C$$



- From the datasheet, Pmax = 150W @ T_r=25°C and c=-0.005 °C^{-1}

$$P(T) = P(T_r)[1 - c(T - T_r)] = 150(1 - 0.005(64 - 25)) = 120.75W$$

- **Observation:**
  Due to irradiance, the temperature increases and the power drops from 150W to 120.75W (≈19% drop)

- End of Part 3

Photovoltaic solar energy training course

Section 2: Solar resources

Part 4

- **Effect of Irradiance on Cell Temperature**
- **Discussion**
- **Examples**

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Effect of Irradiance on Cell Temperature



We discussed earlier the voltage, current and Power of a PV at Normal Operating Cell Temperature 'NOCT', we used the following equations:

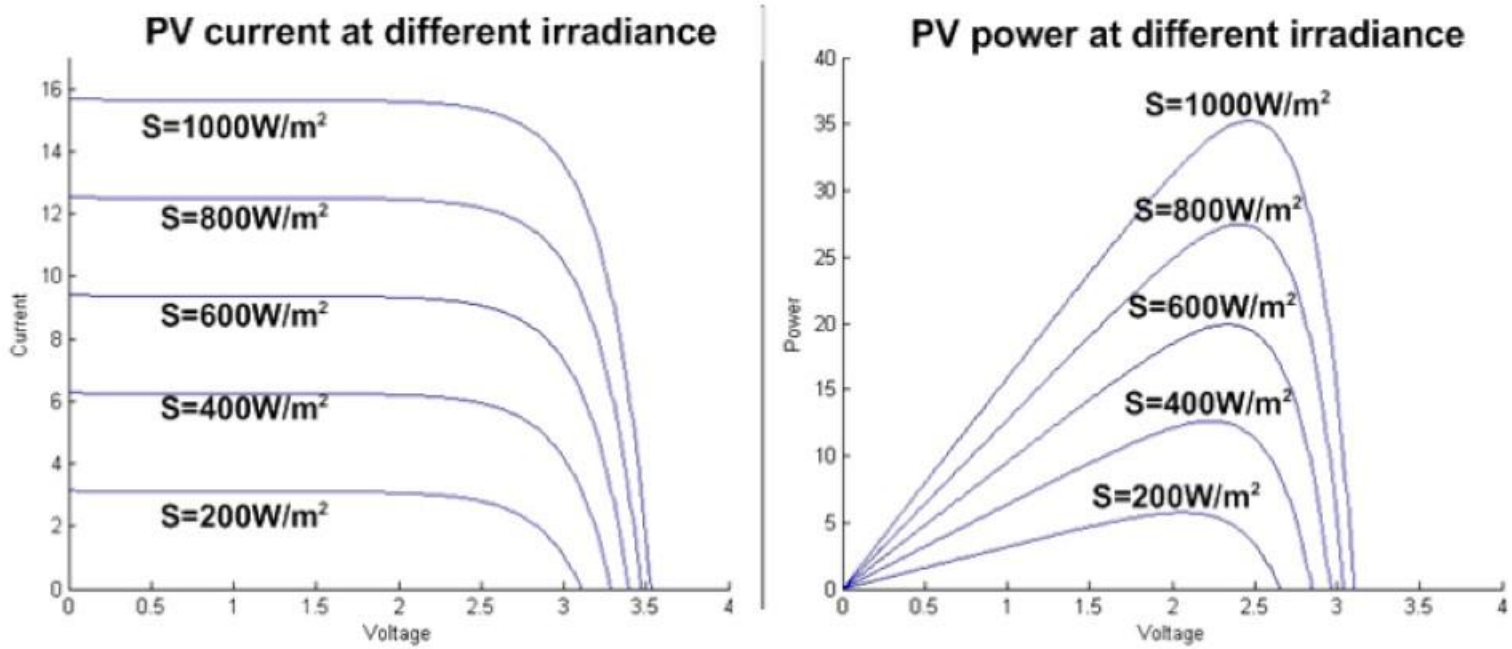
$$T_{cell} = T_{amb} + G\left(\frac{NOCT - 20°}{0.8}\right)$$

$$V_{oc}(T_{cell}) = V_{oc,STC}[1 + a_r(T_{cell} - T_r)]$$
$$I_{sc}(T_{cell}) = I_{sc,STC}[1 + b_r(T_{cell} - T_r)]$$
$$P_{mpp}(T_{cell}) = P_{mpp,STC}[1 + c_r(T_{cell} - T_r)]$$

BUT !!! $V_{oc,STC}$, $I_{sc,STC}$ and $P_{mpp,STC}$ are considered at STC (1000W/m^2) and not on any irradiance G !!!

Effect of Irradiance on Cell Temperature

- In the next step, we need, not only to correct the effect of temperature but also consider the actual value of irradiance, G, which may not be 1000W/m^2.
- From the previous slides we discussed the effect of irradiance on current, voltage and power.
- It is clear that the I_{sc} and the P_{mpp} are proportional to irradiance G (linear relationship), while V_{oc} is not



Effect of Irradiance on Cell Temperature



- So, we can say that if G is dropped by half, I_{sc}, P_{mpp} will also be dropped by half.

- We can conclude that

$$I_{sc}(G) = I_{sc,STC} \times \frac{G}{G_{STC}} = I_{sc,STC} \times \frac{G}{1000}$$

$$P_{mpp}(G) = P_{mpp,STC} \times \frac{G}{G_{STC}} = P_{mpp,STC} \times \frac{G}{1000}$$

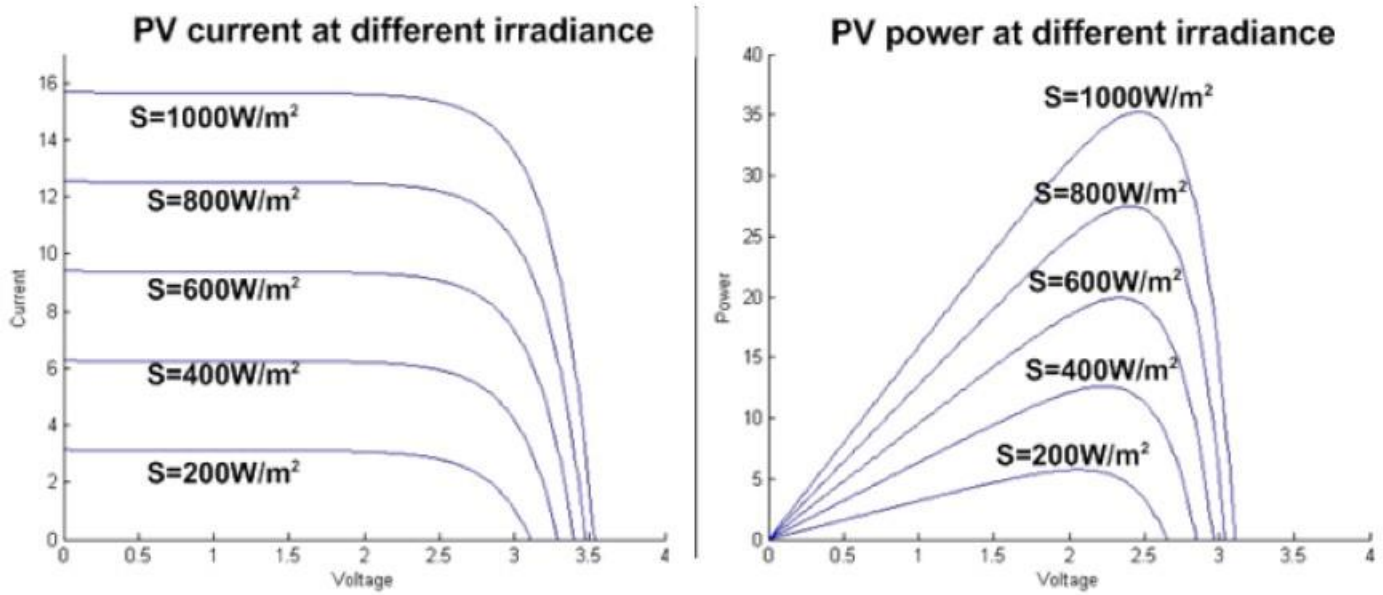
- G is the actual irradiance in W/m^2

Effect of Irradiance on Cell Temperature

- V_{oc} has different story as it is related to the LOG_e of irradiance as was given in,

$$V_{OC} \approx \frac{1}{\lambda} ln\left(\frac{I_{ph}}{I_s} + 1\right)$$

- V_{oc} depends on the I_{ph} which is same as the I_{sc} calculated previously



Effect of Irradiance on Cell Temperature



- We can than reformulate the equations as:

$$I_{sc}(T_{cell}) = I_{sc,STC} \times \frac{G}{G_{STC}}[1 + b_r(T_{cell} - T_r)]$$

$$P_{mpp}(T_{cell}) = P_{mpp,STC} \times \frac{G}{G_{STC}}[1 + c_r(T_{cell} - T_r)]$$

$$V_{oc}(T_{cell}) = \left[V_{oc,STC} + V_t\, ln\left(\frac{I_{sc}(T_{cell})}{I_s} + 1\right)\right][1 + a_r(T_{cell} - T_r)]$$

Conclusion and Discussion

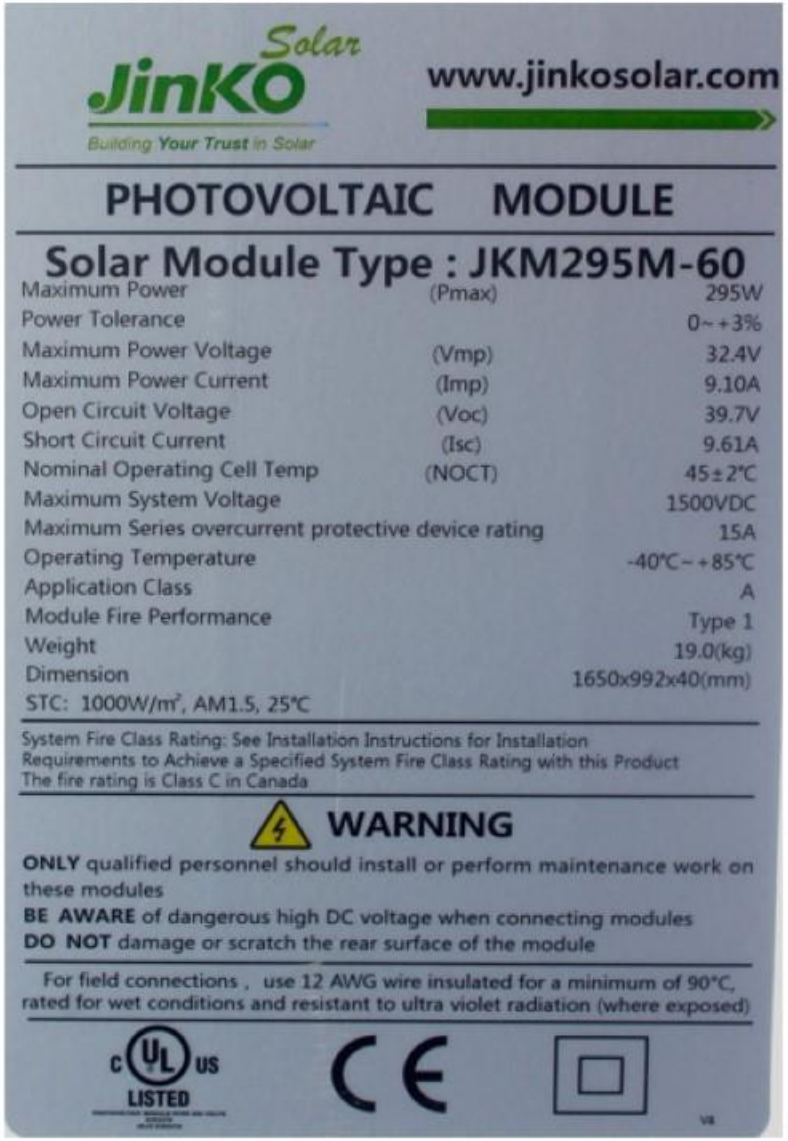
- **Discussion: Why do we need all these equation and why are they useful ?!**

- These equation are required for PV plant design in order to know what are the required components to be connected to the PV panels, such as the DC/DC converters, the DC/AC inverters, the maximum power point trackers, and/or the battery charge controller.
- The designer should consider the climatic variation in the location and make sure of the range of voltage, current and power and respect the attached converters specifications

General Example

- Consider a PV array with the labeled specification.
- assume
  - a:-0.34%C-1 , b:0.037%C-1 , c:--0.48%C-1
  - Isat = 10^{-10}
  - Vt = 0.025V

- Q1: Calculate the V_{oc}, I_{sc} and P_{mpp} at ambient temperature of 35 °C at 1-sun
- Q2: Calculate the V_{oc}, I_{sc} and P_{mpp} at ambient temperature of 35 °C at 0.6-sun
- Q3: 1: Calculate the V_{oc}, I_{sc} and P_{mpp} at ambient temperature of -10°C at 1-sun


JinKO Solar
Building Your Trust in Solar
www.jinkosolar.com

PHOTOVOLTAIC MODULE

Solar Module Type : JKM295M-60

Maximum Power	(Pmax)	295W
Power Tolerance		0~+3%
Maximum Power Voltage	(Vmp)	32.4V
Maximum Power Current	(Imp)	9.10A
Open Circuit Voltage	(Voc)	39.7V
Short Circuit Current	(Isc)	9.61A
Nominal Operating Cell Temp	(NOCT)	45±2℃
Maximum System Voltage		1500VDC
Maximum Series overcurrent protective device rating		15A
Operating Temperature		-40℃~+85℃
Application Class		A
Module Fire Performance		Type 1
Weight		19.0(kg)
Dimension		1650x992x40(mm)
STC: 1000W/m², AM1.5, 25℃		

System Fire Class Rating: See Installation Instructions for Installation Requirements to Achieve a Specified System Fire Class Rating with this Product The fire rating is Class C in Canada

WARNING

ONLY qualified personnel should install or perform maintenance work on these modules

BE AWARE of dangerous high DC voltage when connecting modules

DO NOT damage or scratch the rear surface of the module

For field connections , use 12 AWG wire insulated for a minimum of 90°C, rated for wet conditions and resistant to ultra violet radiation (where exposed)

c UL us LISTED

CE

General Example

- Solution of Q1: Calculate the V_{oc}, I_{sc} and P_{mpp} at ambient temperature of 35 °C at 1-sun

- $T_{cell} = T_{amb} + G\left(\frac{NOCT-20°}{0.8}\right) = 35 + \frac{1kw\times(45-20)}{0.8} = 66.25°C$

- $I_{sc}(T_{cell}) = I_{sc,STC} \times \frac{G}{G_{STC}}[1 + b_r(T_{cell} - T_r)] = 9.61 \times \frac{1000}{1000} \times [1 + 0.00037(66.25 - 25)] = 9.75A$
- $P_{mpp}(T_{cell}) = P_{mpp,STC} \times \frac{G}{G_{STC}}[1 + c_r(T_{cell} - T_r)] = 295 \times \frac{1000}{1000} \times [1 - 0.0048(66.25 - 25)] = 236.5W$

- $V_{oc}(T_{cell}) = \left[V_{oc,STC} + V_t\, ln\left(\frac{I_{sc}(T_{cell})}{I_s} + 1\right)\right][1 + a_r(T_{cell} - T_r)] = \left[39.7 + 0.025\ln(\frac{9.75}{10^{-10}})\right] \times [1 - 0.0034(66.25 - 25)] = 34.65V$

- **Analysis**: @1sun,
  - Cell temperature raises from 35 to 66.25 (31.25°C raise)
  - I_{SC} raises from 9.61 to 9.75A (0.14A raise)
  - V_{OC} drops from 39.7 to 34.65V (5V drop)
  - P_{mpp} drops from 295 to 236.5W (58.5W drop)

General Example

- Solution of Q2: Calculate the V_{oc}, I_{sc} and P_{mpp} at ambient temperature of 35 °C at 0.6-sun

- $T_{cell} = T_{amb} + G\left(\frac{NOCT-20°}{0.8}\right) = 35 + \frac{0.6\times(45-20)}{0.8} = 53.75°C$

- $I_{sc}(T_{cell}) = I_{sc,STC} \times \frac{G}{G_{STC}}[1 + b_r(T_{cell} - T_r)] = 9.61 \times \frac{600}{1000} \times [1 + 0.00037(53.75 - 25)] = 5.827A$
- $P_{mpp}(T_{cell}) = P_{mpp,STC} \times \frac{G}{G_{STC}}[1 + c_r(T_{cell} - T_r)] = 295 \times \frac{1000}{1000} \times [1 - 0.0048(53.75 - 25)] = 152.5W$

- $V_{oc}(T_{cell}) = \left[V_{oc,STC} + V_t\, ln\left(\frac{I_{sc}(T_{cell})}{I_s} + 1\right)\right][1 + a_r(T_{cell} - T_r)] = \left[39.7 + 0.025\ln(\frac{9.75}{10^{-10}})\right] \times [1 - 0.0034(53.75 - 25)] = 36.35V$

- **Analysis**: @0.6sun,
  - Cell temperature raises from 35 to 53.75 (23.75°C raise)
  - I_{SC} = 5.8A
  - V_{OC} = 36.35 V (better voltage due to tiny temperature increase compared to Q1)
  - P_{mpp} = 152.5W

General Example

- Solution of Q3: Calculate the V_{oc}, I_{sc} and P_{mpp} at ambient temperature of -10 °C at 1-sun

- $T_{cell} = T_{amb} + G\left(\frac{NOCT-20°}{0.8}\right) = -5 + \frac{1kw\times(45-20)}{0.8} = 21.25°C$

- $I_{sc}(T_{cell}) = I_{sc,STC} \times \frac{G}{G_{STC}}[1 + b_r(T_{cell} - T_r)] = 9.61 \times \frac{1000}{1000} \times [1 + 0.00037(21.25 - 25)] = 9.6A$
- $P_{mpp}(T_{cell}) = P_{mpp,STC} \times \frac{G}{G_{STC}}[1 + c_r(T_{cell} - T_r)] = 295 \times \frac{1000}{1000} \times [1 - 0.0048(21.25 - 25)] = 300.3W$

- $V_{oc}(T_{cell}) = \left[V_{oc,STC} + V_t\, ln\left(\frac{I_{sc}(T_{cell})}{I_s} + 1\right)\right][1 + a_r(T_{cell} - T_r)] = \left[39.7 + 0.025\ln(\frac{9.75}{10^{-10}})\right] \times [1 - 0.0034(21.25 - 25)] = 40.8V$

- **Analysis**: @1sun,
  - Cell temperature raises from -10 to 21.25 (Still below 25)
  - I_{SC} almost same
  - V_{OC} raises to 40.8Volt (Should be considered in system design)
  - P_{mpp} raises to 300W

```
%% PV parameters at different
T and G
Vmp_stc = 32.4;
Imp_stc = 9.1;
Voc_stc = 39.7;
Isc_stc = 9.61;
Pmax_stc = 295;
a = -0.34;
b = 0.037;
c= -0.48;
NOCT = 45;
N_cells = 60;
Isat = 10e-10;
Vt = 0.025;
G_stc = 1000;
T_stc = 25;
```

```
% PV at new T and new G
Tamb = -10;
G = 1000;
FF_stc = Pmax_stc/(Voc_stc * Isc_stc)

% Step1: find T of the cell , Tc
Tc = Tamb + (G/1000) * (NOCT-20)/0.8

% Isc
Isc = Isc_stc *
(G/G_stc)*(1+(b/100)*(Tc-T_stc))

% Voc
Voc = (Voc_stc + Vt*
(log(Isc/Isat)+1)) * (1+(a/100)*(Tc-
T_stc))

% Pmax
Pmax = Pmax_stc *
(G/G_stc)*(1+(c/100)*(Tc-T_stc))
FF = (Pmax)/(Voc * Isc)
```

References

- https://en.wikipedia.org/wiki/Solar_cell
- http://www.comorinsolar.com/blog-details.php?id=95
- https://www.alternative-energy-tutorials.com/photovoltaics/photovoltaics.html

End of Session 2

Photovoltaic Solar Energy Training Course

Section 3: Power Tracking and Shading Analysis

Part 1

- Mechanical Trackers
- Global Irradiance Calculation
- Irradiance Measurement Instruments
- Mechanical Tracking Techniques
- Electronic Trackers

Part 2

- Maximum Power Point Tracker 'MPPT'
- MPPT Mathematical Modeling
- How Real MPPT works
- Different MPPT Techniques
- Perturb & Observe 'P&O' Technique

Part 3

- DC/DC Converter for MPPT
- Duty Cycle Calculation
- Serial and Parallel PV Panel connection
- Blocking Diode

Part 4

- Physics of PV Cells Shading
- Effect of Shaded Cells
- Bypass Diodes for Shade Mitigation
- Bypass Diodes for Shade Mitigation for Module in Series
- Blocking and Bypass Diodes for Series and Parallel panels

Nabil Karami, PhD

Photovoltaic solar energy training course

Section 3: Power Tracking and Shading Analysis

Part 1

- Mechanical Trackers
- Global Irradiance Calculation
- Irradiance Measurement Instruments
- Mechanical Tracking Techniques
- Electronic Trackers

PV Sun-Power Tracker



- In fact, two different techniques can be used to increase the collection of power from Sun
  1. Mechanical systems (manual or automatically adjusted)
  2. Electronic systems, also called Maximum Power Point Trackers

- PV system can have both to catch as much power from the sun

PV Mechanical Tracker

PV panels can be implemented on:

- Fixed-tilt structure
- Manual adjustable tilt structure (season by season)
- Single axis tracking structure
  - Horizontal axis
  - Inclined axis
  - Vertical axis
- Two or Dual Axis Tracking structure

PV Fixed-tilt Structure

- Due to some mechanical restrictions, PV arrays are implemented on a fixed-tilt structure.
- The best angle to choose is the Latitude angle of the point of implementation.





PV adjustable-tilt Structures



Summer sun

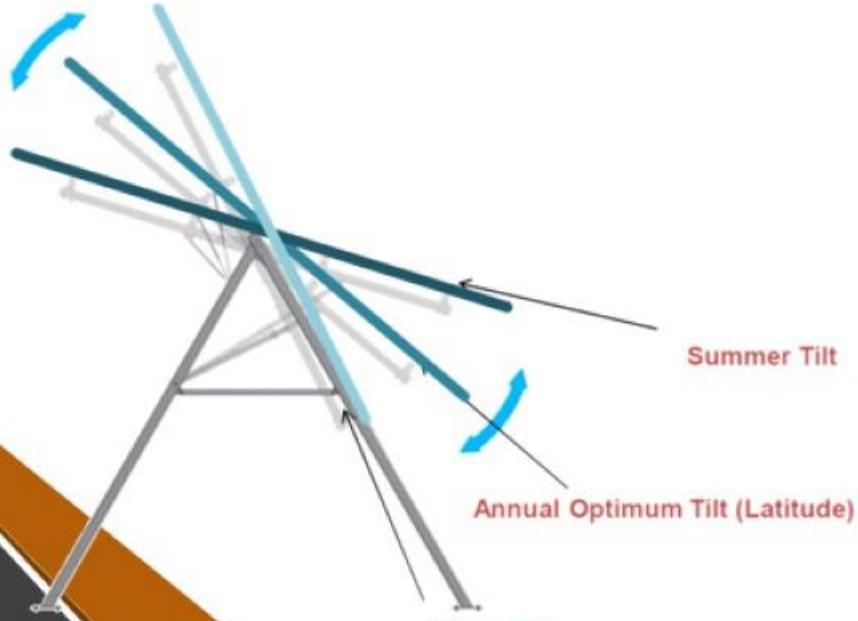


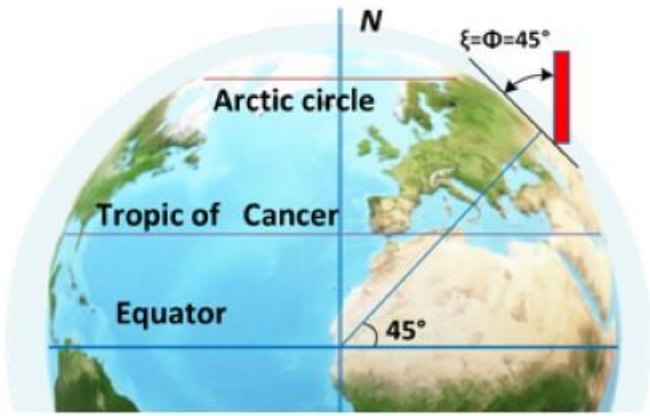
Equinox sun

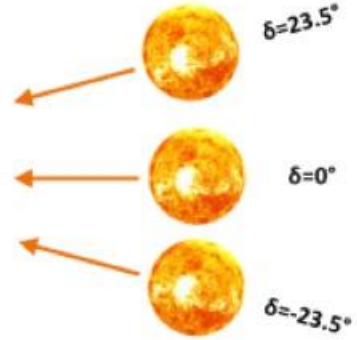


Winter sun

- Some structure allows adjusting the tilt angle
- User may manually adjust the angle every season



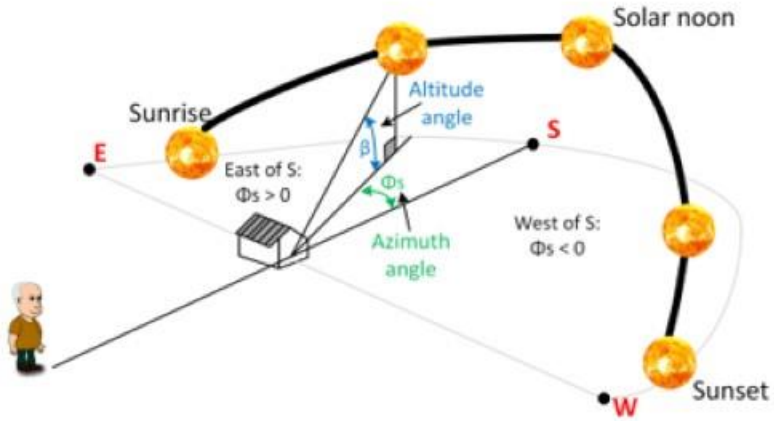




PV Axis Tracking Structures

To improve efficiency of solar energy capture, solar trackers are used to allow the collector to track the movement of the sun across the sky are quite cost effective

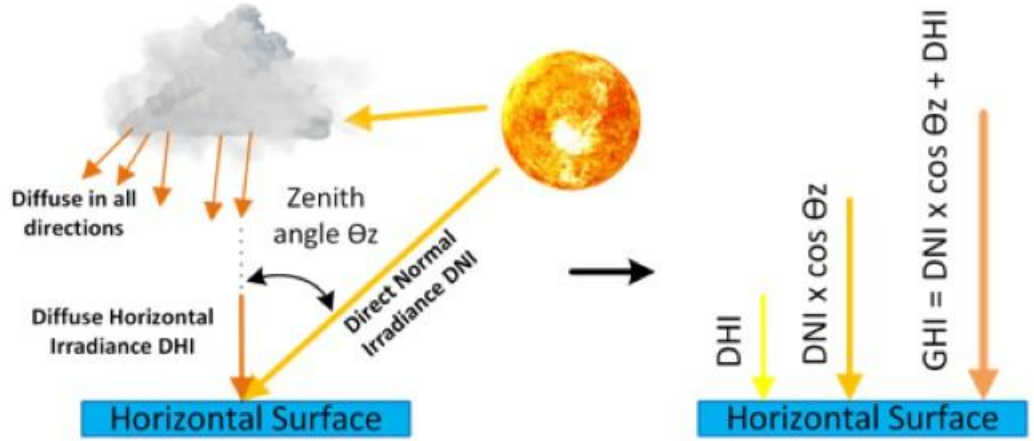
- A solar panel in a fixed orientation between the dawn and sunset extremes will see a motion of 75 degrees to either side
- thus, will lose over 75% of the energy in the morning and evening.
- Rotating the panels to the east and west can help recapture those losses.
- A tracker that only attempts to compensate for the east-west movement of the Sun is known as a single-axis tracker.

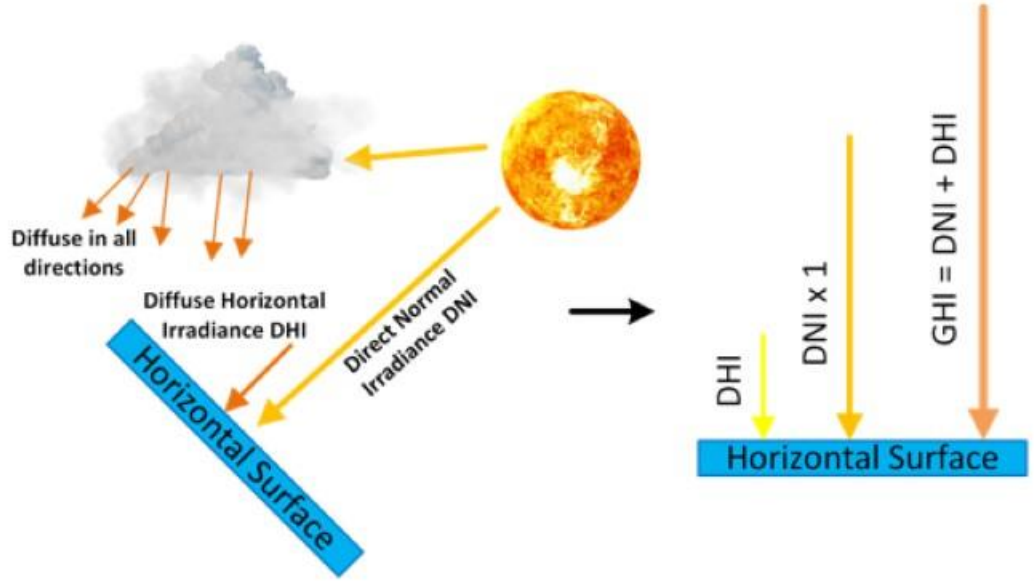




Global Irradiance Calculation

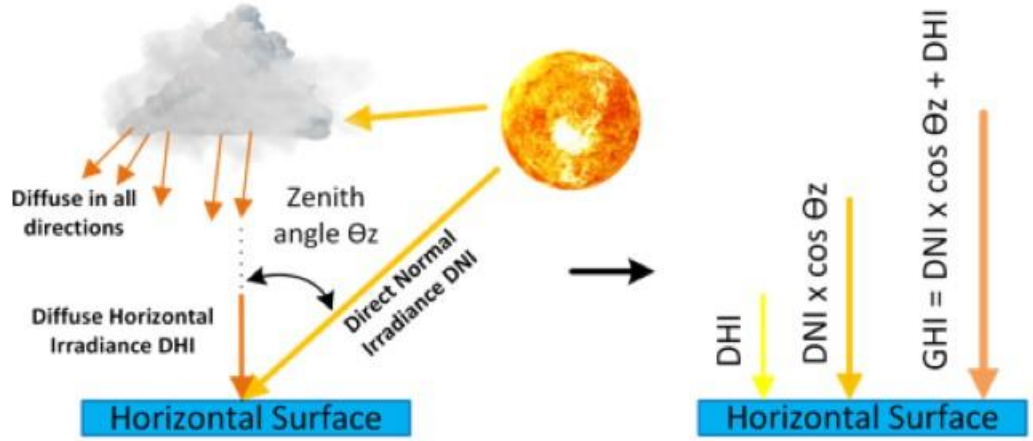
- As mentioned in Section1, Sun light can be direct or diffuse.
- In tracking systems we are interested to collect the maximum direct irradiance.
- Irradiances are:
  1. Direct Normal Irradiance (DNI)
  2. Diffuse Horizontal Irradiance (DHI)



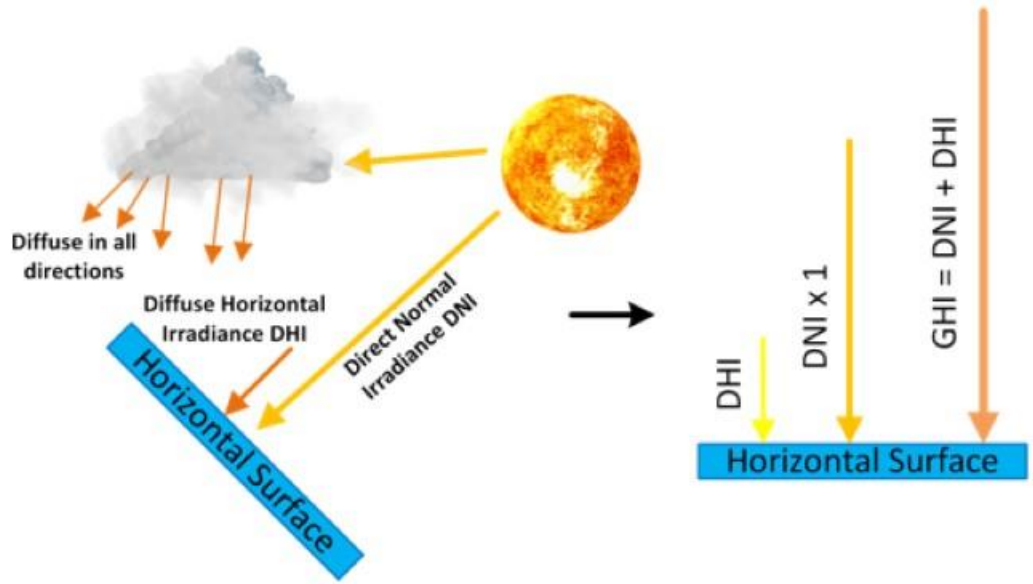


Global Irradiance Calculation

- Global Horizontal Irradiance (GHI) is the total amount of shortwave radiation received from above by a surface horizontal to the ground.

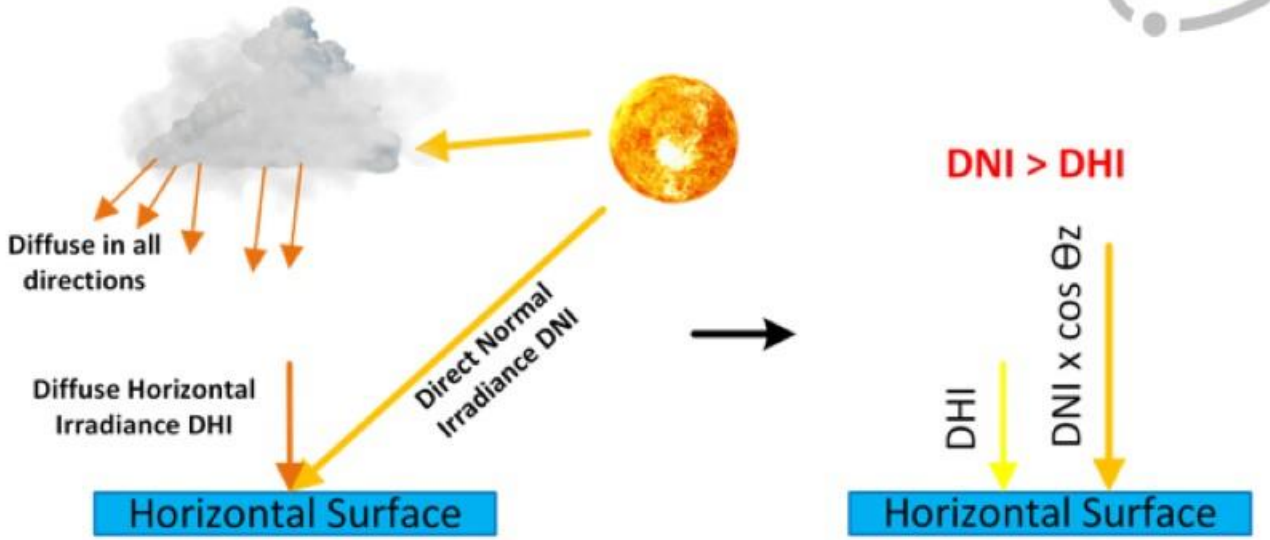


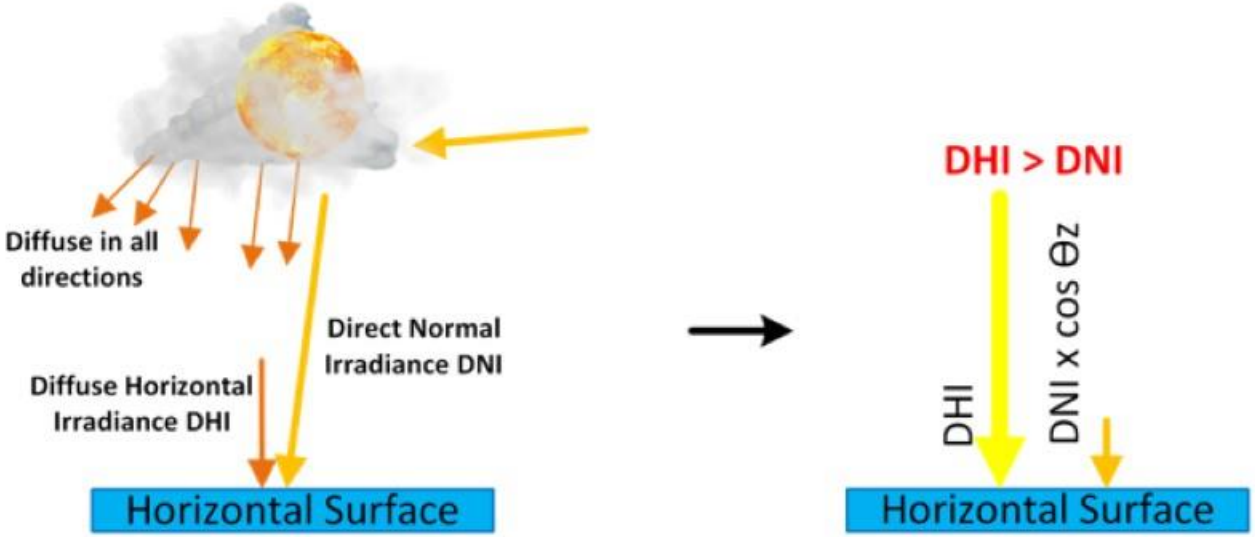
Global Horizontal (GHI) = Direct Normal (DNI) X cos(θz) + Diffuse Horizontal (DHI)



Which Irradiance is Higher !?

- Sometimes it is not required to tilt panel as the diffuse irradiance and higher than direct beam irradiance
- On sunny days,
  Direct > diffuse
- On cloudy days,
  Diffuse > Direct





Irradiance Measurement Instruments

GHI
Measured by a *Pyranometer* with a horizontal sensor

DNI
Measured by a *Pyrheliometer* on a sun-following Tracker

DHI
Measured by a *Shaded-head Pyranometer* under a tracking ball or an adjustable ring







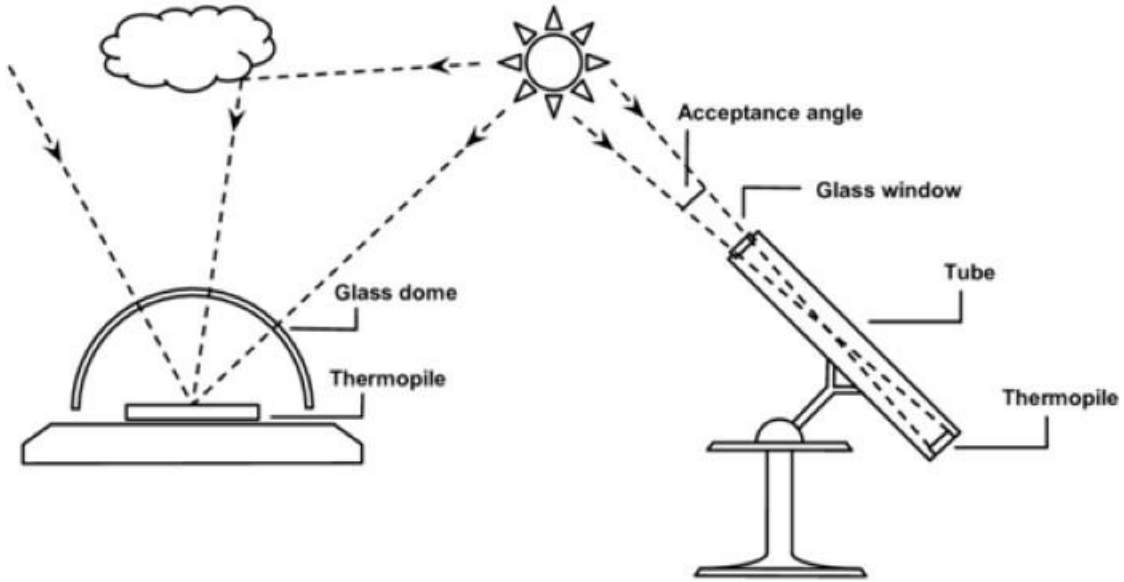
Global Horizontal (GHI) = Direct Normal (DNI) X cos(θz) + Diffuse Horizontal (DHI)

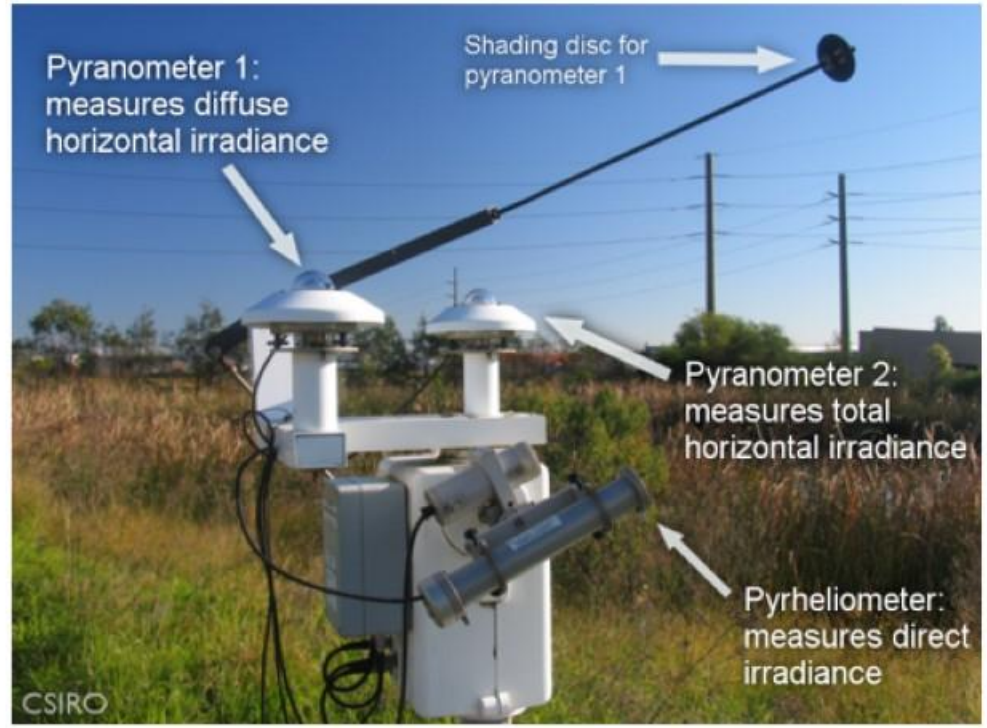
Irradiance Measurement Instruments

GHI
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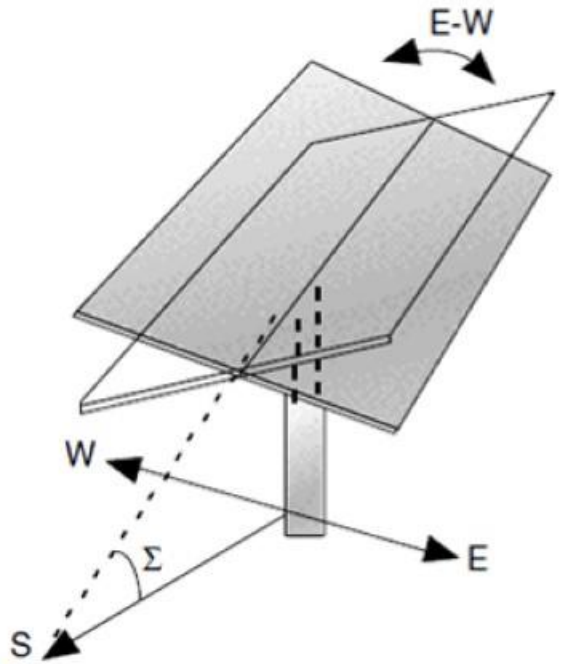


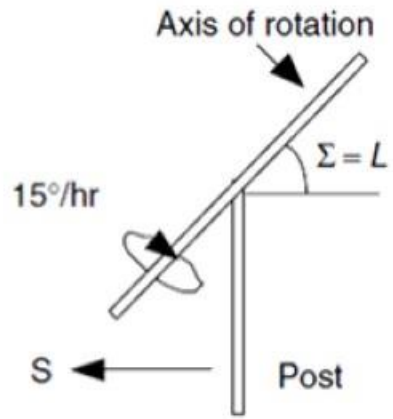


Global Horizontal (GHI) = Direct Normal (DNI) X cos(θz) + Diffuse Horizontal (DHI)

Single-Axis Tracker

Single-axis tracking for photovoltaics is almost always done with a mount having a manually adjustable tilt angle along a north-south axis, and a tracking mechanism that rotates the collector array from east-to-west.



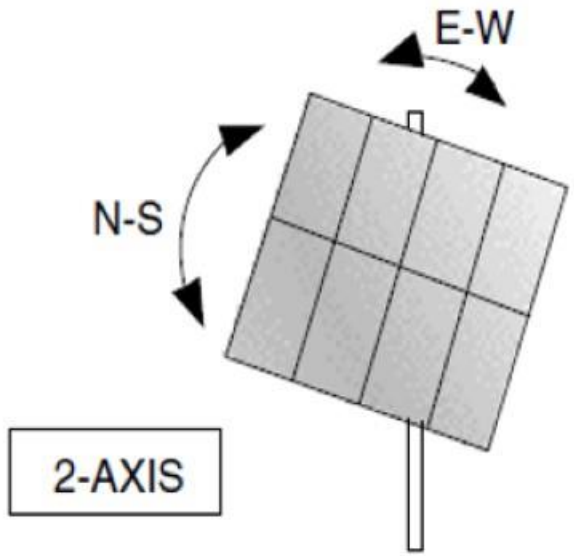


Polar mount



Dual-Axis Tracker

Dual-axis tracking for photovoltaics rotates the collector array from east-to-west and from North to South.



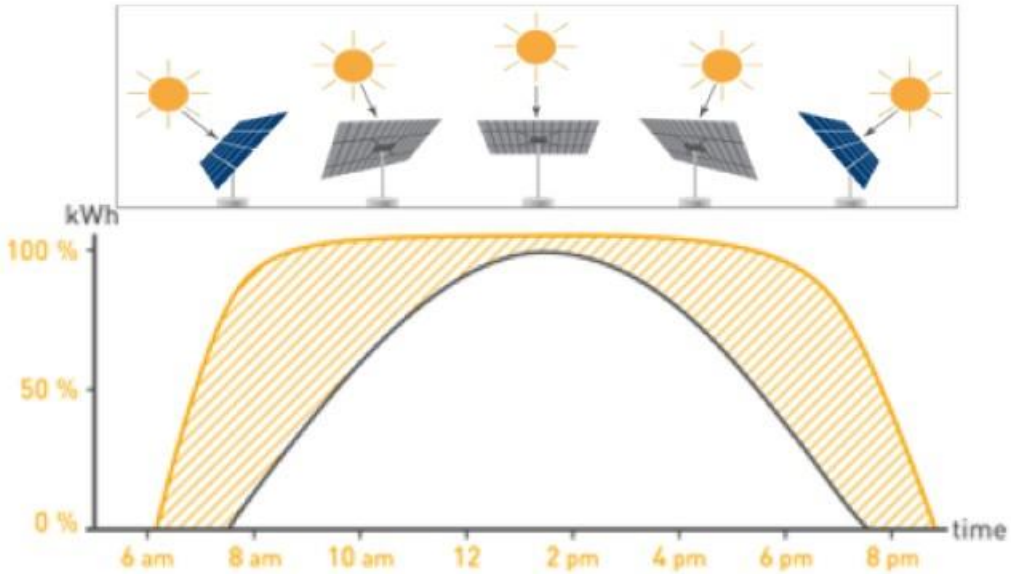


Tracking Effects

- Tracking the sun will increase the collected sun's energy during the day and
- make it uniformly distributed







Mechanical Tracking techniques



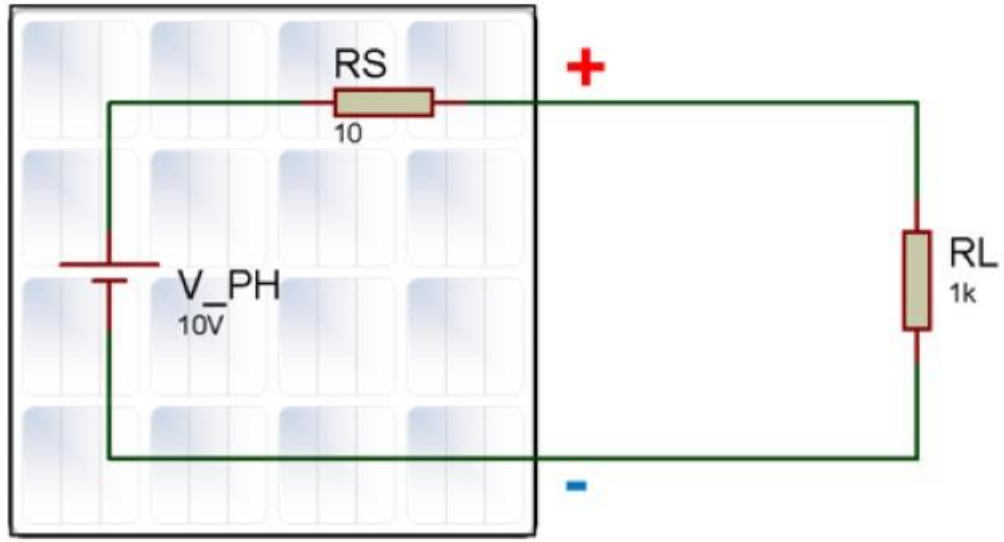
- To track the location of the sun in space, many methods are available, they differ by their controller circuit complexity and accuracy

1. Tracker using light sensors: This technique is based on finding the maximum direct light intensity and move the motors to the best position. This technique is for small size PV and are not accurate as sometimes the diffuse irradiance is dominating the direct one

2. Scheduled tracker: This method is based on a preprogrammed/calculated positions of the sun based on the PV Latitude position and time. This method is very accurate and move the motors every hour for 15 degrees.

Electronic Tracker

- We will assume that the PV circuit model is a battery with a series resistor
- The PV is connected to a load resistor, RL
- The question is: What is the value of RL in order have a maximum power transferred from the source to the load !?!

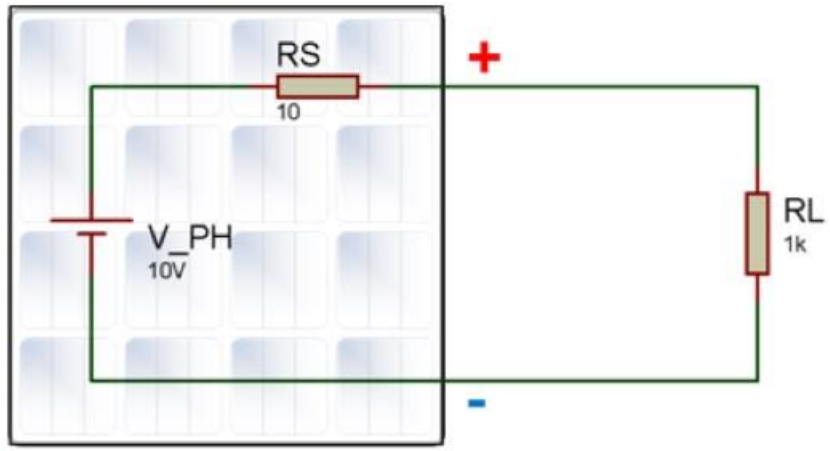


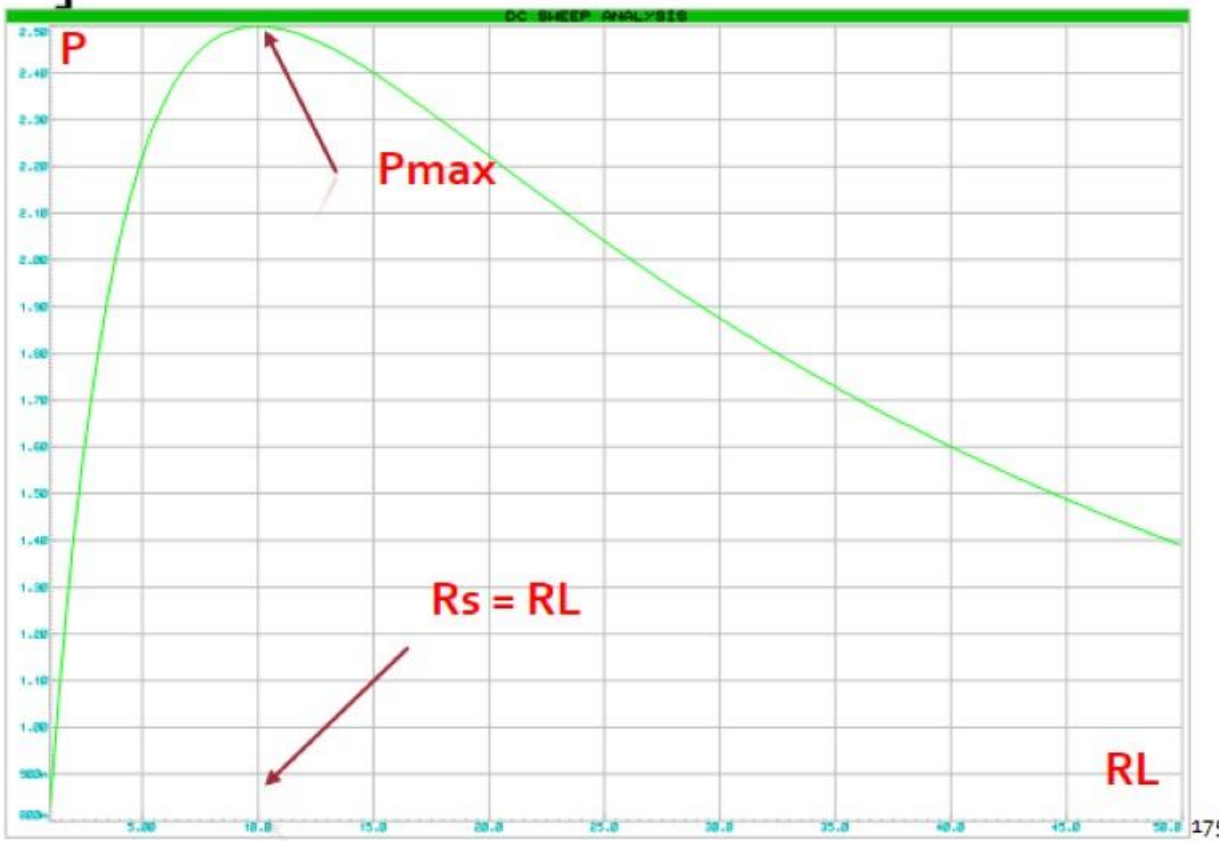
Electronic Tracker

$$I_L = \frac{V_{PH}}{R_S + R_L} \qquad P_L = I_L^2 \times R_L = \left(\frac{V_{PH}}{R_S + R_L}\right)^2 \times R_L$$

$$\frac{dP_L}{dR_L} = V_{PH}^2 \left[\frac{(R_S + R_L)^2 - 2R_L(R_S + R_L)}{(R_S + R_L)^4}\right] = 0 \Rightarrow R_S + R_L - 2R_L = 0 \Rightarrow R_S = R_L$$

$$P_{max} = \frac{V_{PH}^2}{4R_L}$$





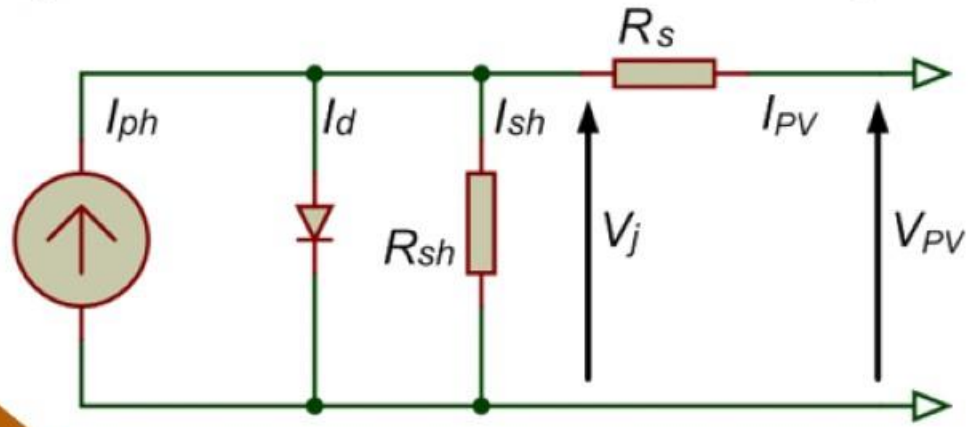
Electronic Tracker

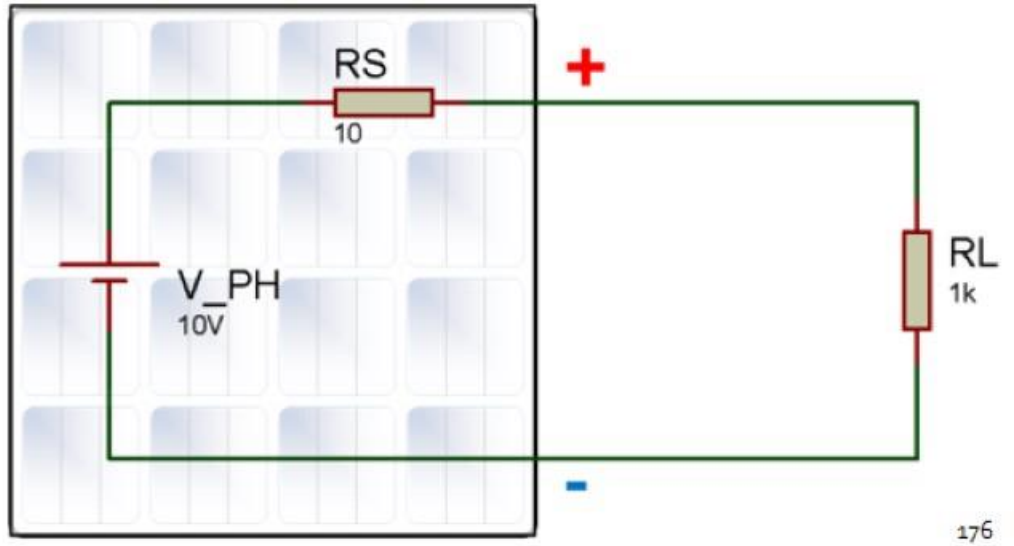
Conclusion: In order to get the maximum power from the source, we have to match the load with the internal resistor of the source.

BUT! Our load has fixed value (how to tune it to match RS ?)

Also, are R_S and I_{ph} fix !?!

The answer is no: Some PV parameters depend on irradiance and temperature and are variable during the day





- End of part 1

Photovoltaic solar energy training course

Section 3: Power Tracking and Shading Analysis

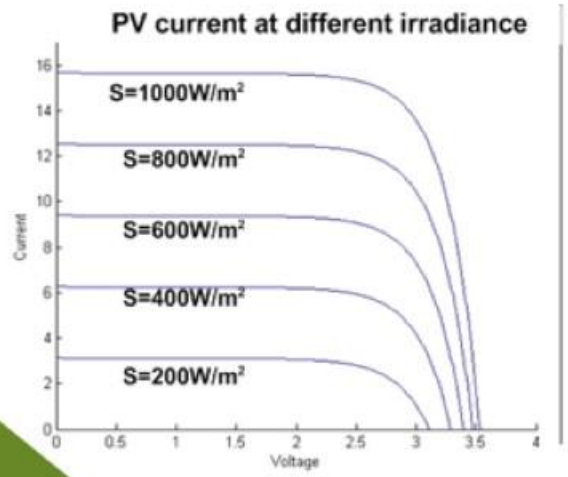
Part 2

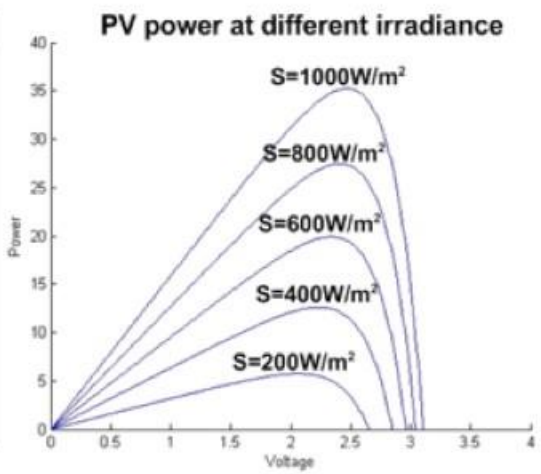
- Maximum Power Point Tracker ‘MPPT’
- MPPT Mathematical Modeling
- How Real MPPT works
- Different MPPT Techniques
- Perturb & Observe ‘P&O’ Technique

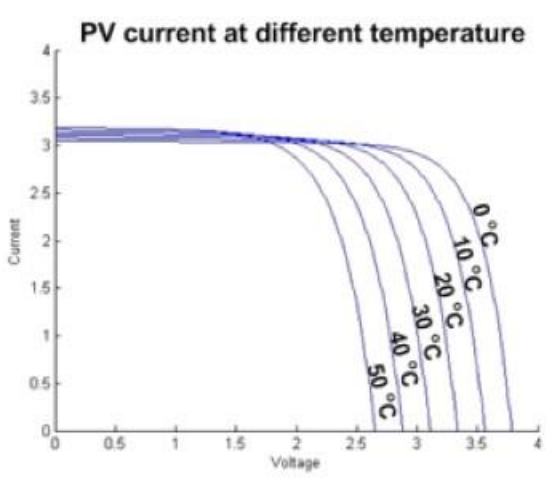
Nabil Karami, PhD

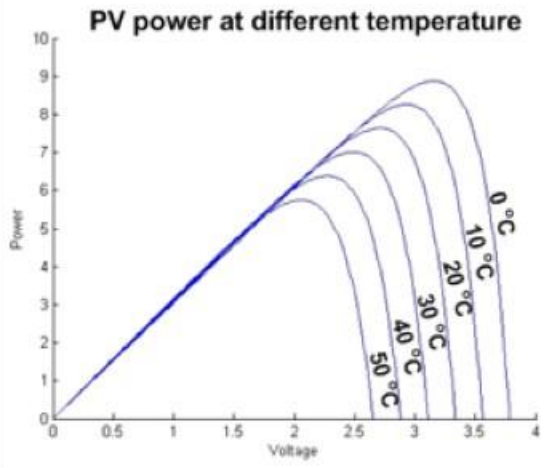
Maximum Power Point Tracker 'MPPT'

- The temperature and the irradiation depend on the atmospheric conditions, which are not constant during the year and not even during a single day;
- They can vary rapidly due to fast changing conditions such as clouds.
- This causes the MPP to move constantly, depending on the irradiation and temperature conditions.
- If the operating point is not close to the MPP, great power drop occur



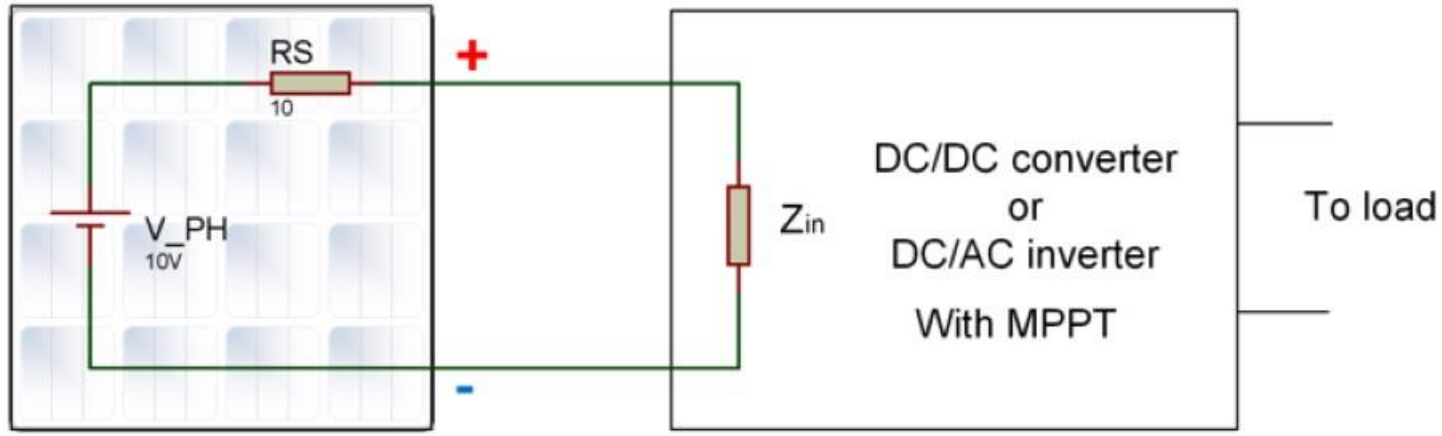






Maximum Power Point Tracker 'MPPT'

- In a modern solar power converter, this task is assigned to the MPPT algorithms.
- Converter can be a DC/DC converter or a DC/AC inverter
- MPPT is simply an **algorithm** to control the converter to change its **input impedance Zin** to match the **internal resistance** of the PV



MPPT Mathematical Modeling



- When examining the typical PV polarization and power curves a point of maximum power is observed.
- This point depends mainly on irradiance and temperature.
- The location of the MPP is unknown, but can be reached, either through calculation models or by search algorithms.
- The curves expressing the behavior of PV power can be written as:

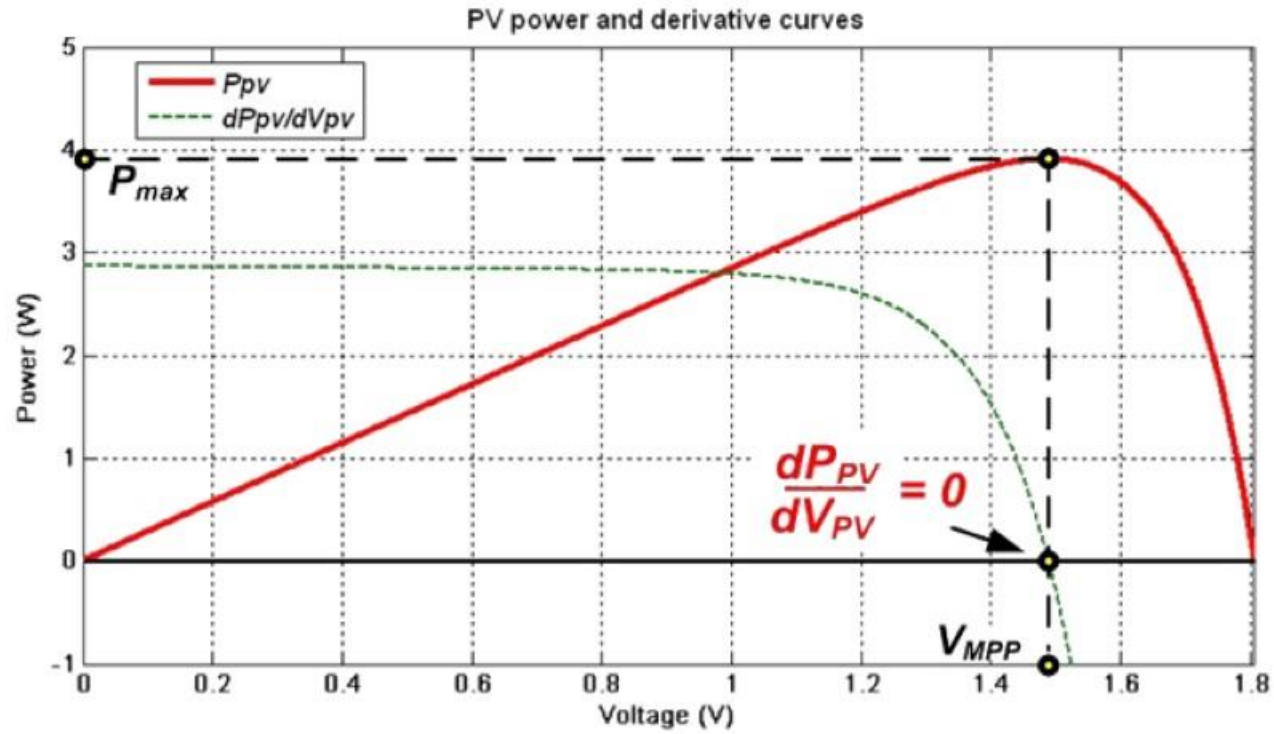
$$P_{PV}(t) = F\left(V_{PV}(t), I_{PV}(t), \gamma(t)\right)$$

where γ denotes all the variables other than the current and the voltage and hence defines the power curve at time t. It depends on the PV parameters and on climatological variables.

MPPT Mathematical Modeling

- MPP tracking is the technique that adjusts the output voltage of the PV in order to extract the maximum available power at any change in input (temperature, irradiance). The MPPT is based on the fact that the derivative of the output power with respect to the output voltage is zero at the MPP, positive on the left of the MPP and negative on the right of the MPP

$$\begin{cases} \dfrac{dP_{PV}}{dV_{PV}} = 0 \quad when \quad V_{PV} = V_{MPP} \\ \dfrac{dP_{PV}}{dV_{PV}} > 0 \quad when \quad V_{PV} < V_{MPP} \\ \dfrac{dP_{PV}}{dV_{PV}} < 0 \quad when \quad V_{PV} > V_{MPP} \end{cases}$$



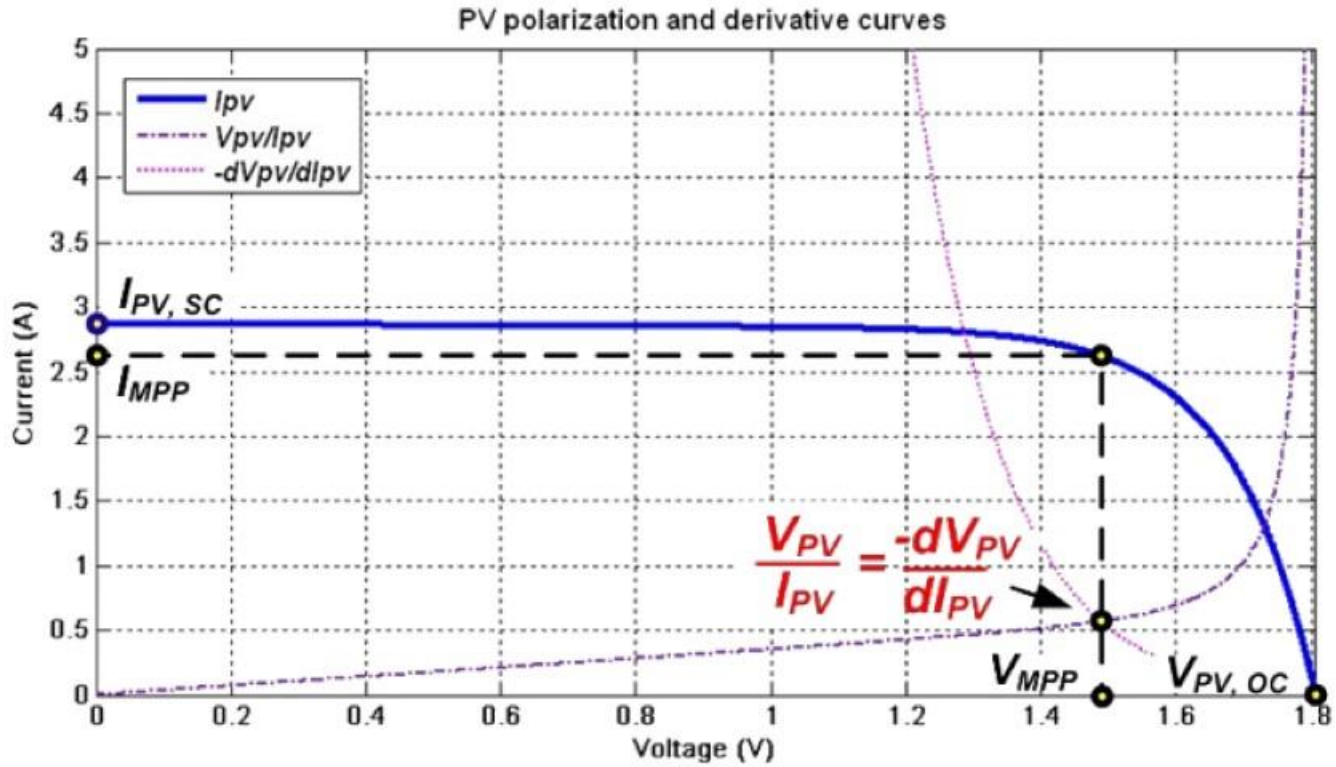
MPPT Mathematical Modeling

- Derivating the output power with respect to the output voltage:

$$\frac{dP_{PV}}{dV_{PV}} = \frac{d(V_{PV} I_{PV})}{dV_{PV}} = I_{PV} + V_{PV} \frac{dI_{PV}}{dV_{PV}}$$

- At MPP, the derivative of power with respect to voltage is zero, therefore:

$$\frac{dP_{PV}}{dV_{PV}} = 0 \Rightarrow \frac{V_{PV}}{I_{PV}} = -\frac{dV_{PV}}{dI_{PV}}$$



MPPT Mathematical Modeling

- The error between the instantaneous and the derivate values is expressed as:

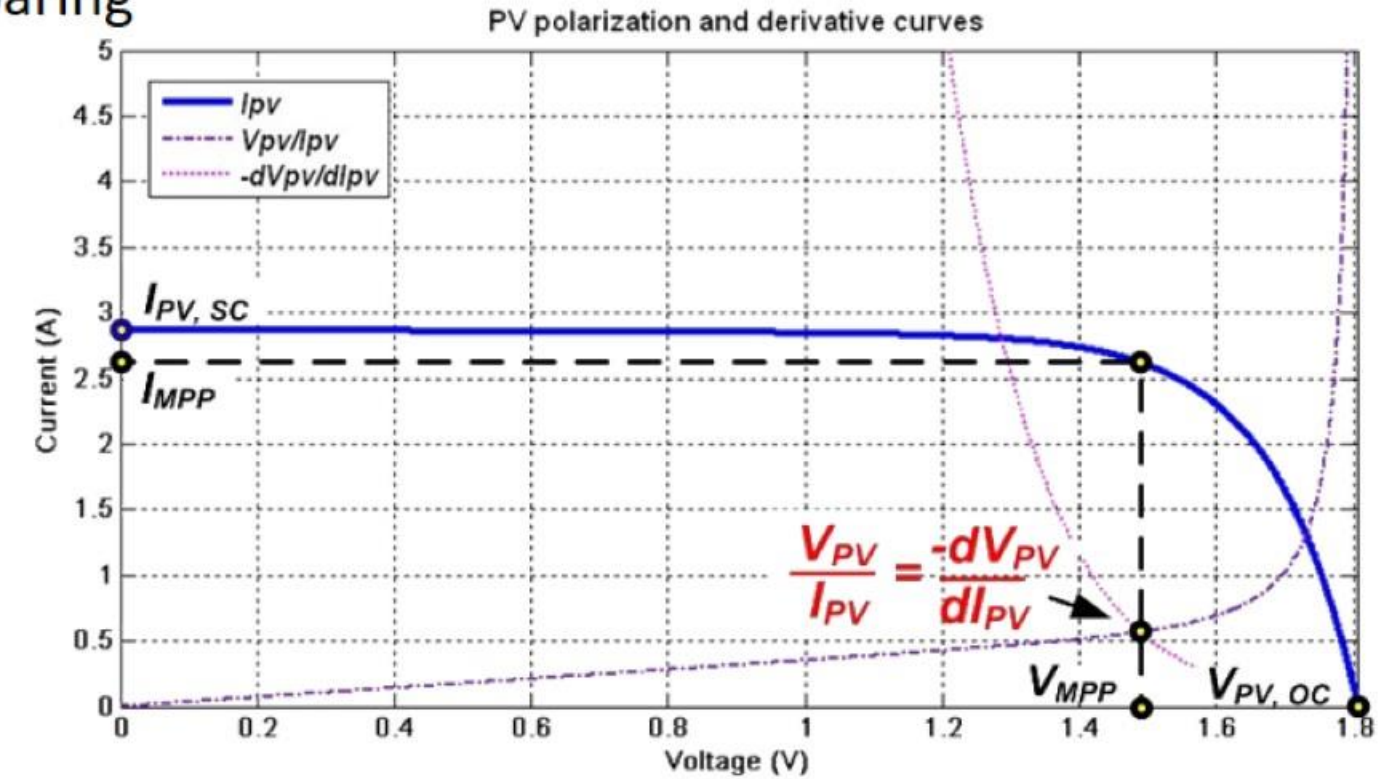
$$\varepsilon = \frac{V_{PV}}{I_{PV}} + \frac{dV_{PV}}{dI_{PV}}$$

- MPP can be tracked by comparing $\frac{V_{PV}}{I_{PV}}$ to $\frac{dV_{PV}}{dI_{PV}}$ as follows

$$\varepsilon = 0 \leftrightarrow \frac{V_{PV}}{I_{PV}} = -\frac{dV_{PV}}{dI_{PV}} \quad at\ MPP$$

$$\varepsilon > 0 \leftrightarrow \frac{V_{PV}}{I_{PV}} > -\frac{dV_{PV}}{dI_{PV}} \quad right\ of\ MPP$$

$$\varepsilon < 0 \leftrightarrow \frac{V_{PV}}{I_{PV}} < -\frac{dV_{PV}}{dI_{PV}} \quad left\ of\ MPP$$



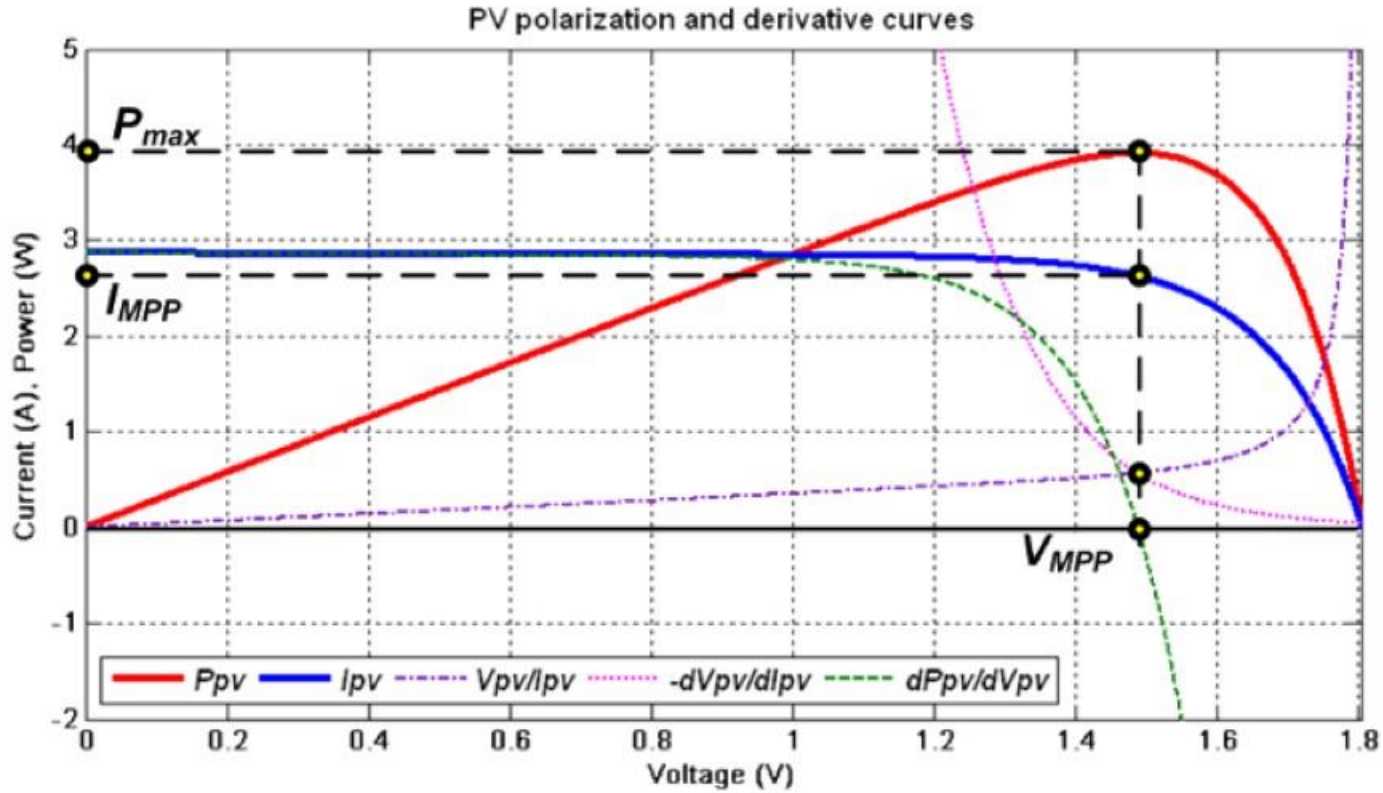
MPPT Mathematical Modeling

$$\begin{cases} \dfrac{dP_{PV}}{dV_{PV}} = 0 & when \quad V_{PV} = V_{MPP} \\ \dfrac{dP_{PV}}{dV_{PV}} > 0 & when \quad V_{PV} < V_{MPP} \\ \dfrac{dP_{PV}}{dV_{PV}} < 0 & when \quad V_{PV} > V_{MPP} \end{cases}$$

$$\varepsilon = 0 \leftrightarrow \frac{V_{PV}}{I_{PV}} = -\frac{dV_{PV}}{dI_{PV}} \quad at\ MPP$$

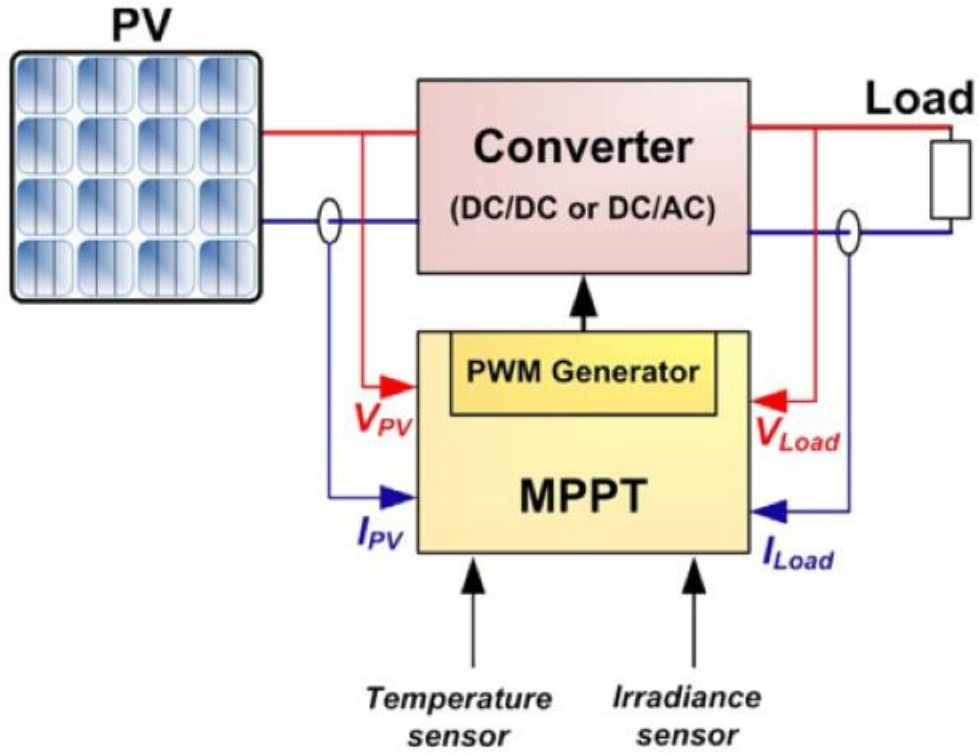
$$\varepsilon > 0 \leftrightarrow \frac{V_{PV}}{I_{PV}} > -\frac{dV_{PV}}{dI_{PV}} \quad right\ of\ MPP$$

$$\varepsilon < 0 \leftrightarrow \frac{V_{PV}}{I_{PV}} < -\frac{dV_{PV}}{dI_{PV}} \quad left\ of\ MPP$$



How MPPT works

- Since the beginning of photovoltaics being used as stand-alone and grid-connected systems, researchers have tried to develop strategies to “squeeze” the PV panel to absorb the maximum power.
- To date, a big number of MPPT algorithm and designs are available in the literature. Each method has its own specifications, limitations and applications.

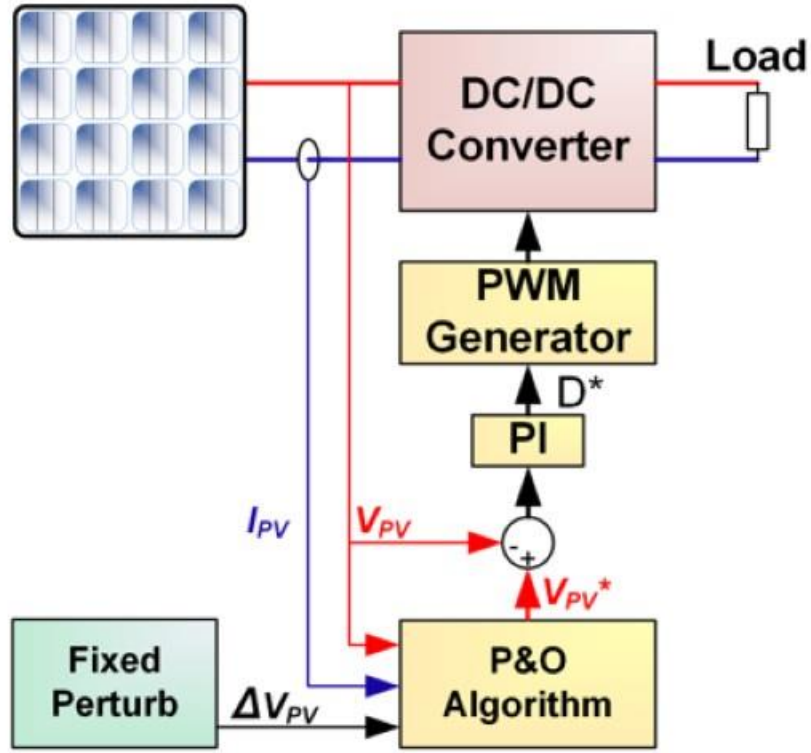


MPPT Techniques

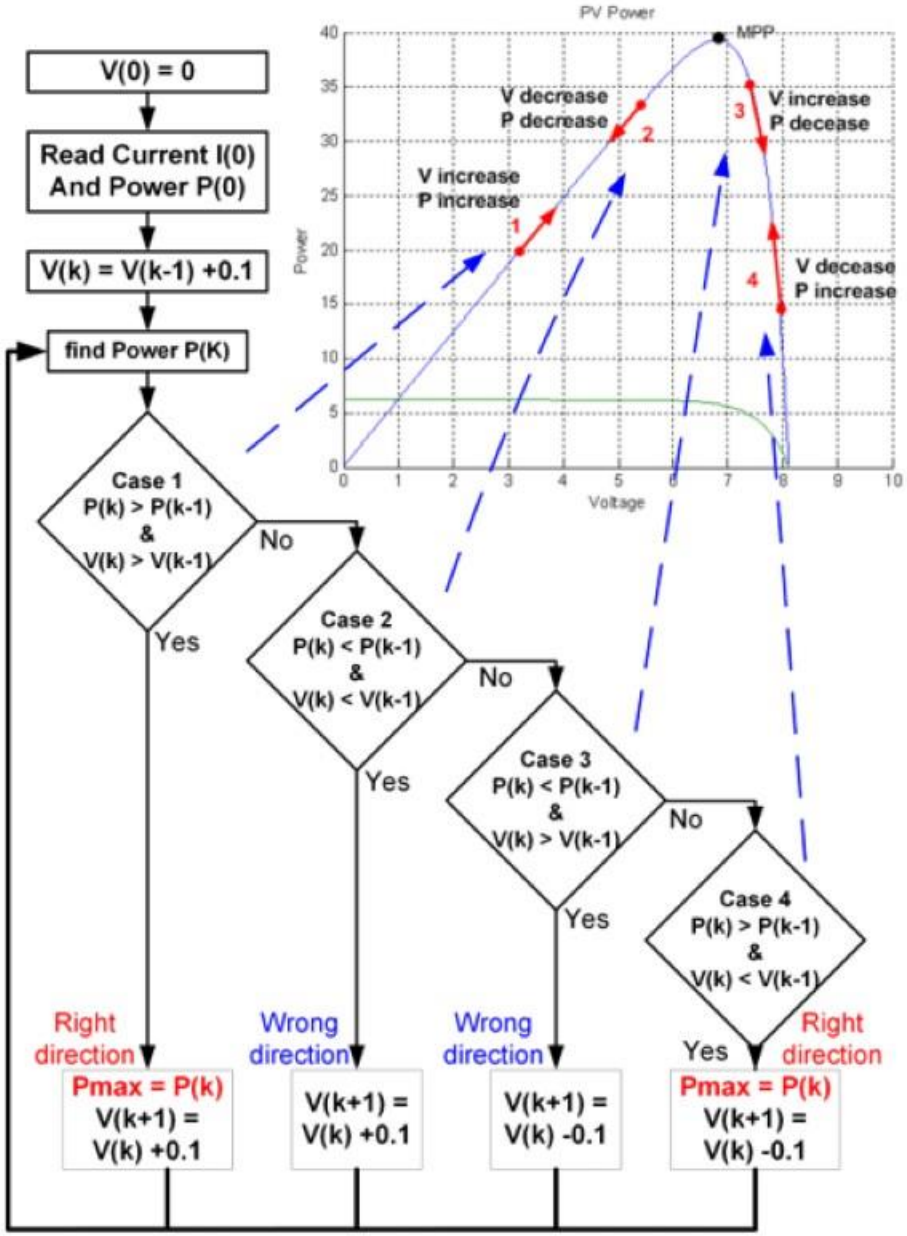
1. **Tracking techniques with constant parameters**: Methods based on this tracking technique use predefined fixed values that characterize the MPP.
2. **Tracking techniques with measurement and comparison**: This technique is based on sensing the external parameters (PV voltage, current, irradiance or temperature) and comparing them with a pre-known MPP.
3. **Tracking techniques with trial and error**: These methods use an attempt at calculation and observe the consequent result, which determines the direction criteria for the next attempt in order to reach the MPP.
4. **Tracking techniques with mathematical calculation**: These Methods define the location of the MPP based on the mathematical calculation of the available data based on equations.
5. **Tracking techniques with intelligent prediction**: These methods use an intelligent learning process that offers the ability to predict the location of the MPP.

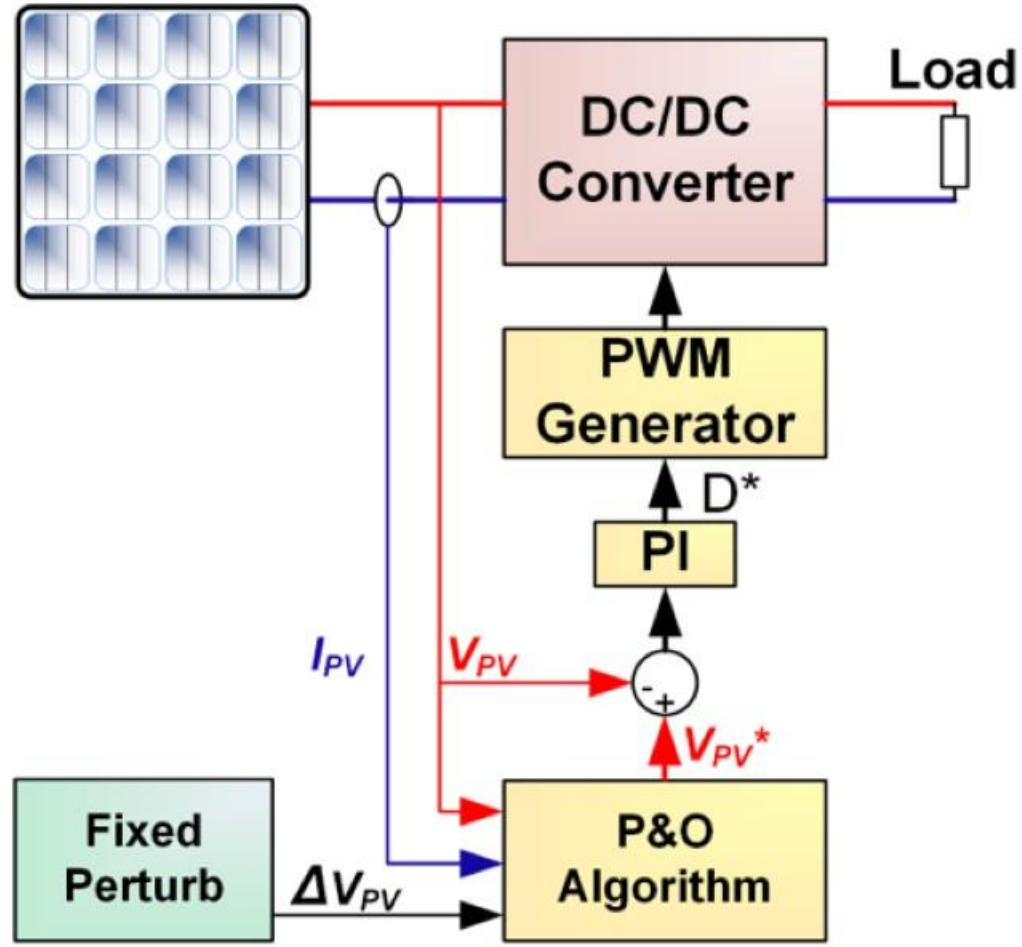
MPPT with trial and error (P&O)

- The Perturb and Observe 'P&O' method is one of the most used methods in.
- This method is based on the trial and error process in finding and tracking the MPP.
- At every cycle, the tracking controller measures the PV current and voltage and deduces the actual PV power, then perturbs the operating point by sweeping the operating voltage and monitoring the variation of power.
- If the power increases, the next perturbation of the operating voltage should be in the same direction.
- However, if the power decreases, the operating voltage is perturbed in the opposite direction.
- This scenario is repeated until reaching the MPP. The maximum point is reached when $dP_{PV}/dV_{PV} = 0$.



MPPT with trial and error (P&O)





- End of part 2

Photovoltaic solar energy training course

Section 3: Power Tracking and Shading Analysis

Part 3

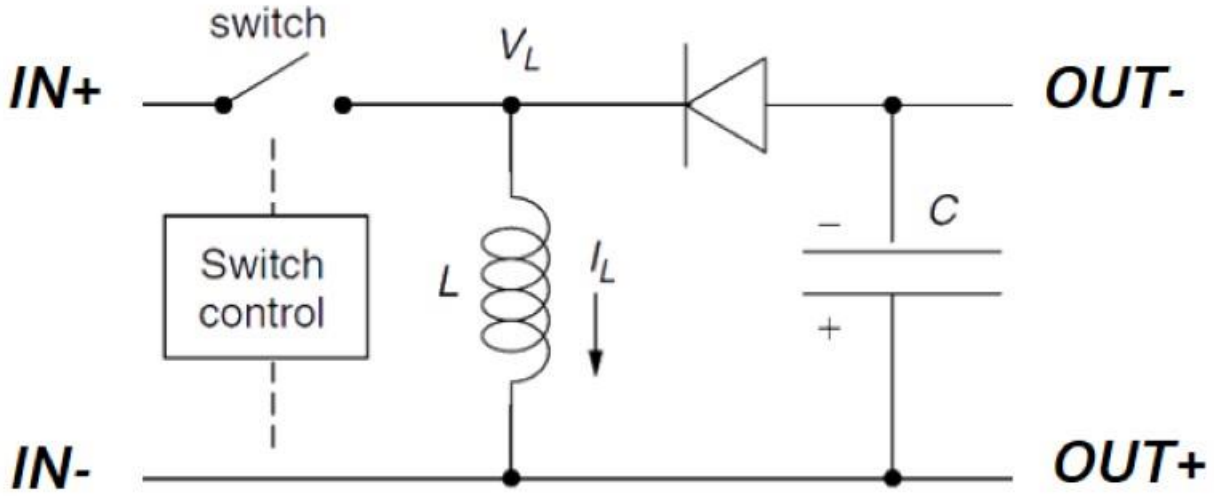
- **DC/DC Converter for MPPT**
- **Duty Cycle Calculation**

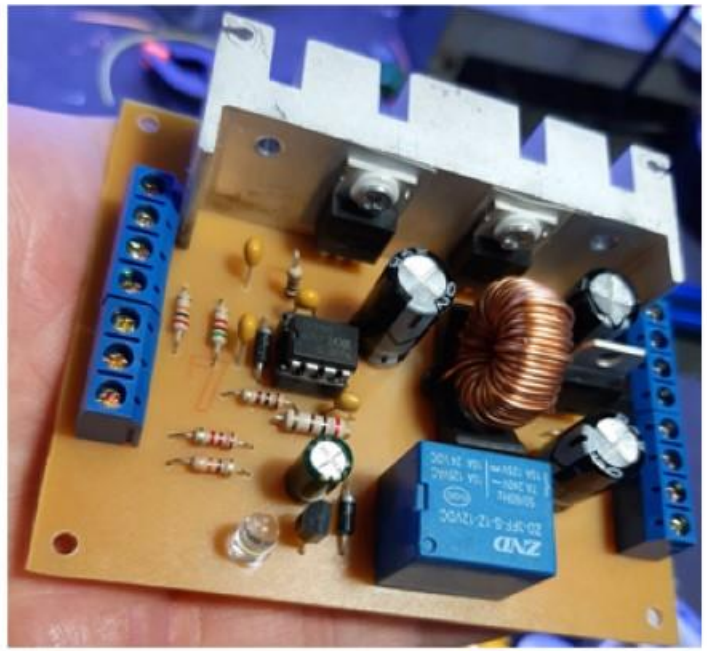
- **Serial and Parallel PV Panel connection**
- **Blocking Diode**

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DC/DC converter for MPPT

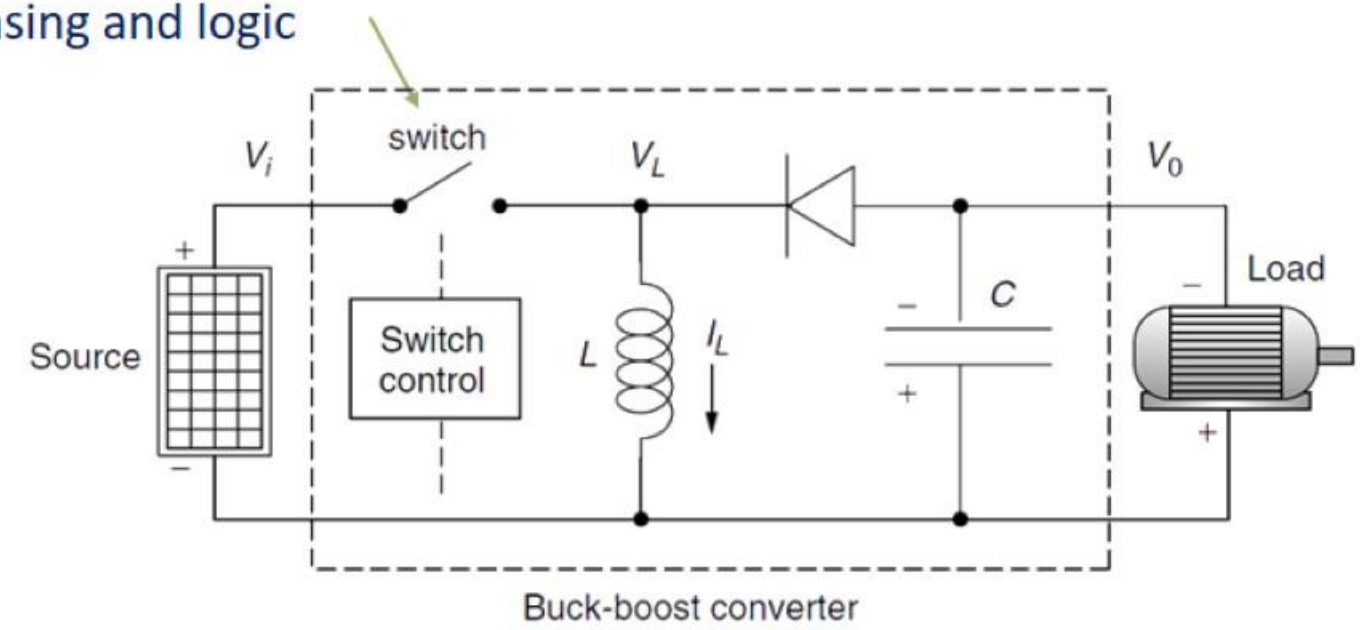
- The key is to be able to convert dc voltages from one level to another, something that was very difficult to do efficiently before high-power, field-effect transistors (FETs) became available in the 1980s and insulated-gate bipolar transistors (IGBTs) became available in the 1990s.
- A buck-boost converter is capable of raising or lowering a dc voltage from its source to whatever dc voltage is needed by the load.





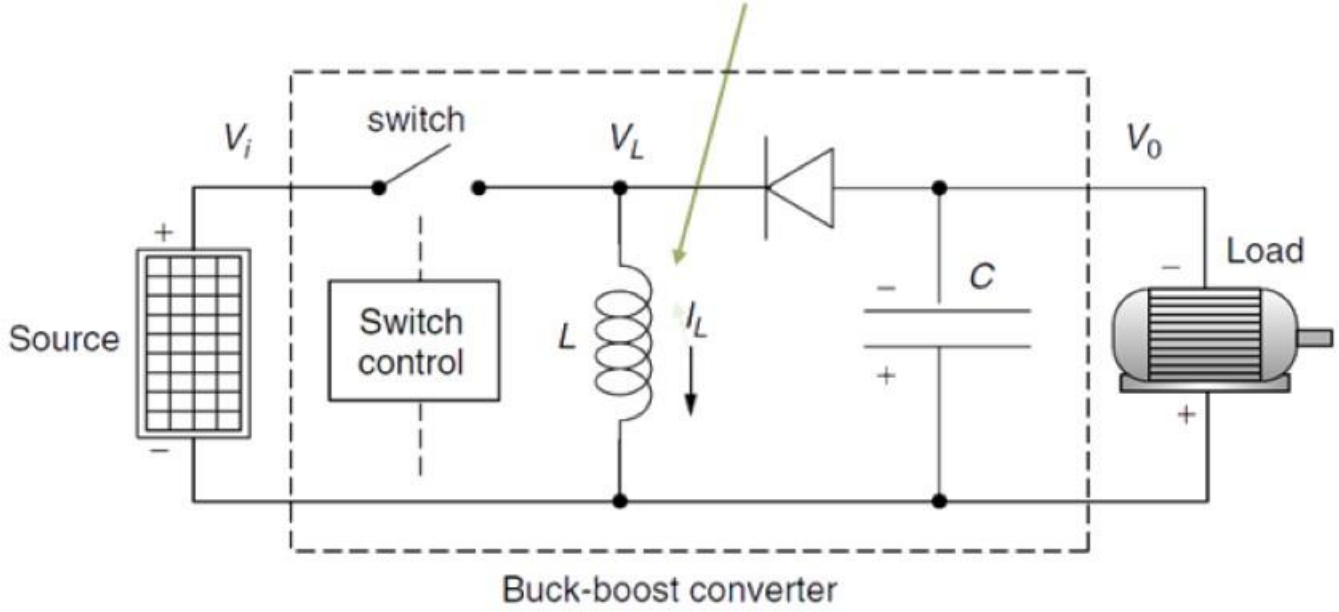
DC/DC converter for MPPT

The transistor switch flips on and off at a rapid rate (on the order of 20 kHz) under control of some sensing and logic circuitry.

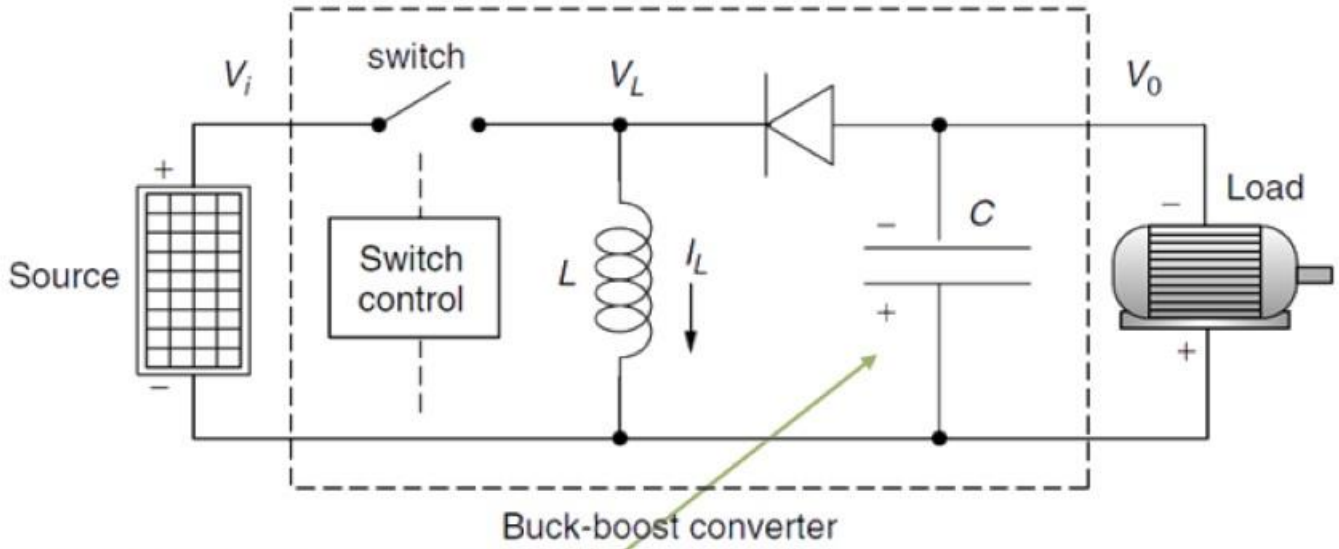


DC/DC converter for MPPT

When the switch is closed, the input voltage $\mathbf{V_i}$ is applied across the inductor, driving current $\mathbf{I_L}$ through the inductor

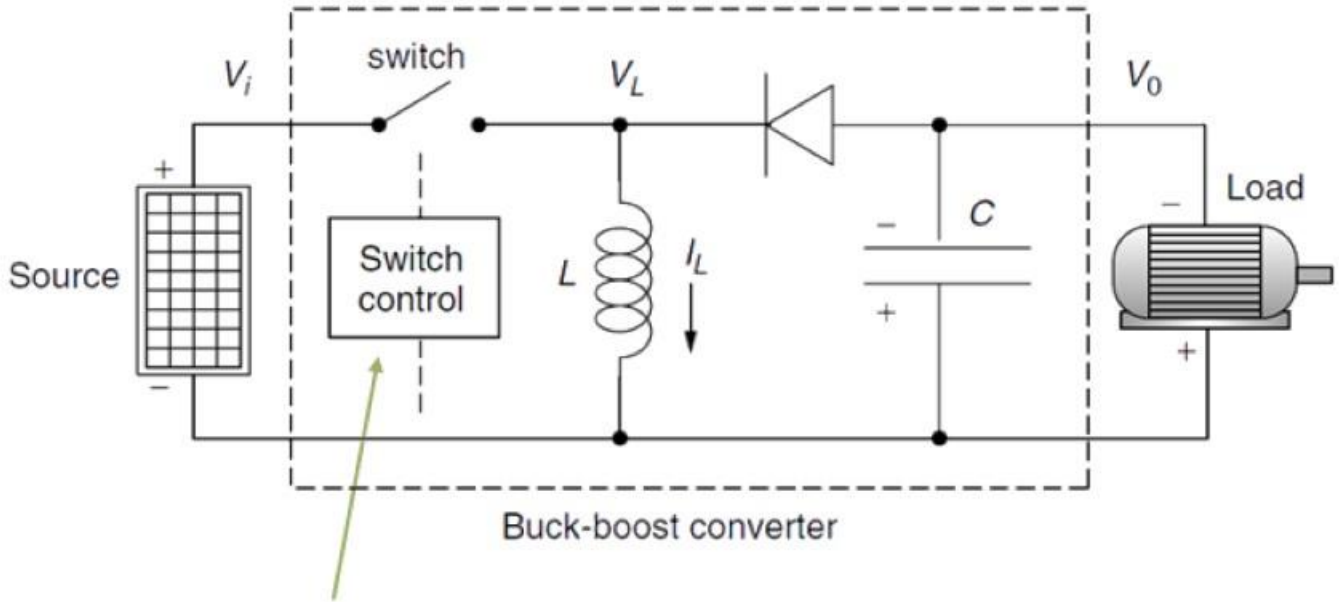


DC/DC converter for MPPT



When the switch is opened, current in the inductor flows through the capacitor, the load, and the diode.

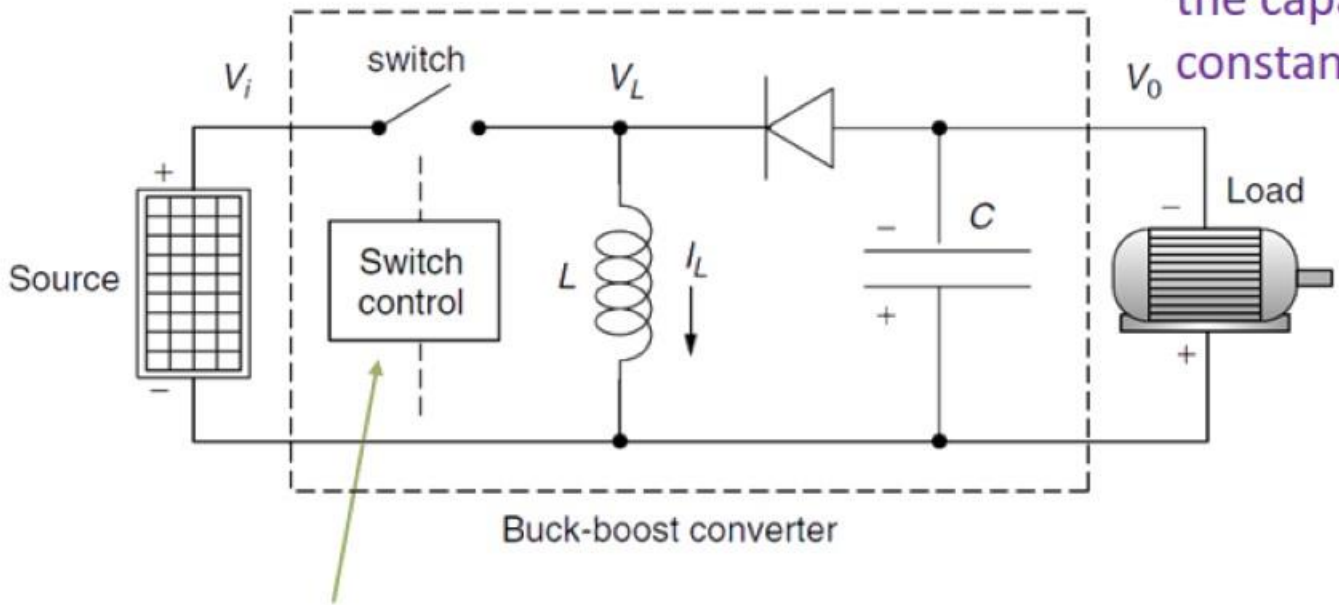
DC/DC converter for MPPT



With a fast enough switch and a large enough inductor, the circuit can be designed to have nearly constant inductor current.

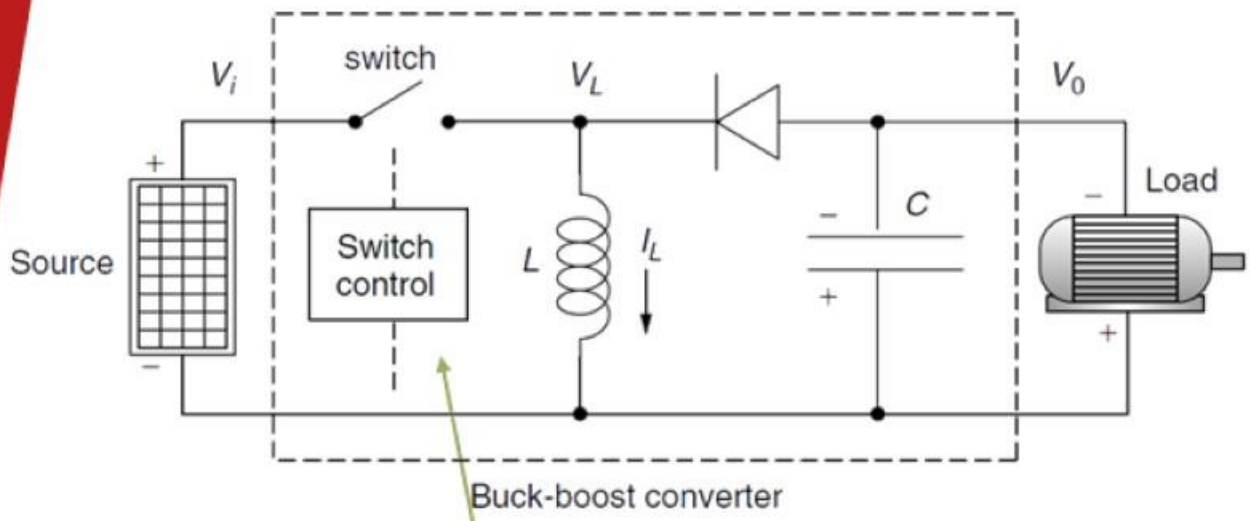
DC/DC converter for MPPT

if the switch is cycling fast enough and the capacitor is sized large enough, the output voltage across the capacitor and load is nearly constant.

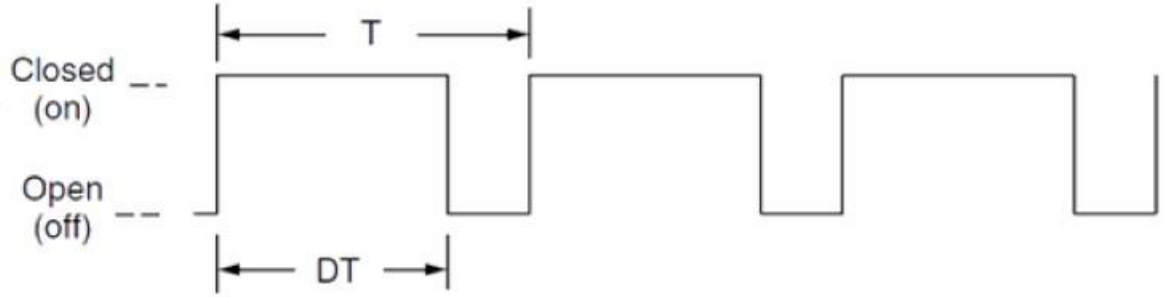


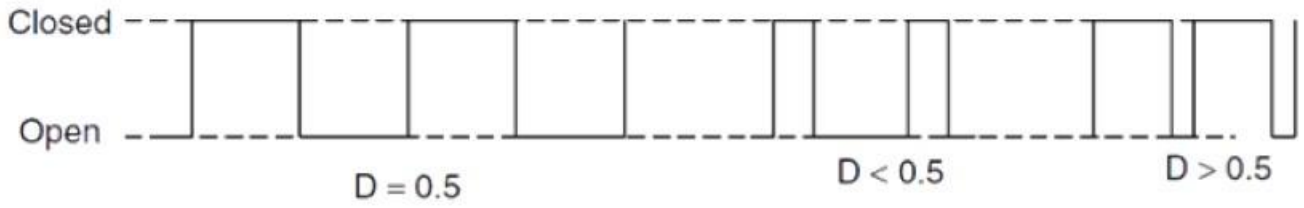
With a fast enough switch and a large enough inductor, the circuit can be designed to have nearly constant inductor current.

DC/DC converter for MPPT



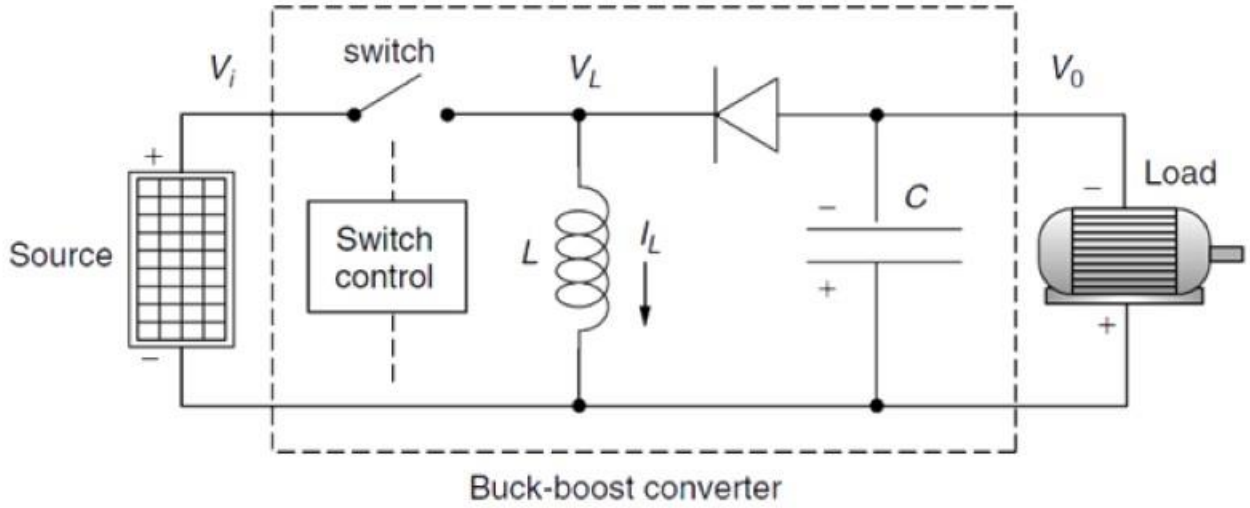
- The duty cycle D (0 < D < 1) is the fraction of the time that the switch is closed.
- This variation in the fraction of time the switch is in one state or the other is referred to as pulse-width modulation (***PWM***).





DC/DC converter for MPPT

- For ***ideal components***, the inductor, diode and capacitor do not consume any net energy over a complete cycle of the switch.
- Therefore the average power into the converter is equal to the average power delivered by the converter; that is, it has 100% efficiency.
- Real MPPTs have efficiencies in the mid-90% range, so this isn't a bad assumption.



DC/DC converter for MPPT



- This equation tells us we can bump dc voltages up or down (there is a sign change) just by varying the duty cycle of the buck-boost converter.
- Longer duty cycles allow more time for the capacitor to charge up and less time for it to discharge, so the output voltage increases as D increases.
- For a duty cycle of 1/2, the output voltage is the same as the input voltage.

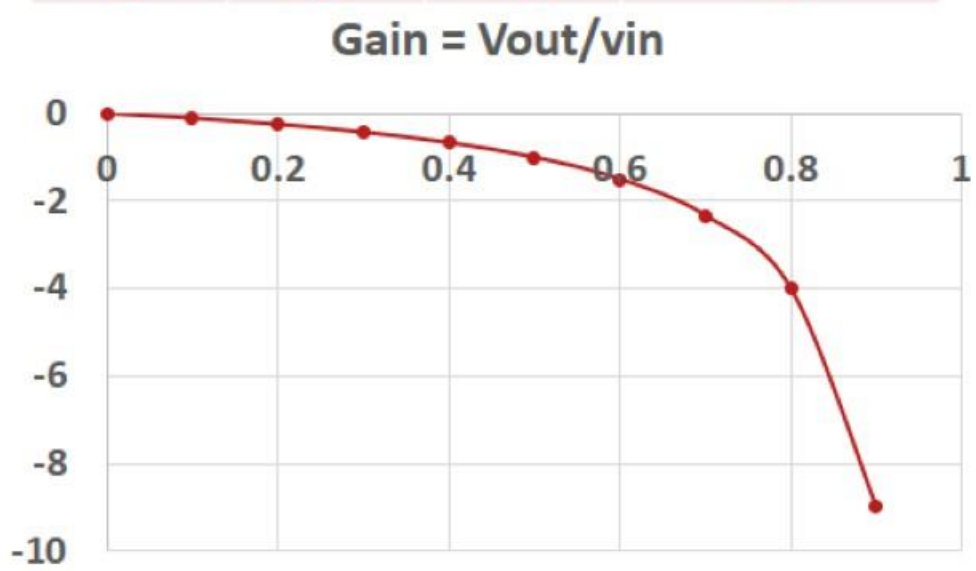
$$\frac{V_{out}}{V_{in}} = -\frac{D}{1-D}$$

DC/DC converter for MPPT

- A duty cycle of 2/3 results in a doubling of voltage, while D = 1/3 cuts voltage in half.
- An actual MPP tracker needs some way for the dc-to-dc converter to know the proper duty cycle to provide at any given instant.
- This can be done with a microprocessor that periodically varies the duty cycle up and down a bit while monitoring the output power to see whether any improvement can be achieved.

$$\frac{V_{out}}{V_{in}} = -\frac{D}{1-D}$$

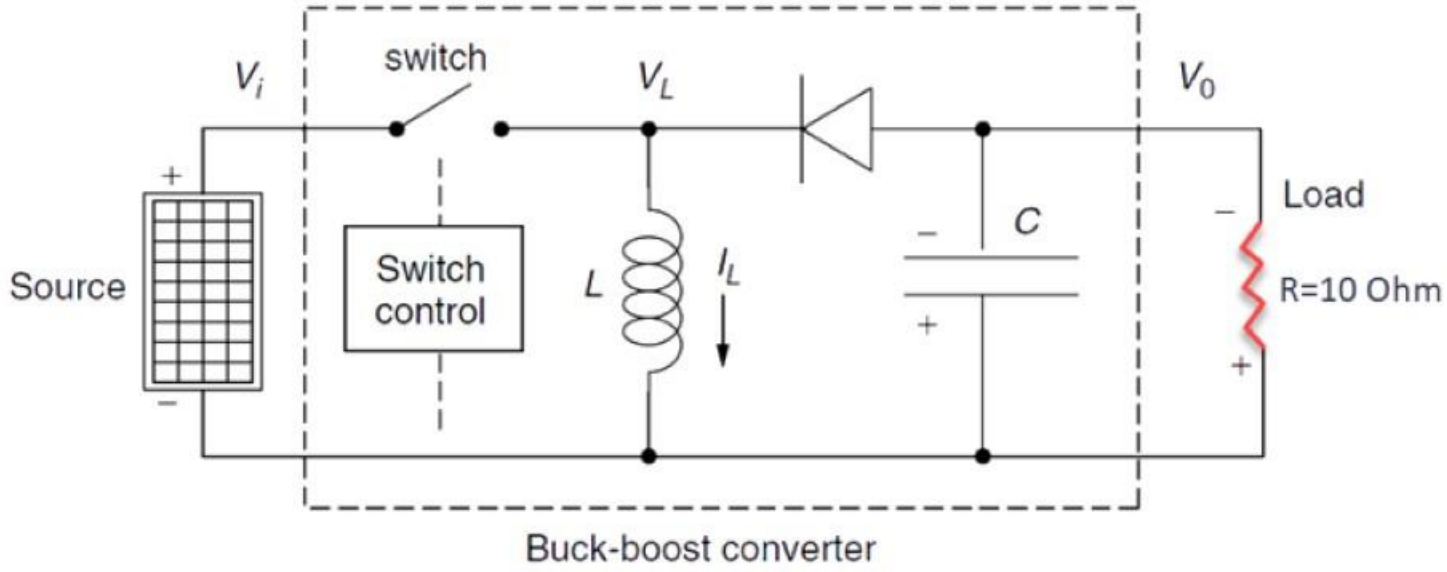
Vin	D	Vout	Gain = Vout/vin
10	0	0	0
10	0.1	-1.11	-0.11
10	0.2	-2.5	-0.25
10	0.3	-4.29	-0.43
10	0.4	-6.67	-0.67
10	0.5	-10	-1
10	0.6	-15	-1.5
10	0.7	-23.33	-2.33
10	0.8	-40	-4
10	0.9	-90	-9



DC/DC converter for MPPT

Example:

Under certain ambient conditions, a PV module has its MPP at V_{mpp} = 17V and I_{mpp} = 6A. What duty cycle should an MPPT have if the module is delivering power to a 10Ω resistance?



DC/DC converter for MPPT

Solution:

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

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

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

$$V_R = \sqrt{102 \times 10} = 31.9V$$

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

Using:

$$\frac{V_{out}}{V_{in}} = -\frac{D}{1-D}$$

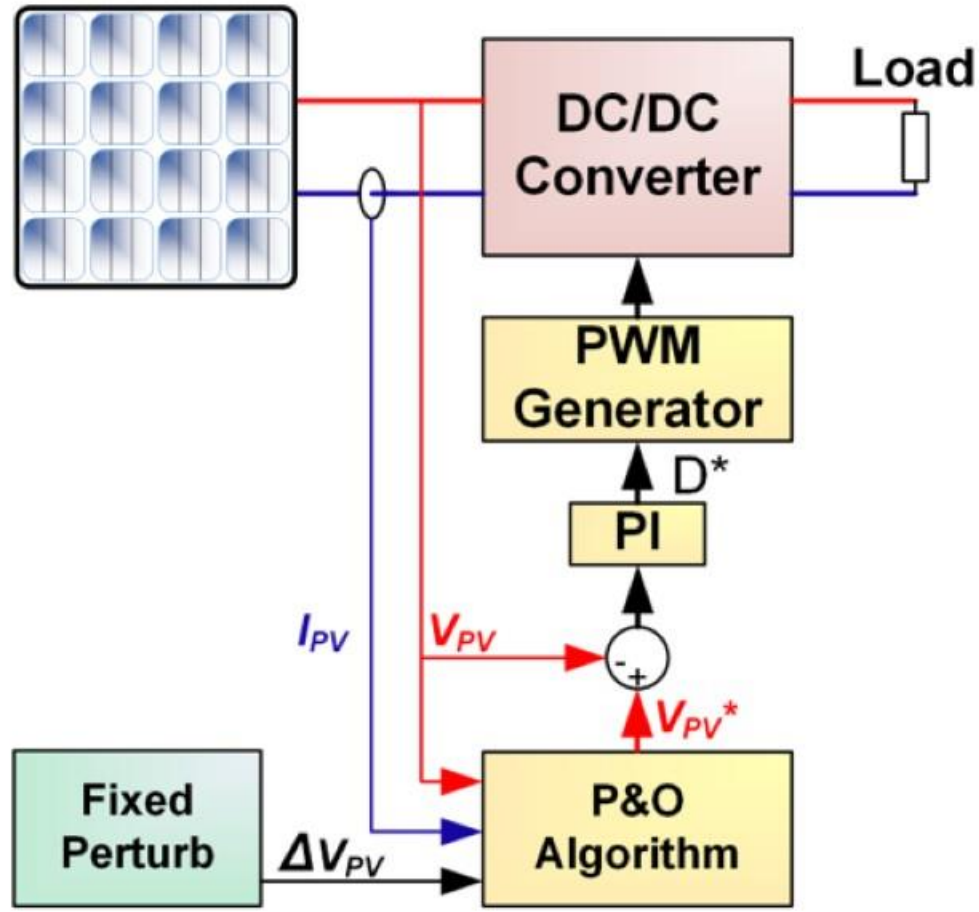
$$\frac{31.9}{17} = -\frac{D}{1-D} = 1.88 \Rightarrow D = 0.65$$

DC/DC converter for MPPT

Remark 1: The calculated duty cycle (D=0.65) is reached by trial and error using the P&O algorithm because the MPP is not known and may change when climatic conditions change.

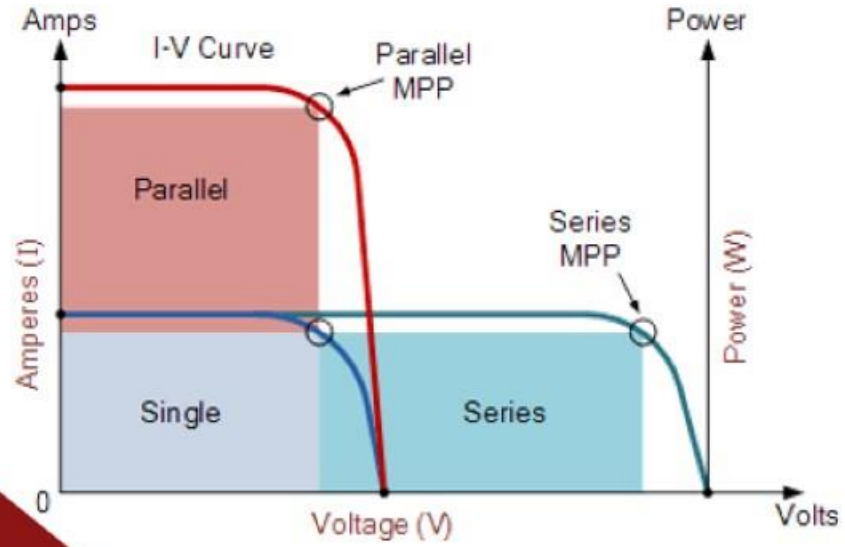
Remark 2: The algorithm always modify the Duty cycle to reach the maximum power point.

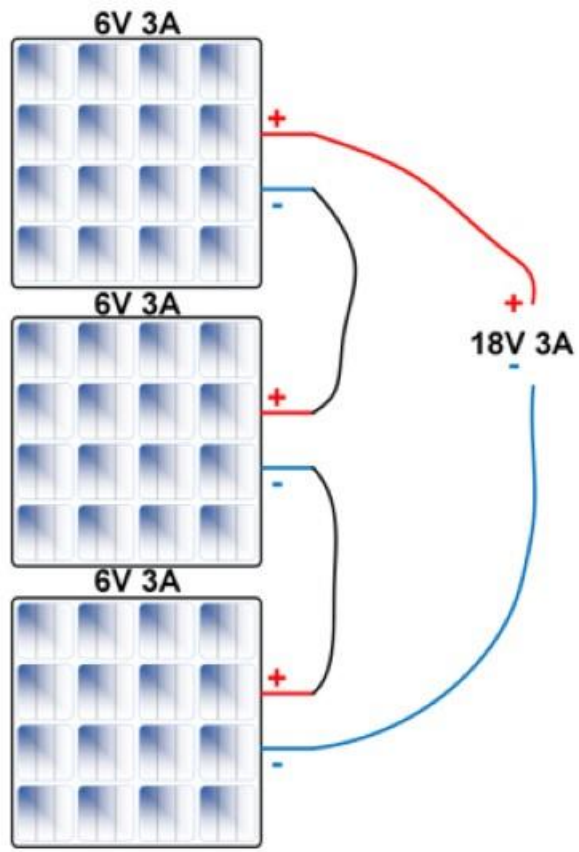
Remark 3: We really don't care for the moment about the voltage and current of the load. Our concern is about the best PV voltage and current

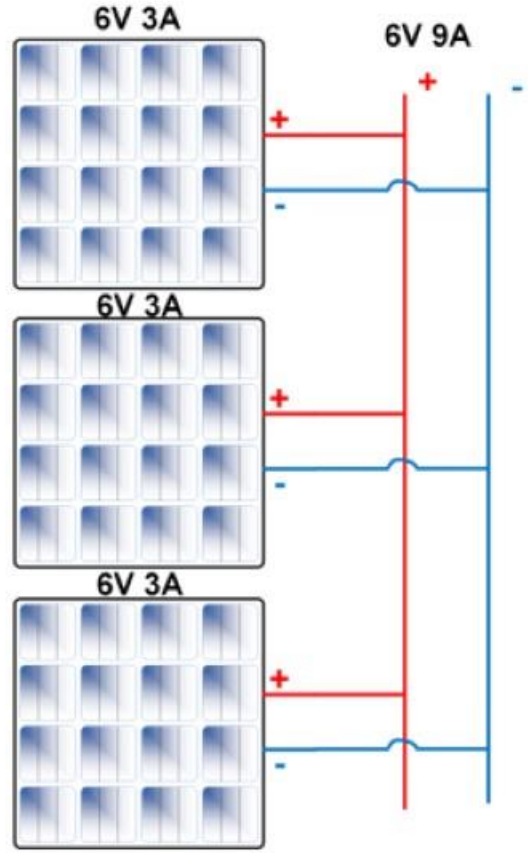


Series and Parallel Panel Connection

- by wiring several solar panels in series we increase the voltage keeping the same current
- while wiring them in parallel we increase the current keeping the same voltage.
- Both configurations have 54W max

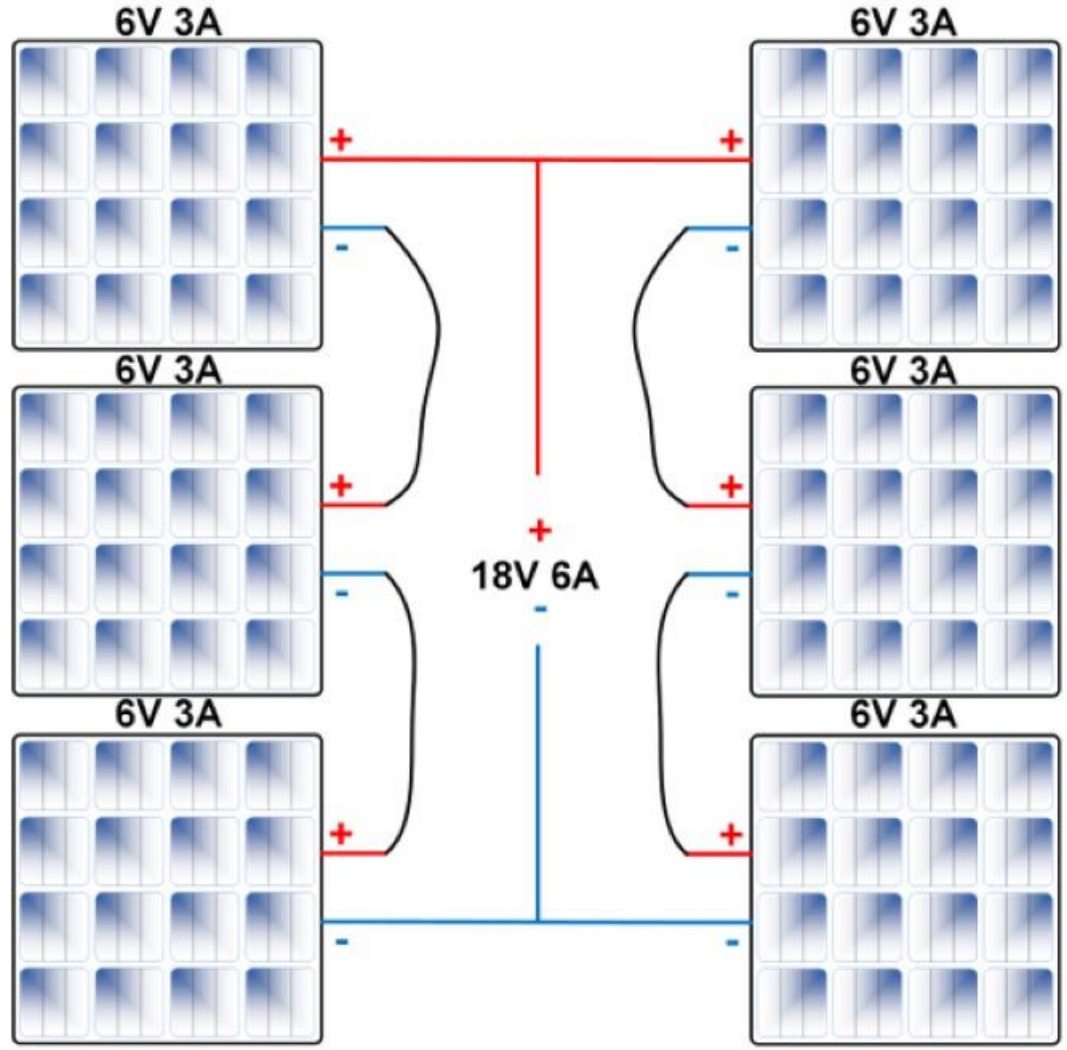






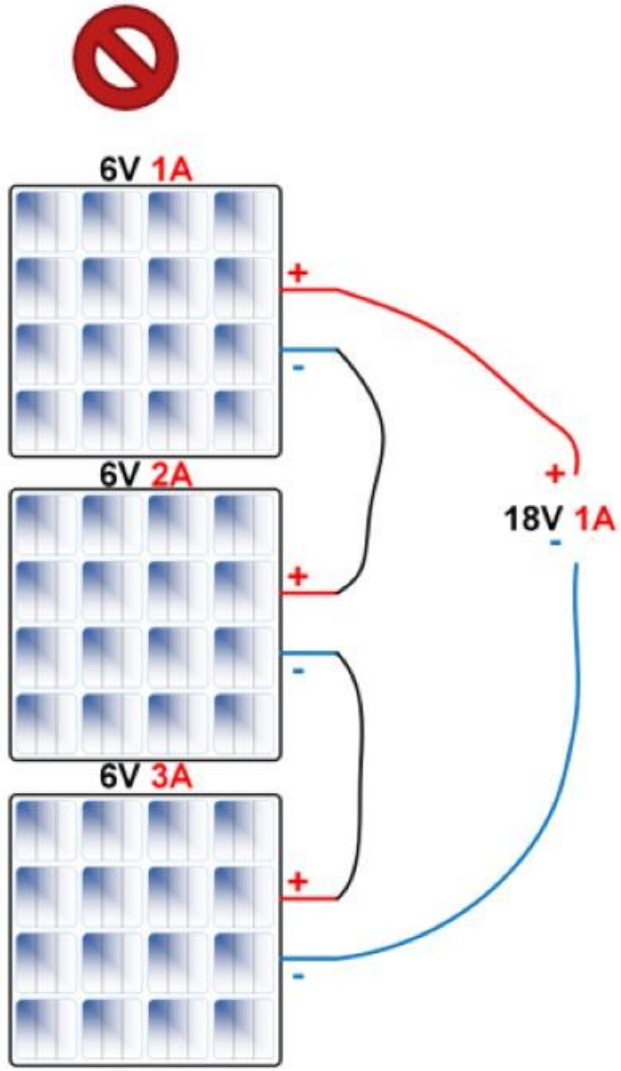
Series and Parallel Panel Connection

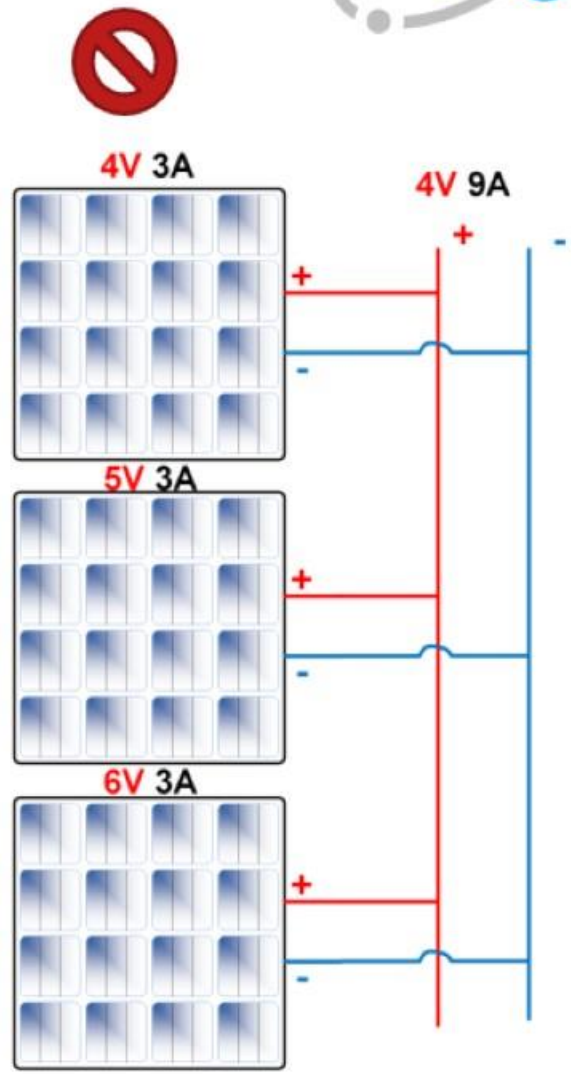
- Also for more current and voltage, panels can be combined in series and parallel.
- Power now is doubled: 108W max



Series and Parallel Panel Connection

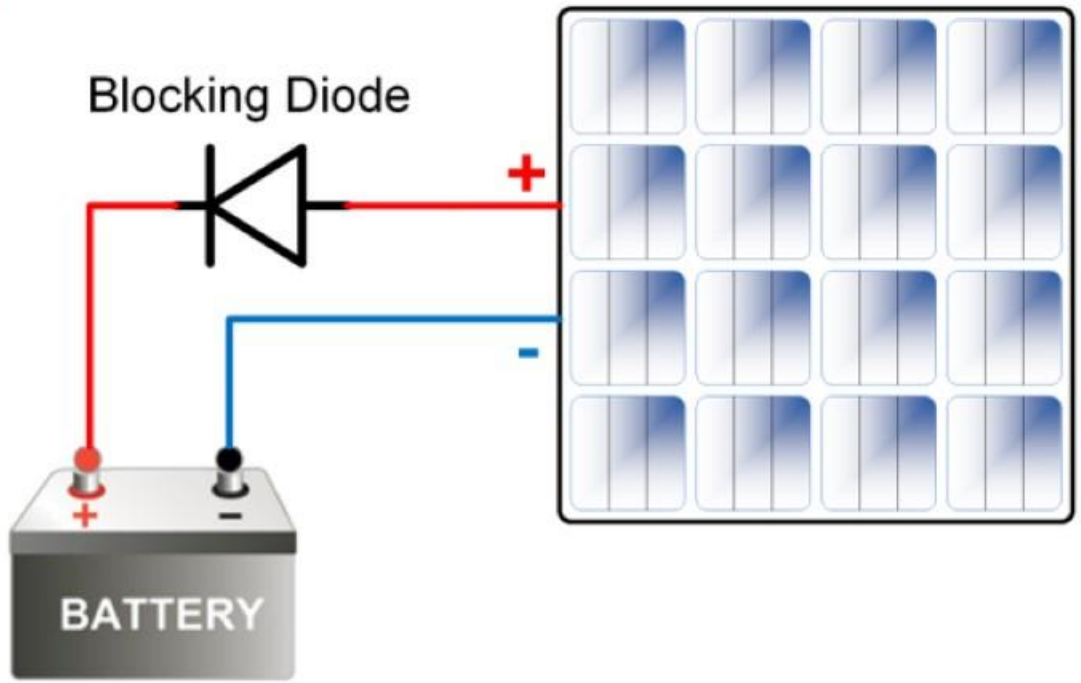
- Typically solar panels of specific or matching current needs to be connected with each other in series.
- And solar panels of specific or matching voltage needs to be connected with each other in parallel.





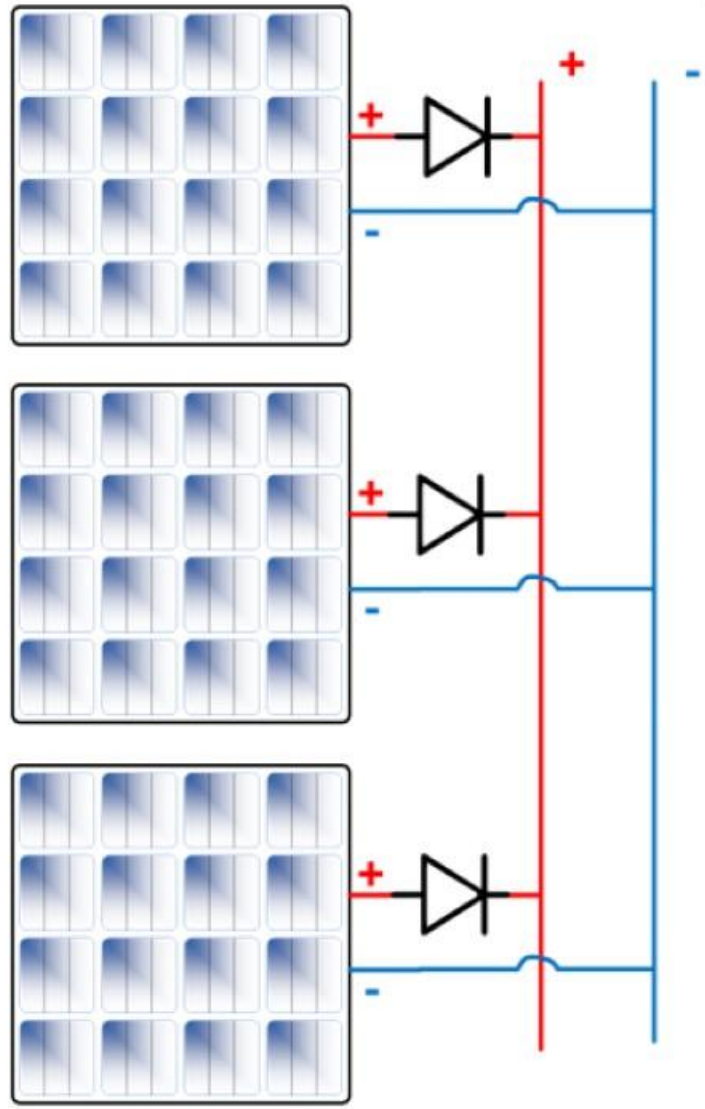
Blocking Diode

- Blocking diodes in series with PV modules are used to prevent the batteries from being discharged through the PV cells at night when there is no sun available to generate energy.
- Diodes voltage rating should be at least two times higher than the V_{OC} of the PV module or the PV string (depending on what they protect),
- While their current rating capacity should be at least 1.4 times higher than I_{SC} of a single PV module (under STC conditions)



Blocking Diode

- Also, in case of parallel combination of PV panels, diode should be placed for each panel to block any current flow from one panel to another especially when one is shaded



- End of Part 3

Photovoltaic solar energy training course

Section 3: Power Tracking and Shading Analysis

Part 4

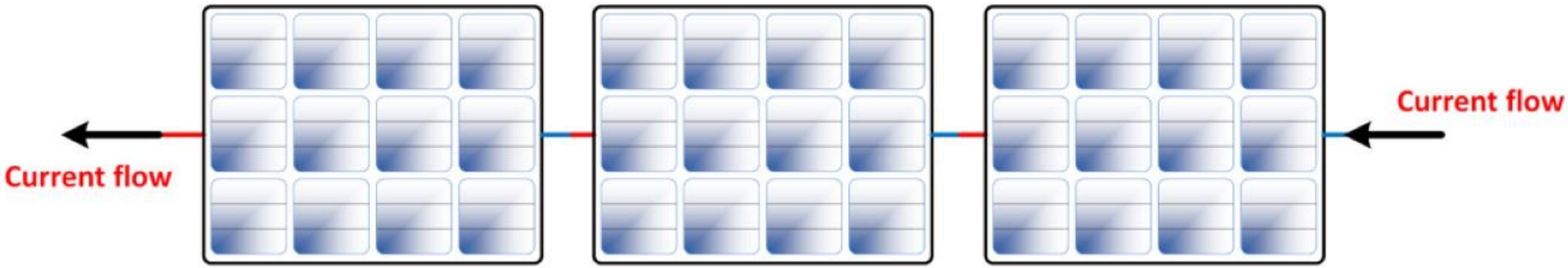
- **Physics of PV Cells Shading**
- **Effect of Shaded Cells**
- **Bypass Diodes for Shade Mitigation**
- **Bypass Diodes for Shade Mitigation for Module in Series**
- **Blocking and Bypass Diodes for Series and Parallel panels**

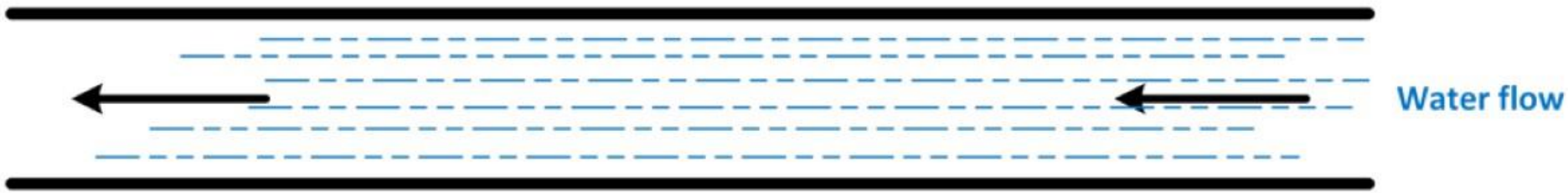
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PV partial Shading Effects

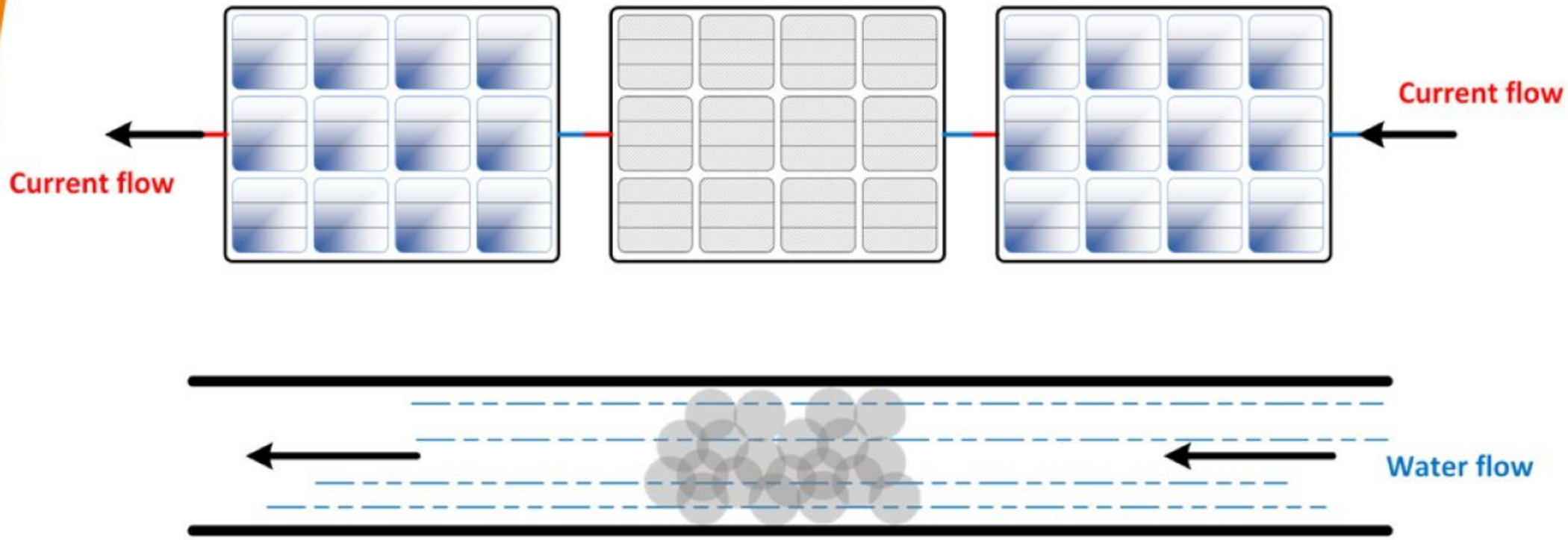


Physics of PV Cells Shading



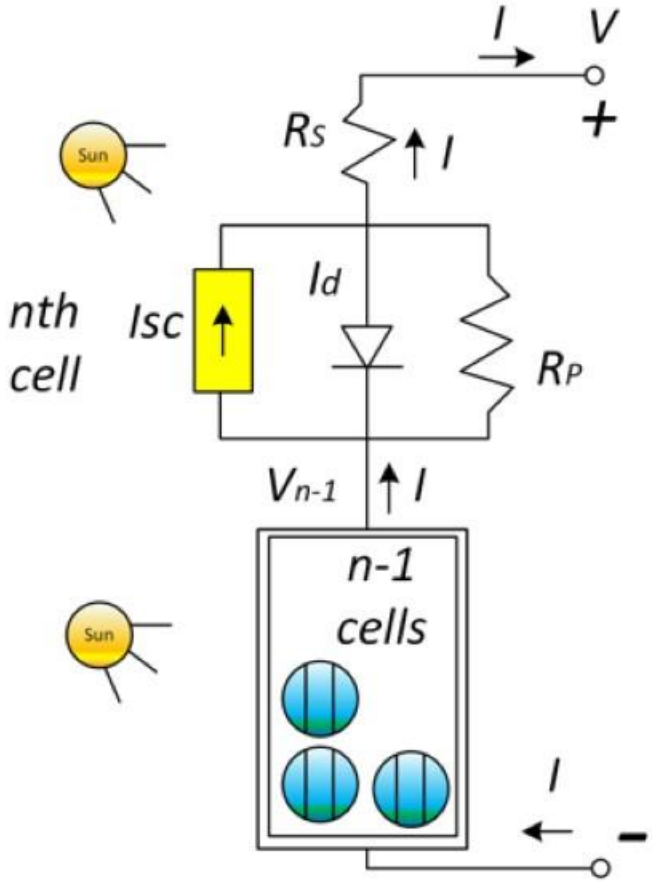


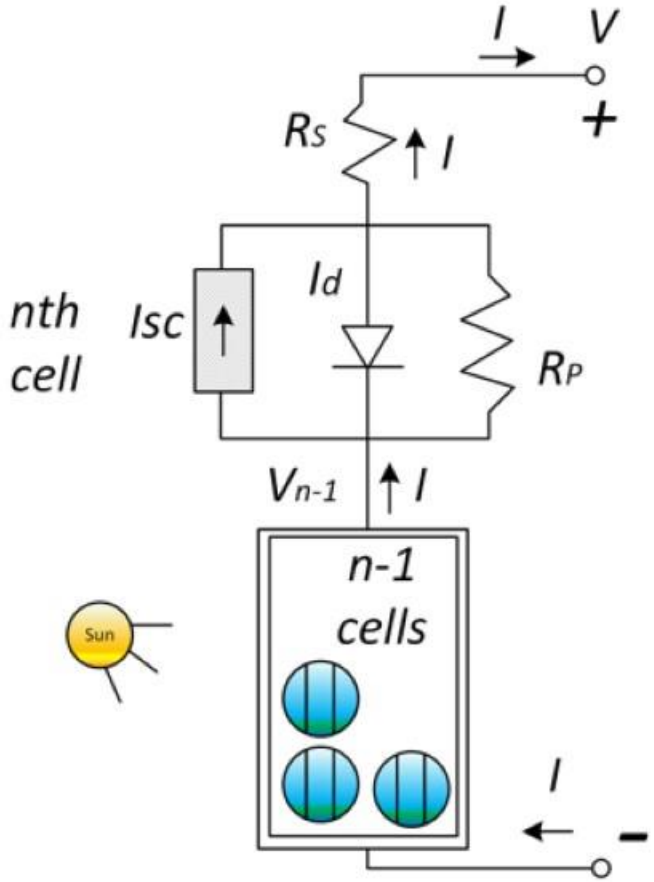
Physics of PV Cells Shading



Effect of Shaded Cell

Consider a module with ***n*** cells where the top cell is either in the ***sun*** or in the ***shade***.



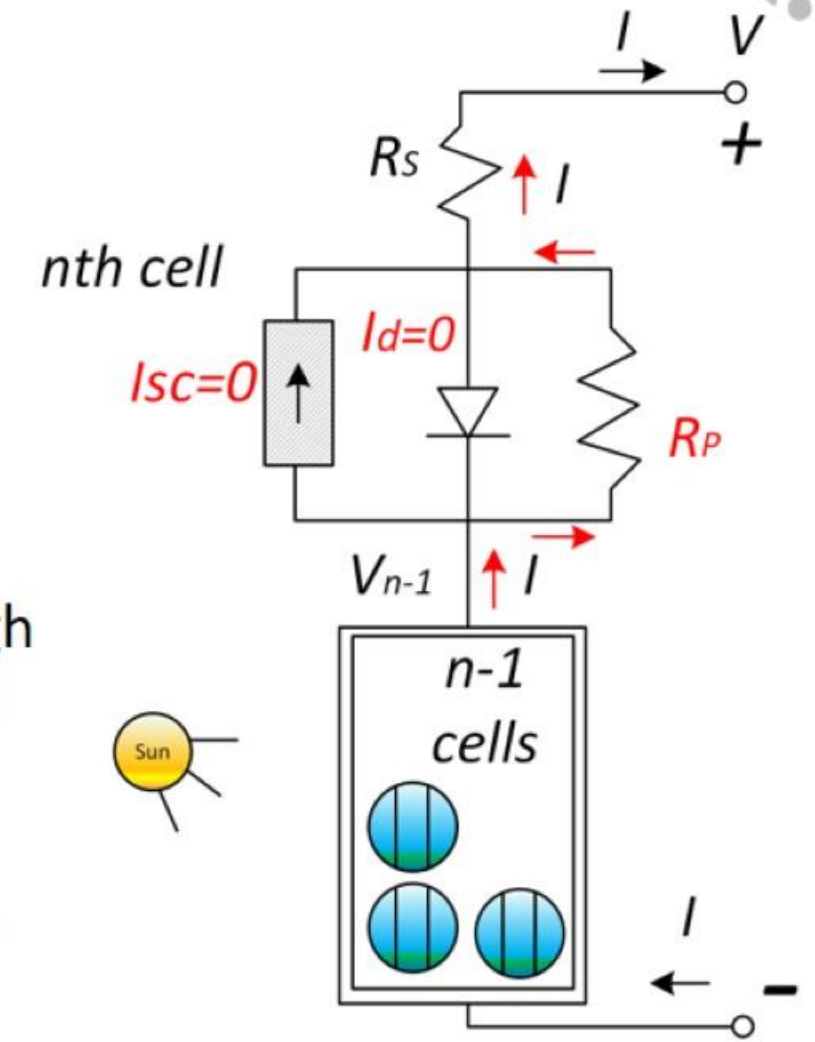


Effect of Shaded Cell

- The top cell is ***shaded*** and its current source I_{SC} has been reduced to zero
- The voltage drop across R_P as current flows through it causes the diode to be reverse biased, so the diode current is also (essentially) zero.

- That means the entire current flowing through the module must travel through both R_P and R_S in the shaded cell on its way to the load

- That means the top cell, instead of adding to the output voltage, actually reduces it.



Shaded Cell

Effect of Shaded Cell

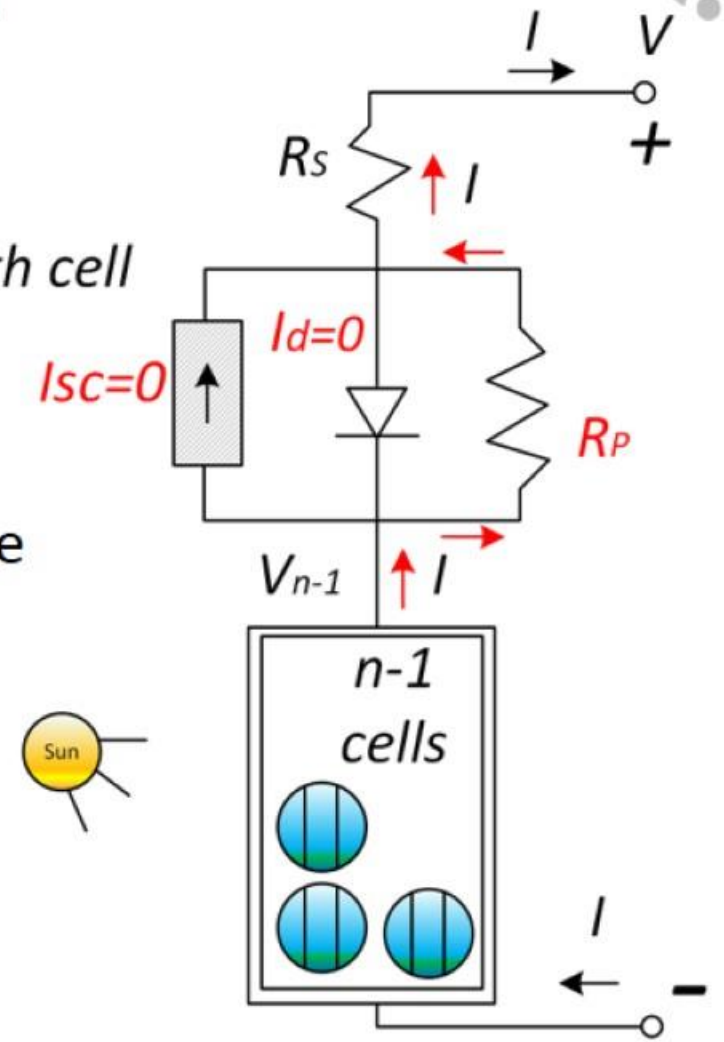
- Consider the case when the bottom $n-1$ cells still have ***full sun*** and still somehow carry their original current *I* so they will still produce their original voltage V_{n-1}.

$$V_{SH} = V_{n-1} - I(R_P - R_S) \qquad \text{(Eq1)}$$

- This means that the output voltage of the entire module V_{SH} with one cell shaded will drop to:

$$V_{n-1} = \left(\frac{n-1}{n}\right) V \qquad \text{(Eq2)}$$

- With all n cells in the sun and carrying I, the output voltage was V so the voltage of the bottom $n-1$ cells will be



Shaded Cell

Effect of Shaded Cell

- Combining (1) and (2) gives:

$$V_{SH} = \left(\frac{n-1}{n}\right)V - I(R_P + R_S) \qquad \text{(Eq3)}$$

- The drop in voltage V at any given current I, caused by the shaded cell, is given by:

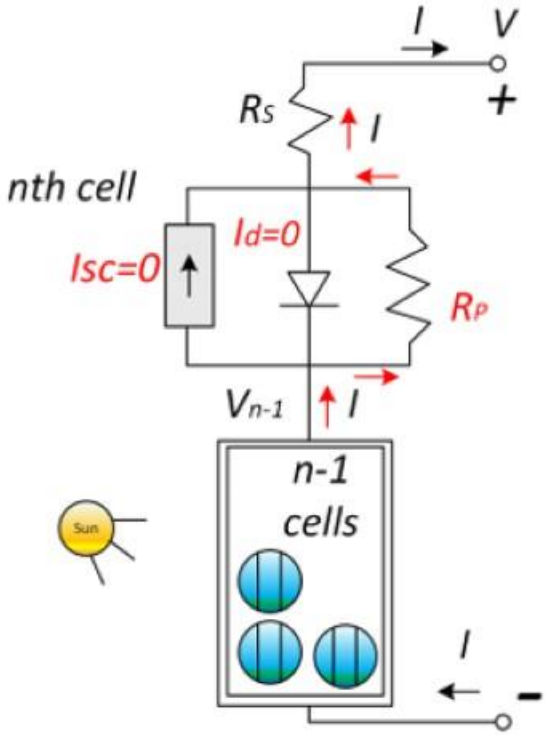
$$\Delta V = V - V_{SH}$$

$$= V - \left(1 - \frac{1}{n}\right)V + I(R_P + R_S) \qquad \text{(Eq4)}$$

$$\Delta V = \frac{V}{n} + I(R_P + R_S) \qquad \text{(Eq5)}$$

- Since the parallel resistance R_P is so much greater than the series resistance R_S, (5) simplifies to

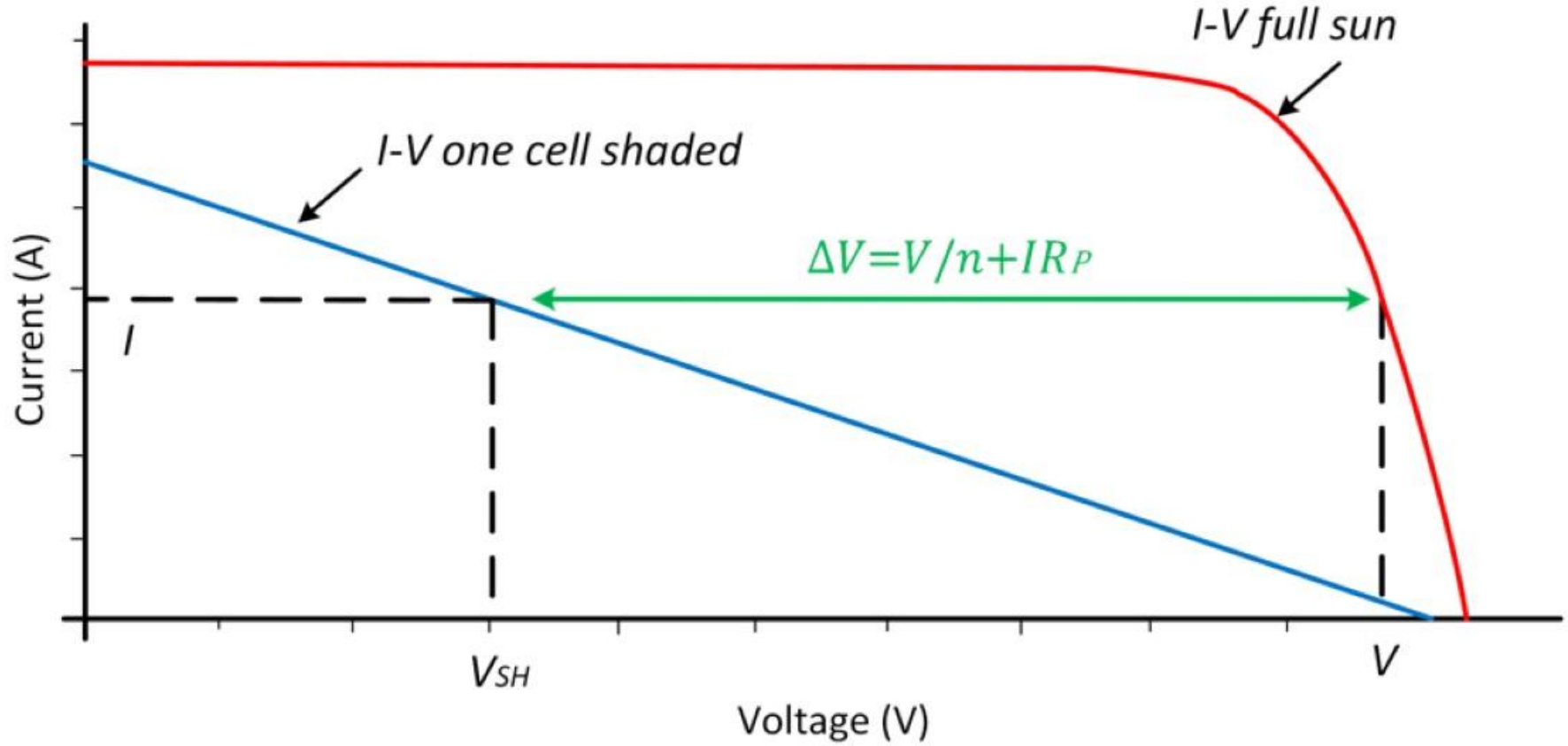
$$\Delta V \cong \frac{V}{n} + IR_P \qquad \text{(Eq6)}$$



Shaded Cell

Effect of Shaded Cell

At any given current, the $I - V$ curve for the module with one shaded cell drops by ΔV. The huge impact this can have is illustrated in the figure below:



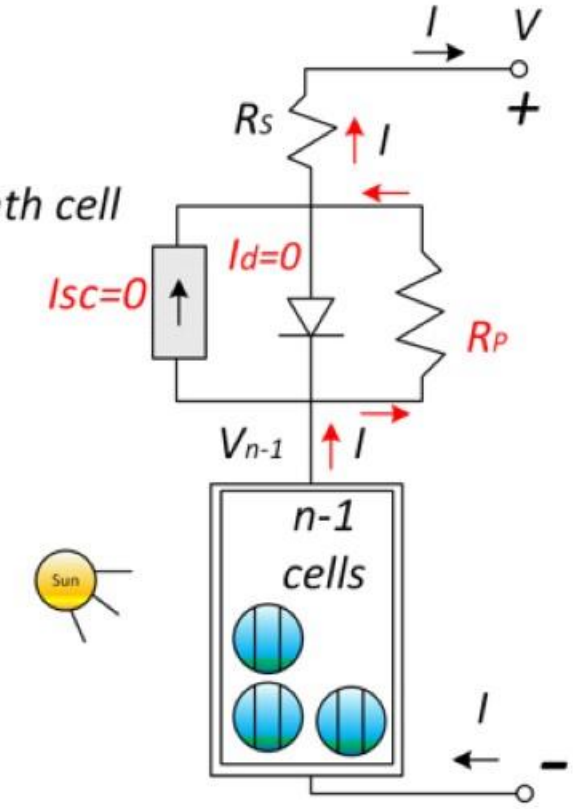
Effect of Shaded Cell

Example - Impacts of Shading on a PV Module

A 36-cell PV module has a parallel resistance per cell of $R_P = 6.6\ \Omega$ *and* series resistance ($0.005\ \Omega$). In full sun and at current **I = 2.14 A** the output voltage was found there to be $V = 19.41\ V$.

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

- What would be the new module output voltage and power?
- What would be the voltage drop across the shaded cell?
- How much power would be dissipated in the shaded cell?



Effect of Shaded Cell

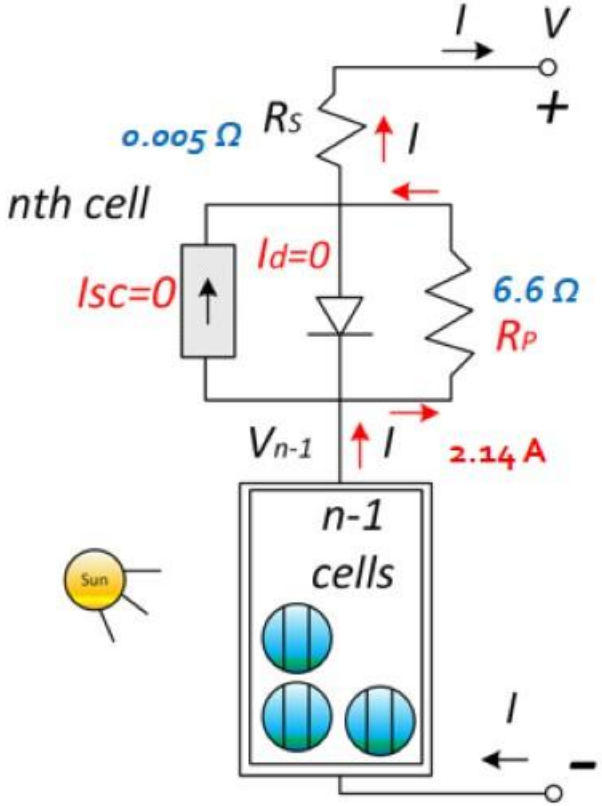
Solution - Impacts of Shading on a PV Module

The drop in module voltage will be: $\Delta V \cong \frac{V}{n} + IR_P = \frac{19.41}{36} + 2.14 \times 6.6 = 14.66V$

The new output voltage will be 19.41 − 14.66 = 4.75 V.

Power delivered by the module with one cell shaded would be: $P_{module} = V\,I = 4.75\ \text{V} \times 2.14\ \text{A} =$ **10.1 W**

(In full sun the module was producing 19.41 × 2.14 = 41.5 W !!)

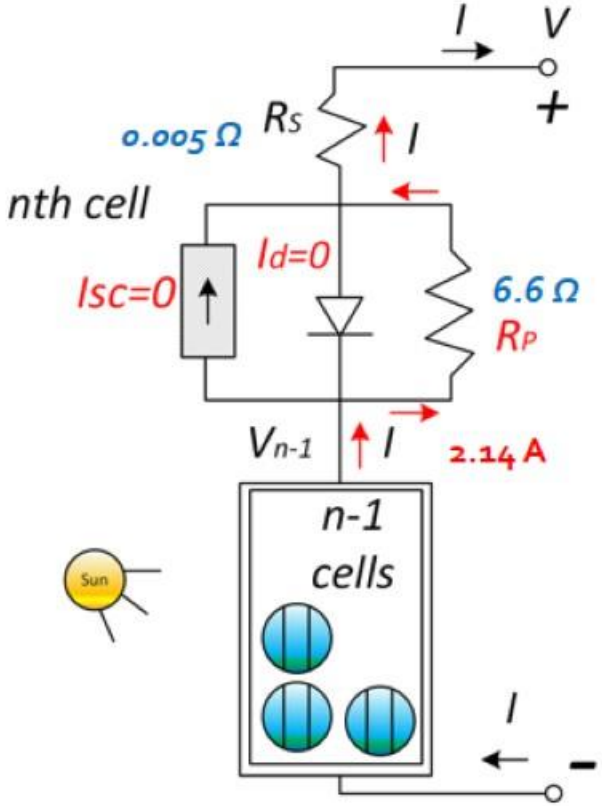


Effect of Shaded Cell

Solution - Impacts of Shading on a PV Module

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:

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



- **Normally a cell in the sun will add about 0.5 V to the module;**
- **this shaded cell subtracts over 14 V from the module !!.**

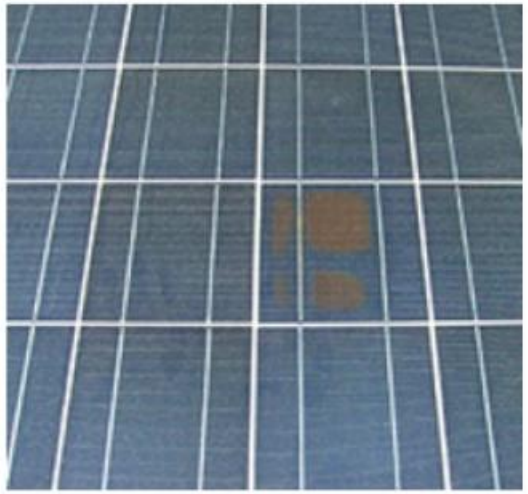
Effect of Shaded Cell

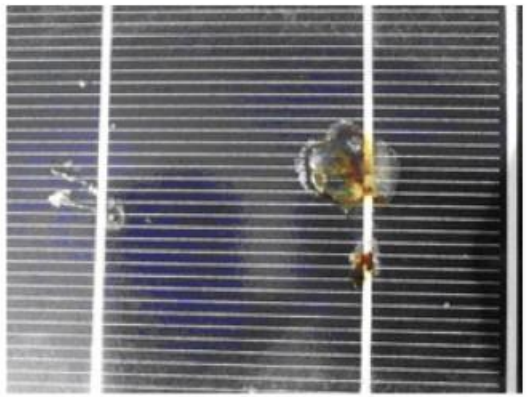
Solution - Impacts of Shading on a PV Module

The power dissipated in the shaded cell is the voltage drop times current, which is:

$$P = V_C I = 14.14 \times 2.14 = 30.2W$$

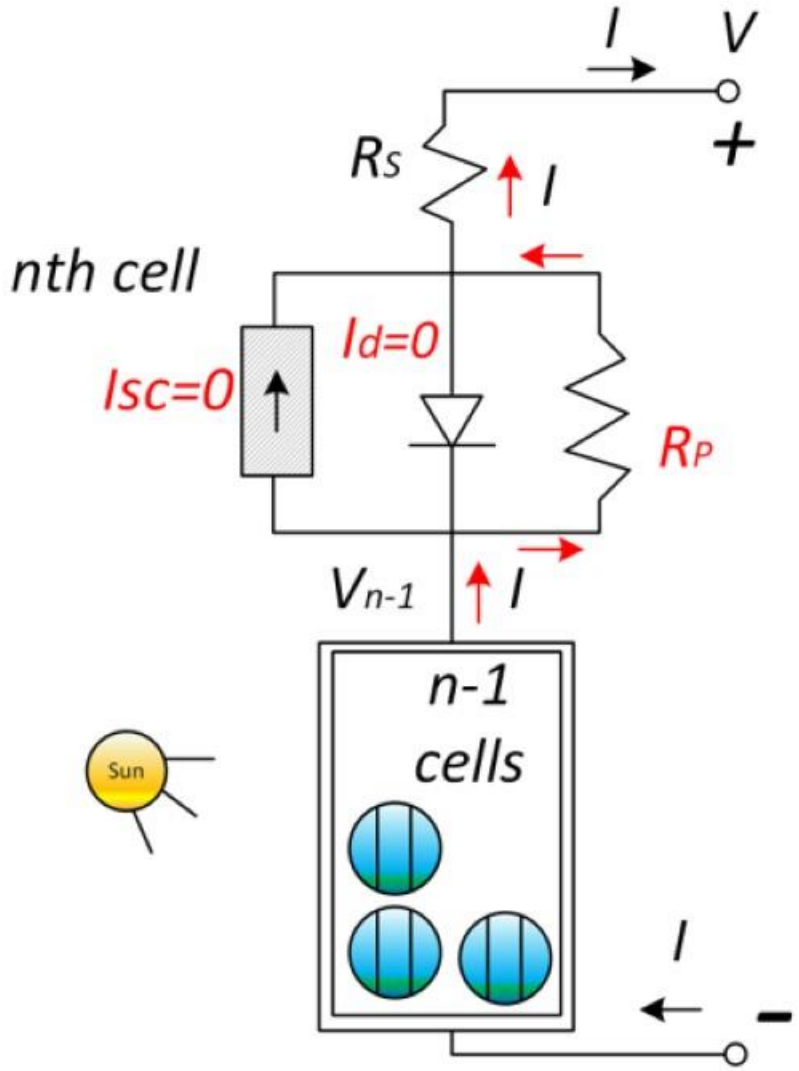
All of that power dissipated in the shaded cell is converted to heat, which can cause a local *hot spot* that may permanently damage the plastic laminates enclosing the cell !!.





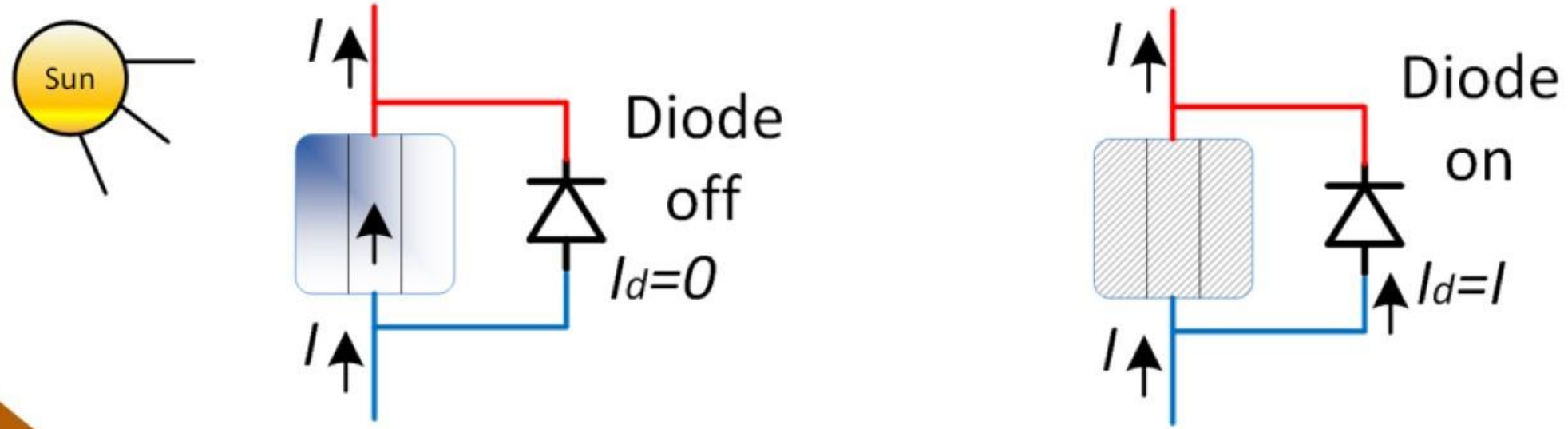
Bypass Diodes for Shade Mitigation

- A Solar cell in full sun operating in its normal range *contributes* about 0.5 V to the voltage output of the module,
- but by looking at the cell equivalent circuit, a shaded cell experiences a *drop* as current is diverted through the parallel and series resistances.
- This drop can be considerable.



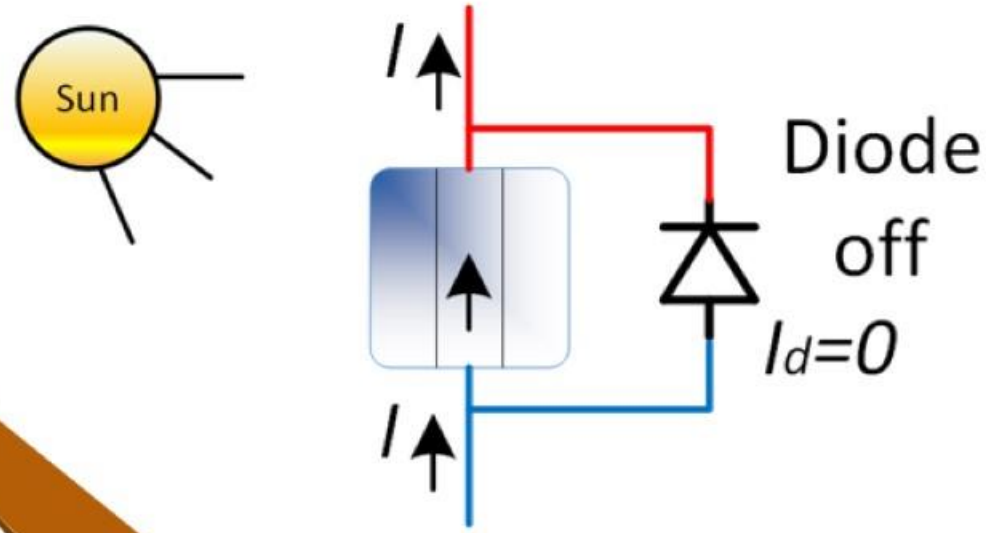
Bypass Diodes for Shade Mitigation

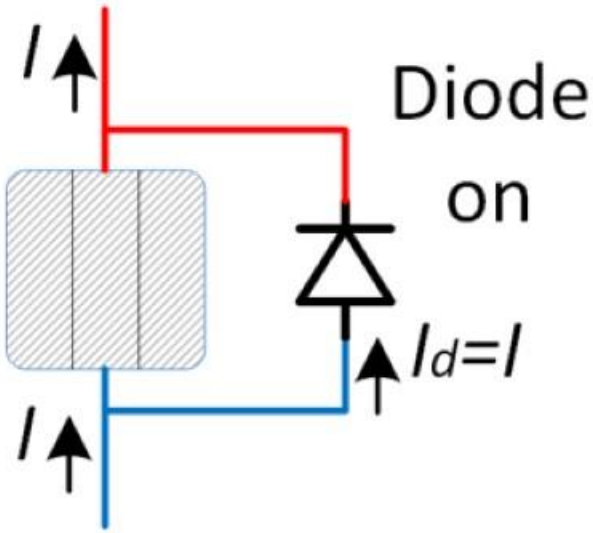
- The voltage drop problem in shaded cells could be corrected by adding a bypass diode across each cell
- When a solar cell is in the sun, there is a voltage rise across the cell so the bypass diode is cut off and no current flows through it; it is as if the diode is not even there.



Bypass Diodes for Shade Mitigation

- When the solar cell is shaded, however, the drop that would occur if the cell conducted any current would turn on the bypass diode, diverting the current flow through that diode.
- The bypass diode, when it conducts, drops about 0.6 V.
- So, the bypass diode controls the voltage drop across the shaded cell, limiting it to a relatively modest 0.6 V instead of the rather large drop that may occur without it.





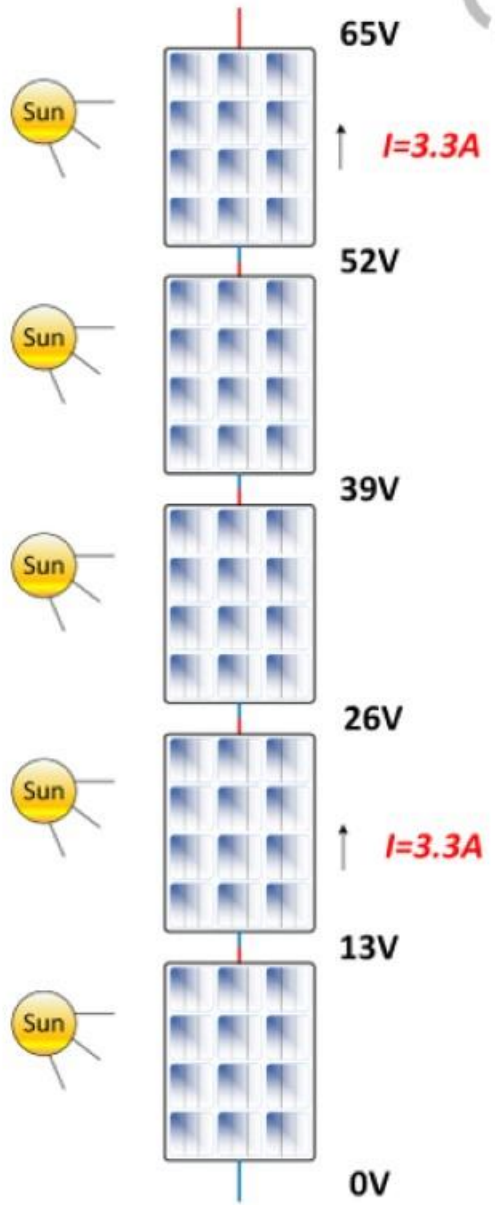
Bypass Diodes for Shade Mitigation

- In real modules, it would be impractical to add bypass diodes across every solar cell,
- but manufacturers often do provide at least one bypass diode around a module to help protect arrays, and sometimes several such diodes around groups of cells within a module.
- These diodes don't have much impact on shading problems of a single module, but they can be very important when a number of modules are connected in series.



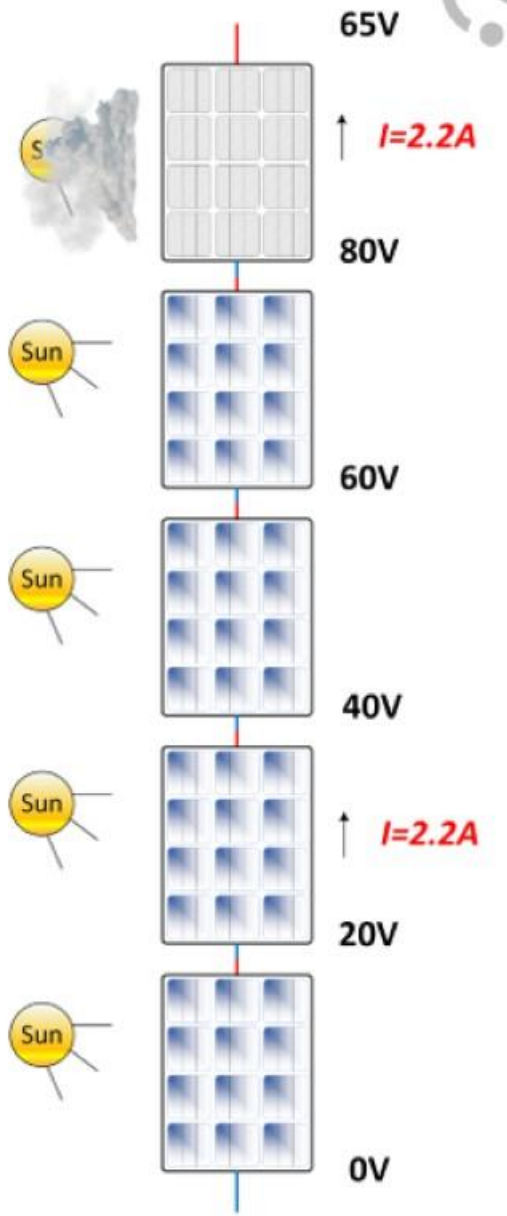
Bypass Diodes for Shade Mitigation – Modules in Series

- Imagine five modules, wired in series, connected to a battery that forces the modules to operate at 65 V.
- In full sun the modules deliver 3.3 A at 65 V.



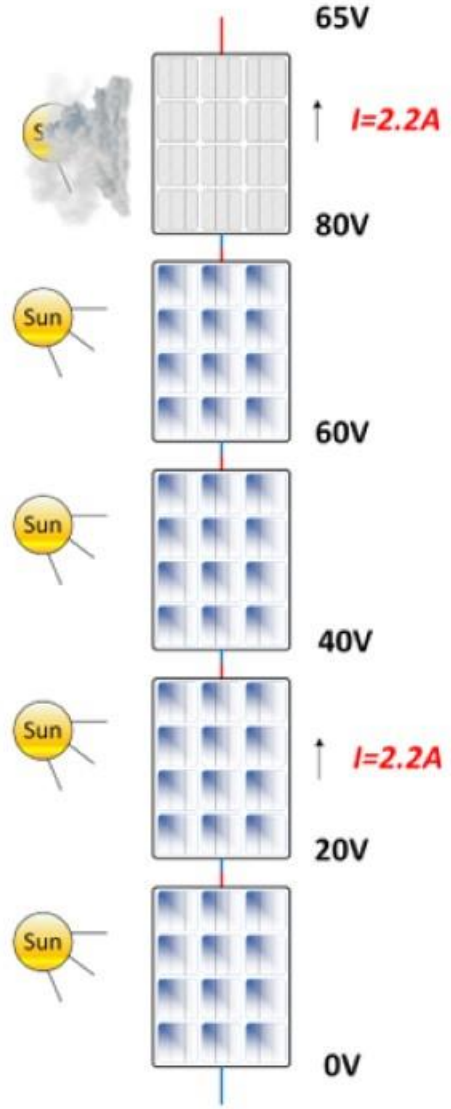
Bypass Diodes for Shade Mitigation – Modules in Series

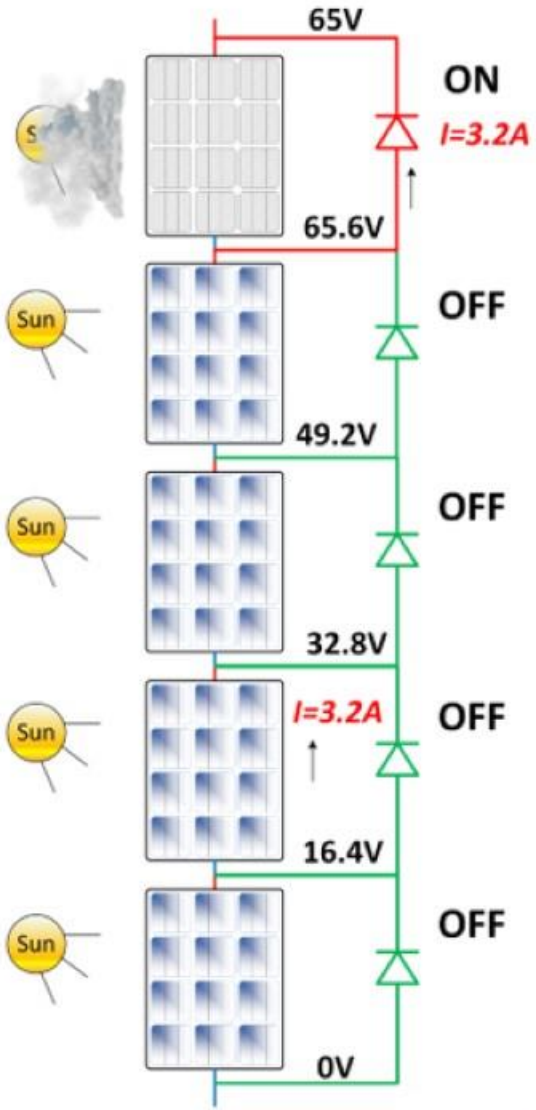
- When any of the cells are shaded, they cease to produce voltage and instead begin to act like resistors (6.6 Ω per cell in this example) that cause voltage to drop as the other modules continue to try to push current through the string.
- Without a bypass diode to divert the current, the shaded module loses voltage and the other modules try to compensate by increasing voltage, but the net effect is that current in the whole string drops.



Bypass Diodes for Shade Mitigation – Modules in Series

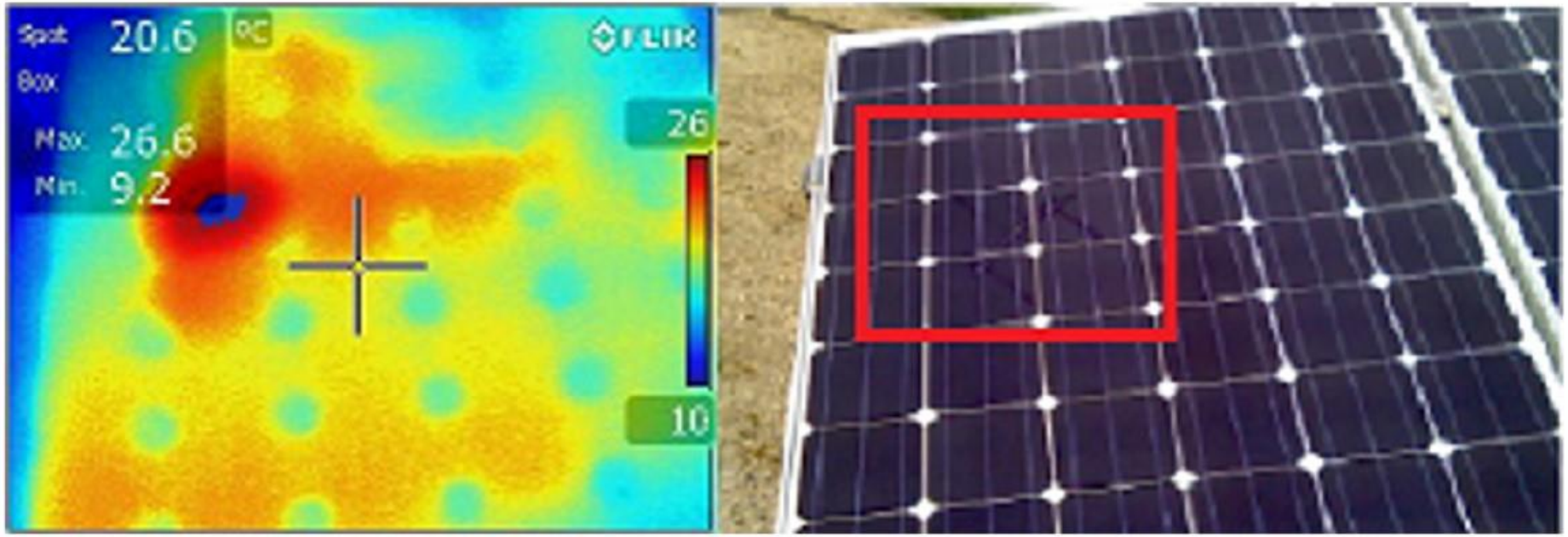
- If, however, bypass diodes are provided, then current will go around the shaded module and the charging current bounces back to nearly the same level that it was before shading occurred
- Bypass diodes help current go around a shaded or malfunctioning module within a string.





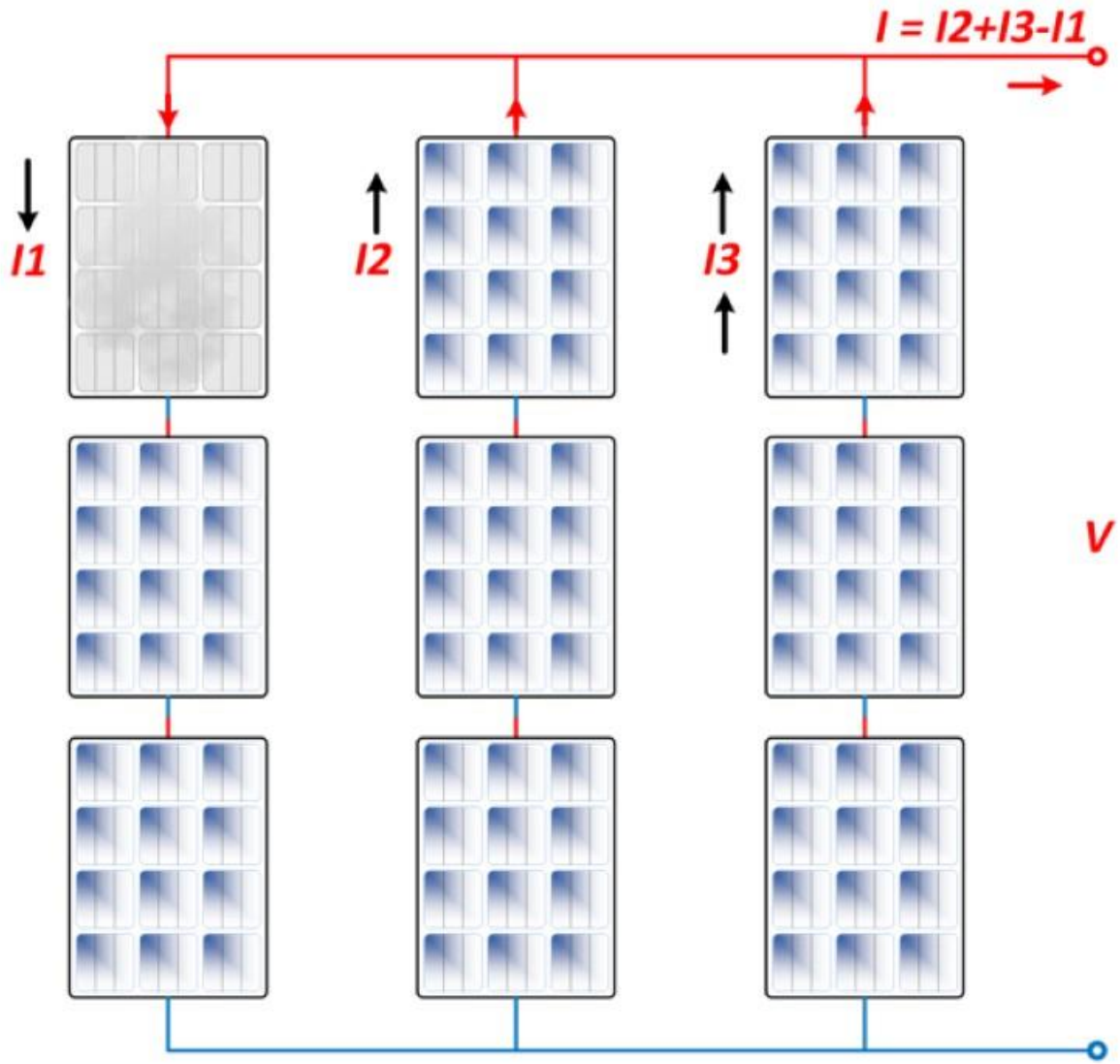
Bypass Diodes for Shade Mitigation – Modules in Series

- This not only improves the string performance, but also prevents ***hot spots*** from developing in individual shaded cells.



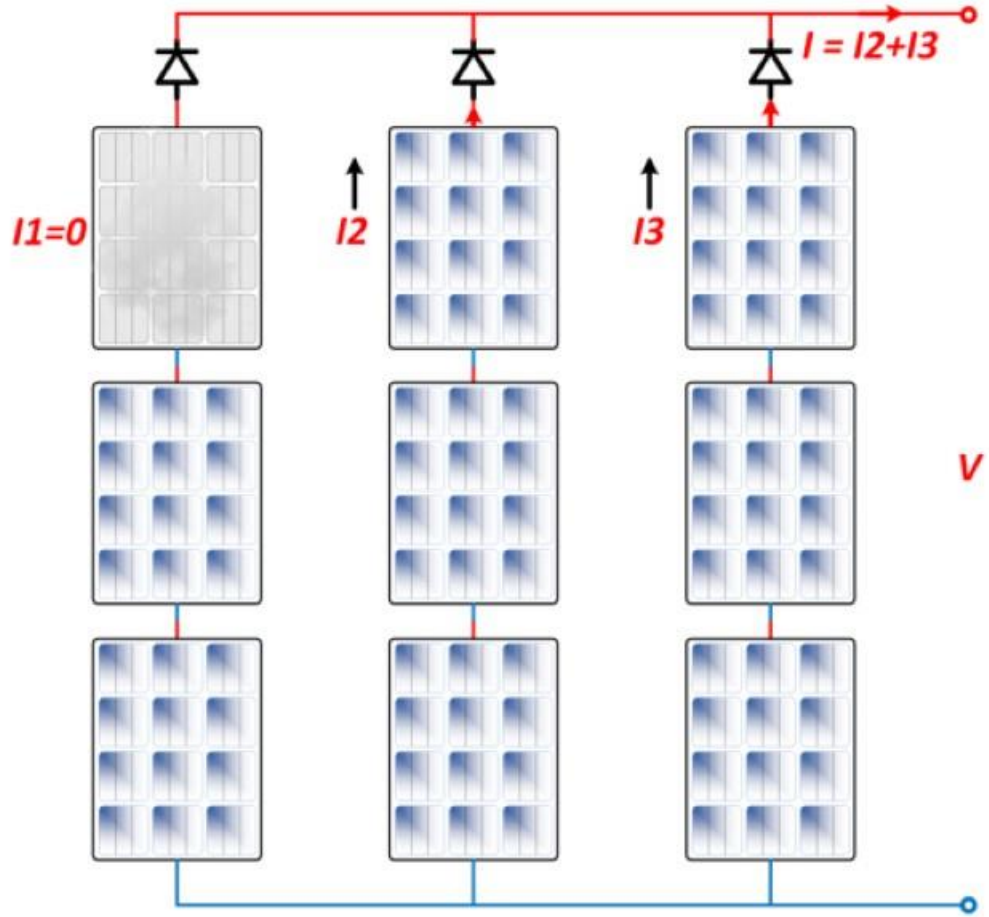
Bypass Diodes for Shade Mitigation – Modules wired in parallel

- When strings of modules are wired in parallel, a similar problem may arise when one of the strings is not performing well.
- Instead of supplying current to the array, a malfunctioning or shaded string can ***withdraw current*** from the rest of the array.



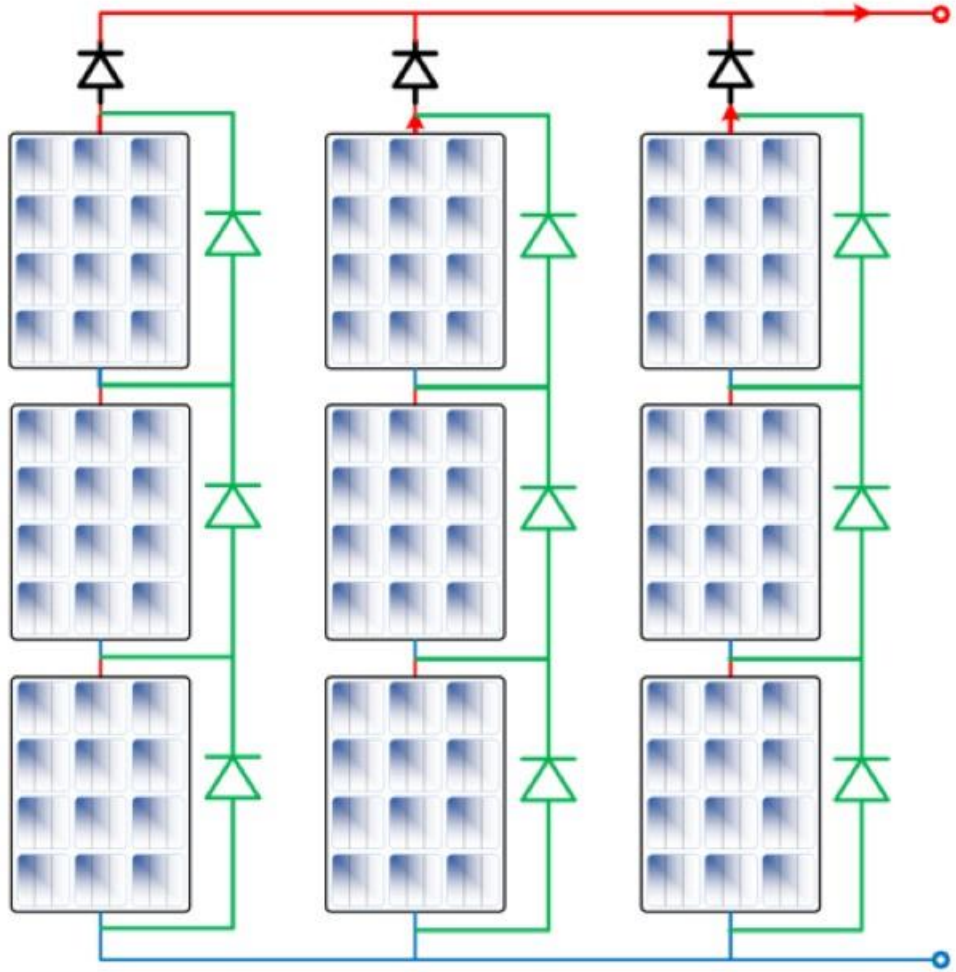
Blocking Diodes for Shade Mitigation – Modules wired in parallel

- By placing ***blocking diodes*** (also called *isolation diodes*) at the top of each string as shown in the figure below, the reverse current drawn by a shaded string can be prevented



Bypass/Blocking Diodes for Shade Mitigation – Modules wired in Series &parallel

- Bypass diode are already implemented in the PV junction box.
- Blocking diode are to be added by the engineer.



Conclusion



- **Intro 1)** When part of a PV module is shaded, the shaded cells will not be able to produce as much current as the un-shaded cells.
- **Intro 2)** Since all cells are connected in series, the same amount of current must flow through every cell.
- **Result:** The un-shaded cells will force the shaded cells to pass more current than their new short circuit current. The only way the shaded cells can operate at a current higher than their short circuit current is to operate in a region of negative voltage that is to cause a net voltage loss to the system.
- The shaded cells will dissipate power as heat and cause “hot spots”. And the shaded cells will drag down the overall IV curve of the group of cells. The effect of this shading is also dependent on how the module is shaded.

Conclusion

Function of a bypass diode: One way to minimize the effect shading has on a single module in a series string, is to use bypass diodes in the junction box. *Bypass diodes allow current to pass around shaded cells and thereby reduce the voltage losses through the module.* When a module becomes shaded its bypass diode becomes "forward biased" and begins to conduct current through itself. All the current greater than the shaded cell's new short circuit current is "bypassed" through the diode, thus reducing drastically the amount of local heating at the shaded area.

References

- https://www.zmescience.com/ecology/renewable-energy-ecology/solar-panels-pros-and-cons-056654/
- https://www.solarpowerworldonline.com/2018/02/fixed-tilt-vs-tracker-one-size-fits-approach-can-limit-solar-production/
- https://www.britannica.com/technology/solar-tracker
- https://csirosolarthermal.wordpress.com/tag/pyrheliometer/

End of Session 3

Photovoltaic Solar Energy Training Course

Section 4: Stand-Alone PV systems

Part 1
- PV Systems
- Stand-alone System Types
- Panels
- Batteries
- Charge Controllers
- Inverters

Part 2
- Cable Sizing/Resistance/Reactance, Loss
- Fuse
- Circuit Breaker
- Surge Protector
- Residual Current Device
- Junction Box
- Earthing and Lightning Protection

Part 3
- Components of a Stand-Alone System
- Sizing Steps of a Solar Home System
- Sizing Steps of a PV Water Pumping System

Part 4
- Challenging example
- Read data from Solar Atlas
- Size the PV, Battery, Inverter
- Design the system
- Calculate the plant area

Nabil Karami, PhD

Photovoltaic solar energy training course

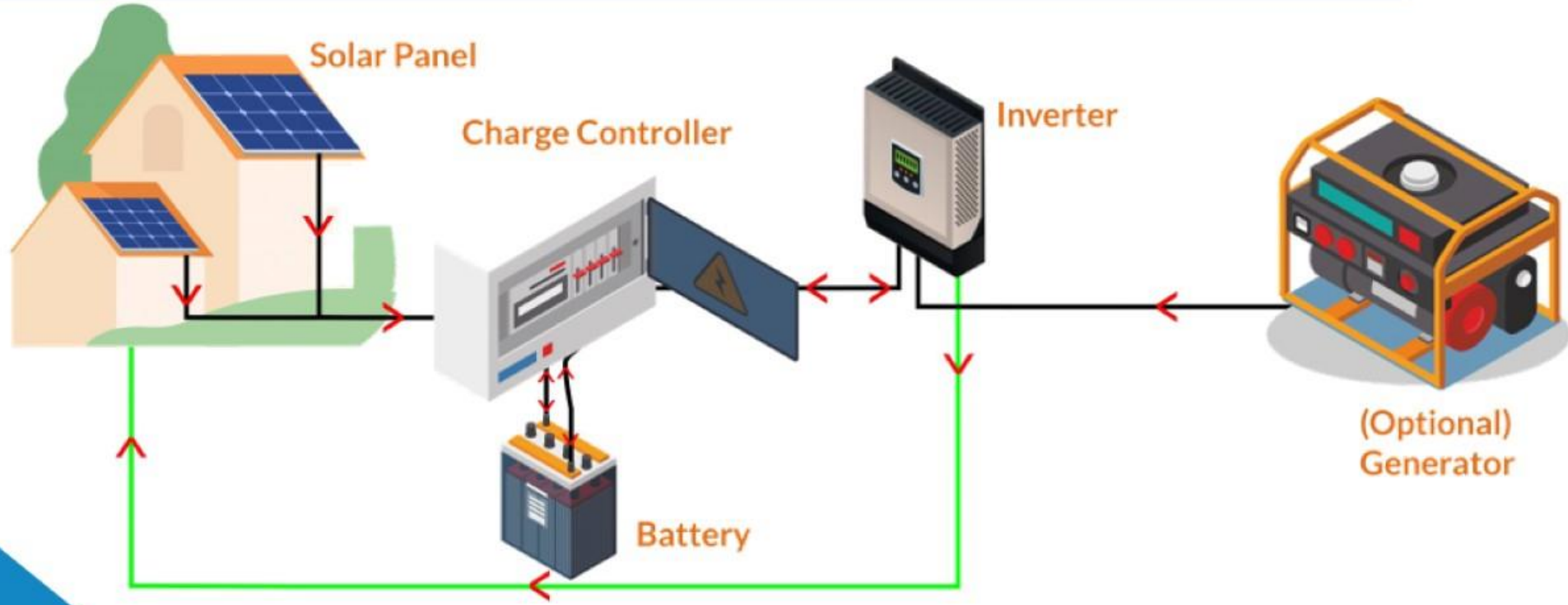
Section 4: Stand-Alone PV systems

Part 1

- PV Systems
- Stand-alone System Types
- Panels
- Batteries
- Charge Controllers
- Inverters

PV Systems

Stand-Alone System
May need other power sources (Hybrid system, Wind generator)
Battery bank (finite source): Cost, sizing, and reliability .
PV modules should be suitable for charging batteries (12, 24, 48V). Parallel or parallel/series connected modules.



PV Systems

Stand-Alone System	Grid-Connected System
May need other power sources (Hybrid system, Wind generator)	No need for other power sources
Battery bank (finite source): Cost, sizing, and reliability .	Grid (infinite source)
PV modules should be suitable for charging batteries (12V or 24 V). Parallel or parallel/series connected modules.	Higher voltage with series-connected modules

Stand-alone System Types



- System with all components
- System without battery storage or inverter:
  - PV supplies DC loads directly
  - DC motors
  - Water pumping, Solar Fountain
- System with battery, without inverter.
  - Solar-powered Garden lights, low-energy lights, small TV, remote telecoms, security systems, medical refrigeration.
- System without battery, with inverter.
  - AC motors for pumping during day time.

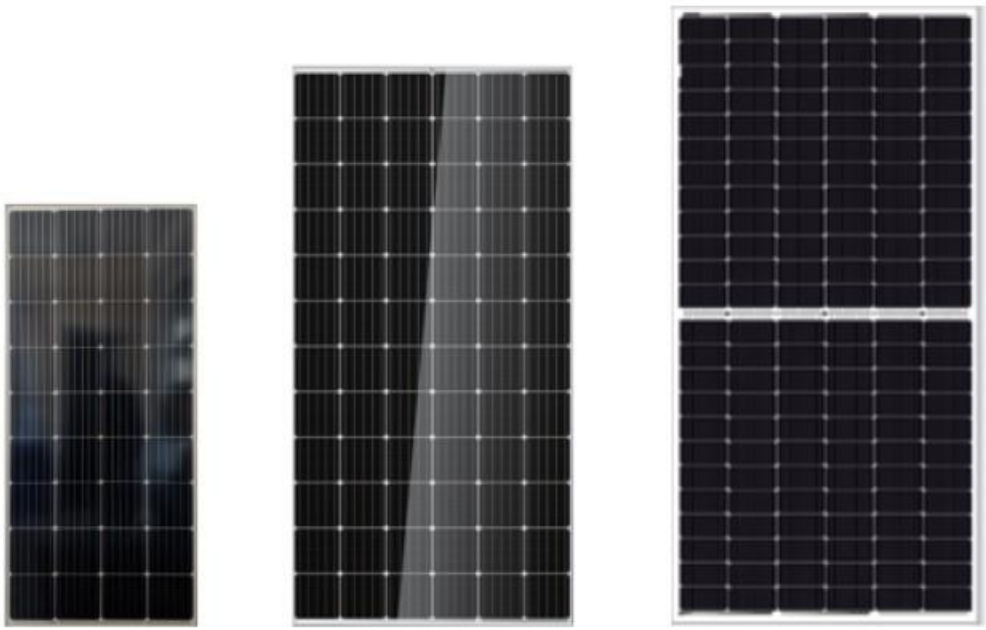
Stand-alone System Types



- ✓ With batteries: independent of sunlight changes
- ✓ Without batteries: confined to daylight hours

PV Panels

- Modules chosen for charging batteries in stand-alone PV systems need to have sufficient cells in series to deliver the required voltage.
  - **Rule 1:** For a 12 V battery this is 36 PV cells (V_{MPP} = 17−19V)
  - **Rule 2:** For a 24 V battery this is 72 PV cells (V_{MPP} = 34−38V).
  - **Rule 3:** For a 48 V battery, this is 144 PV cells (V_{MPP} = 40-42V with extra boost)



PV BOS

- The Balance of Systems (BOS) components include mounting materials for the modules, wire and all wiring components, lighting protectors, inverters, grounding connections and battery containers.
- These can be categorized as:
  - Mechanical BOS components
  - Electrical BOS components











Mechanical systems

Roof-mounted PV system (for roofs with tiles)



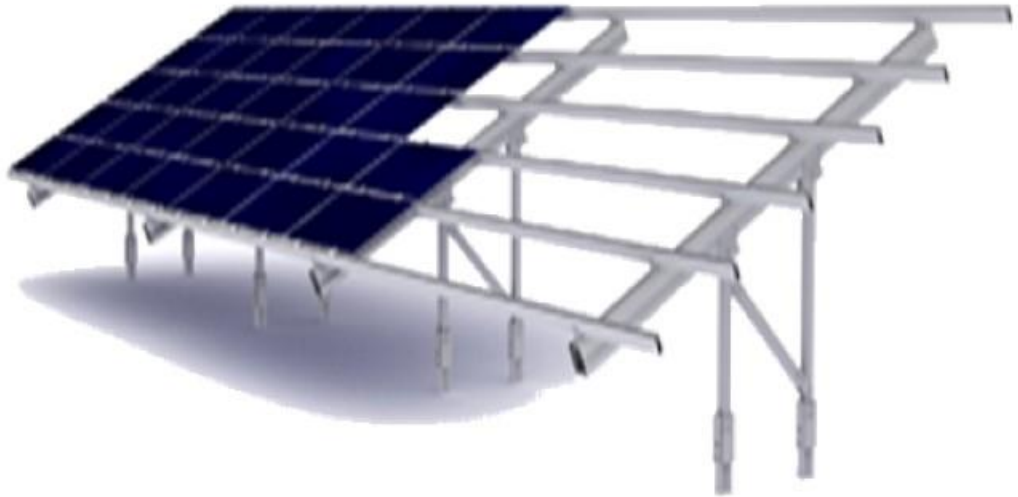
Roof-mounted PV system (for flat roofs)



Open-field fixed-mounted PV system (small system)



Open-field fixed-mounted PV system (large system)



Batteries

- Many different types of rechargeable batteries suitable for PV applications are currently available. Recent technology uses:
  - Lead acid batteries
  - Lithium $LiFePO_4$ batteries







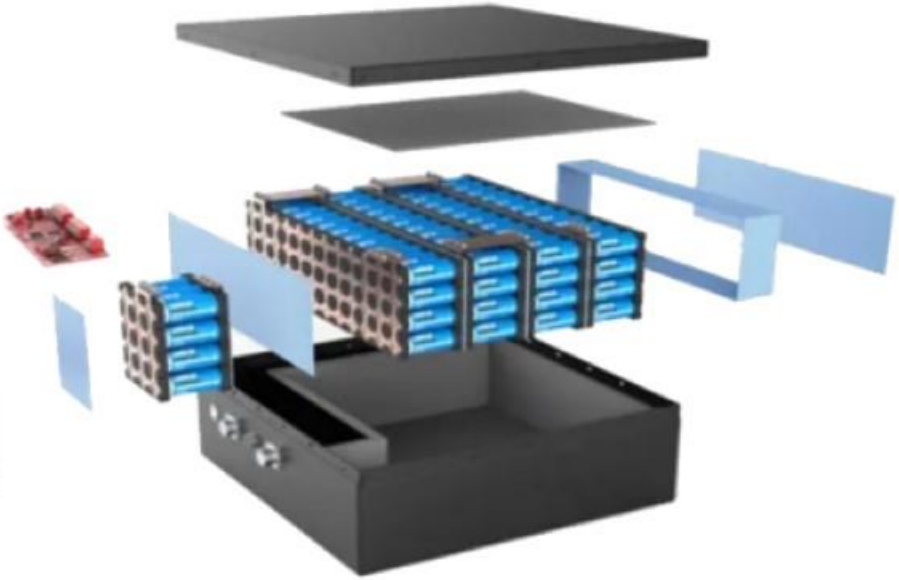
Lithium $LiFePO_4$ Batteries

- Best choice for PV systems (Higher charge/discharge cycles), longest lifespan
- Higher cost compared to Lead Acid battery
- Nominal voltage of Lithium cell is 3.2V
- A battery with 12.8V includes 4 series cells of 3.2V





△ Longer life span
△ Maintenance-free
△ Extremely safe
△ Lightweight
△ Improved efficiency



Lead Acid Batteries

- Second choice for PV systems
- Lower cost compared to Lithium battery
- Nominal voltage of a cell is 2V
- A battery with 12V includes 6 series cells of 2V





Lead Acid Batteries

- Lead acid batteries are mainly categorized in two types:
  - Flooded batteries: Also called wet cells because they have a liquid electrolyte which needs to be regularly topped up with deionized/distilled water
  - Sealed batteries: These batteries have either a gel electrolyte or incorporate a method of recombining the hydrogen and oxygen and do not need to be topped up





Batteries

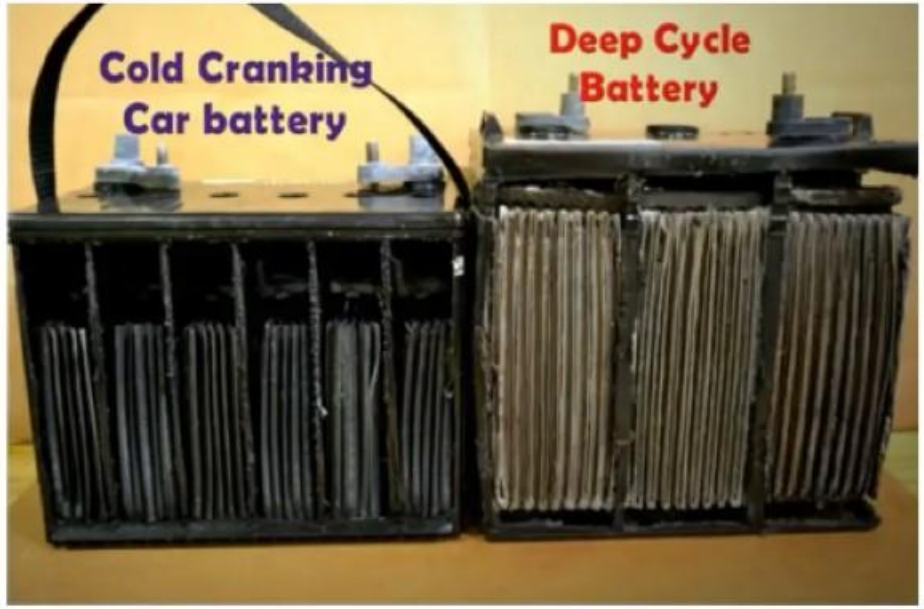
- **General Specs and features of Batteries**
- Batteries are electrochemical devices sensitive to climate, charge/discharge cycle history, temperature, and age.
- For every 1 Ah you remove from your battery, you will need to pump about 1.25 Ah back in to return the battery to the same state of charge (SOC).
- This figure also varies with temperature, battery type and age.

Batteries

- Capacity depends on the discharge time.
- Discharge time should be clear in the technical specification.
- Example: Battery with the following specifications:
  - Nominal voltage 12V
  - can provide 20A for 10 hours
  - → Capacity = 200Ah
  - → Total energy stored = 200Ah x 12V = 2400Wh = 2.4kWh
- Specifications: at 20°C, ~ 1% decrease in capacity per degree in temperature drop

Starter Batteries vs. Solar Batteries

- An important distinction must be made in order to avoid mistakes:
  - Starter batteries for use in cars: The positive and the negative plates are made of extremely thin grid plates. Due to a strong self-discharge of about 10 % per week and low cycle stability, these batteries are less suited to be storage for PV systems
  - Solar batteries: These batteries are advanced starter batteries with enhanced grid plates and increased electrolyte reservoirs and thereby have lower self-discharge.



Batteries

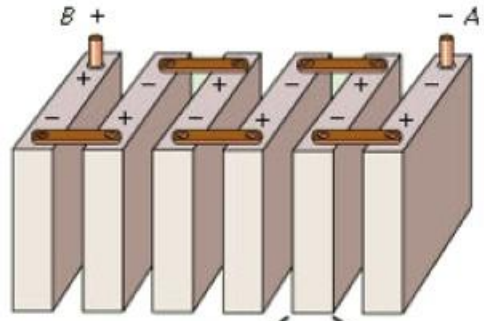


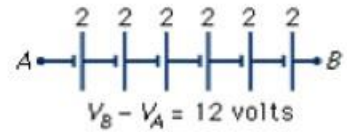
Vehicle Battery	Solar Battery
It supplies large current (hundreds of Amps) for a very short time	It supplies small current for long time
It is not supposed to be substantially discharged	It can be substantially discharged
It is not supposed to withstand cycling (charging-discharging)	It should withstand cycling (charging-discharging)

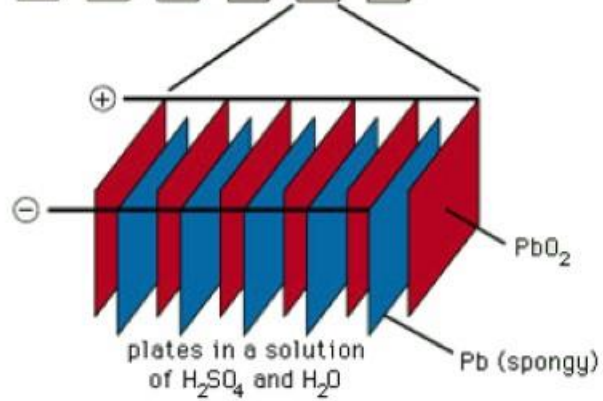
Batteries



- Batteries consist of a number of cells connected in series to give a voltage that is a multiple of the cell voltage.
- To increase the battery stored voltage, in multiples of 12V, batteries are connected in series.
- To increase the battery stored energy capacity, series strings of batteries are connected in parallel as PV module strings are to increase PV array capacity.







Batteries Discharge Constant

- The additional information C10, C20 or C100 indicates that the capacity is only valid when there is a constant load consumption for 10, 20 and 100 hours respectively.
- The capacity of a C10 battery corresponds to a discharge at a constant current *I*, over a period of 10 hours.



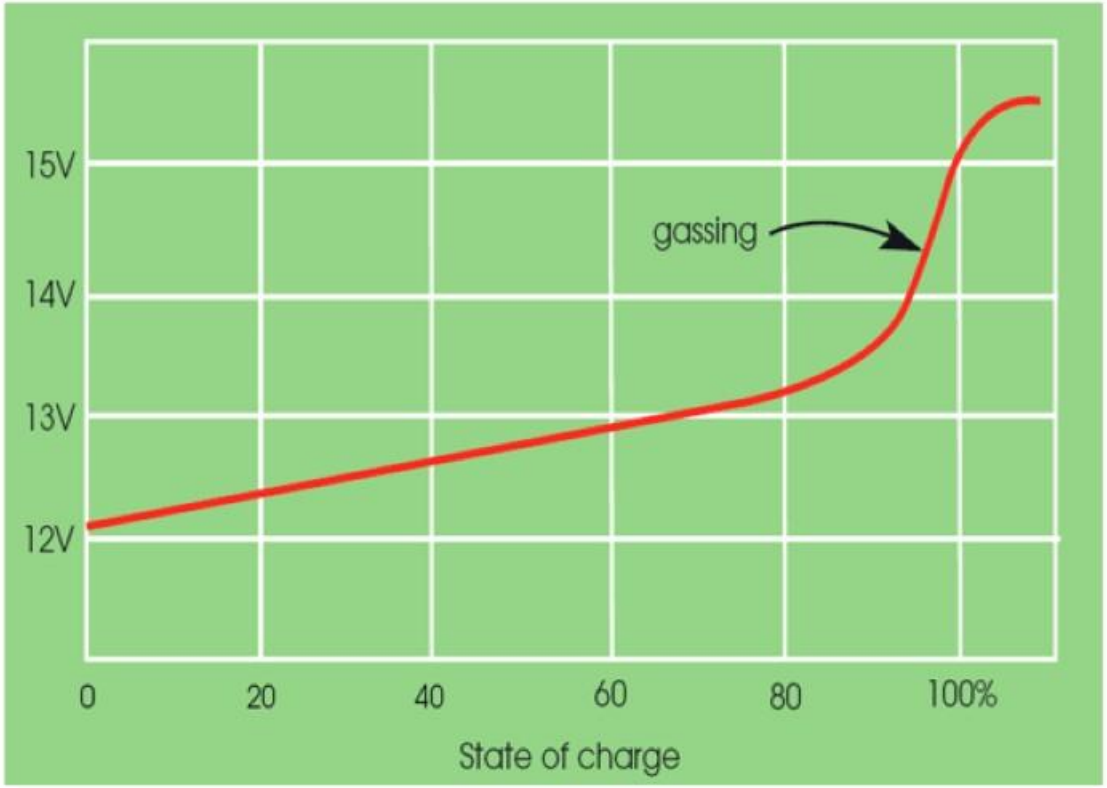
Batteries Discharge Constant

- For example, a 56Ah C14 battery is discharging with current *I* = 3.85A for 14 hours.
- For PV systems longer discharge periods are required, a C100 rating is normally used.
- The Depth of Discharge, "**DOD**" is the percentage of the total capacity removed.



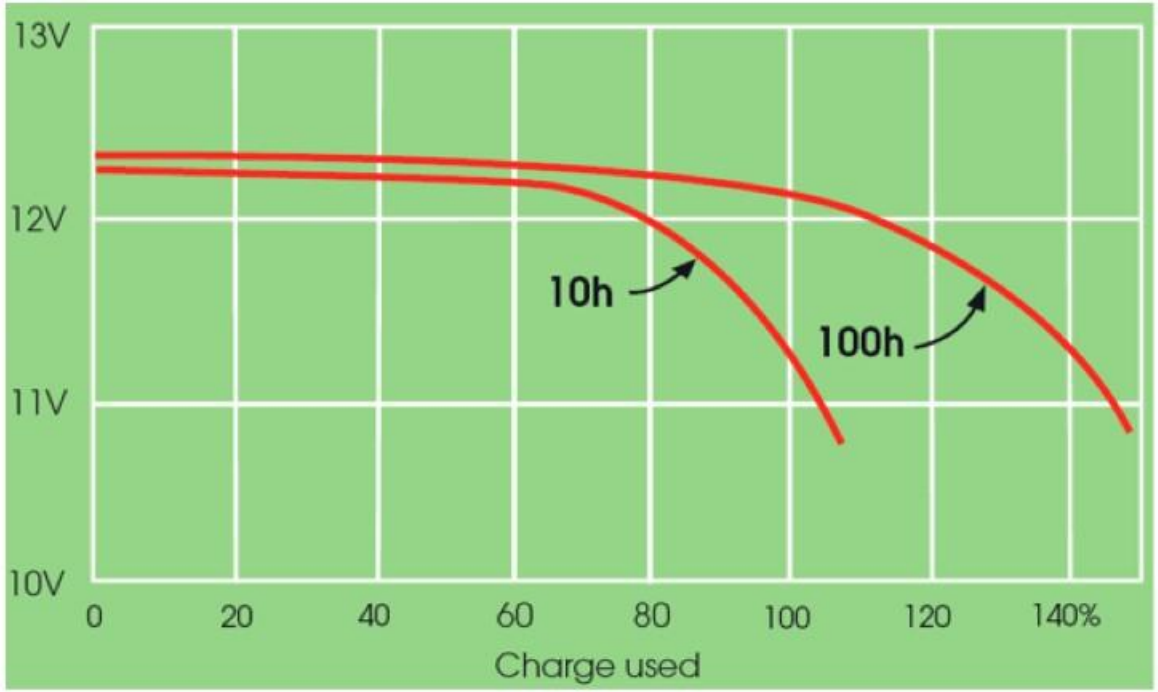
Battery State of Charge SOC

- For a 12V Lead Acid Battery
- Charging at constant current
- State of charge (SOC)
- Initially close to 12V, voltage rises steadily as SOC increases.
- Near final phase, voltage increases rapidly, reaching over 14.8V at SOC of 100% (full charge) .



Battery State of Charge SOC

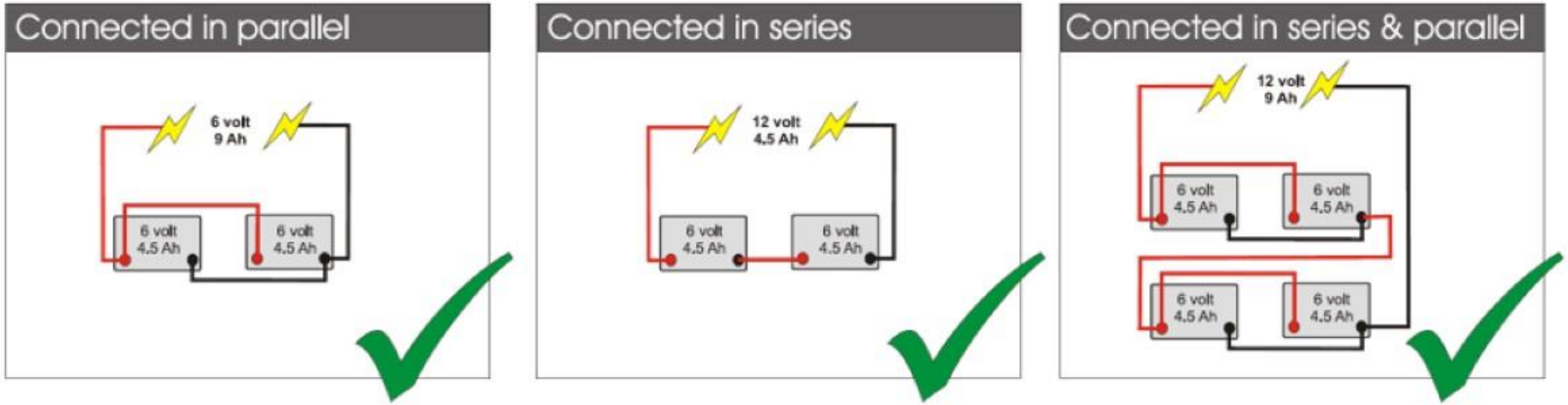
- 12V, 200Ah discharging at constant current
- 10h curve:
  - 20A for 10 hours
  - Voltage decreases from down to ~ 11V (full charge used)
- 100h curve:
  - 2A for 100 hours
  - Voltage holds up better
  - Total available charge is increased.

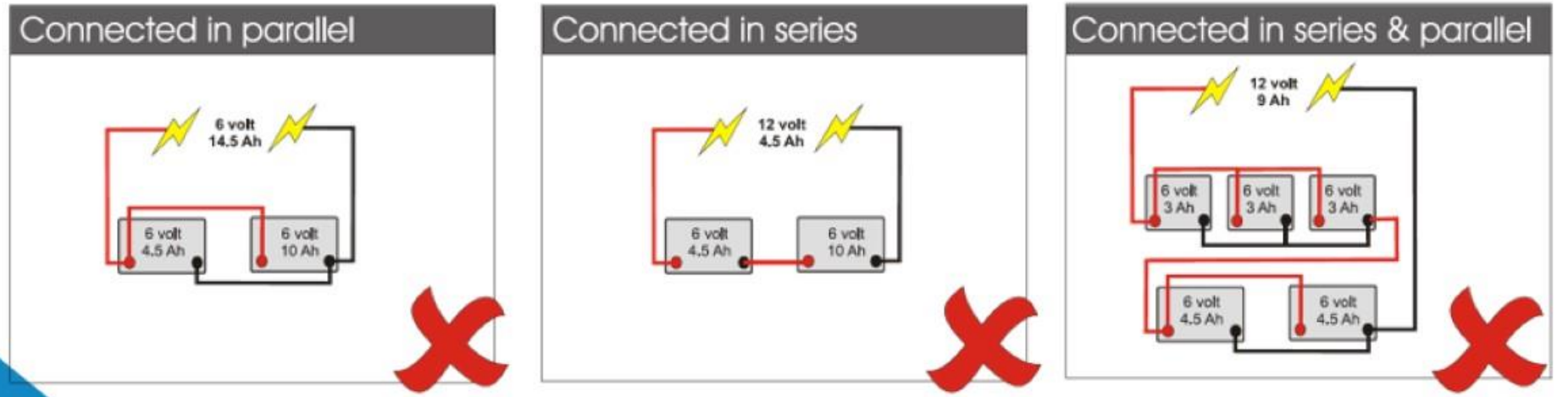


The point of 11V is recommended by the manufacturer to disconnect the load to prevent battery damage

Battery Series/Parallel

- **A common mistake**
- 2 series batteries of 12V 100Ah **are not equal** to a 24V **200Ah** battery





Charge Controller

- The main functions of the charge controller are to:
  - It is used to regulate flow of current
    - from PV array to battery bank.
    - from battery bank to electrical loads.
  - Battery voltage is used as “control signal” to regulate current flow

SystemVoltage	12 V (24 V)
Open-circuit Voltage of PV Array input	< 47 V
Short-circuit current of PV Array input	10 A (20 A)



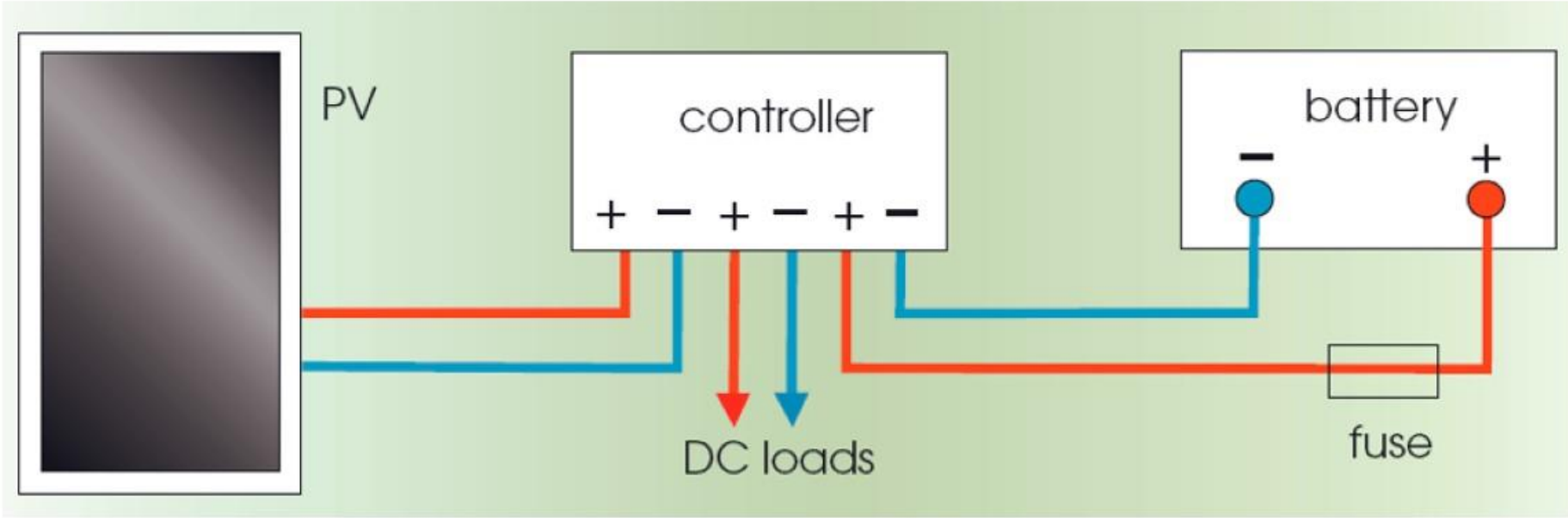
Charge Controller

- It prevents
  - Over-charging when solar electricity supply exceeds demand by disconnecting PV input whenever battery voltage reaches an upper set point (14V to 14.7V)
  - Over-discharging when demand exceeds supply by disconnecting load and/or giving warning when battery voltage falls to a lower set point (~11V).
  - Prevent current flowing into PV array at night (blocking diode inside the controller box)



Charge Controller

- Control and display functions, depending on the price and sophistication, affect system performance and battery life.
- External circuit connections for simple unit.
- Six terminals
- Fuse on the +ve battery terminal to prevent short circuits.



Charge Controller with Maximum Power Point Tracker

- It extracts more energy and improve efficiency of a PV system by working a PV array at its MPP (rather than at a voltage determined by a battery).
- It allows a wide choice of high voltage modules (Large PV modules and thin-film modules produce large voltages; unsuitable for batteries).



(Steca Elektronik GmbH).

Maximum Power Point Tracker

Charge Controllers Types



PWM

- Pulses direct connection from solar panel to battery
- Voltage pulled down to battery voltage

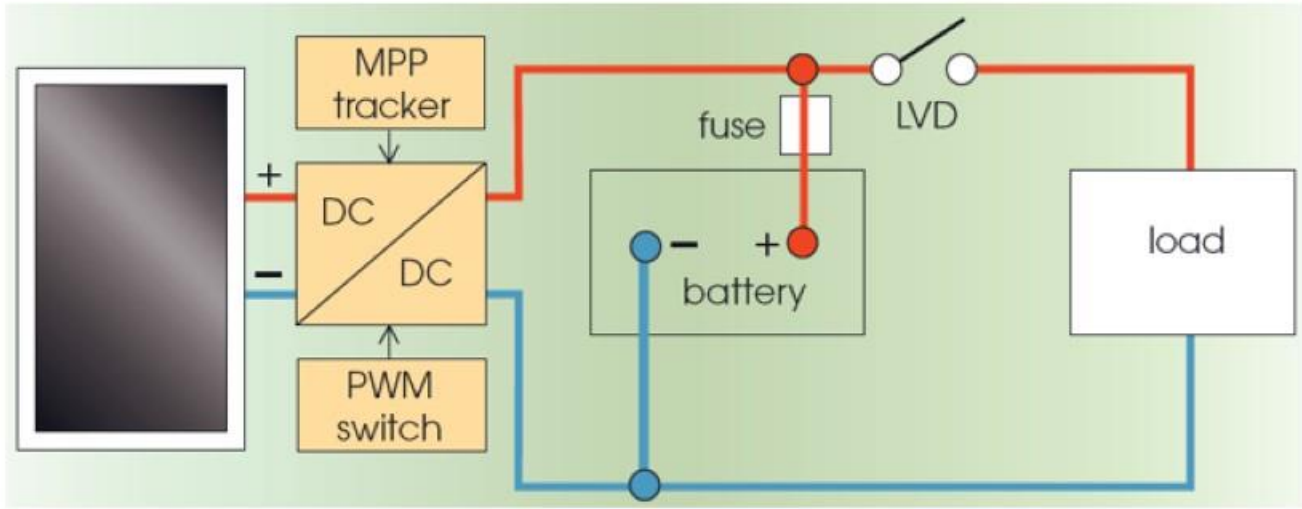


MPPT

- Converts voltage input to battery voltage
- Increases current when voltage drops
- More expensive then PWM

Charge Controller with Maximum Power Point Tracker

- DC/DC converter allows PV array to operate at a different DC voltage from that voltage of battery bank.
- Types: Boost, buck , Buck-boost converters
  - Boost converters: raise input voltage to higher values.
  - Buck converters: reduce input voltage to smaller values.
- Algorithm performs a continuous electronic tracking of the array's MPP.



Inverters for Stand-Alone systems

- It is required when AC load used in the system.
- Solar AC systems are used more and more because it gives a flexibility by using a wide range of consumer electronics, household appliances, electric tools, and machines.

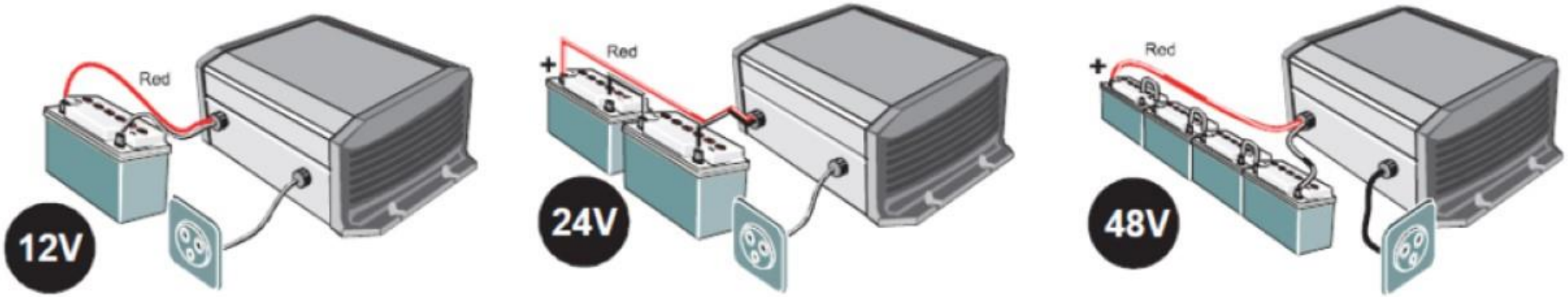






Inverters for Stand-Alone systems

- Inverters convert a DC output from a battery to provide an AC supply for 'standard' appliances which have been designed for use with the mains/grid.
- The inverter is designed to operate at a nominal voltage of 12V, 24V or 48V with higher power rated inverters using higher supply voltages.
- An inverter designed for stand-alone, battery supplied operation generally cannot be used as grid connected.

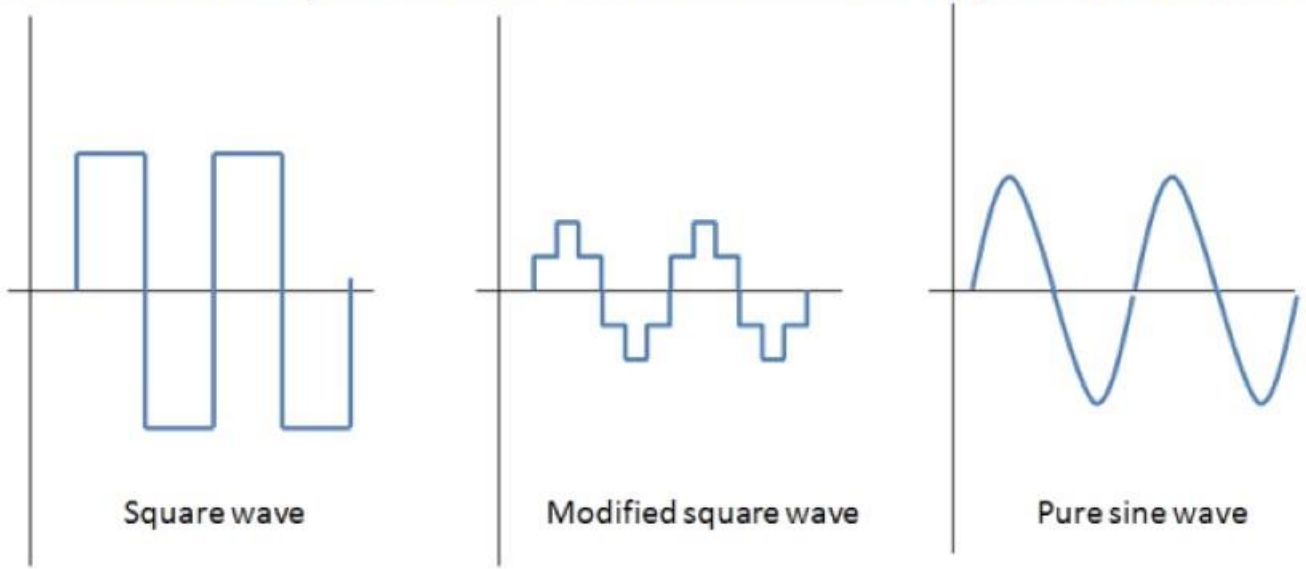


Inverters for Stand-Alone systems

Grid-connected Inverter	Stand-alone inverter
It requires generating AC at precisely the right frequency and phase.	It does NOT require generating AC at electrical utility specifications. However, waveform must suit AC load.
It is connected to PV array and performs MPP tracking.	It is connected to battery bank (charge controller performs MPP tracking).
It deals with variable conditions	It deals with constant DC voltage (more or less).
Careful selection (shading)	Simpler selection (usually shading is not a problem).

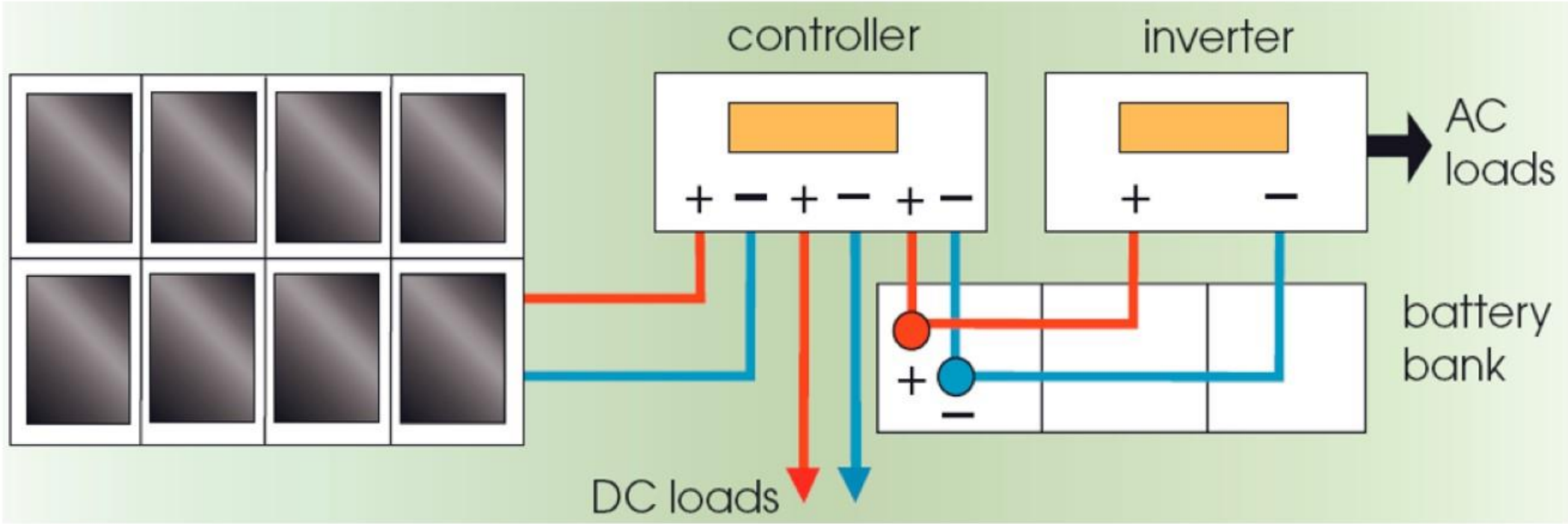
Inverters for Stand-Alone systems

- **Three Inverter techniques are available**
  - **Square wave:** This is the cheapest and is the noisiest electrically. Switching happens at line frequency (50/60 Hz). There is some kind of low pass filtering on the output.
  - **Modified square wave:** This is essentially a very poor version of a sine wave. Switching frequency is low and is again full of harmonic noise.
  - **Pure sine wave:** This is actually generated using rectangular waves switching at much **higher frequency** than line frequency. The duty cycle of the rectangular wave is adjusted on the fly to create an reasonable approximation of a sine wave.



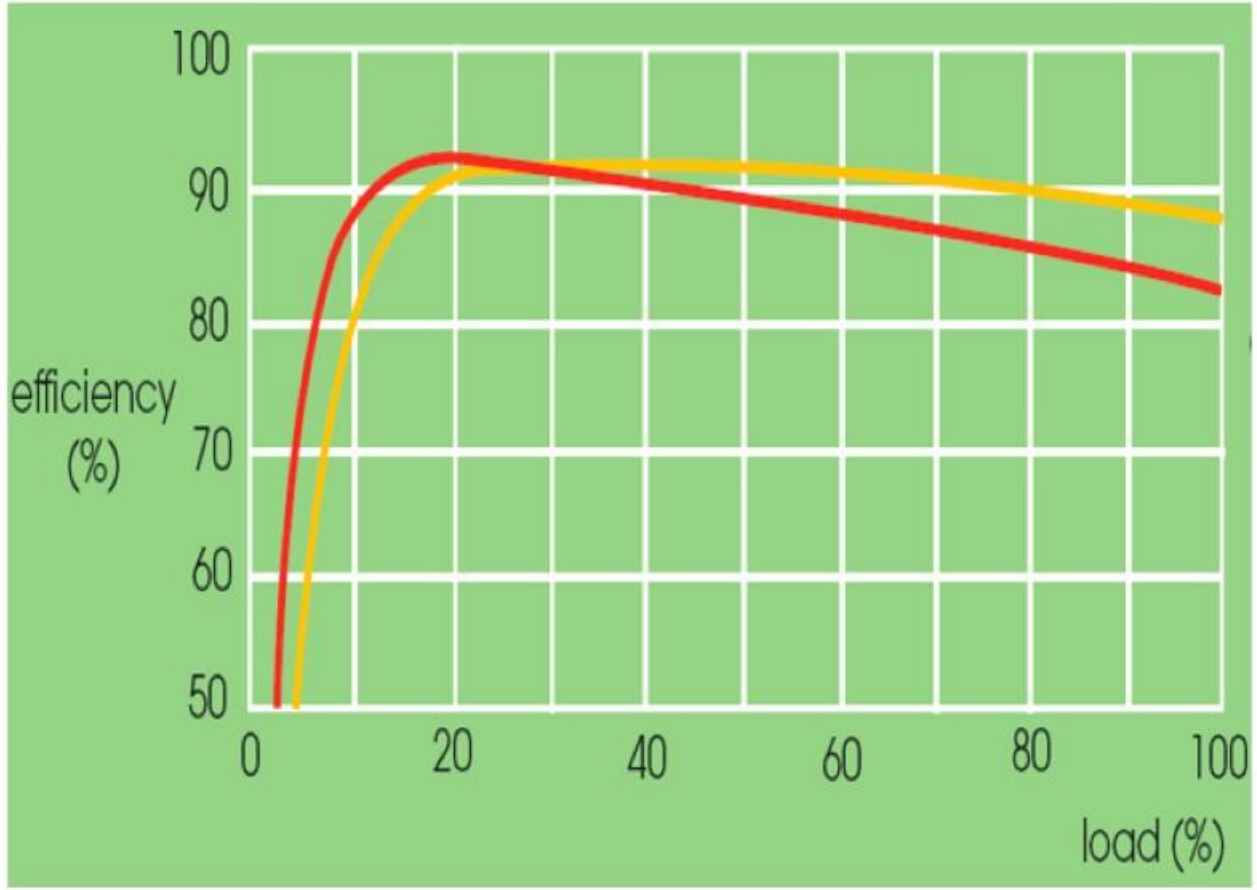
Inverters for Stand-Alone systems

- Fuses are included in controller and inverter.
- Inverters in stand-alone systems can deal with 12, 24, or 48V (according to battery).



Inverters for Stand-Alone systems

- Red: Inverter with low-frequency transformer.
- Orange: Inverter with high-frequency transformer.
  - Load < 10%: Efficiency is very low.
  - Load > 90%: Efficiency is near maximum.
- LF Inverter is better at low load.
- HF Inverter is better at high load.



- End of part 1

Photovoltaic solar energy training course

Section 4: Stand-Alone PV systems

Part 2

- Cable Sizing/Resistance/Reactance, Loss
- Fuse
- Circuit Breaker
- Surge Protector
- Residual Current Device
- Junction Box
- Earthing and Lightning Protection

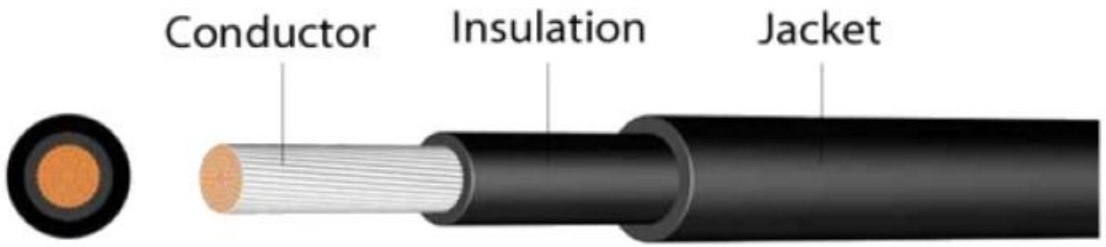
Nabil Karami, PhD

Cables

- Cables should be appropriately rated for expected current and voltage ranges.
- PV cables are likely to be exposed to harsh weather and so should be suitably weather resistant, e.g. UV stable.
- Most PV modules have DC cables with cross sectional area 4 or 6 mm^2.
- For the DC side the cable should have a minimum current rating of:

$$I_{DC,cable} = n \times I_{SC} \times 1.5$$

where n is the number of similar voltage strings connected in parallel and I_{SC} is the PV module short circuit current.



Cables

- For high system voltages, such as in grid connected PV, double insulated cable should be used for safety reasons.
- For the PV the cable should have a minimum voltage rating of:

$$V_{DC,cable} = m \times V_{OC} \times 1.15$$

where m is the number of similar current PV modules connected in series and V_{OC} is the PV module open circuit voltage.



Cable Resistance and Reactance

Resistances and reactances per km of cables

	single-core cables		Multi-core cables	
Nominal section (mm2)	Resistance per km (Ohm/km)	Reactance per km (Ohm/km)	Resistance per km (Ohm/km)	Reactance per km (Ohm/km)
1	22,1	0,176	22,5	0,125
1,5	14,8	0,168	15,1	0,118
2,5	8,91	0,155	9,08	0,109
4	5,57	0,143	5,68	0,101
6	3,71	0,135	3,78	0,0955
10	2,24	0,119	2,27	0,086
16	1,41	0,112	1,43	0,0817
25	0,889	0,106	0,907	0,0813
35	0,641	0,101	0,654	0,0783
50	0,473	0,101	0,483	0,0779
70	0,328	0,0965	0,334	0,075
95	0,236	0,0975	0,241	0,0762
120	0,188	0,0939	0,191	0,074
150	0,153	0,0928	0,157	0,0745
185	0,123	0,0908	0,125	0,0742
240	0,0943	0,0902	0,0966	0,0752
300	0,076	0,0895	0,078	0,075
400	0,0607	0,0876	0,0625	0,0742
500	0,0496	0,0867	0,0512	0,0744
630	0,0402	0,0865	0,0417	0,0749



Single-core cable



Multi-core cable

Cable Voltage Loss

- The voltage drop percentage on a DC cable can be calculated using the formula

$$\Delta V_{\%} = 2 \times \frac{R}{V_{nom}} I_{nom} \times \frac{L}{1000} \times 100$$

- Where,
  - **L** is the length of the cable in meters
  - $\mathbf{I_{nom}}$ is the nominal current of the cable at STC in A
  - $\mathbf{V_{nom}}$ is the nominal voltage of the cable at STC in V
  - **R** is the resistance of the cable per km at the maximum operational temperature (80°C) provided by the datasheet
- The voltage drop on the DC side must not exceed 2% (for the longest path)

Cable Voltage Loss

- For a single phase circuit, the voltage drop percentage on a AC cable can be calculated using the formula:

$$\Delta V_{\%} = 2 \times \frac{\sqrt{R^2 + X^2}}{V_{AC}} I_{nom} \times \frac{L}{1000} \times 100$$

- For a 3 phase circuit, the formula is:

$$\Delta V_{\%} = 1.73 \times \frac{\sqrt{R^2 + X^2}}{V_{AC}} I_{nom} \times \frac{L}{1000} \times 100$$

- Where,
  - **L** is the length of the cable i meters
  - $\mathbf{I_{nom}}$ is the nominal current of the cable at STC in A
  - $\mathbf{V_{AC}}$ is the grid voltage of the cable at STC in V
  - **R, X** are the resistance and reactance of the cable per km at the maximum operational temperature (80°C) provided by the datasheet

Fuses

- Fuses, Miniature Circuit Breakers (MCBs DC/AC) and switches serve similar functions in PV systems because both are used to isolate sections of the system for maintenance or in the event of emergency or malfunction.
- In the DC site, the minimum current rating for the fuses used is given from the following equation:

$$I_{DC,Fuse} = n \times I_{SC} \times 1.25$$

where, n is the number of parallel connected PV modules and I_{SC} is the short-circuit current of the PV module.



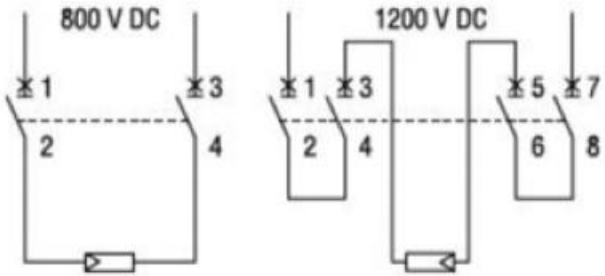
DC Circuit Breakers

- DC distribution board.

Main technical specifications		S800 PV-M
Reference Standards		IEC EN 60947-3
Rated current In	[A]	32, 63, 125
Number of poles		2, 4
Rated voltage Ue (d.c.) 2 poles* (d.c.) 4 poles*	 [V] [V]	 800 1200
Ultimate rated short-circuit breaking capacity Icu (d.c.) 600/800 V (2 poles) * (d.c.) 1200 V (4 poles) *	 [kA] [kA]	 1.5 1.5
Class of use		DC-21A
Operating temperature	[°C]	-25…+60
Mounting		on EN 60715 channel (35 mm) with a quick coupling device

DC MCB





Source: ABB

Fuses

- DC distribution board.

Main technical specifications		E 90/32 PV
Reference Standards		IEC EN 60947-3
Rated service voltage	[Vd.c.]	1000
Class of use		DC-20B
Fuse	[mm]	10 x 38
Type of current		d.c.
Rated current	[A]	32
IP Rating		IP20
Lockable (when open)		Yes
Sealable (when closed)		Yes

DC fuse



Source: ABB

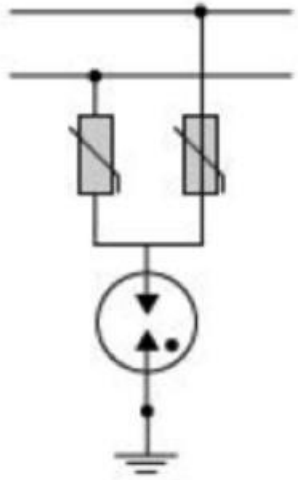
Surge Protectors

- DC distribution board.

I Max	Protection Level (L-L/L-PE) kV
40A	2.8/1.4
	2.8/1.4
	3.8
	3.8

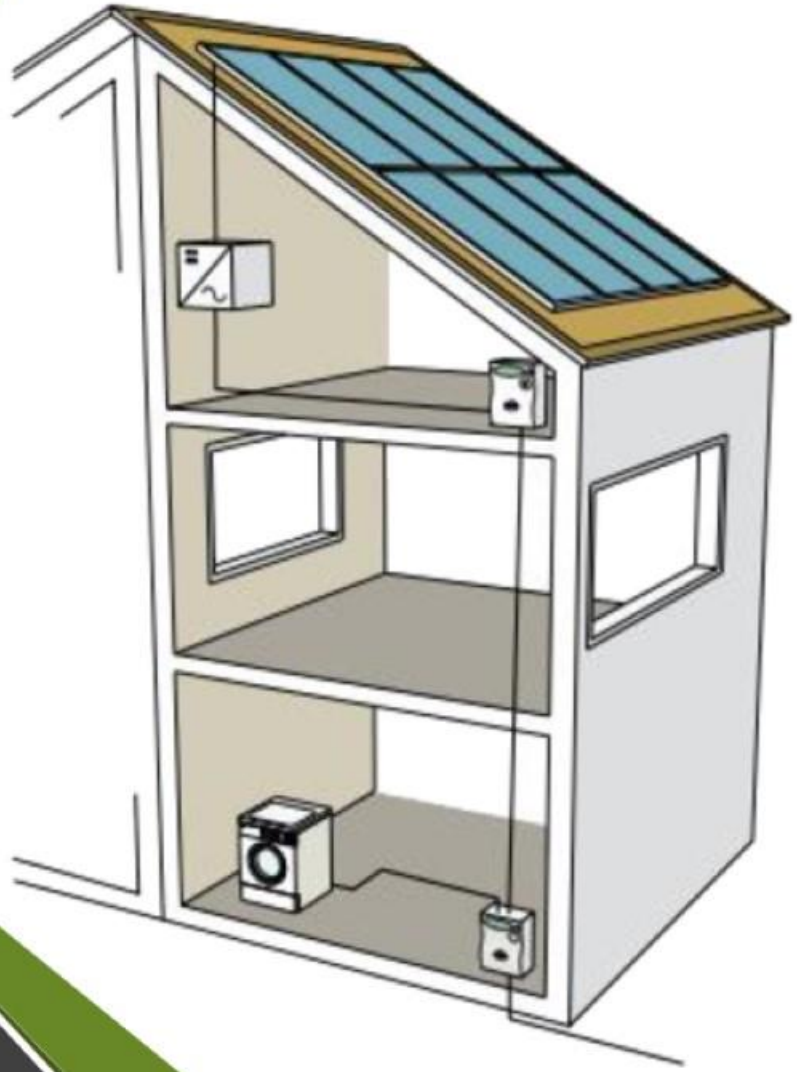
DC SPD

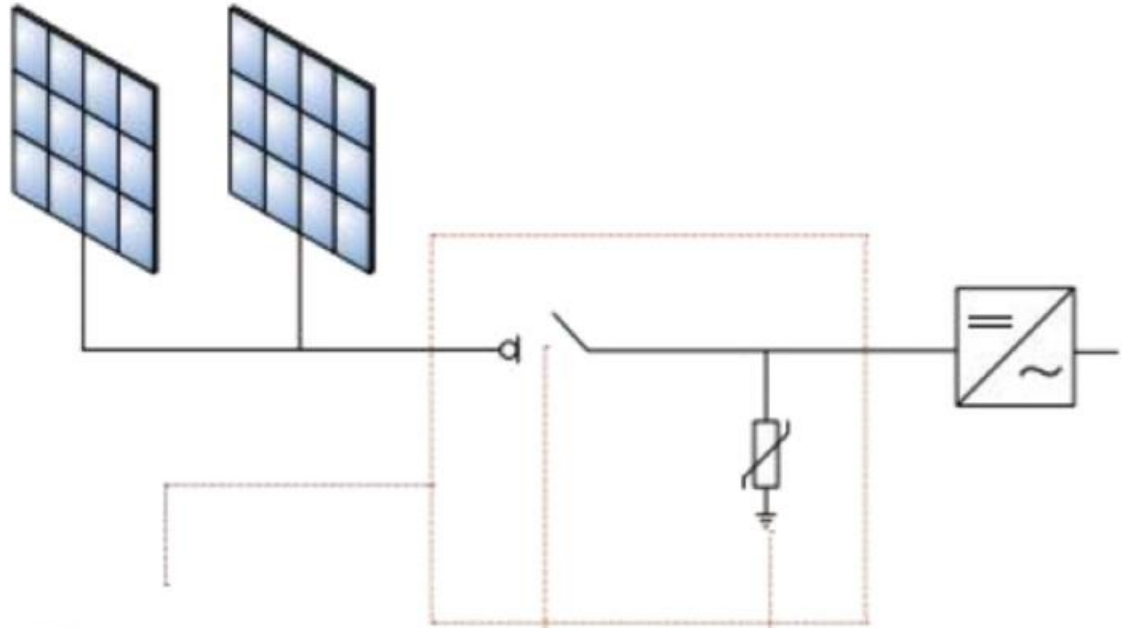




Source: ABB

Fuses, Circuit Breakers Connection









AC Residual Current Device

- AC distribution board.

Main technical specifications	F202 PV B, F204 B
Rated operating current	25, 40, 63, 125A
Rated sensitivity current	30, 300, 500mA
Rated operating voltage	230 ... 400 VAC
Poles	2 ... 4
Type	B, B S (selective version)
Reference Standards	IEC/EN61008 IEC52423

AC RCD



Source: ABB

AC Circuit Breakers

- AC distribution board.

Main technical specifications		S 200M
Reference Standards		IEC 60898, IEC 60947-2 UL 489, UL 1077
Rated operating current	[Vd.c.]	0,5 ... 63 A
Ultimate short-circuit breaking capacity		6, 10, 25 kA
Rated operating voltage	1-pole 2-4 pole	12 ... 230 VAC 12 ... 400 VAC

AC MCB



Source: ABB

AC Surge Protective Device

- AC distribution board.

Main technical specifications	OVR T2
Rated operating voltage	230V and 400V AC
Poles	1, 2, 3, 4
Maximum discharge current	15, 40, 70kA
Residual current	< 1
Voltage protection level	1.2 .... 3.8kV
Standards	IEC 61643-1 IEC 61643-11

AC SPD



Source: ABB

Junction Boxes / Cable Glands

- AC distribution board.

AC consumer unit



Description	Dimensions
IP65 consumer unit P/smoke grey 4M	140 x 220 x 140
IP65 consumer unit P/smoke grey 8M	205 x 220 x 140
IP65 consumer unit P/smoke grey 12M	275 x 220 x 140
IP65 consumer unit P/smoke grey 8M 1 row	380 x 220 x 140
IP65 consumer unit P/smoke grey 24M 2 rows	275 x 370 x 140
IP65 consumer unit P/smoke grey 36M 2 rows	380 x 370 x 140

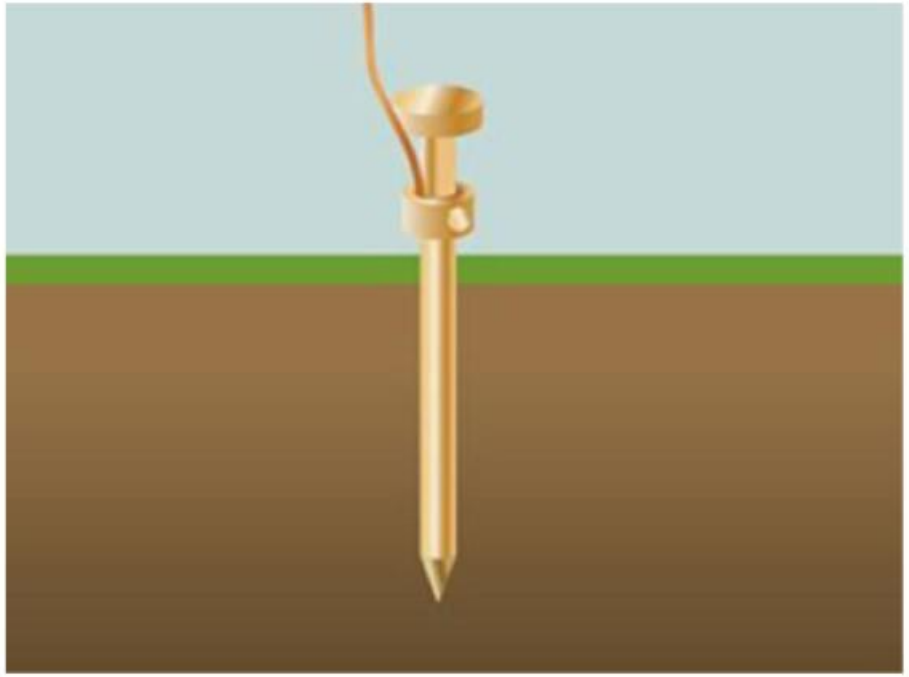
Cable glands



Source: ABB

Earthing & Lightning protection

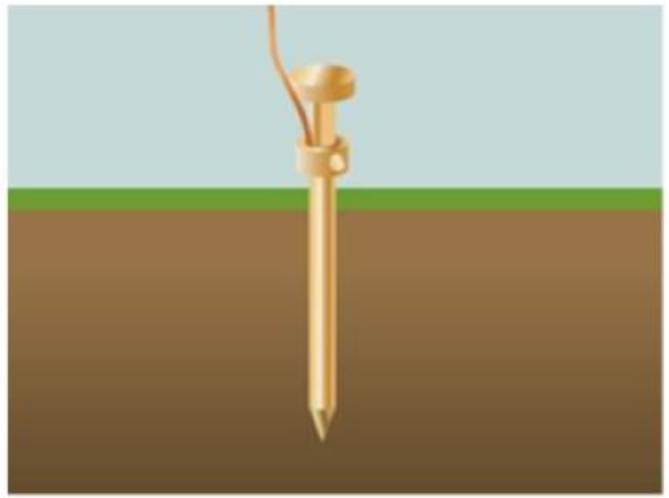
- Why the need for Earthing/Grounding?
  - To limit voltages due to line surges, lightning or unintentional contact with higher voltage lines.
  - To stabilize the voltages and provide a common reference point which it the earth.
  - To provide a path in order to facilitate the operation of overcurrent devices such as Residual Current Devices (RCDs).



Earthing & Lightning protection

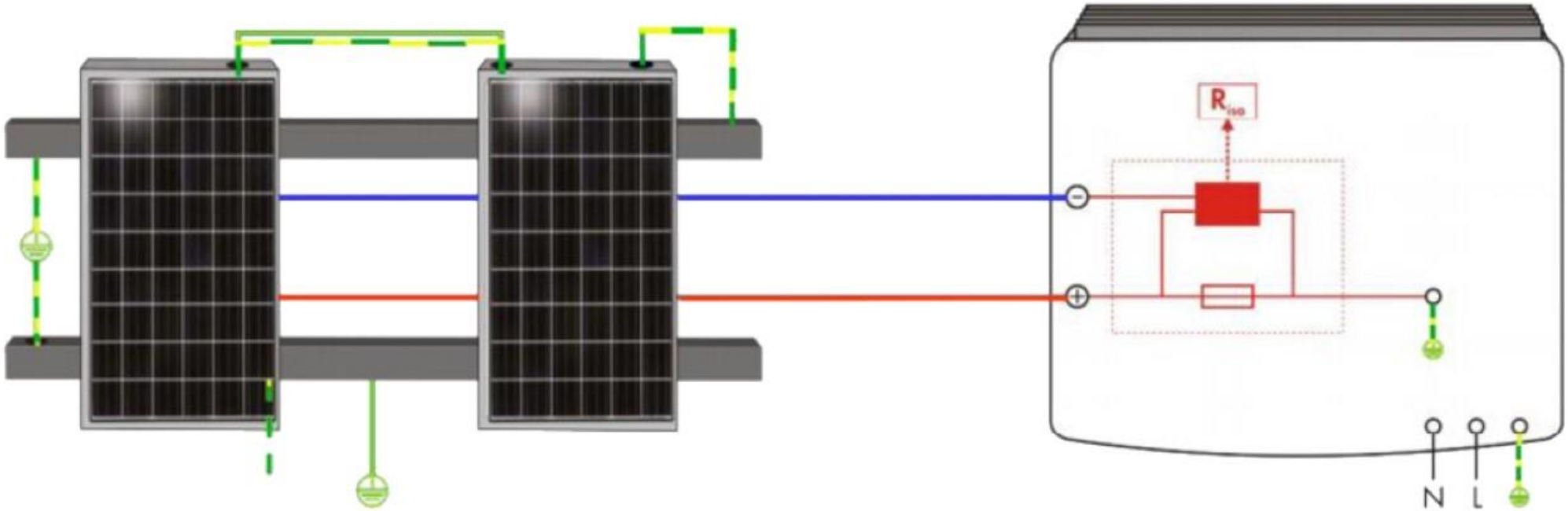
- PV arrays are assembled with modules mounted on frames usually made of metal (aluminum).
- It is common practice to connect the conducting frame to earth (or ground the structure) to establish a zero potential and also to provide a path for any possible lightning strikes to be discharged to the ground.





Earthing & Lightning protection

- Inverter earthing is necessary when there are free conducting parts which can be easily electrified and carry electricity either directly or indirectly.



Earthing & Lightning protection



- Lightning is an ultra-rapid transient phenomenon with highly destructive energy.
- The main effect of lightning is electrical overvoltage which exposes the electrical installations to a serious risk malfunction and destruction.
- The unit of measurement of the instantaneous overvoltage is kV/µs.
- The over voltages come either from the electricity network or from the earth.
- However, lightning is likely to strike appropriately earthed structures and so it is often useful to put a lightning rod of some sort to attract the lightning before it strikes the array.

- End of part 2

Photovoltaic solar energy training course

Section 4: Stand-Alone PV systems

Part 3

- Components of a Stand-Alone System
- Sizing Steps of a Solar Home System
- Sizing Steps of a PV Water Pumping System

Nabil Karami, PhD

Stand-Alone PV System Components

Why Stand-Alone

- Remote and independent applications
- Diesel generators (Pollution and Cost)
- Very expensive to connect from local electricity utility (grid network) to your location.



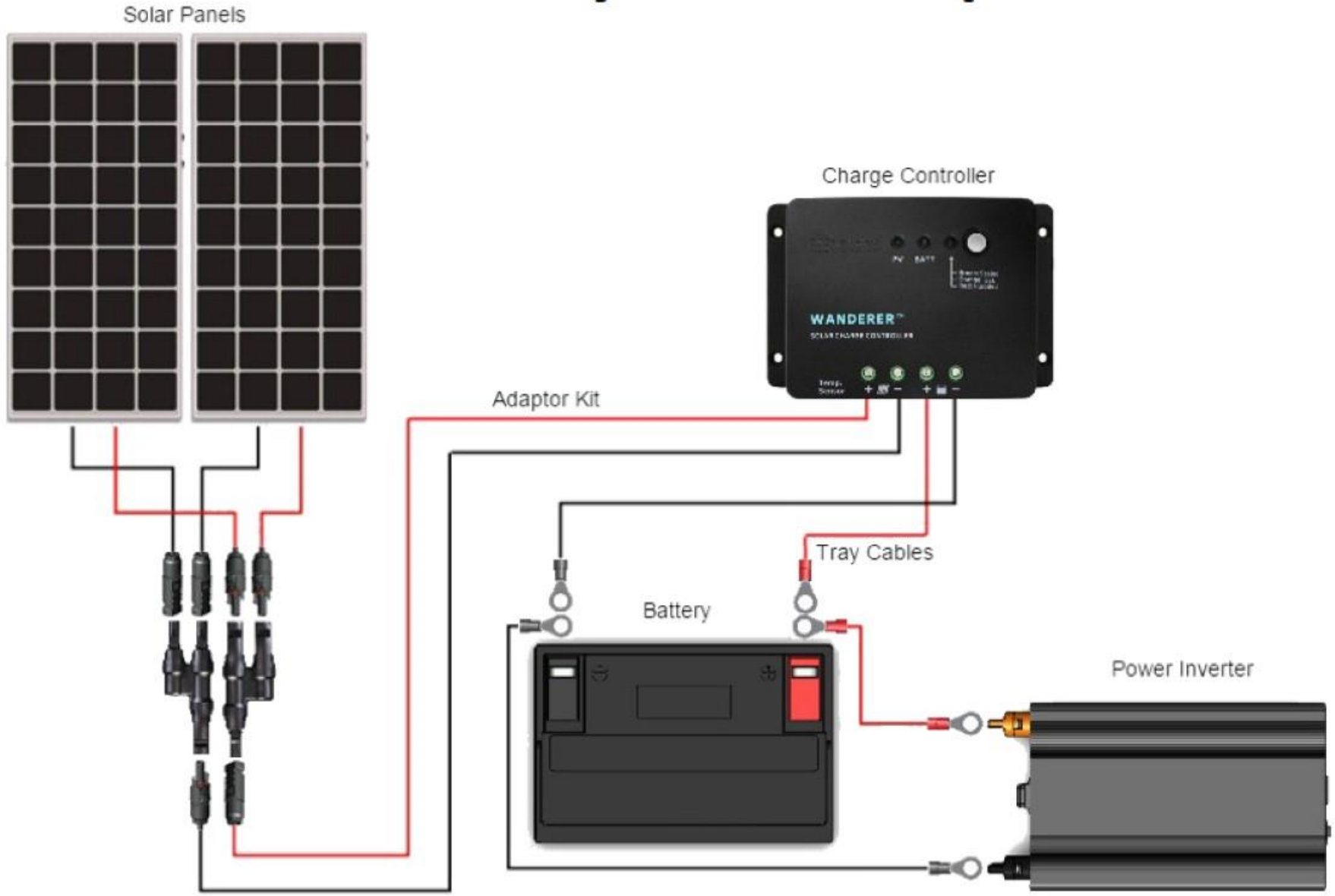
Stand-Alone PV System Components

Components

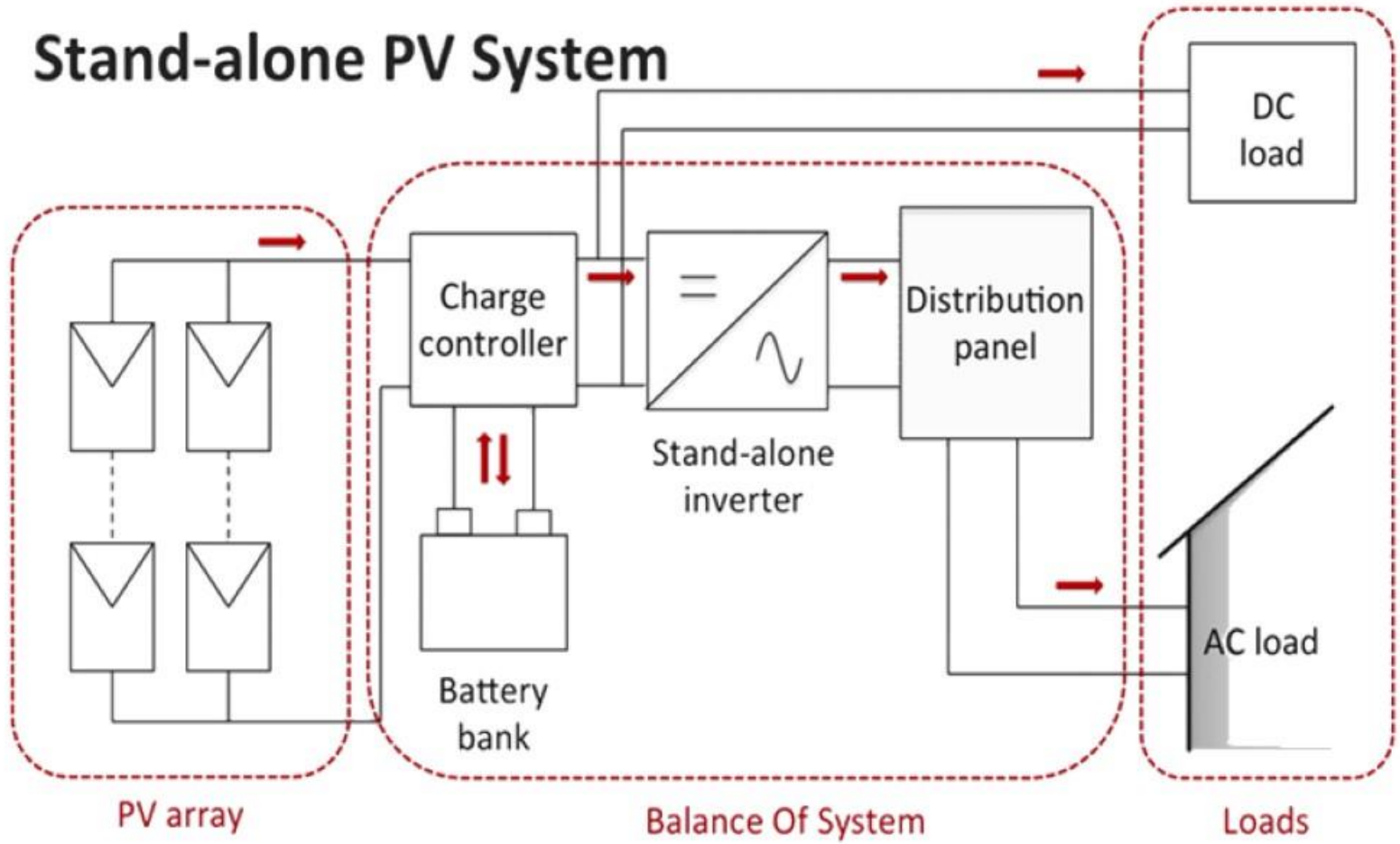
1. PV array
2. Wind generator
3. Charge Controller
4. Battery bank
5. Inverters
6. Fuse box
7. Electrical Loads



Stand-Alone PV System Components



Stand-Alone PV System Sizing



Stand-Alone PV System Sizing

Introduction

- Design is primarily for stand-alone systems rather than grid-connected systems because:
  - Independent PV systems lack the support of a powerful electricity grid acting as a flexible 'source and sink'.
  - A stand-alone system, especially when powered by PV alone, cannot realistically achieve total reliability.
- There is inevitably a trade-off between reliability and cost, forcing the system designer (and customer) to face some difficult choices.
- We shall often refer to arrays and battery banks, terms appropriate for medium-size and larger systems, but our approach is also valid in principle for small systems containing a single PV module and battery.

Stand-Alone PV System Sizing

Issues to Consider

- Sizing methods based on practical experience and 'rules of thumb' are quite often used and may provide sensible, cost effective solutions without much appreciation of the background science.
- PV sizing software is also widely available, although there is always a danger of using inaccurate input data or failing to appreciate the underlying assumptions.
- Our approach is intermediate in sophistication yet sufficiently detailed to highlight the main technical issues.
- Failure of the electrical supply may be life-threatening as well as highly inconvenient and expensive, so reliability is obviously a major requirement for PV systems used to power refrigerators for storing vaccines and medicines in remote hospitals.
- In a holiday home used mainly in the summer months, occasional supply failure may be quite tolerable.

Stand-Alone PV System Sizing

❖ Peak Sun Hours

- Peak Sun Hours (peak hours) involves compressing the total radiation (direct plus diffuse) received throughout the year into an equivalent duration of *standard* 'bright sunshine' (1 kW/m^2).
- The same concept may be used for daily radiation.
- "Peak Sun Hours" is a concept needed in design of PV systems.
- Example:
  - If an inclined array receives an average insolation of 3 kWh/m^2 per day in April, this is considered equivalent to 3 peak hours.
  - So that, an array rated at (say) 2 kWp is predicted to yield 3 × 2 = 6 kWh/day.
- Although it is an approximation that tends to be over-optimistic for arrays receiving a high proportion of diffuse radiation, it offers a very straightforward way to estimate array output in a particular location.

Sizing of a Solar Home Stand-Alone System



❖ Steps to follow to size PV system with Battery

1. Collect load data
2. Check sun-hours per day
3. Size the PV
4. Select and Configure the PV
5. Size the Battery
6. Select the Configure the batteries
7. Select the inverter

Sizing of a Solar Home Stand-Alone System

❖ Design Example 1
Solar Home System (SHS)

➢ Step 1: Collect data and calculate the required energy/day

- The total amount of electricity required in an average day
- This is a basic information needed to size the PV system;
- we identify the electrical appliances in this home, the power that each appliance consumes, and the average amount of daily use.

Sizing of a Solar Home Stand-Alone System



- The total estimated consumption for the whole system is *2.211 kWh per day.*

#	Appliance	Rated power (W)	number of items	hrs/day	Wh/day
1	Light	11	7	3	231
2	TV	50	1	3	150
3	Computer	50	1	2	100
4	Refrigerator	80	1	12	960
5	Kettle	1000	1	0.1	100
6	Microwave Oven	700	1	0.3	210
7	Food Mixer	400	1	0.15	60
8	Washing Machine	800	1	0.5	400
		Total			**2211**

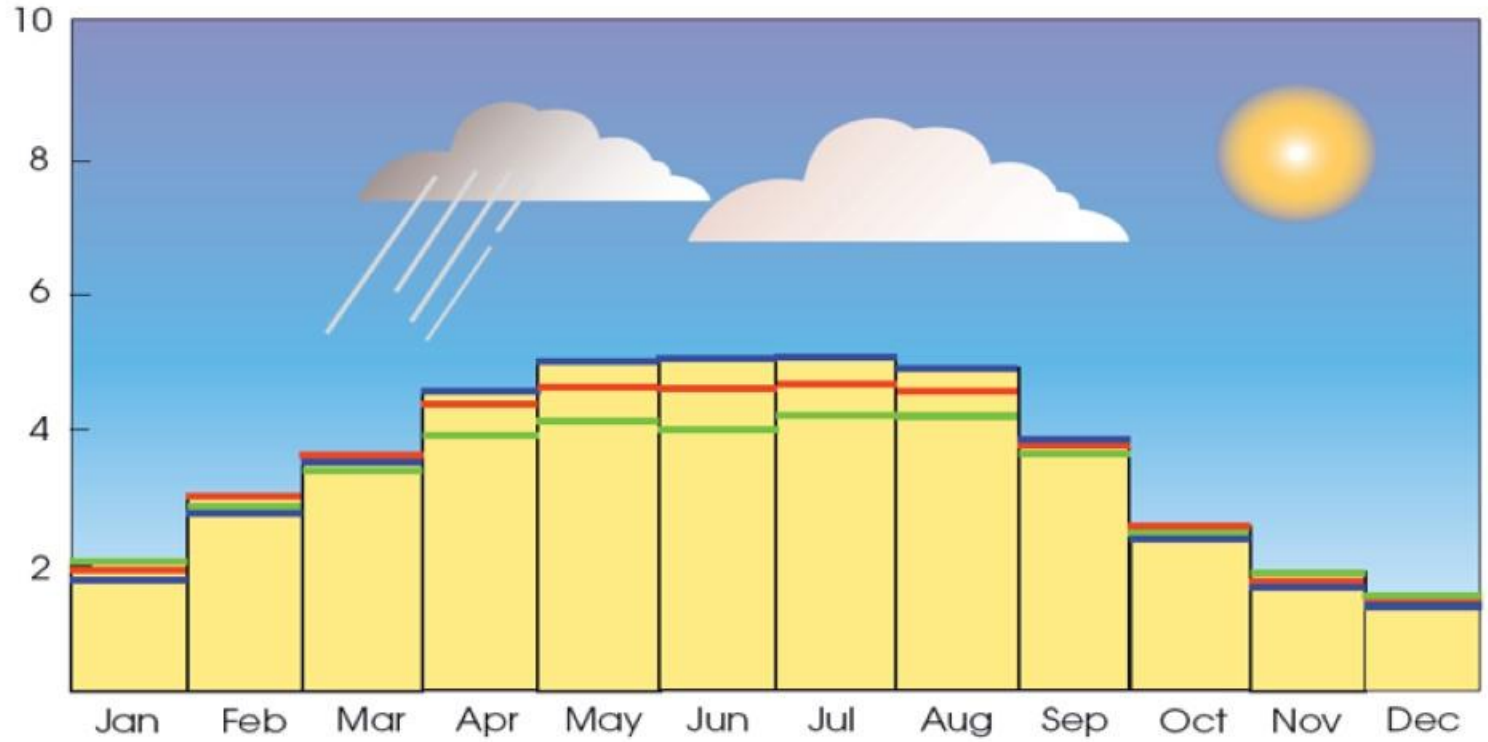
Sizing of a Solar Home Stand-Alone System

Step 2: Check insolation map and the sun-hours/day

- Daily Solar Radiation for the location of SHS
- Selecting Tilt angle and Design Month
  - Location of latitude of 48 ºN (Southern Germany) is used in this example.
  - A figure for daily solar radiation in kWh/m^2 on south-facing inclined PV arrays for a location at different tilt angles can be used for sizing the array.

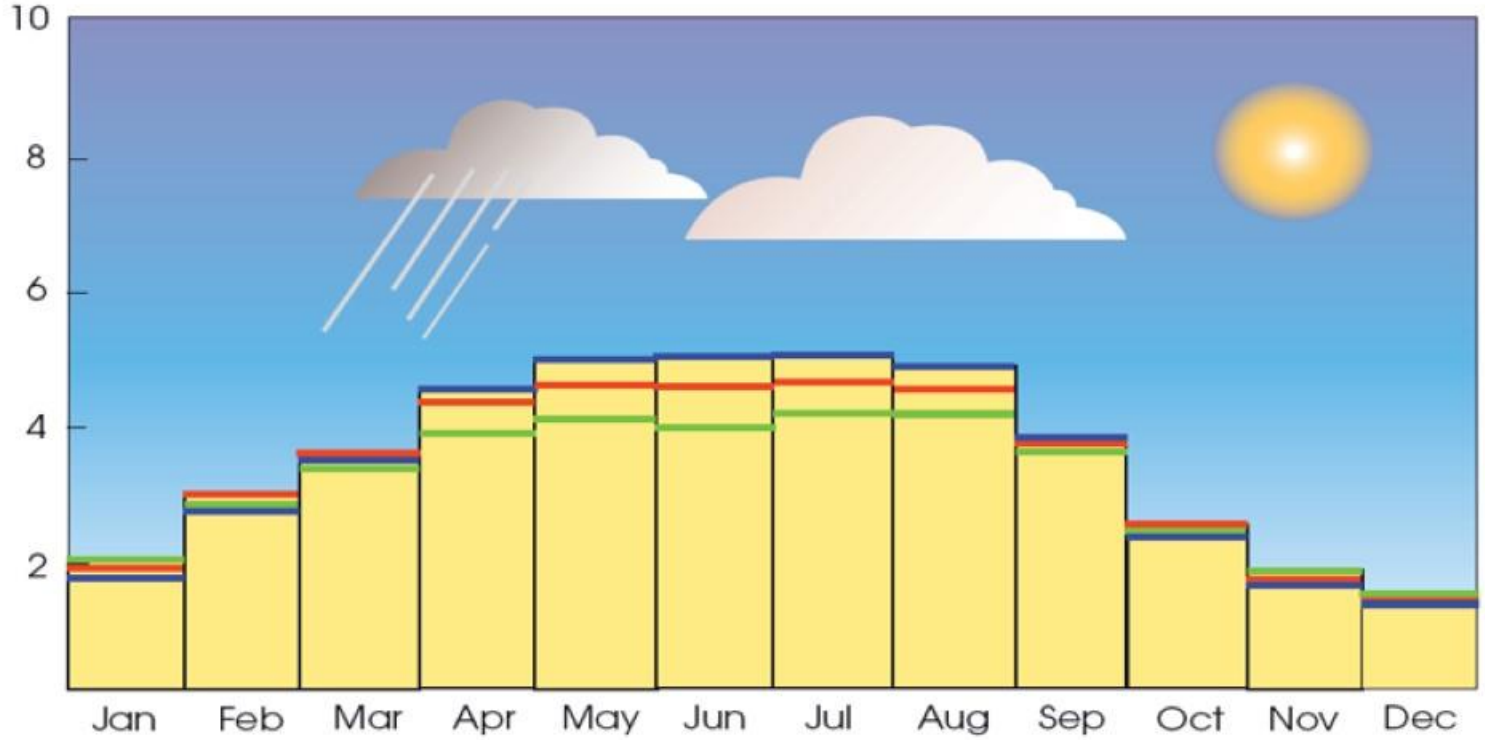
Sizing of a Solar Home Stand-Alone System

- Daily solar radiation in kWh/m^2 on south-facing inclined PV arrays for a location at latitude 48°N. The three values of array tilt are: 33° (blue); 48° (red); and 63° (green)



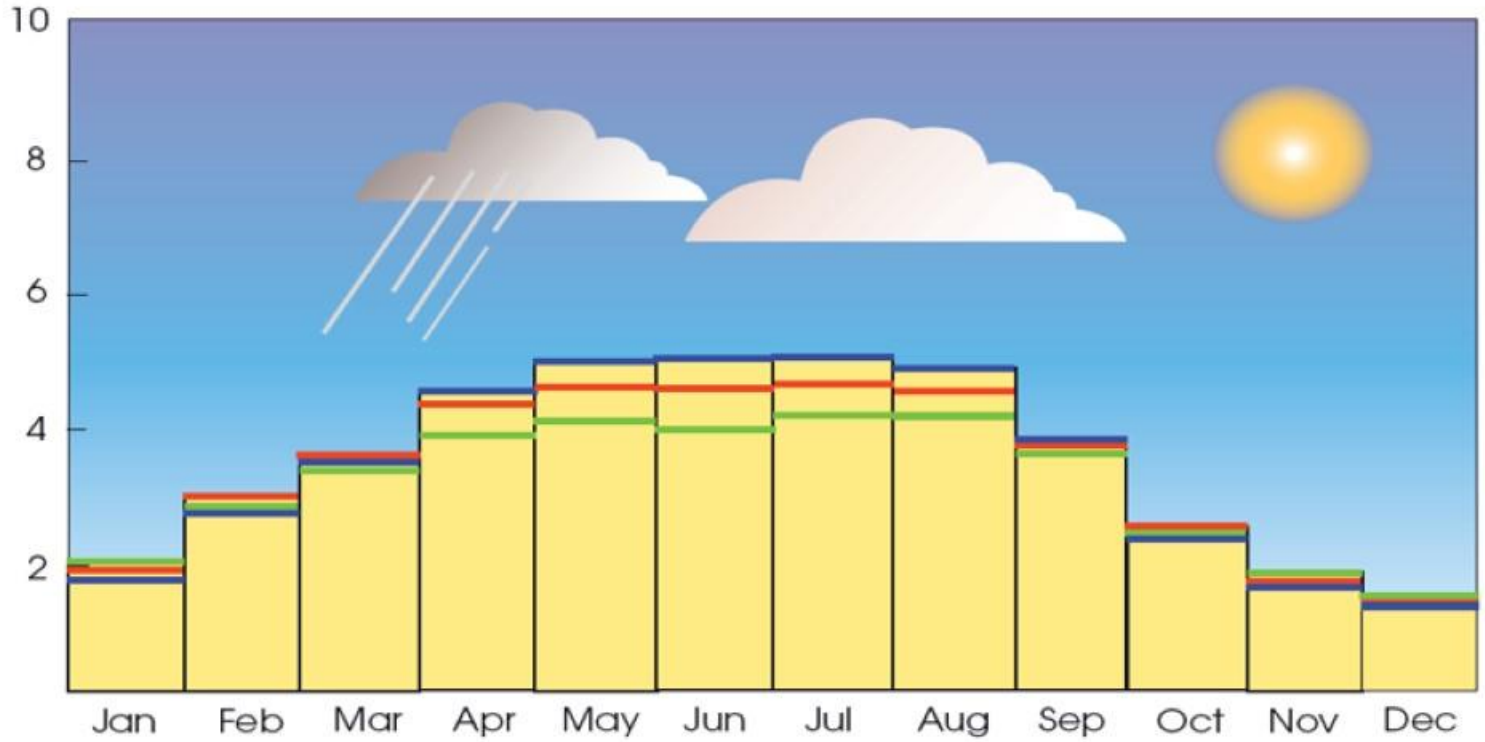
Sizing of a Solar Home Stand-Alone System

- As expected, 33° does best over the summer months when the Sun is high in the sky.
- A tilt of 48° gives good results around the time of the equinoxes in March and September.
- A tilt of 63° is marginally preferable over the winter months.



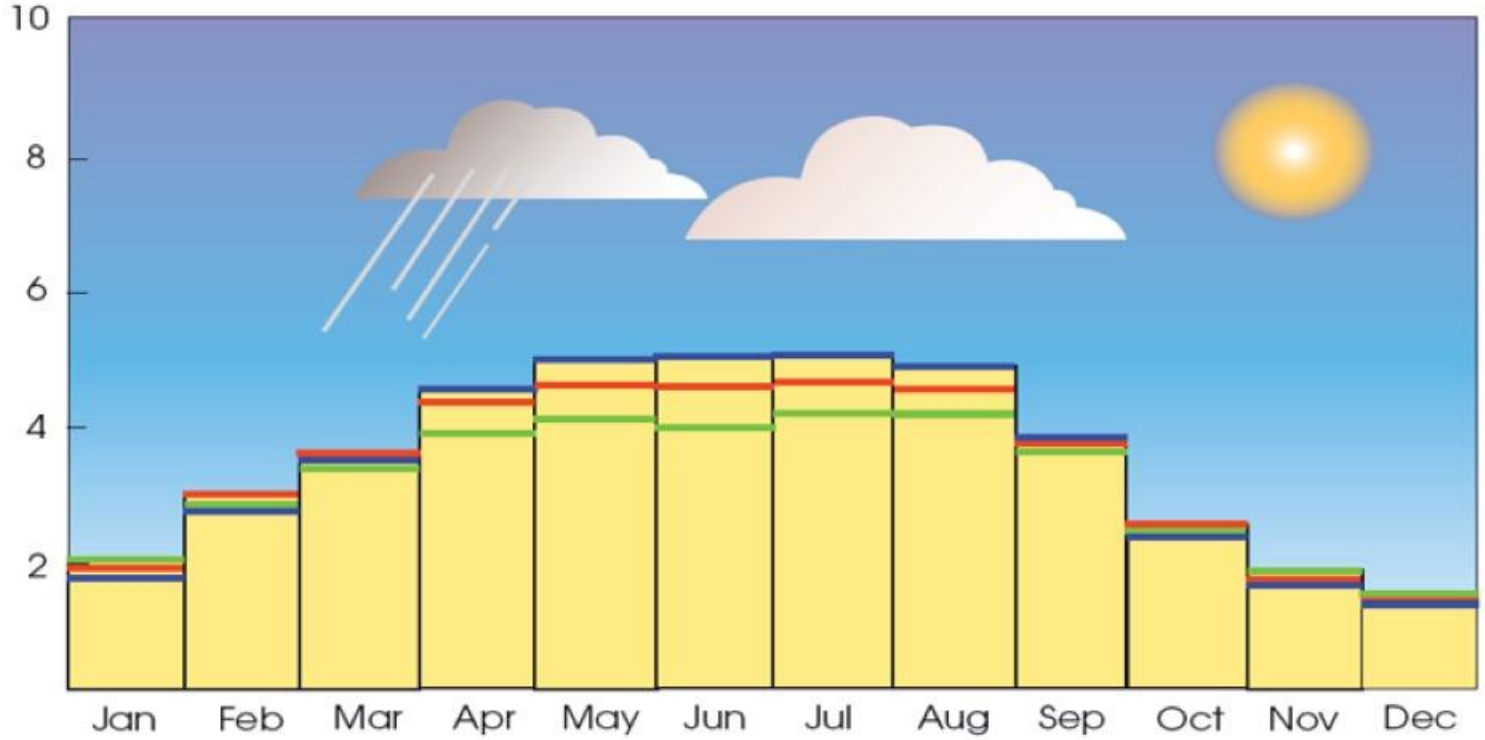
Stand-Alone PV System Sizing

- We also see that radiation levels in December are only about one third of those in midsummer, so a PV array big enough to supply the home's electricity in December would be three times oversized in June.
- Choosing an array to cope with the 'worst' month of the year would be a very expensive option.



Sizing of a Solar Home Stand-Alone System

- The 'worst' month is now taken as March, for which the average daily radiation is 3.5 kWh/m^2
- The homeowners will have to take decision to use less electricity over the winter months, unless the total is boosted by an alternative energy source. Or perhaps they will agree to forgo use of the refrigerator, microwave oven and washing machine, and cut down on the drinking of coffee!



Sizing of a Solar Home Stand-Alone System



Step 3: Size the PV

- The PV should be designed to satisfy the required load energy during the day

$$P_{PV} = \frac{E_D}{S_p \times \eta} \times \Delta$$

- **E_D :** the average daily amount of electricity available for running the home' s appliances
- **S_p :** the number of peak sun hours per day in the month of interest
- **η:** the overall system efficiency
- **Δ:** Uncertainty factor (usually 20% more) also called oversizing factor

Sizing of a Solar Home Stand-Alone System



- **What is the system Efficiency 'η'**
  - PV modules → 0.85
  - Battery bank → 0.85
  - Charge controller, blocking diodes, and cables → 0.92
  - Inverter → 0.9
  - **η = 0.85 x 0.85 x 0.92 x 0.9 = 0.6**

Sizing of a Solar Home Stand-Alone System



- **Why oversizing PV array?**

- Due to uncertainties and vagaries of the weather, oversizing a PV array by a reasonable amount – say 20% – is often recommended.
- In practice, it is hard to predict how components will behave in variable sunlight and ambient temperatures, or how the system will actually be used by the homeowners

Sizing of a Solar Home Stand-Alone System

- $P_{PV} = \frac{E_D}{S_p \times \eta} \times \Delta = \frac{2211Wh}{3.5h \times 0.6} \times 1.2 = 1264W_P$

  Where Δ is the oversizing factor

- We therefore predict that a PV array rated at just over 1200 Wp will supply the daily load requirement of 2211 Wh during the months March to September.

Sizing of a Solar Home Stand-Alone System



Step 4: Select and Configure PV Module

- As designer, you have lot of choices of PV technology, efficiency, price..
- If a PV module of **150 Wp** is to be used for this system, then **8 Modules** have to be implemented.
- 150 Wp x 8 Modules = 1200 Wp

Sizing of a Solar Home Stand-Alone System



Step 5 : Sizing the Batteries

- The battery sizing varies depend on the client life style and the location of the system.
- We care about the stored energy in cloudy days and will oversize the batteries to overcome PV power loss.
- Five days of usable battery storage is often regarded as a good compromise between reliability and cost.

Sizing of a Solar Home Stand-Alone System

- Calculation of the battery capacity 'C'

$$C = \frac{N \times E_D}{D \times \eta_{inv}}$$

- **N:** number of days of storage
- **E_D:** the daily electricity requirement
- **D:** the allowable depth-of-discharge of the battery bank
- **η_{inv}:** the efficiency of the inverter, assuming an AC supply is required.

Sizing of a Solar Home Stand-Alone System



- Capacity of Battery Bank:

$$C = \frac{N \times E_D}{D \times \eta_{inv}} = \frac{5days \times 2200Wh/day}{0.8 \times 0.9} = 15354Wh$$

- Battery Voltage (V_B): 24V **(don't use 12V if power > 1kW)**
- Charge Capacity = C / V_B = 15.3 kWh/24V = **638Ah**

- **Comments:** The usable capacity of the battery bank is less than its nominal, rated, capacity because complete discharge must be avoided.
- As with the PV array, it may be sensible to oversize the battery bank somewhat – or to treat it as modular, with the option of upgrading it later.

Sizing of a Solar Home Stand-Alone System



Step 6: Select and Configure Battery Bank

If the selected batteries have the following specifications:

- 12V
- 175Ah Charge capacity

Then,

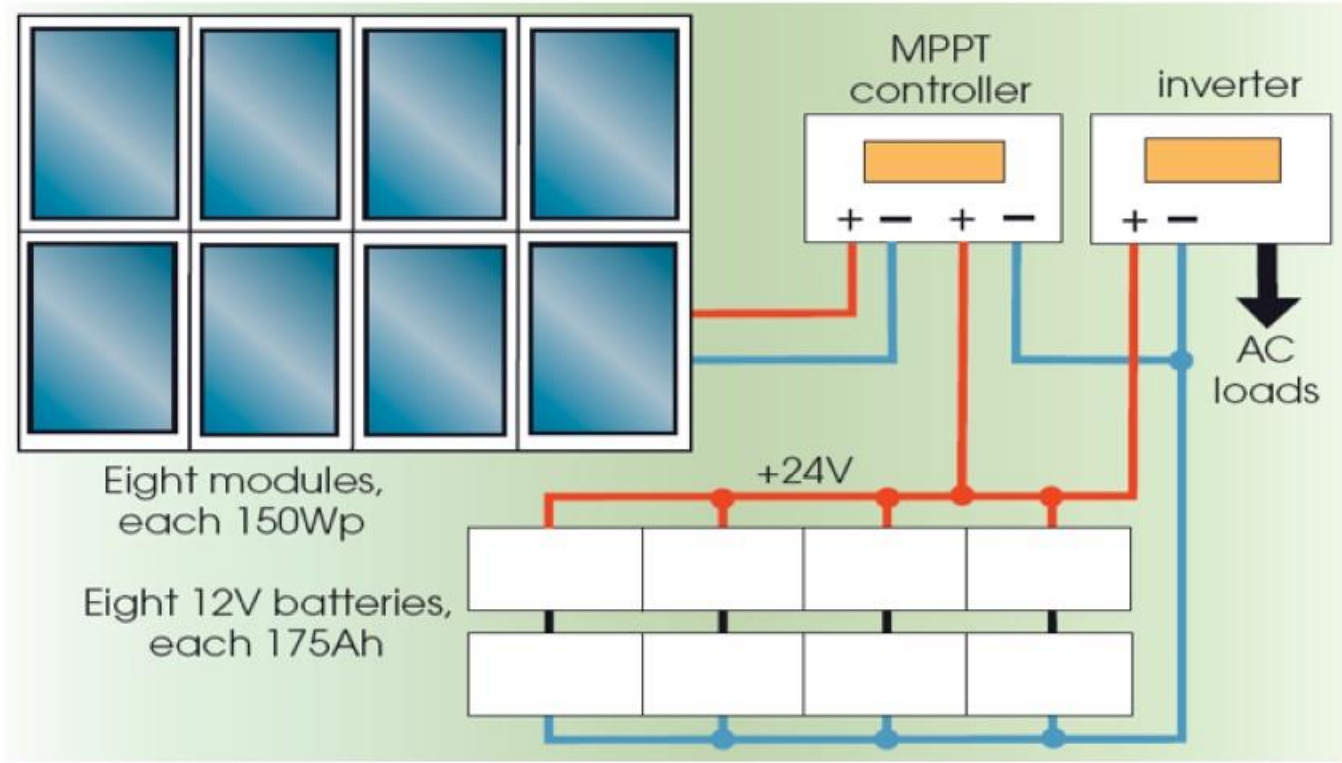
- Each two batteries are connected in series to provide a voltage of 24V
- Eight batteries have to be used with Four pairs of batteries connected in parallel.

The total charge capacity is 4 x 175Ah = 700Ah (this is larger than 638Ah → 10% oversizing – good practice).

Sizing of a Solar Home Stand-Alone System

❖ Design of Solar Home System (SHS)

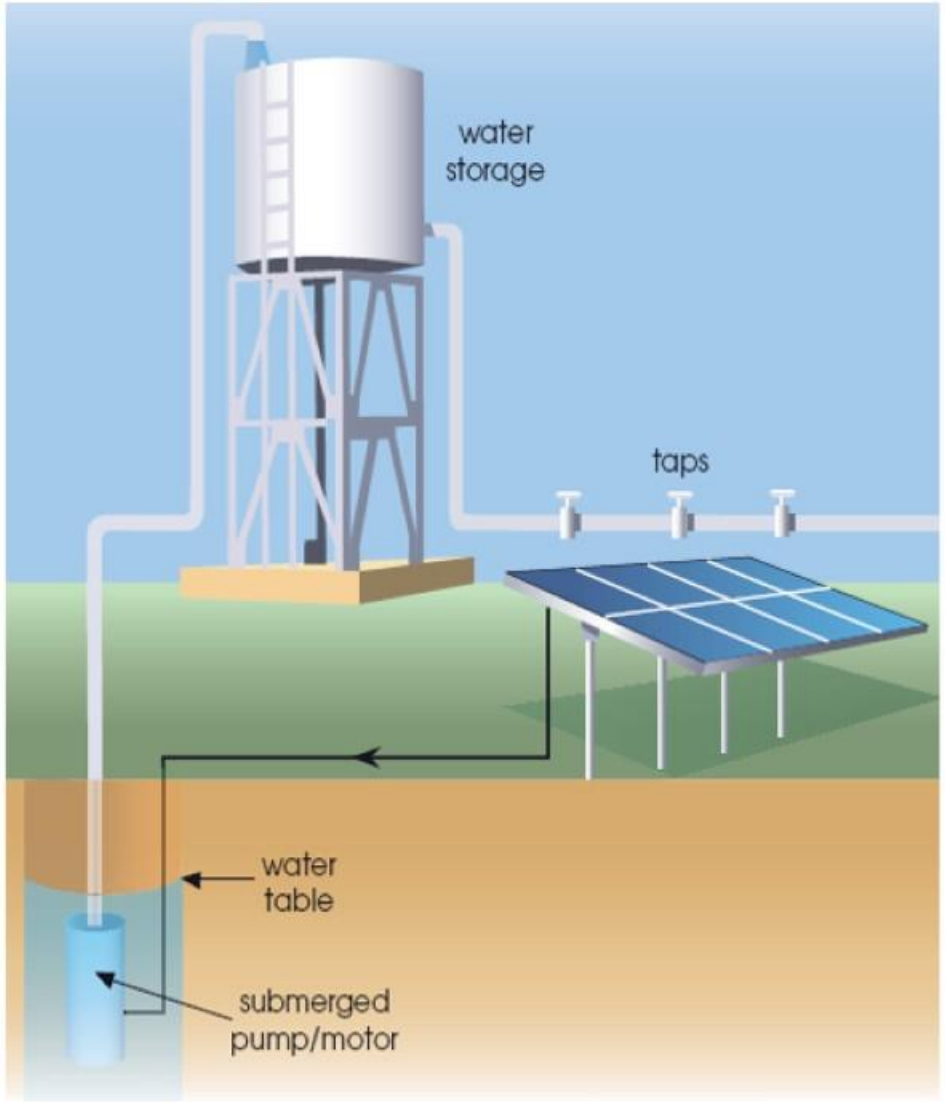
- The electricity yield, and hence system reliability, could be further improved at modest cost by specifying a MPPT charge controller.
- The modules could be connected in series, or series/parallel.
- The batteries are connected as four parallel strings of two units each to give 24V DC.



Sizing of a Solar Water-Pump System

- **Design Example 2:**
  PV Water Pumping

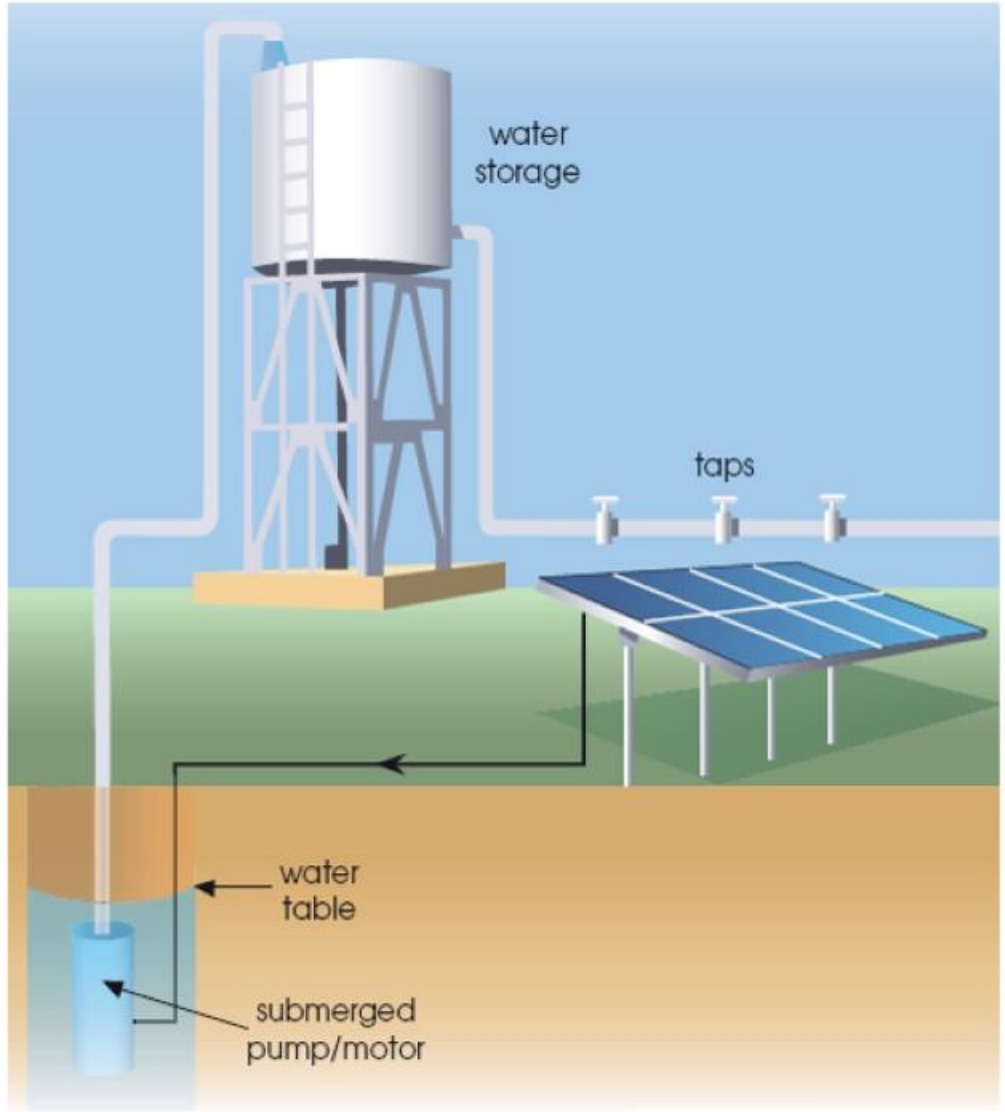
- It is one of the most successful applications of stand-alone PV in developing countries.
- By the year 2000 over 20 000 PV-powered systems were in use worldwide and the pace of installation continues.



Sizing of a Solar Water-Pump System

- **Operation**

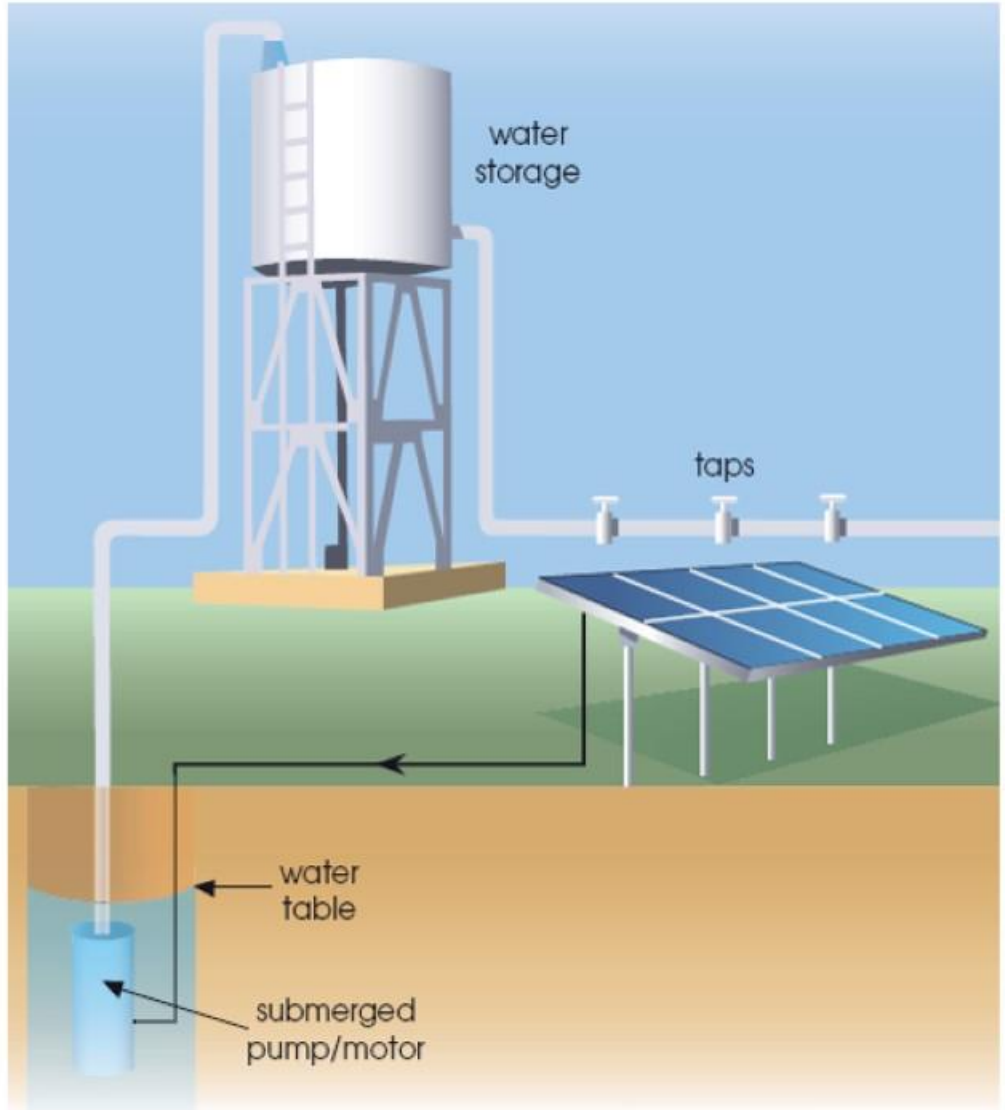
- A submersible pump/motor raises water to a storage tank whenever sunlight falling on the PV array is sufficiently strong.
- From there it is fed by gravity to one or more taps.



Sizing of a Solar Water-Pump System

- **Steps to follow to size the system**

1. Select the pump
2. Select the motor
3. Calculate the hydraulic energy
4. Size the PV array



Sizing of a Solar Water-Pump System

Step1: Selecting Pump:

- Centrifugal
- Displacement (or volumetric)

- **Comments**:
- Centrifugal pumps are widely used to raise water against pumping heads up to about 25 m (the height difference between the water table and tank's input pipe). Multi-stage versions can cope with higher heads.
- A centrifugal pump has an impeller that throws water against its outer casing at high speed, the kinetic energy then being converted to a pressure head by an expanding output pipe.
- Centrifugal pumps are compact, robust, and well - suited to PV applications, but they are not normally self-priming and must therefore be kept submerged. This makes them suitable for pump/motors positioned below the water table.

Sizing of a Solar Water-Pump System

Step2: Selecting Motor

- DC
  - Permanent-magnet / Carbon Brushes
  - Brushless
- AC

- **Comments:**
  - DC are generally more efficient than AC ones, but more expensive.
  - AC motors are very rugged and need little or no maintenance, so are suitable for submersion at the bottom of a well;
  - but inverters are needed to convert PV electricity to AC, adding to the capital cost.

Sizing of a Solar Water-Pump System

Step 3: Calculate the hydraulic Energy

- The required hydraulic energy E_h

$$E_H = 0.0027 \times V_w \times H_w \left(\frac{kWh}{day}\right)$$

  - $\boldsymbol{H_w}$ is the height of the holding tank's input pipe above the water table in meters.
  - $\boldsymbol{V_w}$ is volume of water in cubic meters per day

- *Specifications:* 15 m^3/day and the tank's inlet pipe is 20m above the water table. So that

$$E_H = 0.0027 \times 15 \times 20 = 0.81 \left(\frac{kWh}{day}\right)$$

Sizing of a Solar Water-Pump System

Step 4: Sizing the PV Array

- The peak power of the array (P_{PV}) is approximately

$$P_{PV} = \frac{E_H}{S_P \times \eta}$$

  - S_p is the number of peak sun hours for the particular location
  - η is the overall system efficiency.

- So, if the location has an insolation equivalent to 3 peak sun hours per day, then the PV array needs a peak power:

$$P_{PV} = \frac{0.81}{3 \times 0.25} = 1.08kWp$$

Sizing of a Solar Water-Pump System



- The peak sun hours are normally chosen for the 'worst' month to ensure continuity of supply throughout the year.
- The system efficiency must take account of electrical losses in the motor and cabling, hydraulic and friction losses in the pump and pipework, and mismatch between the motor and the PV that prevents the array from working at its maximum power point.
- An average efficiency of about 40% is fairly typical for a centrifugal pump and, together with other losses, gives a typical system efficiency of around 25%.
- MPP tracking controller based on a DC to DC converter may be inserted to improve matching and increase efficiency.

- End of Part 3

Photovoltaic solar energy training course

Section 4: Stand-Alone PV systems

Part 4

- Challenging example
- Read data from Solar Atlas
- Size the PV, Battery, Inverter
- Design the system
- Calculate the plant area

Nabil Karami, PhD

Stand-Alone PV System Sizing



- **Challenging Example 3: Real case study of a Stand alone PV system**
- A client having a small factory for semi-handmade soap industry is planning to go off-grid with a PV system able to supply 10A for 8 hours at 220V.
- He asked for the design of the required PVs, batteries and space.

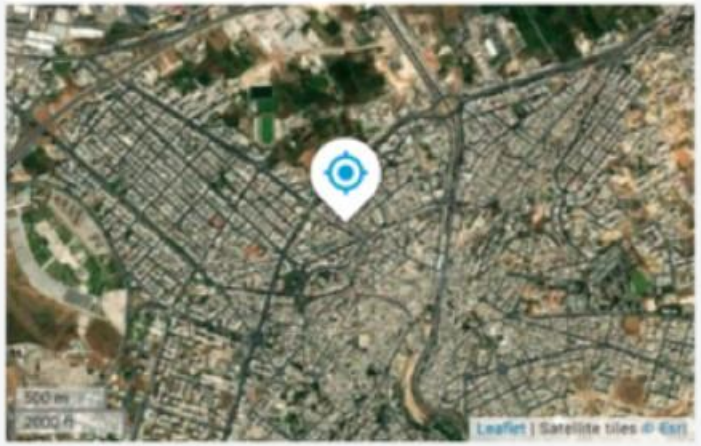
Stand-Alone PV System Sizing

- The challenge in this design is that the working hours are during sun-light period which is different than home solar system as the PV energy is saved in batteries during the day and used at night.
- Collecting data from Global Solar Atlas (globalsolaratlas.info) about the irradiance/ angles…
- The factory is located in Tripoli, Lebanon, at 34.4°N

SITE INFO

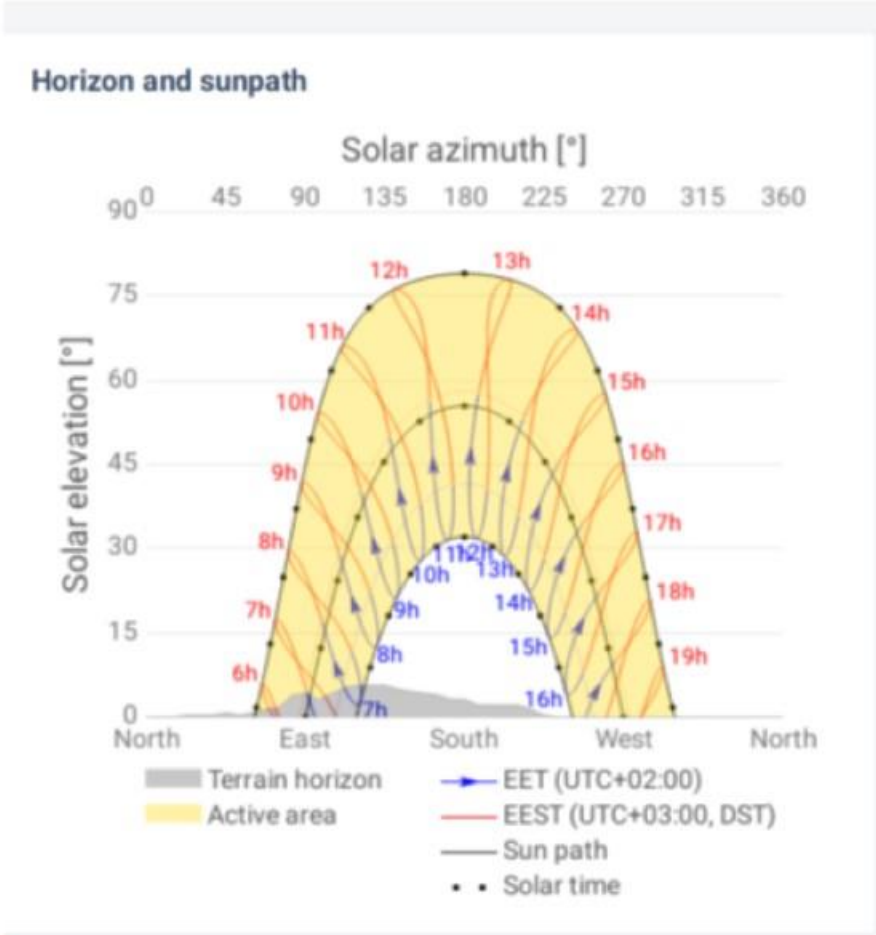
Map data		Per year	
Specific photovoltaic power output	PVOUT specific	1671.6	kWh/kWp
Direct normal irradiation	DNI	1955.6	kWh/m²
Global horizontal irradiation	GHI	1895.7	kWh/m²
Diffuse horizontal irradiation	DIF	648.4	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	2106.0	kWh/m²
Optimum tilt of PV modules	OPTA	28 / 180	°
Air temperature	TEMP	21.8	°C
Terrain elevation	ELE	26	m

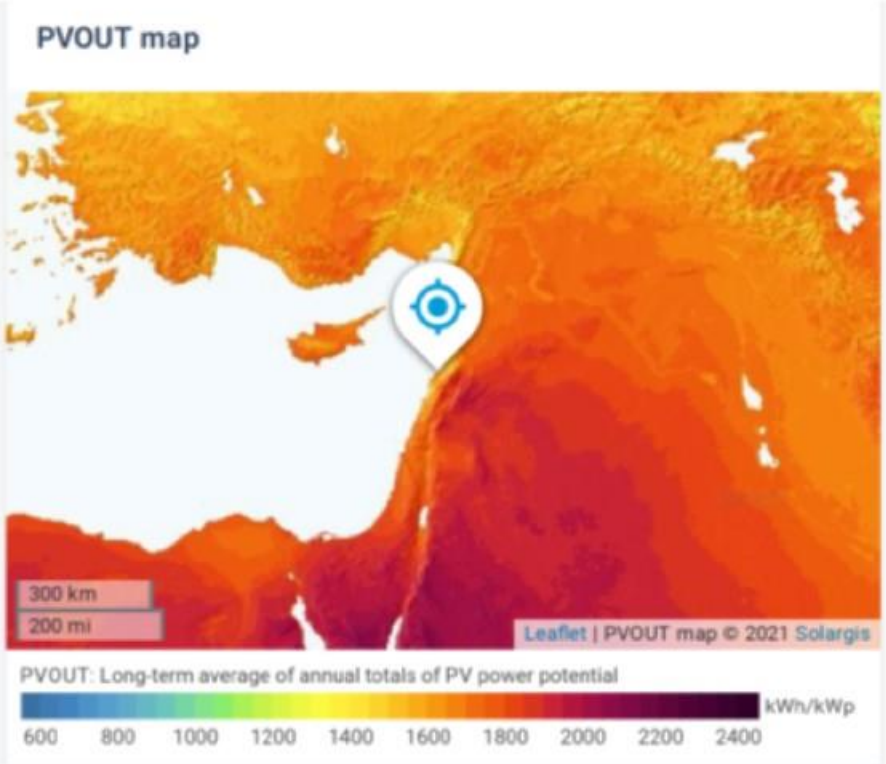
Map



Stand-Alone PV System Sizing

- from Global Solar Atlas (globalsolaratlas.info) …





Stand-Alone PV System Sizing

- from Global Solar Atlas (globalsolaratlas.info) …

Average hourly profiles

Total photovoltaic power output [kWh]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5					0	0	0					
5 - 6				0	1	1	1	0	0			
6 - 7		0	1	2	3	3	2	2	2	1	0	0
7 - 8	1	2	4	5	6	6	5	5	5	5	4	2
8 - 9	5	5	7	7	8	9	8	8	8	8	7	5
9 - 10	7	8	9	10	10	11	11	11	11	10	9	7
10 - 11	8	9	11	11	12	12	12	12	12	11	10	8
11 - 12	8	10	11	11	12	12	12	13	12	11	10	8
12 - 13	8	9	11	11	12	12	12	12	12	10	9	8
13 - 14	7	8	9	10	10	11	11	11	10	9	8	7
14 - 15	6	7	8	8	8	9	9	9	8	6	6	5
15 - 16	3	4	5	5	6	6	6	6	5	3	2	2
16 - 17	0	1	2	2	3	3	3	3	2	0	0	0
17 - 18			0	0	1	1	1	1	0			
18 - 19					0	0	0	0				
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	54	63	77	83	91	95	95	94	88	75	64	52

Stand-Alone PV System Sizing

- from Global Solar Atlas (globalsolaratlas.info) …

Average hourly profiles

Direct normal irradiation [Wh/m^2]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5					1	10	2					
5 - 6				35	188	280	231	97	38			
6 - 7		13	127	244	393	507	466	406	337	154	50	
7 - 8	164	202	317	366	519	626	590	543	508	398	327	184
8 - 9	322	335	415	458	602	711	679	635	602	502	437	351
9 - 10	386	410	512	531	660	763	746	707	676	588	500	413
10 - 11	420	458	555	569	691	790	779	738	716	598	531	442
11 - 12	434	467	536	573	687	793	786	750	710	576	536	446
12 - 13	420	457	519	560	675	780	778	739	672	543	519	435
13 - 14	397	430	481	525	643	748	755	700	613	491	474	401
14 - 15	353	380	436	473	583	706	705	628	526	401	396	339
15 - 16	255	310	357	398	503	629	626	529	423	272	233	203
16 - 17	35	130	225	291	396	521	509	398	264	43	12	8
17 - 18			17	81	221	337	324	160	26			
18 - 19					12	37	37	2				
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	3185	3593	4497	5105	6772	8238	8011	7030	6112	4566	4014	3221

Stand-Alone PV System Sizing

Sizing the PVs

- The total energy required by the client is:

$$E_D = V \times I \times hrs = 220 \times 10 \times 8 = 17600Wh$$

- This energy should be supplied by the PV
  - Considering 5.5 hrs of sun light/day
  - System efficiency η of 70%
  - Oversizing factor Δ of 10%
- The PV power is calculated as

$$\mathrm{P_{PV}} = \frac{\mathrm{E_D}}{\mathrm{S_p} \times \eta} \times \Delta = \frac{17600}{5.5 \times 0.7} \times 1.1 \approx 5000W_P$$

Stand-Alone PV System Sizing

- From Global Solar Atlas, the power that can be collected per year is 2085kWh/m^2 per year

PV system configuration

Pv system: **Medium size comercial**

Azimuth of PV panels: **Default** (180°)

Tilt of PV panels: **34°**

Installed capacity: **17.6 kWp**

Annual averages

Total photovoltaic power output and Global tilted irradiation

28.327	2084.9
MWh per year	kWh/m^2 per year

Monthly averages

Total photovoltaic power output



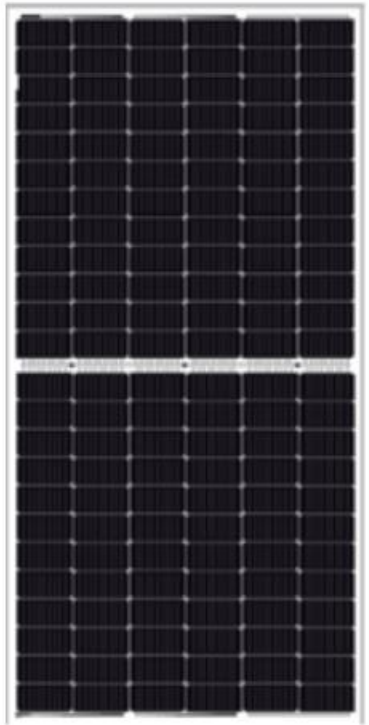
Stand-Alone PV System Sizing

Sizing the PVs

- The PV selected is 445W Mono PERC, half cell module, half cut.
- The number of panels required is:

$$\#of\ Panels = \frac{Required\ Power}{Power\ of\ one\ Panel} = \frac{5000}{445} \approx 12$$

ELECTRICAL CHARACTERISTICS (STC)	445W
Module System Voltage (v)	1500
Open Circuit Voltage - Voc (V)	49.35
Short Circuit Current - Isc (A)	11.47
Maximum Power Voltage - Vmpp (V)	41.28
Maximum Power Current - Impp (A)	10.79
Module Efficiency - η' (%)	20.5



Stand-Alone PV System Sizing

Sizing the Batteries

- The total energy required by the client is: 17600Wh/day

$$E_D = V \times I \times hrs = 220 \times 10 \times 8 = 17600Wh$$

- This same energy should be supplied by the batteries
  - Considering no cloudy day reserve, N=1
  - Battery DOD of 80%
  - Inverter Efficiency of 95%
- The Battery power is calculated as

$$C = \frac{N \times E_D}{D \times \eta_{inv}} = \frac{1 \times 17600Wh/day}{0.8 \times 0.95} \approx 23160Wh$$

Stand-Alone PV System Sizing

Sizing the Batteries

- The battery selected is 150AH Lithium 48V
- The Number of batteries required is

$$\#of\ batteries = \frac{Required\ Capacity}{Capacity\ of\ one\ Battery} = \frac{23160}{150} \approx 3$$



Battery Lithium 150AH Model: LIFePO4 48V 7.5KWH
Specifications:
- Capacity: 150Ah
- Voltage: 48V
- > 3000 cycle
- Dimensions 545x535x 194mm, weight 95.5Kg
Made in China
2 years warranty

Stand-Alone PV System Sizing

Selecting the Inverter

- The inverter is selected to have the following specs:
  - Pure sine wave output
  - MAX PV Array Open Circuit Voltage: 450V
  - Can provide the power to the load without battery
  - Combining solar system, AC utility, and battery power source to supply continuous power
  - Overload, short circuit and Deep discharge protection



Stand-Alone PV System Sizing

Important Inverter specs

BATTERY	
Normal voltage	48VDC
Floating Charge Voltage	54.8VDC
Overcharge Protection	60VDC
SOLAR CHARGER & AC CHARGER	
Maximum PV Array Open Circuit Voltage	**450VDC**
Maximum PV Array Power	5000W
PV Array MPPT Voltage Range	**150~430 VDC**
Maximum Solar Charge Current	80A
Maximum AC Charge Current	60A
Maximum Charge Current	80A

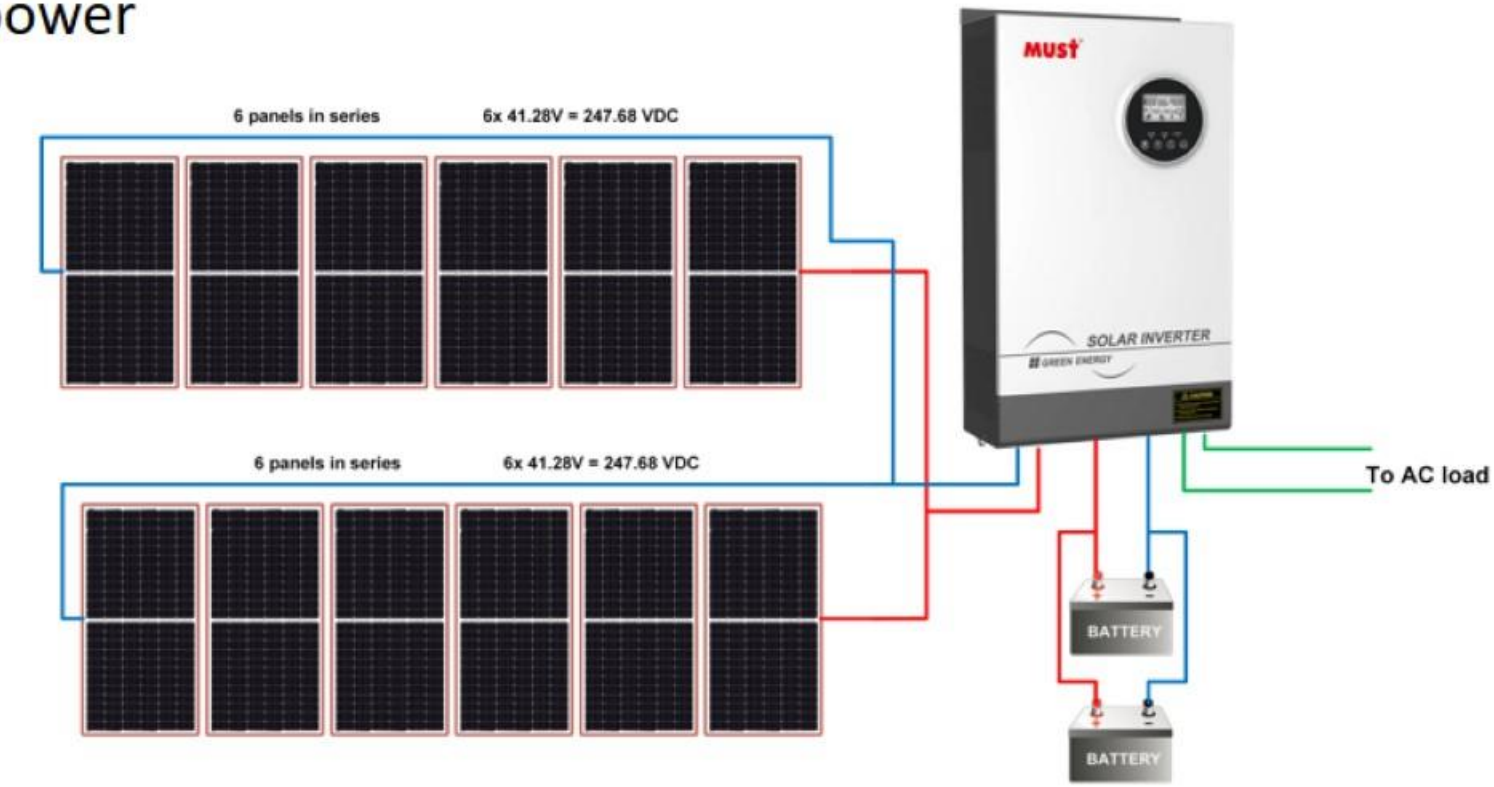


Stand-Alone PV System Sizing

Discussion

Based on the calculations, the number of batteries is 3.

Client decided to buy only two batteries as he will control his load in case of no solar power

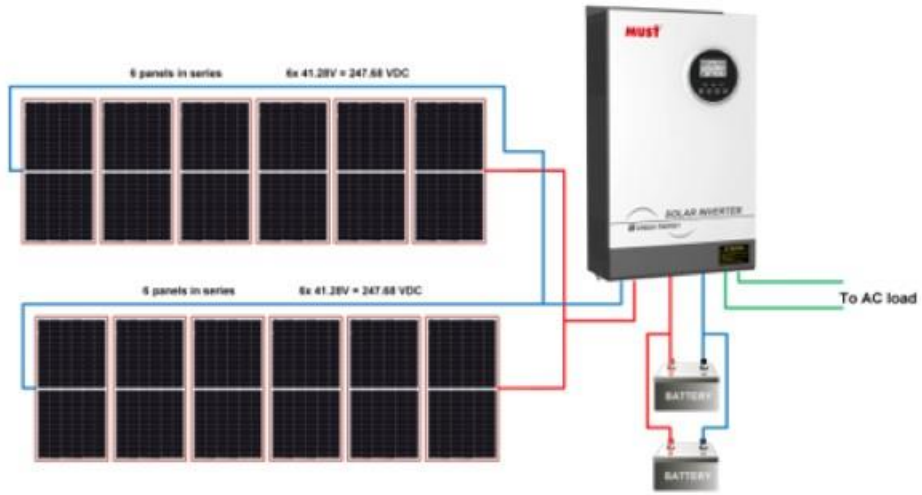


Stand-Alone PV System Sizing

Discussion

Based on the calculations, the number of batteries is 3.

Client decided to buy only two batteries as he will control his load in case of no solar power



Stand-Alone PV System Sizing

- Panels are mounted on a ground structures
- The size of each panel is 2102 x 1040mm, which is 2.2m^2 for each panel.
- The total surface area is 12 x 2.2m^2 = 26.4m^2
- Due to inclination of (ξ=44°) , the ground area required for the panels is:

$$G_A = N \times H \times Cos(\xi) \times W$$

$$G_A = 12 \times 2.102 \times Cos(44) \times 1.040 = 18.9m^2$$



References

- https://sunedisoninfra.com/blog/solar-inverter-and-its-types/
- https://www.mustsolar.com/ph1800-pro-series-pure-sine-wave-high-frequency-solar-inverterpv450v-3-5-2kw/
- https://www.mustsolar.com/ph1800-pro-series-pure-sine-wave-high-frequency-solar-inverterpv450v-3-5-2kw/

End of Session 4

Photovoltaic Solar Energy Training Course

Section 5: Grid-Connected PV System

Part 1
- Grid Connected Inverters
- Inverter Types
- String Inverter Vs. Micro Inverters
- Grid Connected PV Systems Topology
- Inverter Compatibility
- Inverter Standards
- Inverter Safety
- Inverter Power Factor

Part 2
- Grid-Connected PV System Components
- Inverters
- Junction box
- Cables
- Energy Flow meter

Part 3
- Grid Connected PV sizing
- Steps and Example

Part 4
- Quiz

Nabil Karami, PhD

Photovoltaic solar energy training course

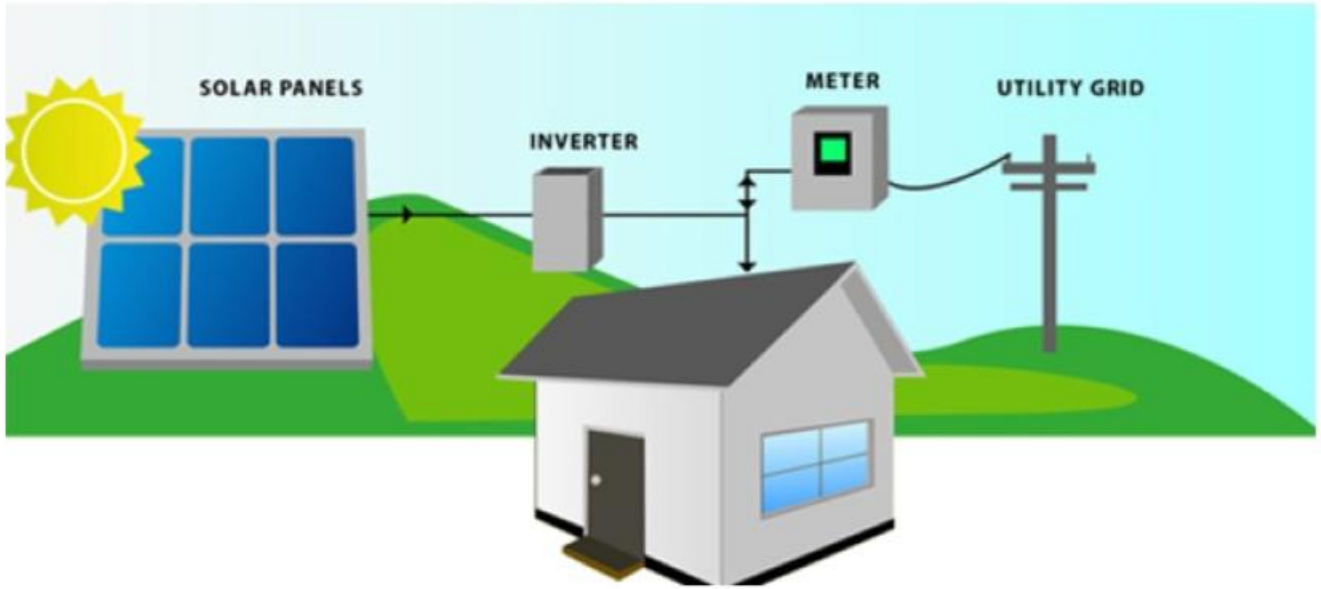
Section 5: Grid-Connected PV System

Part 1

- Grid Connected Inverters
- Inverter Types
- String Inverter Vs. Micro Inverters
- Grid Connected PV Systems Topology
- Inverter Compatibility
- Inverter Standards
- Inverter Safety
- Inverter Power Factor

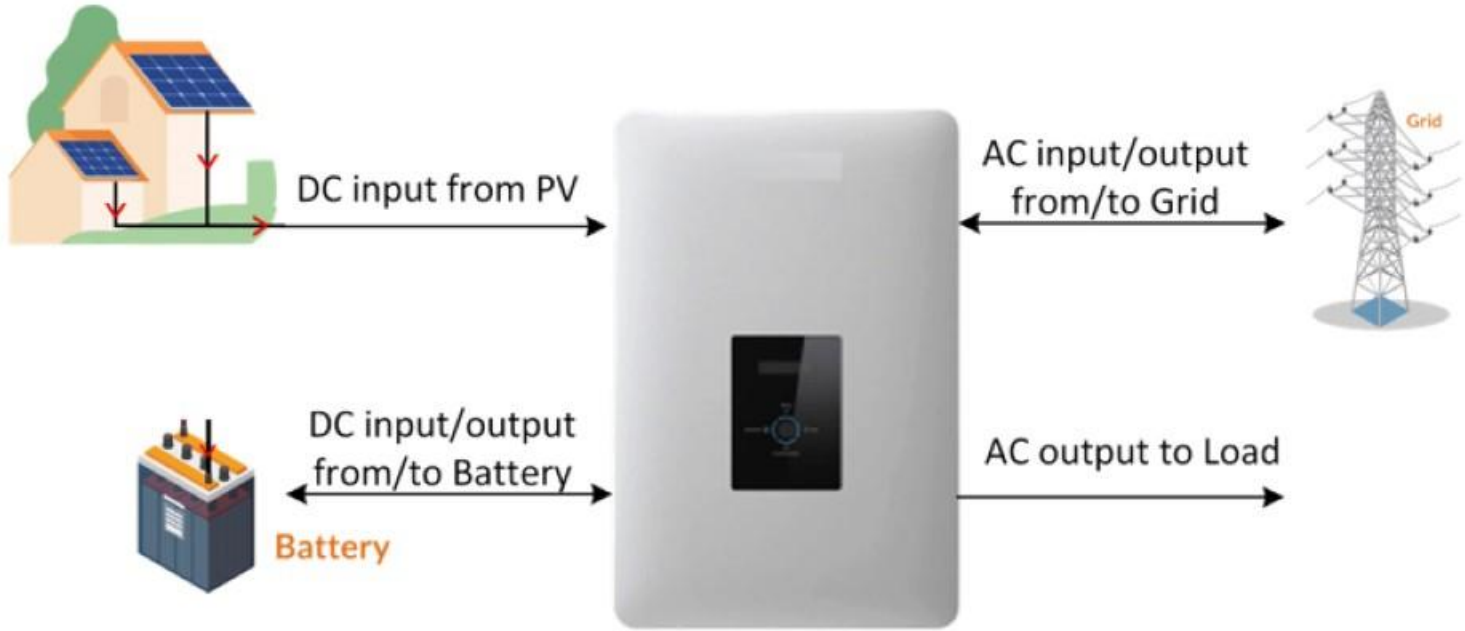
Grid-Connected Inverters

- Solar panel inverters are categorized as grid-connected (also called grid-tied) inverters and off-grid inverters.
- Grid-connected inverters work by taking Direct current from your solar panels and converting it to alternating current which is then fed into the state grid even as you use it in various appliances.
- This means that the balance of your power output is used in the grid. When your power goes off you can get power from your balance.



Grid-Connected Inverters

- This means that whenever you have extra power produced from your solar system, it will flow into the grid system and be credited to your power account from which you can take when your solar power goes off.
- These inverters are used to achieve AC power at the voltage used in the main grid though line-commutation, where the grid signal is used to **synchronize** the inverter with the grid.



Grid-Connected Inverter Types

- Grid-connected inverters are categorized according to the power capacity of the PV installation:
  - String inverters
  - Multi-string inverters
  - Micro inverters
  - Central inverters





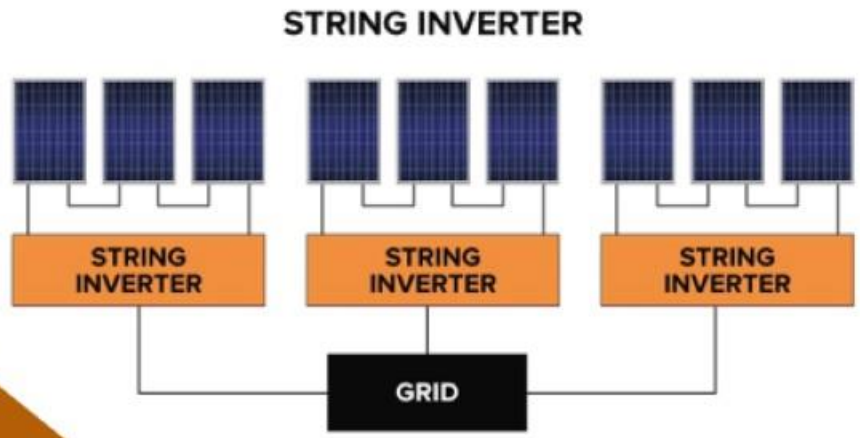




Grid-Connected Inverter Types

Single-string inverters:

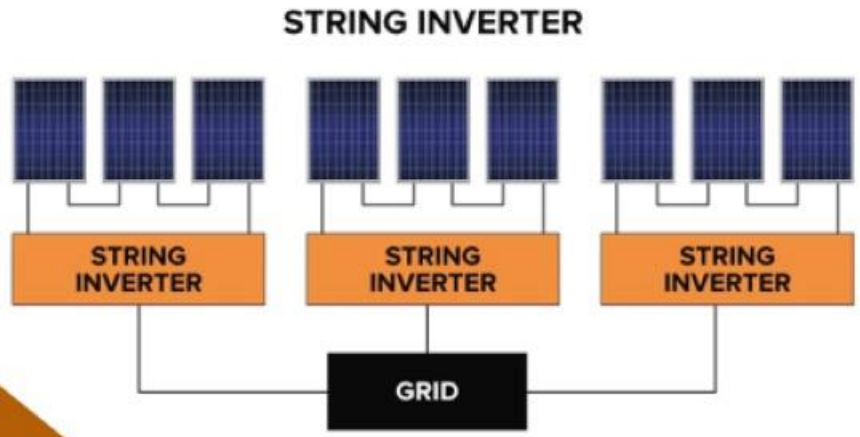
- These are the most pocket-friendly inverters. They are a good choice if all your panels are exposed to a lot of sunlight or if they all face the same direction.
- Each row of panels is called a string, and that string is attached to an inverter.





Grid-Connected Inverter Types

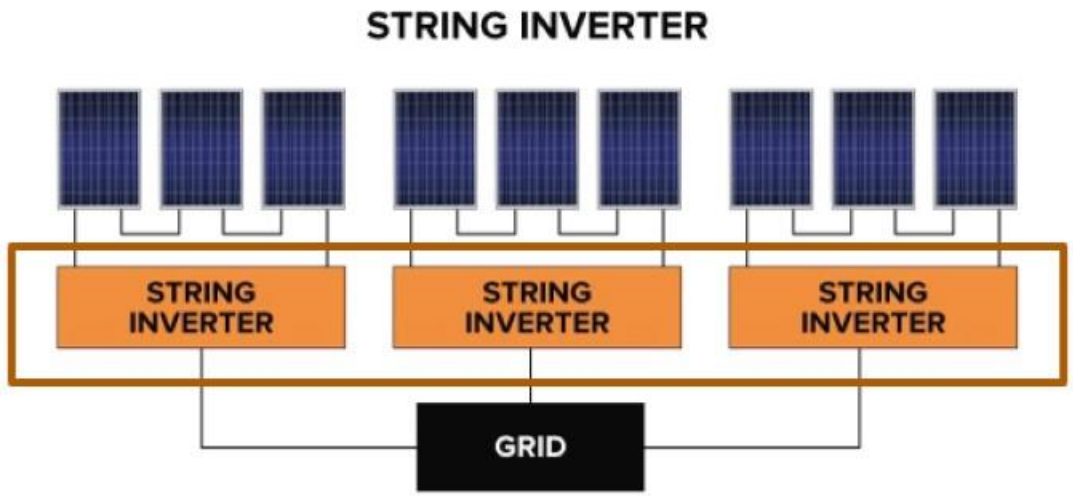
- If a panel on the string does not receive enough light, then it will drag the performance of all the others down to its level.
- The main features of single-string inverters are:
  - Each inverter has only one MPP tracker
  - The string should be composed of modules of the same technology and electrical characteristics





Grid-Connected Inverter Types

- **Multi-string inverters:** These inverters are a combination of the single-string and central inverters. Their size is about 3 kW to 20 kW.
- On the PV array side they consist of several single-string inverters but on the grid side they are like central inverters. The main features of multi-string inverters are:
  - Several integrated MPP trackers
  - Each inverter can have many strings connected, each string with different orientations, inclination and power ratings

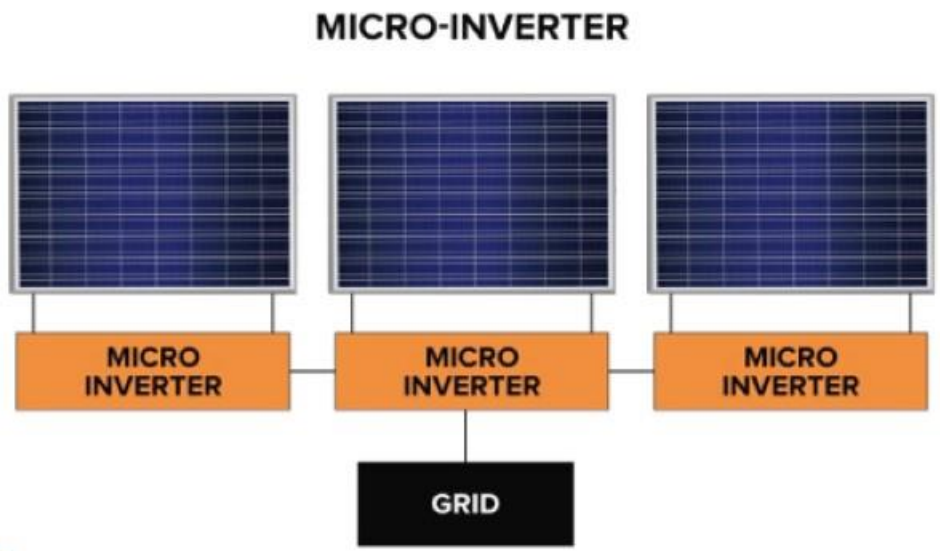


Multi-string inverters

Grid-Connected Inverter Types

Module inverters / controllers inverters / Micro inverters

- These are installed on each panel and they convert the DC power into AC power right at the panel.
- They are more efficient than string inverters because a single panel will not affect the performance of any other panels.

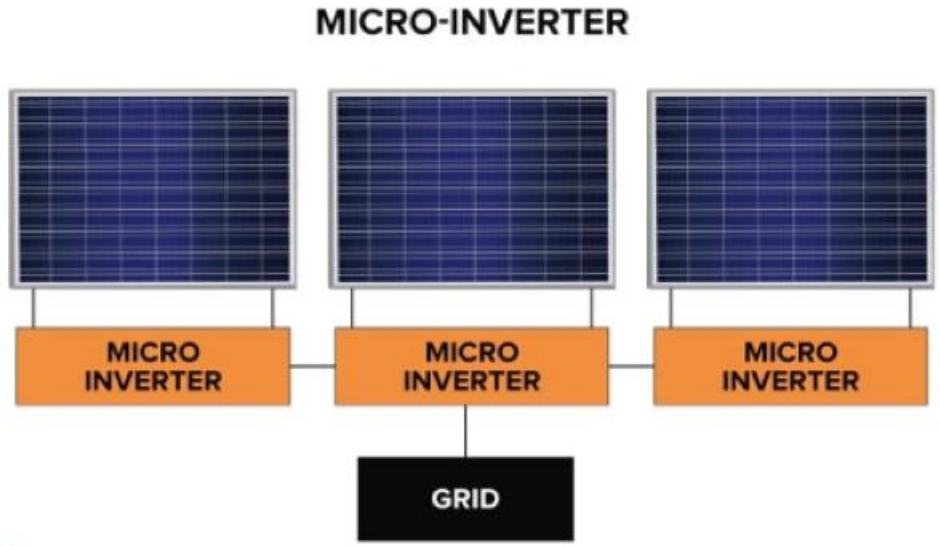




Grid-Connected Inverter Types

Module inverters / controllers inverters / Micro inverters

- They are a good solution for homes where one or more of the panels are in the shade.
- They are expensive, so they should only be purchased if necessary.
- These are small inverters for single modules or module pairs.



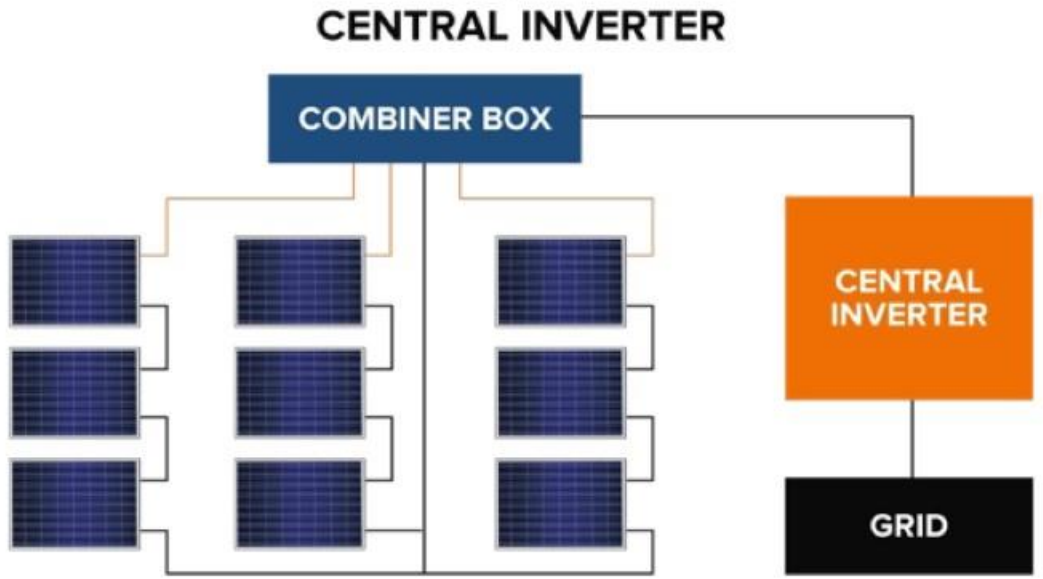


Grid-Connected Inverter Types

Central inverters

- are similar to string inverters but they are much larger and can support more strings of panels.
- Instead of strings running directly to the inverter, as with string models, the strings are connected together in a common combiner box that runs the DC power to the central inverter where it is converted to AC power.



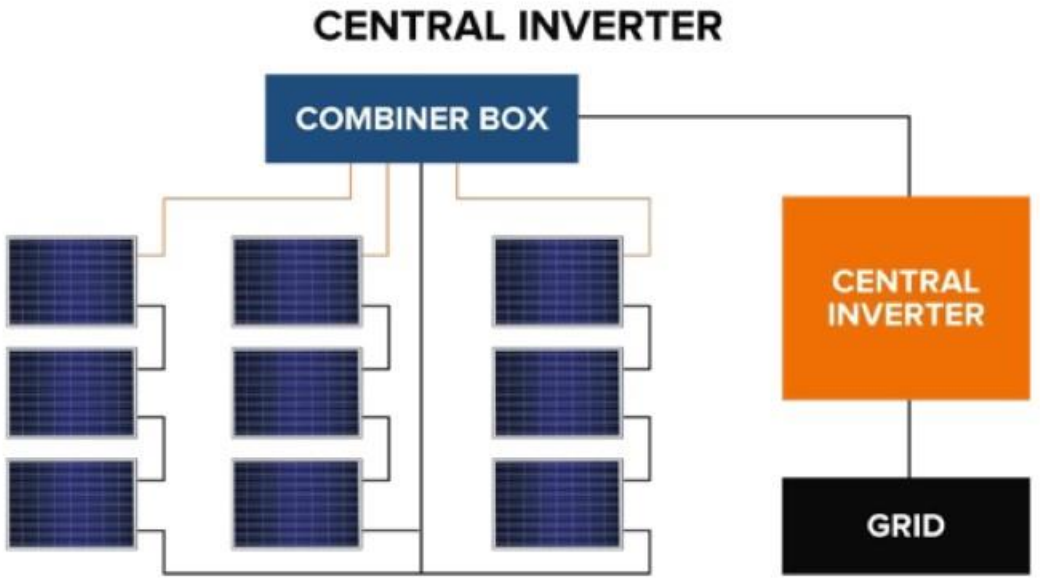


Grid-Connected Inverter Types

Central inverters

- Central inverters require fewer component connections but require a pad and combiner box.
- They are best suited for large installations with consistent production across the array.

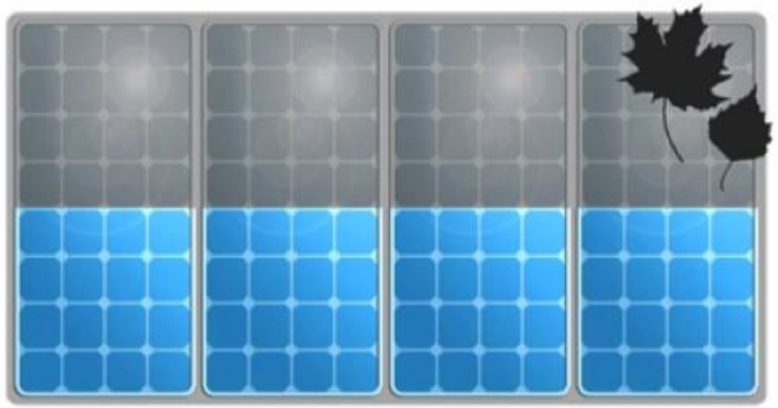




String Inverter vs. Micro Inverter

- **String inverters** have been around a long time, thus giving them the status of the most common type in the inverter industry.
- The downside to string inverters is that if one panel is partially shaded it can lower the production of the whole string.
- Your whole array will be generating less power possibly because of one solar module's potential.

String Inverter



- **Pros and Cons of String Inverters:**
- + The technology is more established
  + Lower cost
  – Weaker warranty
  – Production limited to the weakest panel

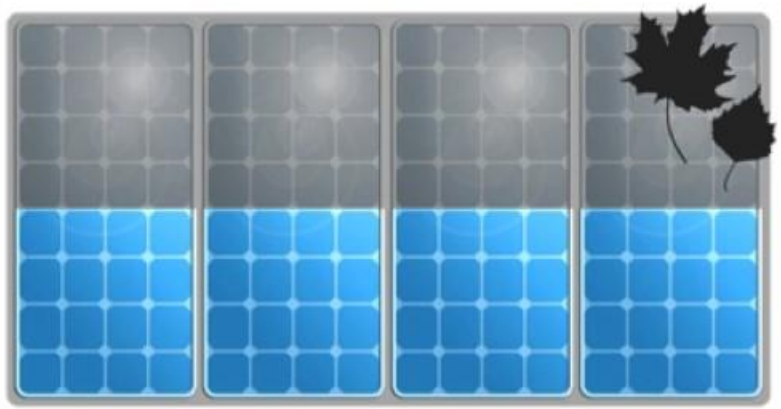
String Inverter vs. Micro Inverter

- **Microinverters**' biggest advantage lies in the fact that each panel's current is being converted at the source.
- If one module's production decreases from shade, angle, or failure, the rest of the production is maintained at peak production. This is more likely to happen in residential pv systems as houses face many directions with many roof angles.
- **Pros and Cons of Microinverters:**
- + Array production not decreased by the weakest link
  + Easy to expand the pv system
  + More efficient conversion
  + Monitoring of each panel via browser/apps
  – More expensive



String Inverter vs. Micro Inverter

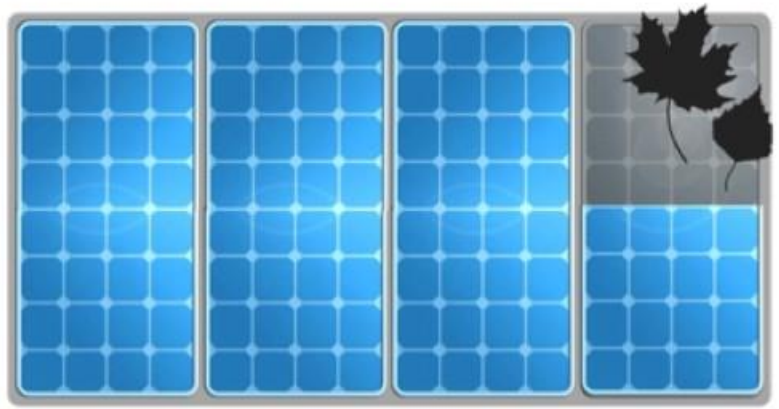
String Inverter



50% 50% 50% 50%



Microinverters

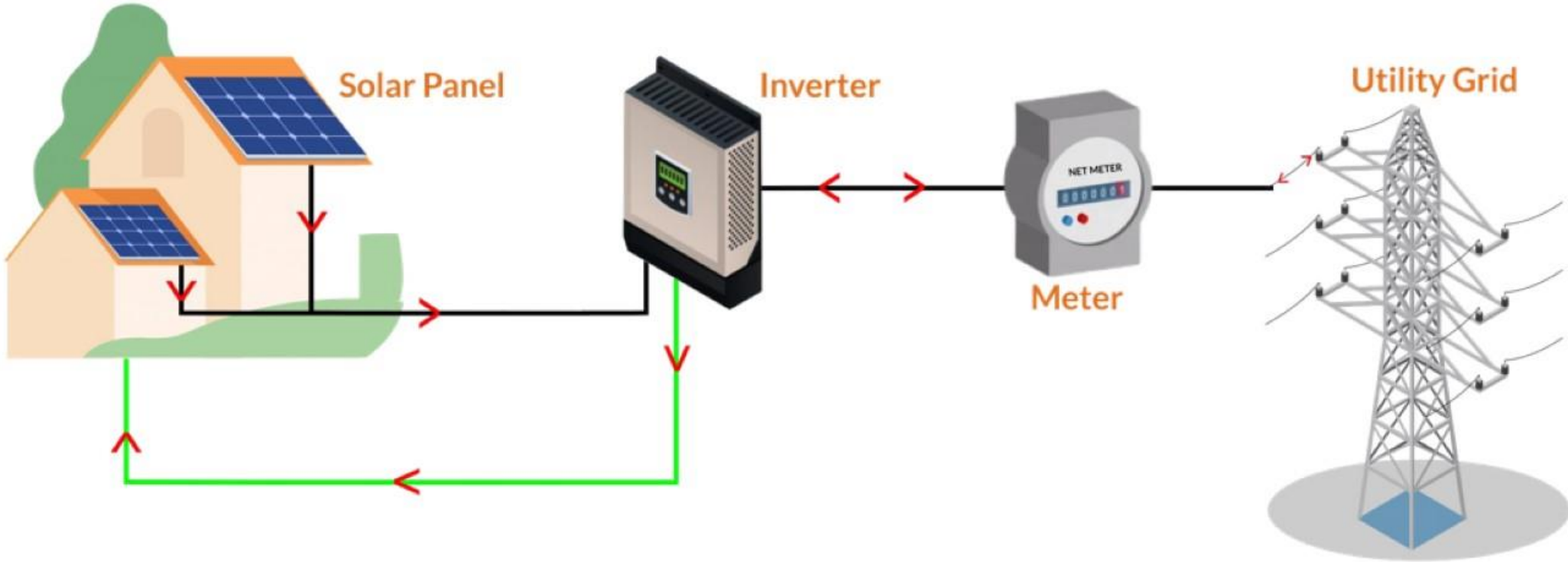


100% 100% 100% 50%



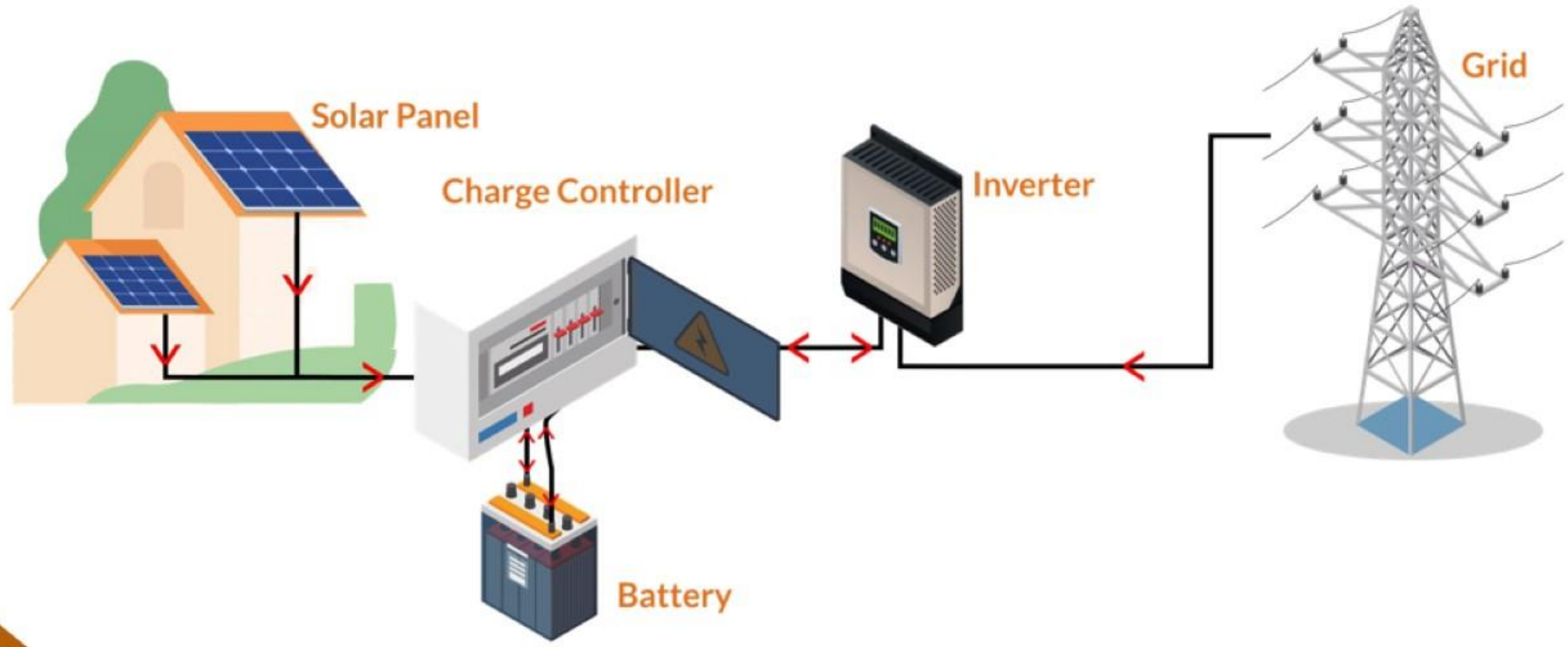
Grid-connected PV Systems topology

Grid Connected PV system with net metering



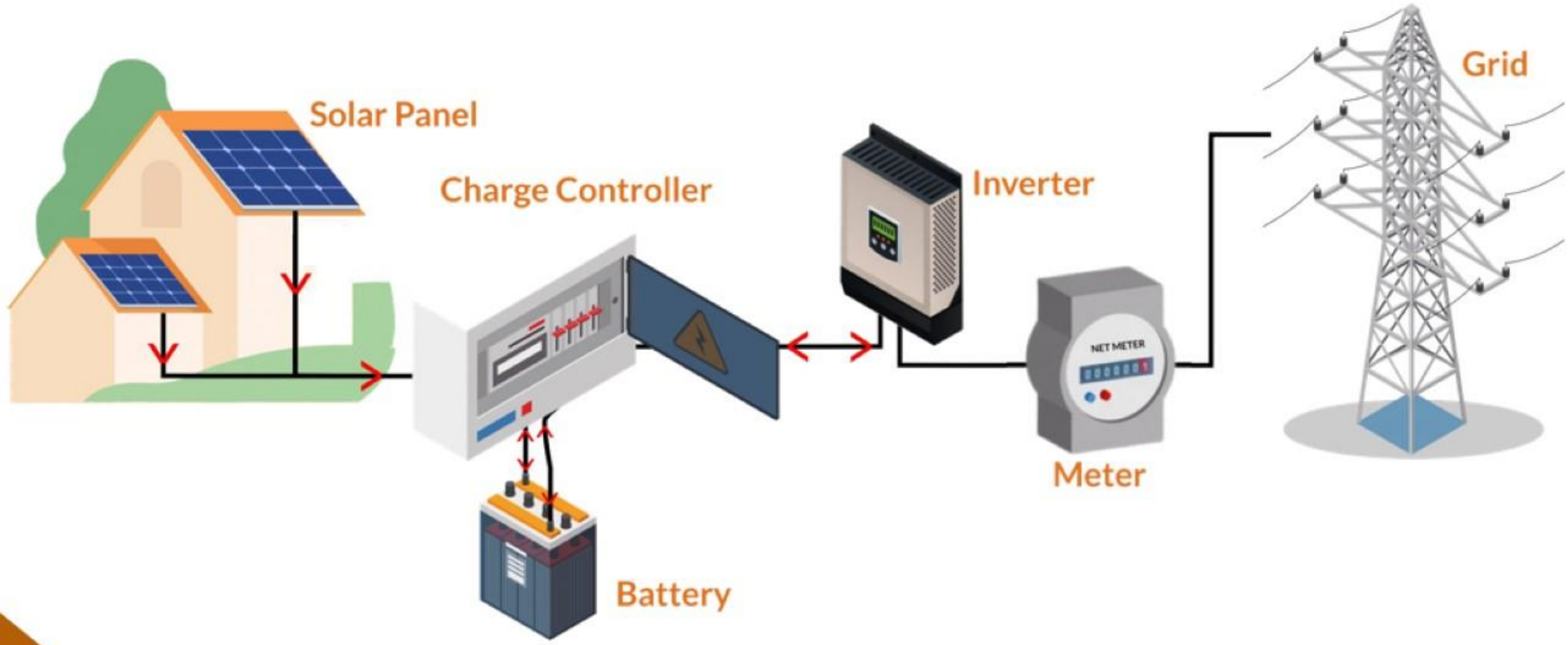
Grid-connected PV Systems topology

Grid Connected PV system with battery storage (Hybrid system)



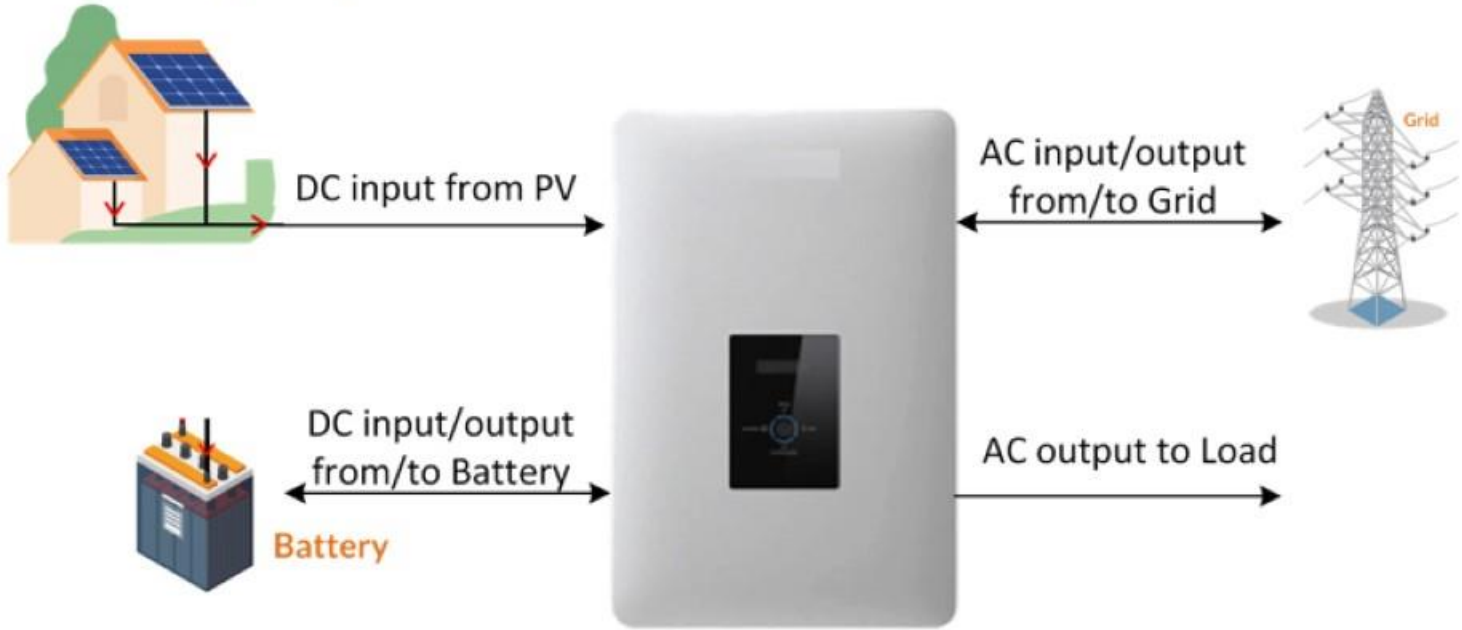
Grid-connected PV Systems topology

Grid Connected PV system with battery storage (Hybrid system) and net metering



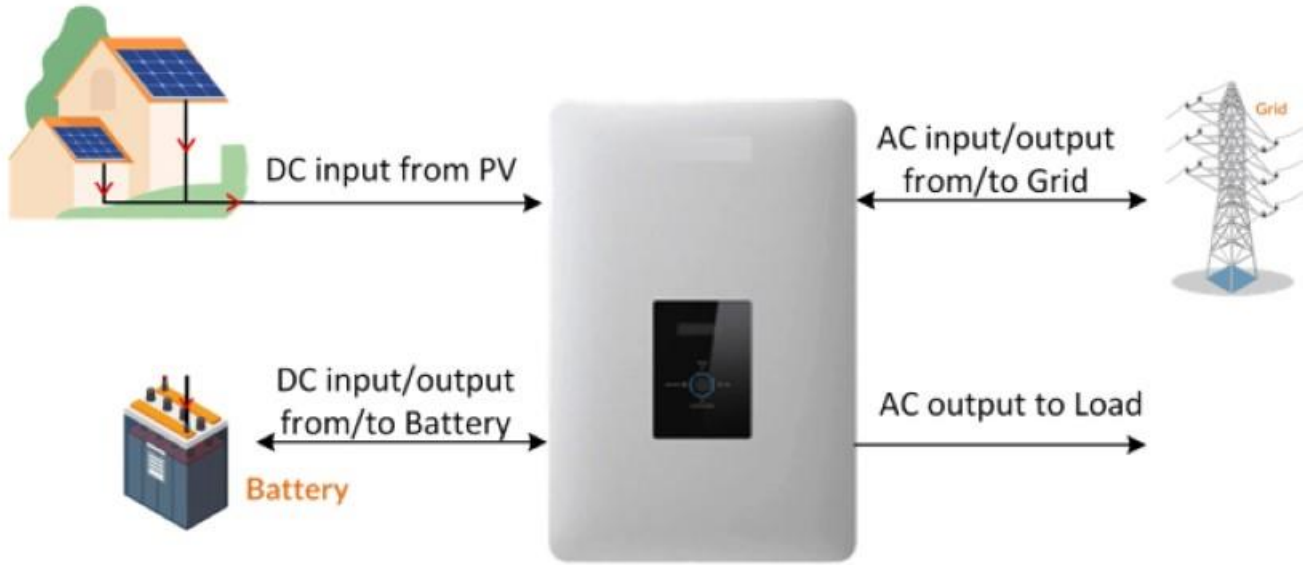
Inverter Compatibility

- The following parameters are important for ensuring compatibility between inverter and PV array:
  - DC maximum input power of the inverter
  - DC peak current input
  - DC peak voltage input
  - MPP voltage range input



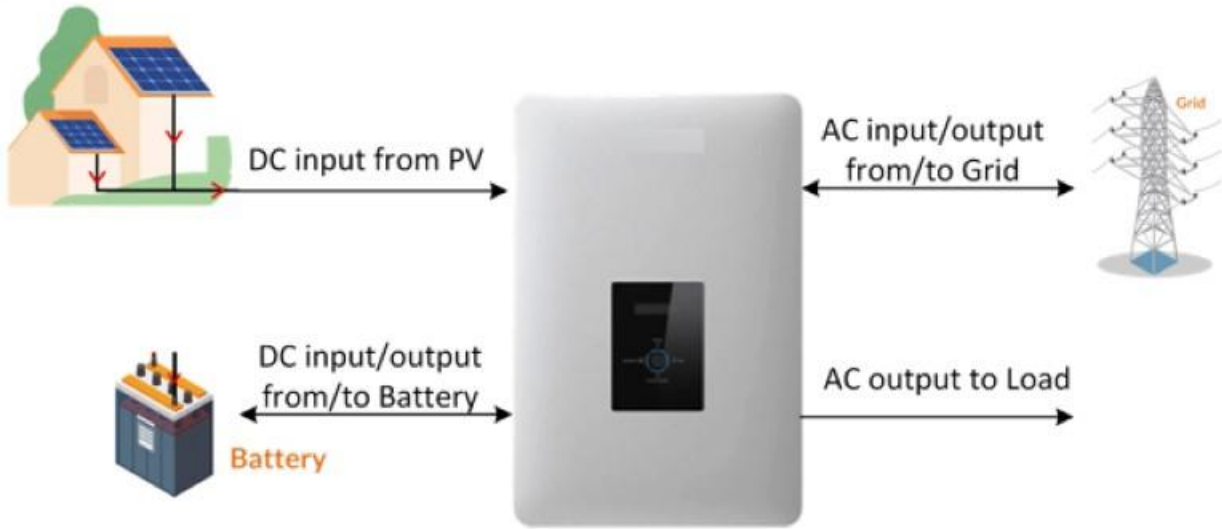
Standards/Regulations

- Grid connected PV involves connection to the electricity supply network which is governed by strict regulations regarding safety (of consumer and maintenance personnel).
- Also, it involves the quality of supply (to ensure stability of the network and quality of service provided to consumers).



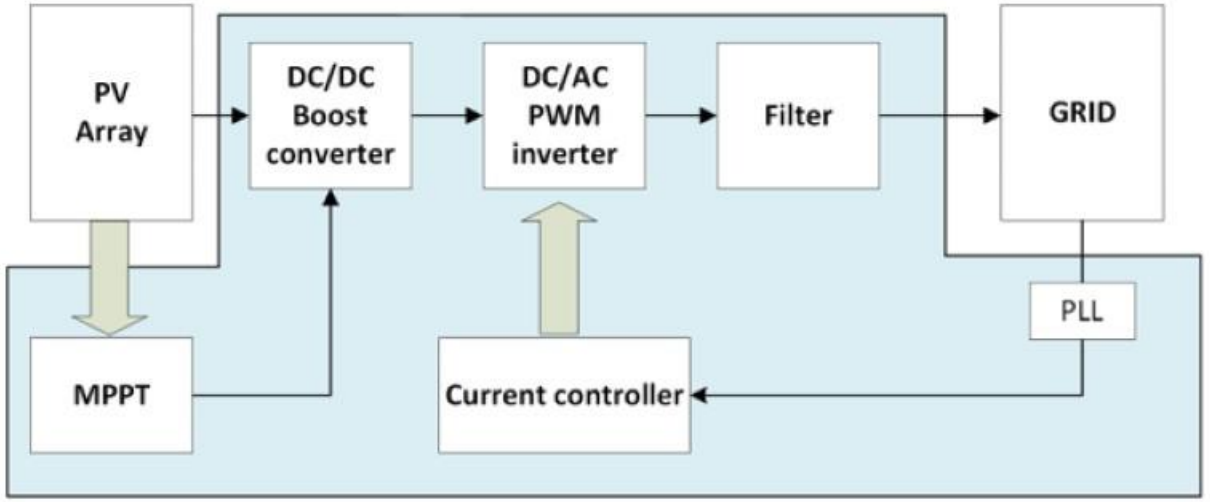
Standards/Regulations

- In terms of safety of operation, the requirements are principally for rapid disconnection from the grid in the event of grid failure.
- This means that the PV inverter is not allowed to operate 'islanded' or isolated from the grid.
- The reason for this is to protect maintenance personnel who would assume that the shut-down grid was not live and it would not be appropriate for the PV inverter to generate in such circumstances.



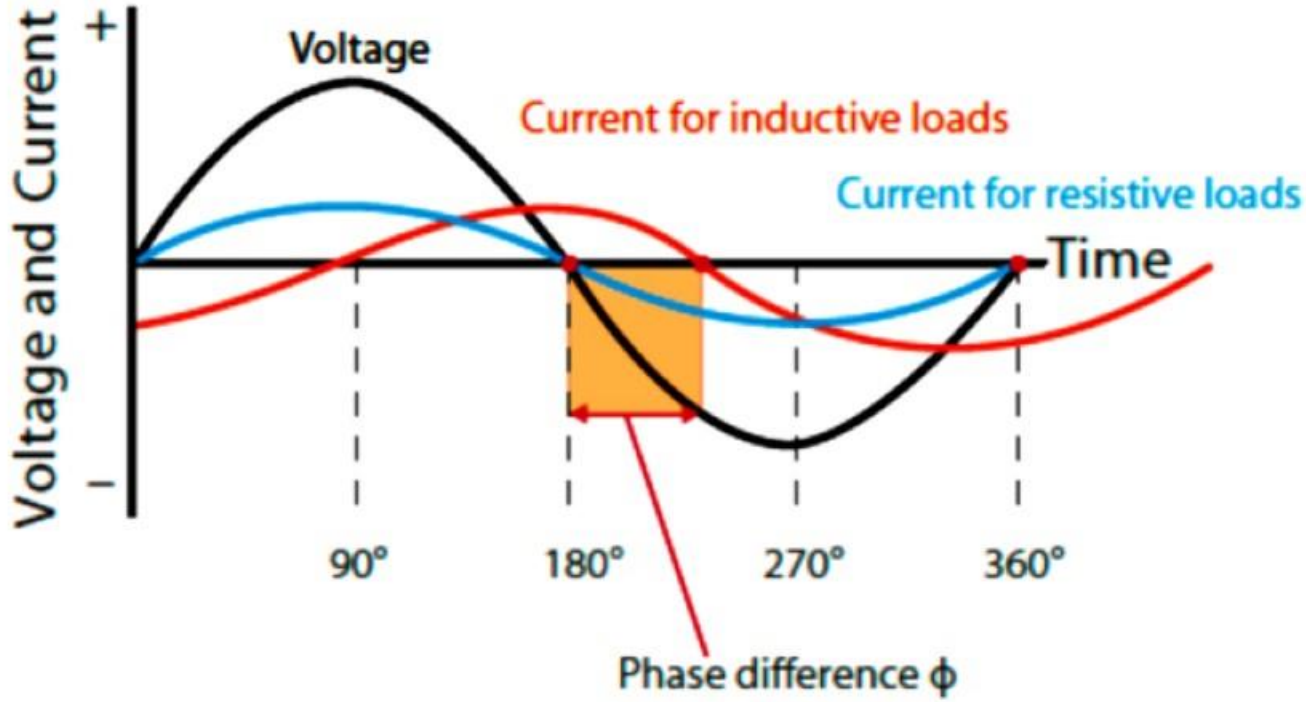
Power Quality

- In terms of power quality the requirements are for limited harmonic distortion and frequency and voltage staying within limits (although these parameters are not dependent on the inverter as both frequency and voltage are essentially fixed by the grid).
- For this purpose focus is concerned with the inverter which is considered utility interactive provided that it meets the requirements of EN 50160. These standards ensure that the inverter output waveform has less than 5% total harmonic distortion (THD) and that the inverter will disconnect from the grid if grid power is lost



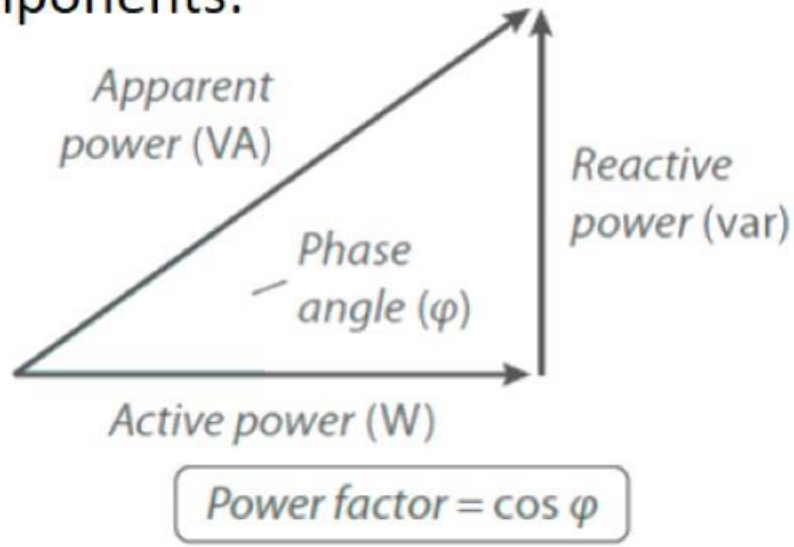
Power factor (PF) of PV systems

- As the integration of PV increases it is important to safeguard the gird and this can happen with the use of power factor.
- The power factor is a parameter that indicates the phase difference between the AC current and voltage signals.



Power factor (PF) of PV systems

- The energy consumed by a device per second is defined as the apparent power S and is measured in VA.
- The apparent power S comprises of two power components:
  - Active power$P$ (W)
  - Reactive power$Q$ (VAr)



- The Power Factor defines the percentage of the apparent power which is consumed as active power:

$$pf = \frac{P}{S} = \cos\phi$$

- End of part 1

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Section 5: Grid-Connected PV System

Part 2

- **Grid-Connected PV System Components**
  - **Inverters**
  - **Junction box**
  - **Cables**
  - **Energy Flow meter**

Nabil Karami, PhD

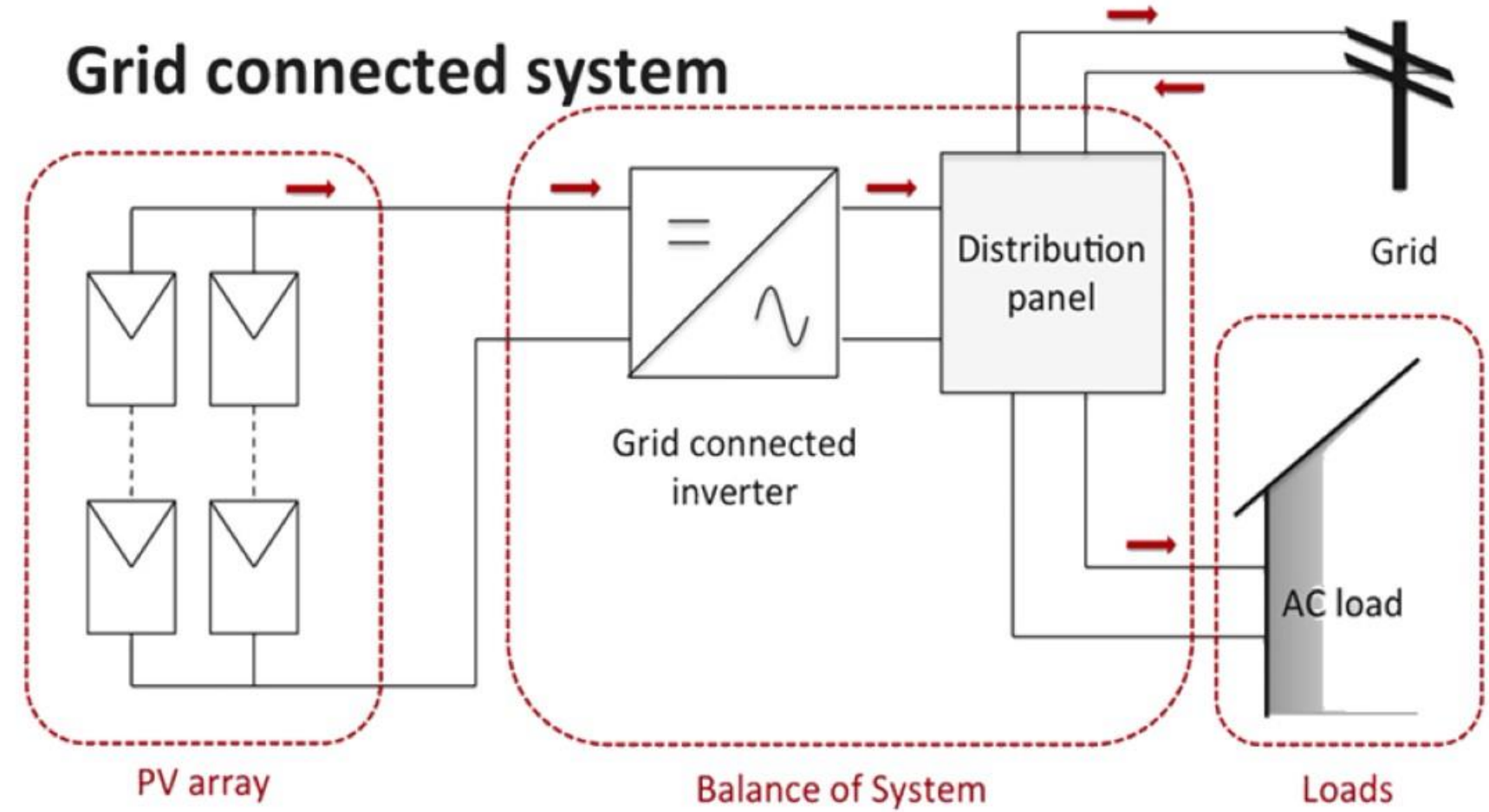
Grid-Connected PV System

❖ Introduction

- Grid-connected (grid-tied) systems: interfaced to an electricity grid.
- Major advantage:
  - Output of PV array is fed into the grid when not required in the home, …
  - Output of PV array is not enough (home needs power that cannot be provided the PV array) , power is imported from the grid.



Grid-Connected PV System Components



Grid-Connected PV System Components

❖ Components

- PV array: mounted on the roof.
  1. PV Combiner Unit
  2. Protection Unit
  3. Inverter
  4. Energy-Flow Metering
  5. Fuse Box
  6. Electrical Loads
  7. Junction Box
  8. Supply Cable



Grid-Connected PV System Components

❖ Inverter

- Inverters are hearts of grid-connected systems.
- It extracts as much as DC power as possible from PV array and converts it into AC power at the right voltage and frequency for feeding into the grid or supplying domestic loads.



Grid-Connected PV System Components

❖ Inverter Operation

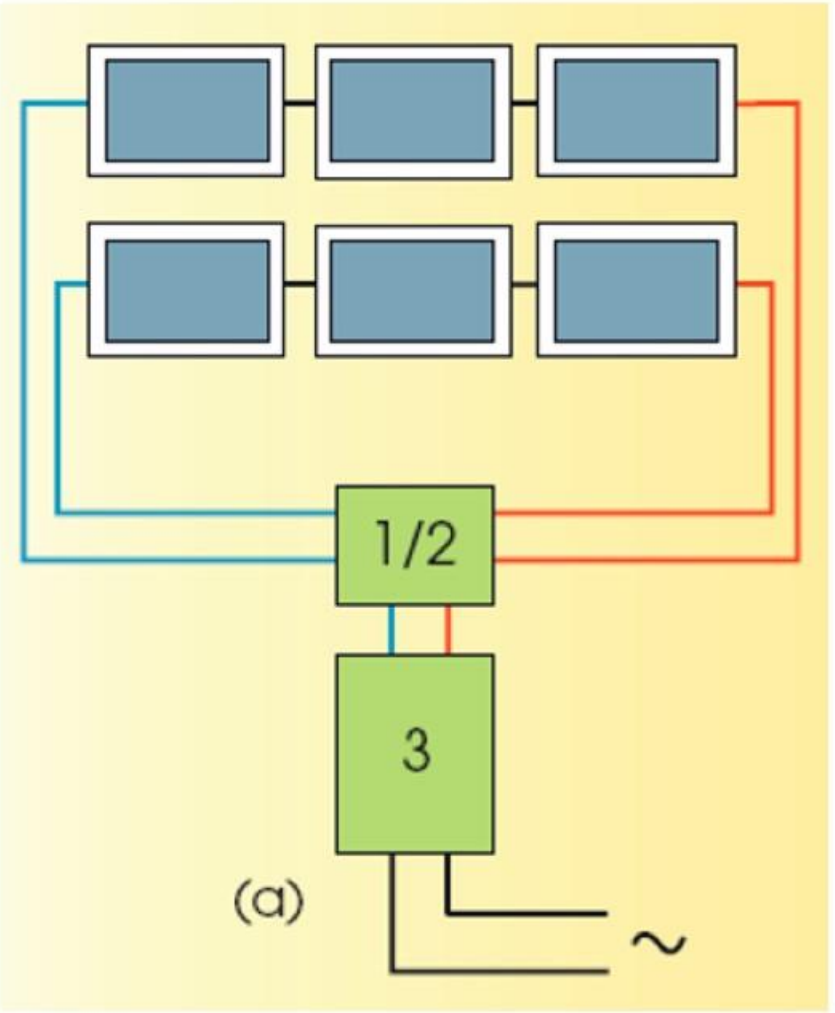
- Inverters must be able to handle power output of a PV array over a wide range of sunlight conditions.
- Inverter system design is challenging.
- Conversion Efficiency up to 98% over much of range. It drops if operated below 25% of its maximum power rating.
- In large systems with multiple inverters, all power is fed into one inverter at sunrise, other inverters are brought into play as sun rises in the sky.



Grid-Connected PV System Components

❖ Central Inverter

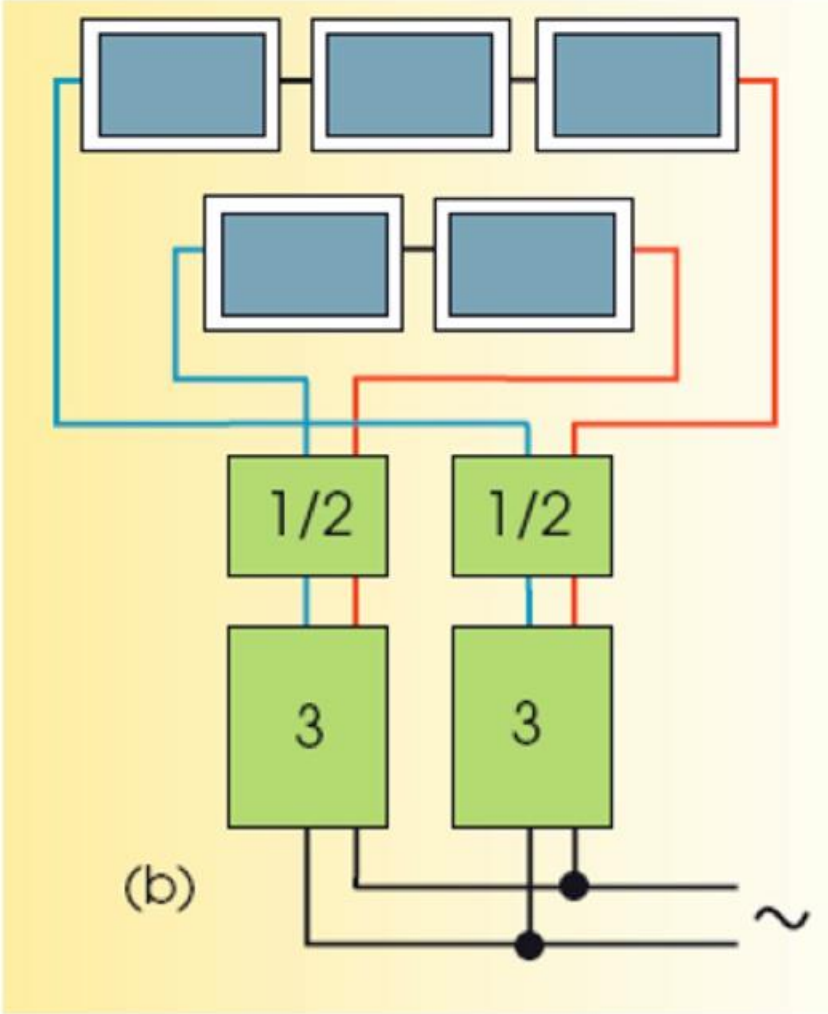
- Modules are assumed to be of the same specifications (type, ratings, orientation, without shading).
- Two strings of three modules each.
- Strings are paralleled in the combiner/protection units (1/2) and fed into a single central inverter (3).
- Inverter Input Voltage: (3 x individual module voltage)
- Inverter Input Current: (2 x individual module current)
- MPP selected by inverter for the whole array ensures that all modules work at, or close to, their maximum output.



Grid-Connected PV System Components

❖ String Inverter

- Two dissimilar strings (number of modules, type, ratings, orientation, shading).
- Each string has a combiner/protection unit (1/2) and fed into its own string inverter (3).
- Each string produce different output.
- Each string has its own inverter and is operated at its own MPP.
- Multi-string inverter is an alternative.



Grid-Connected PV System Components



❖ Cooling of Inverters

- Example:
  - 5 kWp inverter
  - 96 % efficiency
  - → 200 W must be dissipated
  - Proper cooling of the inverter
- Outdoor mounting
- North-facing wall
- Cooling fan
- Cooling issue becomes more significant as power increases.

Grid-Connected PV System Components

❖ Disconnection of Inverters

- Inverter must be disconnected itself automatically,
  - If Grid is turned off for maintenance or fault,
  - If grid voltage, frequency, and impedance are outside the specified specifications.

Grid-Connected PV System Components

Cabling

- Double-insulated DC wires from PV modules to inverters
- UV and water- resistant
- Designed for low voltage drop (< 2%).
- Long strings (reducing the current and increasing voltage)



Grid-Connected PV System Components

❖ PV Combiner/Protection Units

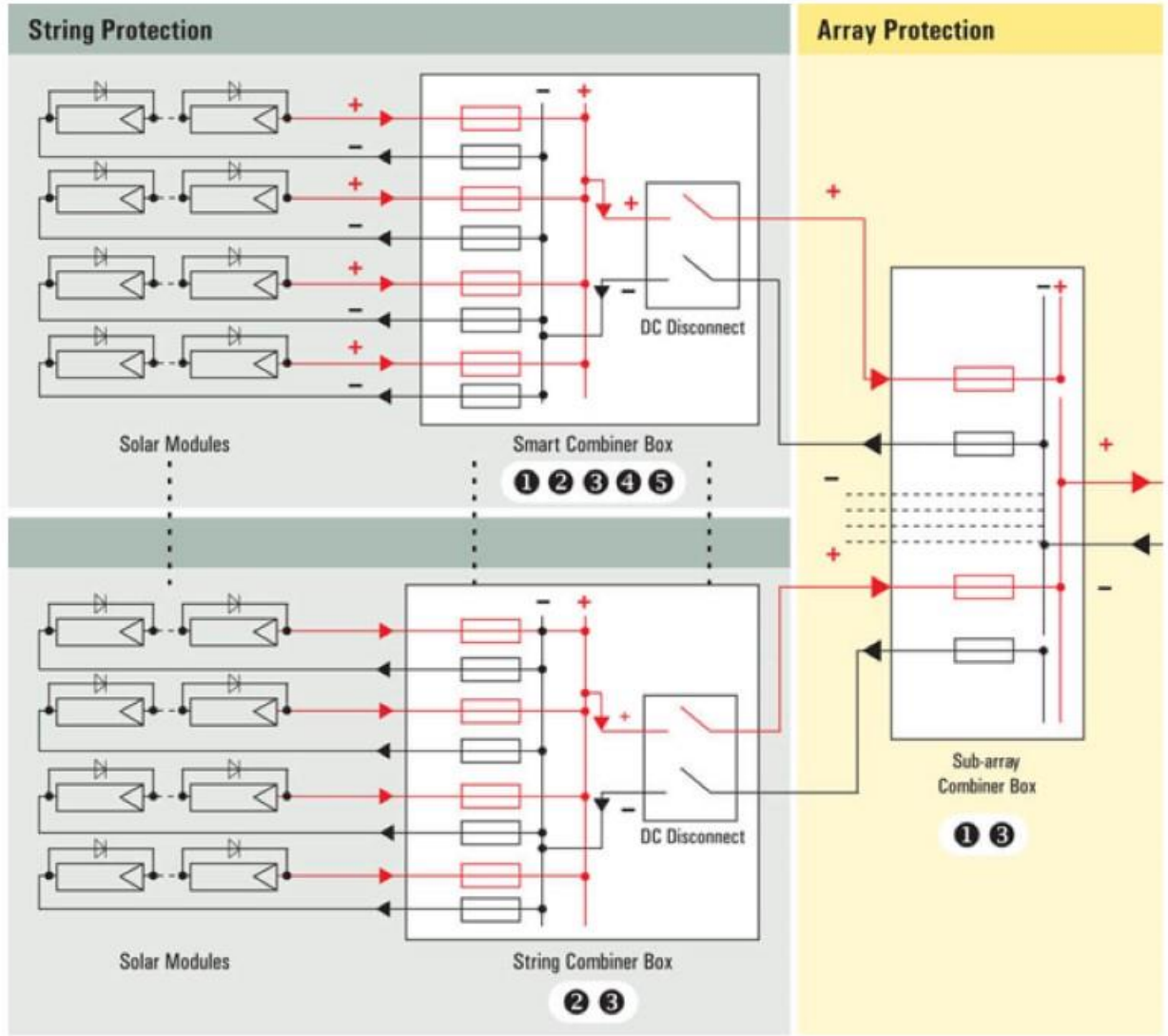
- Combiner unit acts as junction box for the modules strings (usually parallel).
- Fuses for each string
- Surge protection against lightening
- Main DC isolator for maintenance and testing
- Earthing (local regulations – Codes)





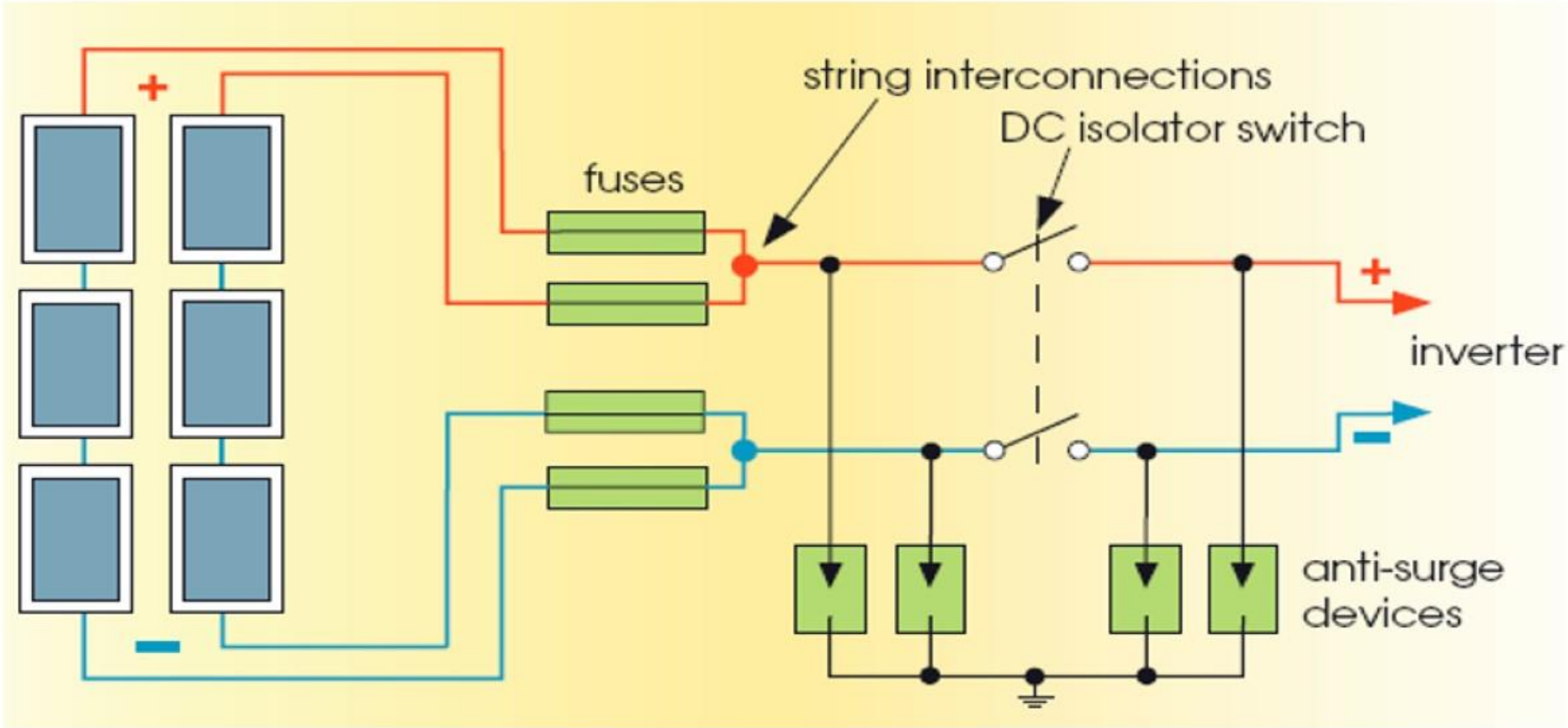
Grid-Connected PV System Components

❖ PV Combiner/Protection Units



Grid-Connected PV System Components

❖ PV Combiner/Protection Units



Grid-Connected PV System Components

❖ Energy-Flow Metering

- Twin kWh meters
- Bidirectional meter (net metering)
- Differential tariff
- Data-logging facility



- **End of Part 2**

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Section 5: Grid-Connected PV System

Part 3

- **Grid Connected PV sizing**
- **Steps and Example**

Nabil Karami, PhD

Grid-Connected PV sizing

- The sizing of grid connected and building mounted PV systems is dominated by space and/or cost constraints.





Grid-Connected PV sizing

- The following methodology could be used to size a grid-connected PV system:
  - Step 1: Site survey and cost
  - Step 2: Deciding on the initial number of modules needed
  - Step 3: Checking the module voltages
  - Step 4: Inverter selection
  - Step 5: Checking voltage limits and module configuration
  - Step 6: Array configuration – inverter compatibility
  - Step 7: Final system design

Grid-Connected PV sizing

Case Study

- A Cyprus-based suburban family home is prepared to invest a maximum of €8700 in a grid-connected PV system.
- The available roof surface area is 40 m^2 (length= 8 m and width = 5.0 m) and is free of any shading obstacles.
- The orientation of the roof is due south and it is inclined at an angle of 30°.
- The estimated net installed cost at present of a grid-connected PV system is 1.5 €/W_p.
- The yearly solar irradiation in Cyprus in the Plane of Array "POA" of 30° is 2000 kWh/m^2/yr.

Grid-Connected PV sizing

- Details of inverter used:
  - Nominal Power rating (Maximum DC PV power $P_{PV,\ MAX}$): 5200 W
  - Maximum DC input Voltage $V_{PV,\ MAX}$: 750 V
  - Minimum DC input Voltage $V_{PV,\ MIN}$: 125 V
  - Maximum DC input Current $I_{PV,\ MAX}$: 15 A
  - MPP Voltage range: 175 V – 500 V
  - Multi-string inverter - string inputs: 2 strings
- the temperature at the location ranges from -10 °C to 40 °C
- the module temperatures are expected to range from -10 °C to 70 °C

Grid-Connected PV sizing

- The surface area required for a 1 kWp mono-c-Si array is 7m2 (roof-mounted). The exact dimensions of the mono-c-Si module used are 1.7 m × 1 m (length × width)
- The PV module has the following characteristics:
  - P_{MPP}: 235 W_p V_{MPP}: 29.5 V I_{MPP}: 8.06 A V_{OC}: 36.6 V I_{SC}: 8.66 A
  - α : 2.0 mA/ °C β:-168.63 mV/ °C
- The surface area including shading required for a 1 kWp mono-c-Si array is 15 m^2 (open field fixed-mounted)
- **Design a system considering that the home owner requires the highest possible output from it.**

Grid-Connected PV sizing

Step 1: Site survey and cost

- First divide the amount of money available by the estimated cost of the system:

$$\frac{€\,8700}{1.5\ €/\mathrm{W_p}} = 5800\ \mathrm{W_p}$$

- And divide the available roof surface area by the module type, mono-c-Si in this case:

$$\frac{40\ \mathrm{m^2}}{7\ \mathrm{m^2/kW_p}} = 5.71\ k\mathrm{W_p}$$

- So the largest array we can get on the roof is 5.71 kWp which is within the budget.

Grid-Connected PV sizing

Step 2: Deciding on the initial number of modules needed

- In making an initial estimate of how many modules are required the following data is needed:
  - peak power of the array (kWp)
  - dimensions of roof surface area available (length and width)
  - module dimensions
  - PV string sizing

Grid-Connected PV sizing

- Module selection:
- We are provided with the mono-c-Si module to be chosen for the system. In order to do an initial estimate of the number of modules required, divide the initial estimation of array peak power arrived in Step 1 by the peak power of the chosen module.

$$\frac{\text{Array peak power}}{Module\ peak\ power} = Initial\ estimate\ of\ number\ of\ modules\ required$$

$$= \frac{5710}{235} = 24.29\ modules$$

- The initial estimate gives us 24 modules (24 × 235 Wp= 5640 Wp)

Grid-Connected PV sizing

- Surface area requirements and possible module layout configurations:
- Now we need to check whether the 24 modules will fit on the roof.

- Modules laid out in landscape format:

$$\frac{Roof\ length\ 8\ \mathrm{m}}{Module\ length\ 1.7\ m} = 4.7\ modules$$

$$\frac{Roof\ width\ 5\ \mathrm{m}}{Module\ width\ 1\ m} = 5\ modules$$

- This gives a maximum of 20 modules which can fit in landscape format (4 × 5 modules)

Grid-Connected PV sizing

- Modules laid out in portrait format:

$$\frac{Roof\ length\ 8\ \mathrm{m}}{Module\ width\ 1\ m} = 8\ modules$$

$$\frac{Roof\ width\ 5\ \mathrm{m}}{Module\ length\ 1.7\ m} = 2.9\ modules$$

- This gives a maximum of 16 modules which can fit in portrait format (8 × 2 modules)
- The initial estimate of 24 modules cannot be accepted at this point because of area constraints.
- The maximum amount of modules will be selected therefore 20 modules will be fit in landscape format.

Grid-Connected PV sizing

Step 3: Checking the module voltages

- Now the voltage values of the modules must be determined at 10°C to 70°C.
- The highest voltages are achieved in winter when the modules are cold and the lowest in summer when the modules are warm.

$$V_{OC}(\text{at } -10\,^{\circ}\text{C}) = V_{OC(25\,^{\circ}C)} + \left[(T_{mod(-10\,^{\circ}C)} - T_{STC}) \times \beta\right]$$

$$V_{OC}(\text{at } -10\,^{\circ}\text{C}) = 36.6 + (-35 \times -0.1686) = 42.5\,V$$

$$V_{MPP}(\text{at } -10\,^{\circ}\text{C}) = 29.5 + (-35 \times -0.1686) = 35.4\,V$$

$$V_{MPP}(\text{at } 70\,^{\circ}\text{C}) = 29.5 + (45 \times -0.1686) = 21.9\,V$$

Nabil Karami

Grid-Connected PV sizing

Step 4: Inverter selection

- Select an inverter based on the following criteria:

$$0.90 \ldots 0.95 \times Inverter\ power\ rating = PV\ array\ peak\ power$$

- The PV array peak power is 20 × 235 Wp= 4700 Wp
- A selection of an inverter with a nominal power rating of between 4.95 kW to 5.22 kW would be correct.

Grid-Connected PV sizing

Step 5: checking voltage limits and module configuration

- The aim of this step is to decide on the number of modules in a string. The string voltage needs to be within both the upper and lower limit of the inverter MPP voltage range. The open-circuit voltage of the string also needs to be checked to ensure that it is below the maximum and minimum inverter input voltage.

$$Maximum\ number\ of\ modules = \frac{V_{MPP,MAX}}{V_{MPP(\text{at } -10\ ^\circ\text{C})}} = \frac{500}{35.4} = 14.12$$

$$Minimum\ number\ of\ modules = \frac{V_{MPP,MIN}}{V_{MPP(\text{at } 70\ ^\circ\text{C})}} = \frac{175}{21.9} = 7.99$$

- So in order to stay within the voltage range input at which the inverter will track the MPP of the array the number of modules in each string must not be fewer than 8 and not be more than 14.

Grid-Connected PV sizing

- The maximum voltage at the inverter input will occur at -10 °C during open-circuit operation.
- The number of modules in strings must be revised so that under no circumstance does the string voltage go above the maximum DC voltage input of the inverter $V_{PV,\,MAX}$ (750 V).

$$Maximum\ number\ of\ modules = \frac{V_{PV,MAX}}{V_{OC(\text{at } -10\ ^\circ\text{C})}} = \frac{750}{42.5} = 17.6$$

- So the original figure of 14 modules can be retained since this is below the maximum DC voltage input $V_{PV,\,MAX}$.

Grid-Connected PV sizing

Step 6: Array configuration – inverter compatibility

- Now it is necessary to check if the total number of modules originally decided upon in Step 2, can be divided into an amount of strings acceptable by the inverter (the selected inverter has 2 string inputs)

$$\frac{\text{Planned number of modules}}{\text{Number of modules per strings}} \leq \text{number of strings}$$

$$\frac{20}{14} = 1.42 \leq 2$$

Grid-Connected PV sizing

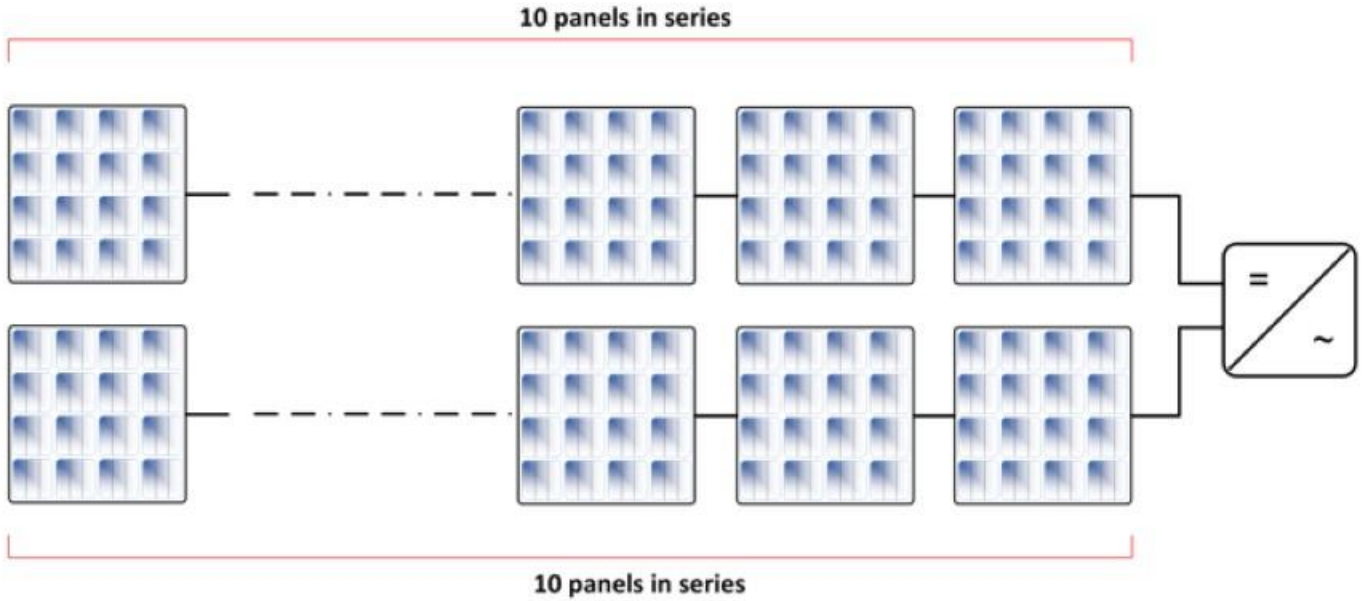
- The 20 PV modules selected can be connected to the inverter using 2 strings. The strings must be designed with a maximum of 14 modules and minimum of 8.
- As a rule of thumb always try to balance out the two strings (although this does not really matter for multi-string inverters because of the two different MPP trackers).

- Therefore the two strings can be designed such that:
- String A: 10 × 1 modules (10 modules connected in series)
- String B: 10 × 1 modules (10 modules connected in series)

Grid-Connected PV sizing

Step 7: Final system design

- PV: The 20 PV modules, 4700 Wp in 2 two strings
- PV arrangement mounting: Horizontal arrangement.
- Inverter: Nominal power 4.95 kW to 5.22 kW.
  - String A: 10 × 1 PV module (10 modules connected in series)
  - String B: 10 × 1 PV module (10 modules connected in series)



Grid-Connected PV sizing



- In practice, the peak performance ratio of grid connected PV systems will be up to 80% irrespective of geographical location.
- Local site conditions will then reduce the PR, perhaps as low as 50% before considered uneconomic.
- The two factors which reduce PR are high temperature and low radiation.
- A simple shading object can reduce PR significantly depending on precise location and corresponding daily and seasonal movement of the shadows cast.

References

- https://www.itekenergy.com/inverters/10-best-solar-inverter-brands-for-your-solar-panels/
- https://www.itekenergy.com/inverters/10-best-solar-inverter-brands-for-your-solar-panels/

- https://sunedisoninfra.com/blog/solar-inverter-and-its-types/
- https://www.solarpowerworldonline.com/2012/02/cabling-101/

End of Session 5

SECTION 1: QUIZ

1.1. The solar insolation just outside the earth's atmosphere referred to as the solar constant, and is equal to:

- a) 1.0 kW/m2
- b) 1.36 kW/m2
- c) 1.30 kW/m2
- d) 1.06 kW/m2

1.2. The solar radiation can be represented with energy carrier particles called

- a) Photons
- b) Nucleus
- c) Electron
- d) Atom

Nabil Karami

SECTION 1: QUIZ

1.3. Calculate the declination angles at

- 15 February
- 4 June
- 15 May
- 24 August

1.4. Find the maximum extraterrestrial irradiance (at 12PM) on a horizontal surface over Marseille (France) on October 23rd

1.5. Calculate the position of the sun at 11 AM of 12 June at Latitude 20 degrees

SECTION 2: QUIZ

2.1. As temperature increases, the PV efficiency increases. (True/False)

2.2. The maximum PV power is achieved at the maximum PV current and maximum PV voltage. (True/False)

2.3. The PV power generation depends to visible light, UV light and Infrared light. (True/False)

2.4. Calculate the theoretical power, the maximum power and fill factor of a PV with

- V_{OC} = 20, I_{SC} = 5 , V_{mpp} = 18, I_{mpp} = 4.
- Show the formula and draw the characteristic curves.

SECTION 2: QUIZ

2.5. Calculate the efficiency of the PV of 0.25 m^2 with a rated power of 30 watt.

2.6. Circle the right answer (s):

- a) Photovoltaic is a technology involving the direct conversion of solar radiation into AC electricity using solar cells.
- b) Photovoltaic is a technology involving the indirect conversion of solar radiation into DC electricity using solar cells.
- c) Photovoltaic is a technology involving the direct conversion of solar radiation into DC electricity using solar cells.
- d) Photovoltaic is a technology involving the indirect conversion of solar radiation into AC electricity using solar cells.

2.7. Circle the right answer(s)

Power delivered by a photovoltaic system will be a function of :

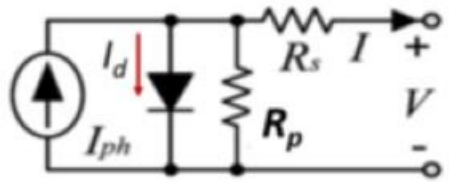
- a) Solar intensity,
- b) Spectral variations associated with overcast conditions,
- c) Ambient temperature, and wind speed
- d) What type of load the photovoltaics are supplying.

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SECTION 2: QUIZ

2.8. Circle the right answer The Effect of Rs and Rp on PV Cell is that

- a) By increasing Rp and decreasing Rs both reduce the area of the maximum power rectangle.
- b) By increasing Rp and increasing Rs both reduce the area of the maximum power rectangle.
- c) By decreasing Rp and increasing Rs both reduce the area of the maximum power rectangle.
- d) By decreasing Rp and decreasing Rs both reduce the area of the maximum power rectangle.



2.9. Circle the right answer(s) The Concept of NOCT is:

- a) Ambient Temperature Tamb = 20 C
- b) Solar Cell Temperature T = 25 C
- c) 1-sun irradiance
- d) Wind Speed = 1 m/s
- e) Air Mass AM = 1.5
- f) Solar irradiation = 0.8 kW/m^2

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SECTION 2: QUIZ

2.10. Consider a PV array rated at 1.5 kW under STC. With the following conditions:

- Module NOCT is 48°C.
- DC power output at the MPP drops by 0.5%/°C above the STC temperature of 25°C.

(a) Estimate its ac output under PTC conditions if there is:

- a 3% array loss due to mismatched modules,
- dirt loss is 4%,
- and the inverter has an efficiency of 90%.
- Ambient temperature of 20 °C

(b) Estimate the daily energy that the 1.5 kW array described in part (a) would deliver if the average daily maximum temperature is −3.0°C.

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SECTION 3: QUIZ

3.1. Circle the right answer:

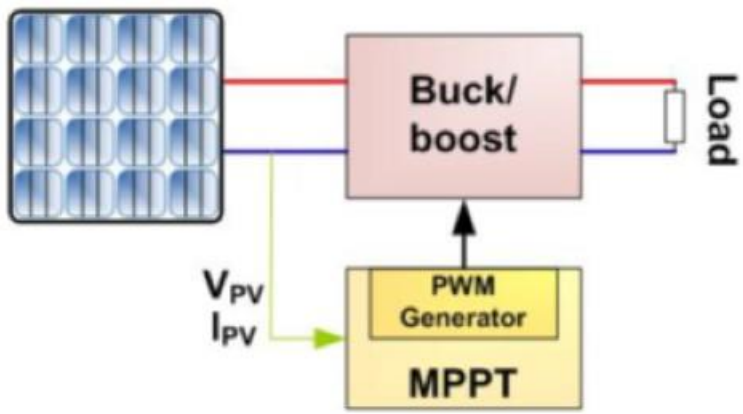
- a) A buck-boost converter is capable of raising or lowering an AC voltage from its source to whatever AC voltage is needed by the load.
- b) A buck-boost converter is capable of raising or lowering a DC voltage from its source to whatever AC voltage is needed by the load.
- c) A buck-boost converter is capable of raising or lowering a DC voltage from its source to whatever DC voltage is needed by the load.
- d) A buck-boost converter is capable of raising or lowering a AC voltage from its source to whatever DC voltage is needed by the load.

3.2. The purpose of using a maximum power point tracker (MPPT) is:

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SECTION 3: QUIZ

3.3. In the figure below, and under certain ambient conditions, a PV module has its maximum power point at V_{mpp} = 17 volts and I_{mpp} =6 A. What duty cycle should an MPPT (driven by a 100% efficient buck-boost converter) have if the module is delivering power to a 10 Ohm resistance?

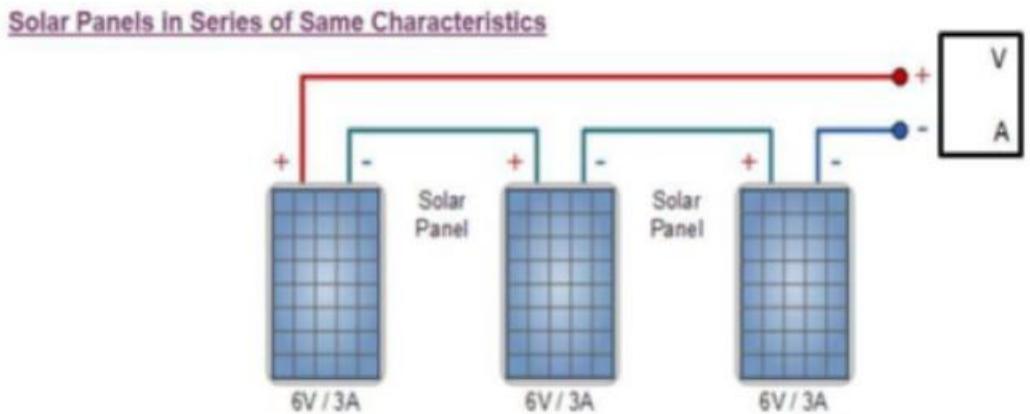


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SECTION 3: QUIZ

3.4. What are the voltage and current values for the following connection of the three solar cells?

- a) 6 volts and 9 amps
- b) 18 volts and 9 amps
- c) 6 volts and 3 amps
- d) 18 volts and 3 amps



SECTION 3: QUIZ

3.5. In case of having strings of modules are wired in parallel, how can you overcome the problem of shading in case one of the strings became a shaded string?

3.6. A PV module is made up of *n* identical cells, all wired in series.
In full sun and with 0.5 V as junction voltage of each cell, the current flowing in each cell is I = 2.14A.
The parallel resistance R_P = 6 Ω and series resistance R_S = 0.005 Ω.
In full sun, the power of the module is 41.54 W.
However, when one of the PV cells is shaded the drop in module voltage is 13.11V.
Compute the number of solar cells forming the PV module?

Assume that when one cell is shaded and the given current somehow stays the same.

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SECTION 3: QUIZ

3.7. In A 72-cell PV module has a parallel resistance per cell of R_P = 6.6 Ω and series resistance (R_S = 0.01 Ω). In full sun and at current I = 4.28 A the output voltage was found there to be V = 38.82 V. If one cell is shaded and this current somehow stays the same, then:

- (a) What would be the new module output voltage?
- (b) What would be the new power?
- (c) What would be the drop in the module output power?
- (d) What would be the voltage drop across the shaded cell?
- (e) How much power would be dissipated in the shaded cell?
- (f) What would be the new module output voltage if a bypass diode was used? (Hint: assume the voltage across diode is -0.6)

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SECTION 3: QUIZ

3.8. Circle the right answer.

Global irradiance simply is the sum of

- a) Direct-beam radiation and reflected radiation
- b) Diffuse radiation and reflected radiation
- c) Direct-beam radiation and diffuse radiation
- d) Direct-beam radiation, reflected radiation, and diffuse radiation

3.9. Circle the right answer(s).

The device Pyranometer

- a) Measures the total radiation arriving from all directions
- b) Measures only the reflected beam radiation
- c) Measures just diffuse beam radiation
- d) Measures just direct beam radiation

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SECTION 3: QUIZ

3.10. Circle the right answer(s).

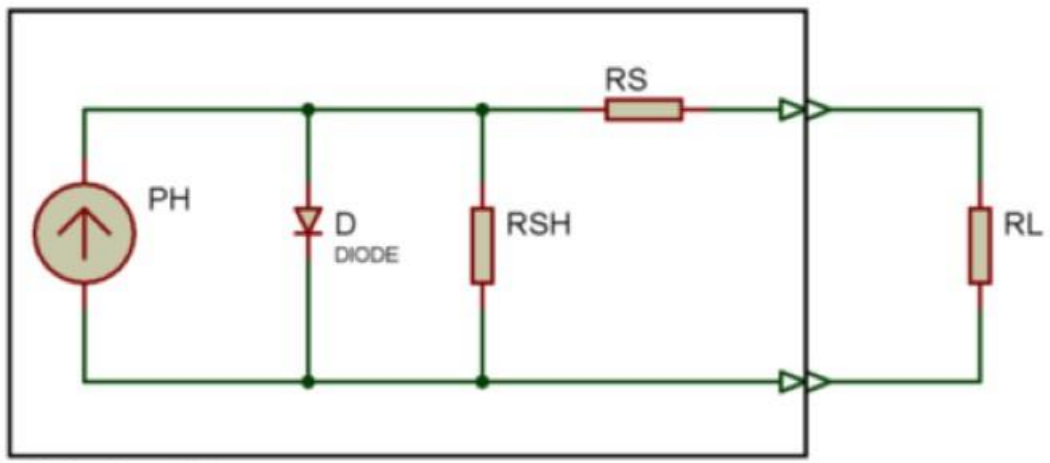
The device Pyrheliometer

- a) Measures the total radiation arriving from all directions
- b) Measures only the reflected beam radiation
- c) Measures just diffuse beam radiation
- d) Measures just direct beam radiation

3.11. The advantage of the P&O MPPT algorithm is that it can be implemented on any PV size without knowing its parameter. (True/False)

SECTION 3: QUIZ

3.12. The PV cell circuit model is presented in the figure below. For simplicity, the current source, the PN junction and the shunt resistor can be replaced by a voltage source. Prove that the PV power is maximized when the load resistance RL matches the series resistance RS.
(Hint: Calculate the output Voltage and Power for different values of RL). Conclude the role of the MPPT.



PV circuit model

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SECTION 4: QUIZ

4.1. A power sizing is required to supply the following home alliances with rated power and utilization period.

- a: Calculate the Wh/Wk of each device and conclude the total Wh/Wk, and the average Wh/day.

#	Device	rated Power (W)	# of items	Hrs/day	Days/Week	Wh/Wk
1	Room Lamp	100	3	6	7	
2	Coffee maker	2200	1	0.1	7	
3	Water heater	1500	1	3	4	
4	AC	1200	3	4	7	
5	Kitchen Lamp	100	1	6	7	

- b: Having 6 sun-hours/day, calculate the required power (W) from a PV system without storage. Assume that the shading derate factor is 95%, the inverter efficiency is 96%, the module temperature derate factor is 88%, the wiring derate is 99%, the module soiling derate is 95% and the module mismatch derate is 98%.
- c: Having PV's of 1m2 and 150W, calculate the number of PV required to supply the calculated power in 'a'.

SECTION 4: QUIZ

4.2. A power It is required to design a PV stand-alone system for a client having the following loads at 220V.

a. Calculate the energy/week of each type of load and the total required energy/week

#	Appliances	rating power	number of items	hrs/day	days/Week	Wh/Wk
1	room lamps	60	2	7	7	
2	Coffee maker	1200	1	0.2	7	
3	Hair dryer	1500	1	0.1	3	
4	Refrigerator	90	1	24	7	
5	kitchen lamp	100	1	6	7	
6	TV	80	1	2	7	

- b. Calculate the average energy/day
- c. Calculate the average power (Watt)
- d. Calculate the average current for a 220V system.
- e. Assuming that the system efficiency is 90% and the sun-hours/day is 4. Calculate the PV power required to supply the client loads.

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SECTION 4: QUIZ

- f. Having a single PV with the specs represented in Table , Calculate the number of PVs required
- g. What is the total dimension of the PV panels?
- h. Show 4 different arrangements of the PV panels and mark the required length and width in each case.
- i. Calculate the range of V_{oc}, V_{mpp}, I_{sc}, I_{mpp} of each PV for temperature between 0 and 80 degrees.
- j. What would be the highest PV power and at what temperature?

PV data	Input
P_{MPP} (W)	235
V_{MPP} (V)	29.5
I_{MPP} (A)	8.06
V_{OC} (V)	36.6
I_{SC} (A)	8.66
α (A/°C)	0.002
β (V/°C)	-0.169
Price (S)	230
Size (m2)	1.6
Length	1.6
Width	1

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SECTION 5: QUIZ

5.1. An energy efficient house in Alanya (Turkey) is to be fitted with a rooftop PV array that will annually displace all of the 3600 kWh/yr of electricity that the home uses. How many kW (DC, STC) of panels will be required? (Assume that the average sun-hours per year is 5.7)

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SECTION 5: QUIZ

5.2. The peak power required to power the appliances of a house using a PV system is estimated to be 5 kW. If the cost of the inverter (DC-to-AC) is 1$/Watt,

a. calculate the cost of the inverter to be used in the PV system powering this house

b. If the 5 kW is used during 5 hours, what is the required energy to power this house?

c. If the average sunshine hours is 5, compute the peak power to be delivered by the PV panels

d. Assume an average cost of $5000 to purchase and install a 1 kW PV panels, compute the cost of the PV panels needed for this house

e. We will assume, in order not to discharge the battery more than 50% that the batteries will be able to store twice the amount of energy we use. Calculate the energy to be stored in the bank of batteries.

f. Assume the cost of batteries is about $100 per kWh of storage, compute the cost of batteries needed for this house

g. Assume the lifetime of deep cycle batteries is 3 years, what is expected lifetime of the batteries used in this PV system?

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SECTION 5: QUIZ

- h. Compute the upfront cost paid for the inverter, the PV panels, and the batteries
- i. Assume 30 years the lifetime of PV panels; compute the number of times we have to replace the batteries, and the total life-cycle cost of the batteries
- j. Compute the total life-cycle cost of the PV system
- k. Compute the number of kWh used over the lifetime of the system
- l. Compute the life cycle cost per kWh

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