Solar Energy for a Decarbonised Future - Knowledge Transfer for Environmental Education and Awareness (SolAware)

Summer Training 2023-2024

Session 4: Photovoltaic Design Basics and Load calculation

A Project Funded by the British Council Between University of Mosul & Teesside university on Research Environment

This Session is divided into two parts

Photovoltaic Design Basics(Part1)

PV system Load Calculation(Part 2)

Photovoltaics System (Part1)

Learning objective

This lecture is about to learn the following as key factors before designing a PV system

- ❑ **Site analysis.**
- ❑ **Shading and tools.**
- ❑ **Guide to roof assessments.**
- ❑ **Wind loading, weight loading, lag bolt calculation, and Ballast system.**
- ❑ **Optimal panel location criteria.**
- ❑ **Ground mounting criteria.**
- ❑ **Utility scale.**
- ❑ **Inverters and battery location.**
- ❑ **Benefits of Larger Solar Power Plants**

Designing a PV system– Site Analysis

Site selection

When visiting a potential site for PV system installation, it is of great importance to do the assessment of the location. This provides valuable information on where to put the solar panels and its orientation, roof mount or ground mount, shading affects etc.

- ❑ Preliminary idea about the site from Google earth. Provides some basic insights about the site.

Physical visit to the site, take the following kits:

- Measuring tape – To take measurement of the available space.
- Solar pathfinder – Analyse the shading affect.
- Camera – taking pictures of the location.
- Ladder – For climbing.
- Notepad and pen – Taking notes i.e. measurement, drawings etc.
- Flashlight (torch) -

Visiting Google earth to get initial idea about the location. Gives idea if there is any barriers which can impact the power production i.e. a forest, or a tree. Also, tells you about the slope of the roof.

Solar pathfinder kit

Designing a PV system– Site Analysis

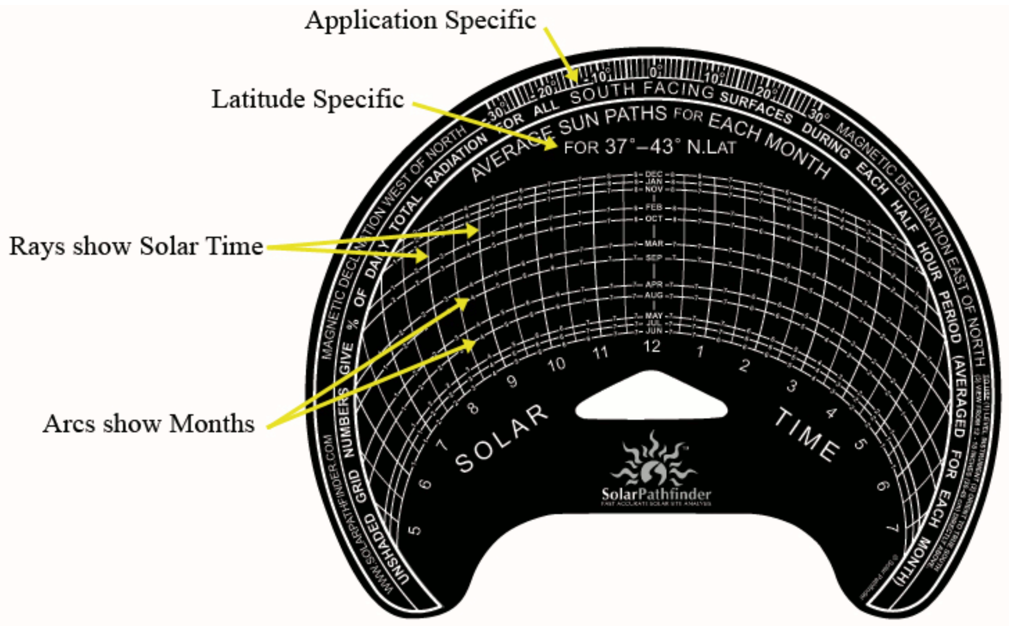
Solar Pathfinder kit

Purpose – To analyse the shading of the selected location (since the late 1970).

The kit is manufactured by US based company called – Solar Pathfinder (https://www.solarpathfinder.com/PF)

The kit consist of the two main components:

Dome section



Sun path Diagram

Designing a PV system– Site Analysis

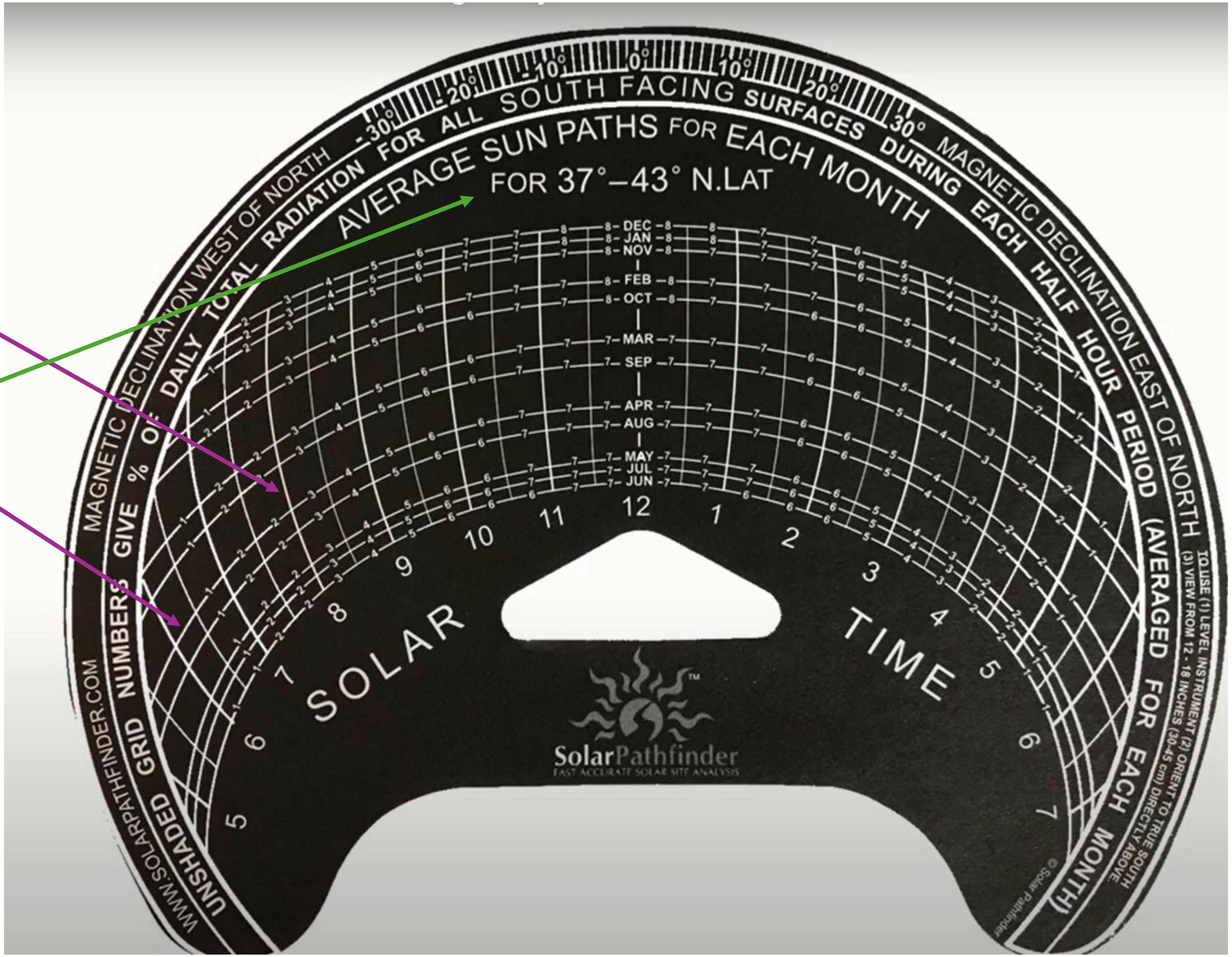
Understanding sun path diagram

Vertical lines – solar time

Concentric arc – average path per month of the year

Latitude of the location

Check the latitude of your location and use according to it.



Designing a PV system– Site Analysis

Understanding sun path diagram

Small numbers along each monthly arc indicate the percentage of solar radiation in half-hour increment. For example, for the month of May between 10 am and 10:30 am, the radiation available is 6%, and between 10:30am and 11 am it is 7%

The number adds up to 100% of the solar radiation potentially available during that month.

Solar Energy (kWh)

Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
2024	24.7 ↑	34.3* ↓	65.8 ↓	103.0* ↓	128.0 ↓	80.3* ↓	---	---	---	---	---	---	436.1* ↓
2023	24.9 ↑	34.7* ↓	56.6 ↓	65.4 ↓	156.8 ↑	174.1* ↑	130.1 ↓	112.9 ↓	90.9 ↑	54.4 ↑	27.6* ↑	14.2 ↓	942.6* ↓
2022	18.5 ↓	31.4* ↓	68.2 ↓	122.0* ↑	146.8 ↓	151.3* ↑	160.0 ↑	132.5 ↑	82.8* ↓	58.2 ↑	22.8* ↓	15.2 ↑	1009.7* ↑
2021	24.8 ↑	44.9* ↑	88.6 ↑	160.2* ↑	165.3 ↑	148.7* ↑	139.2 ↓	101.7 ↓	80.0* ↓	42.4 ↓	26.9* ↑	12.4 ↓	1035.1* ↑
2020	---	31.1 ↓	75.6 ↑	122.8 ↑	174.3 ↑	136.8 ↓	137.8 ↓	110.9 ↓	90.5* ↑	42.4 ↓	23.4* ↓	15.7 ↑	961.3* ↓
Max	24.9	44.9	88.6	160.2	174.3	174.1	160.0	132.5	90.9	58.2	27.6	15.7	1035.1
Avg	23.2	35.3	71.0	114.7	154.2	138.2	141.8	114.5	86.1	49.4	25.2	14.4	968.0
Min	18.5	31.1	56.6	65.4	128.0	80.3	130.1	101.7	80.0	42.4	22.8	12.4	436.1

https://crondallweather.co.uk/daily-monthly-and-seasonal-solar-energy-w-m2-statistics-for-crondall/

Designing a PV system– Site Analysis

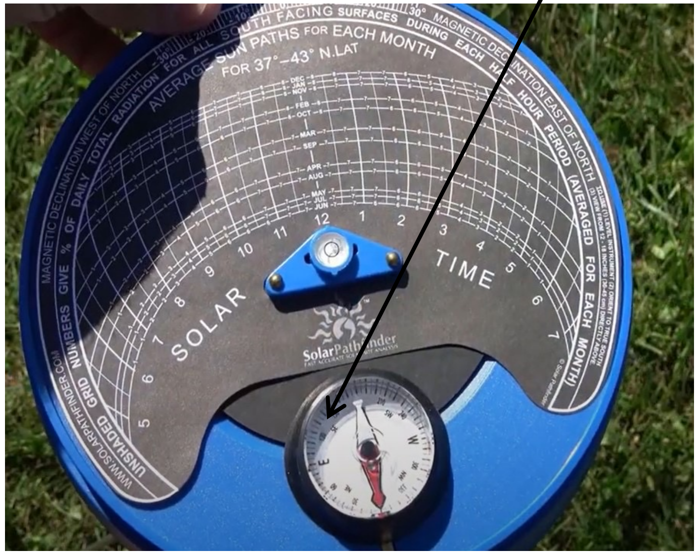
How to use solar path finder to analyse the shading?

The very first thing to do is to set up the solar path finder kit. There are 3 main parts of the path finder:

- ❖ The base and tripod.
- ❖ Instrument section.
- ❖ Sun path chart.

The base is set on a tripod in a level position.

Magnetic compass



Rotate the instrument until the magnetic compass is pointing north.

Sun path chart can also be rotated separately to adjust for magnetic declination so that the chart face true south

Designing a PV system– Site Analysis

Shading analysis is done based on two things at the same time:

- ❑ The panoramic view of the site reflected on the dome, and
- ❑ The sun path chart through the dome.

The objects are reflected on the dome over the sun path chart. This shows the shading occurs during the time and months

Designing a PV system– Site Analysis

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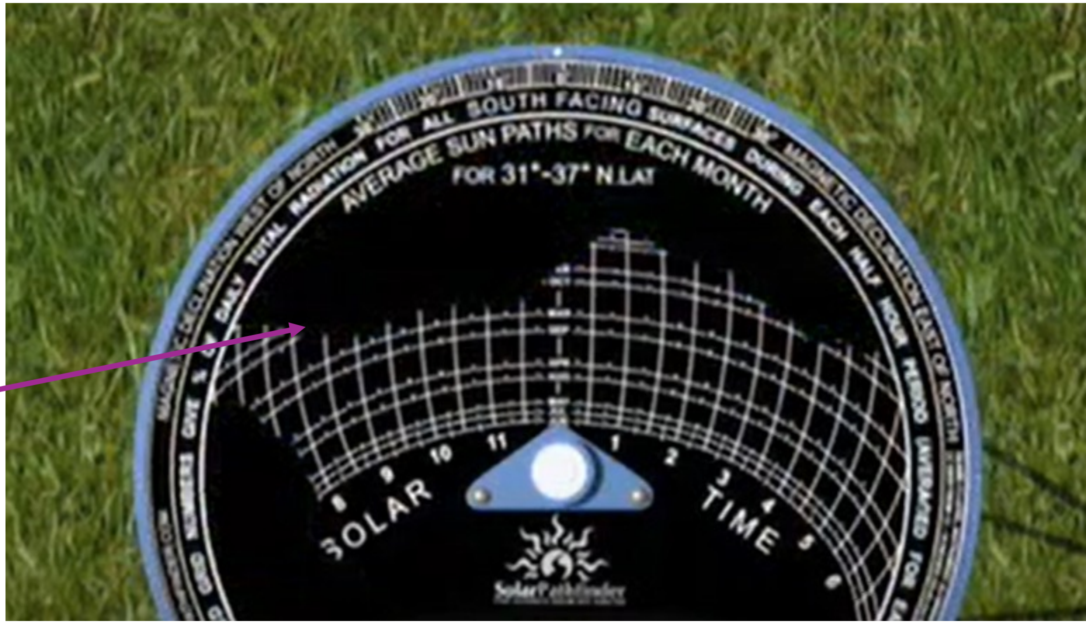
- The sun path chart through the dome.



Object reflected on the dome over sun path arcs at the location during the time and months indicated.

Use the marking pen to draw the shaded path on the chart.

Do the shading analysis between 10 and 12pm all throughout the year. (Check solar window lecture for the reason)

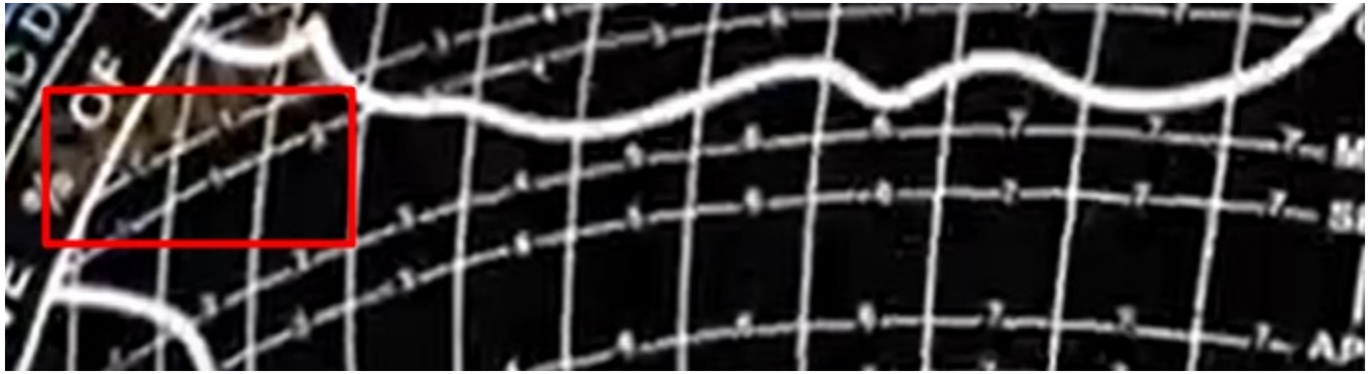
Designing a PV system– Site Analysis

Taking readings from sun path chart.

Add the number of the unshaded region of each sun path arc for each month.

The sum is the percentage of local irradiation data available for each month.

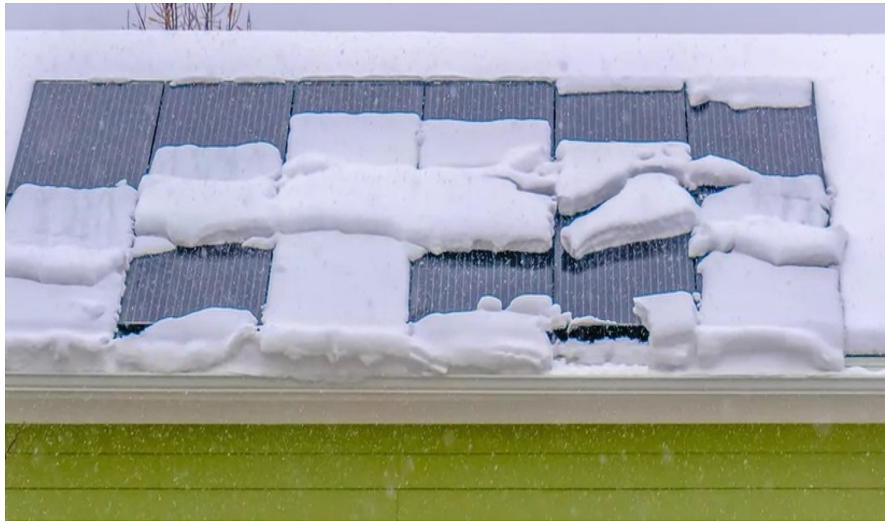
Provides instantaneous information of available solar radiation and helps to find optimal solar panels installing location.



Designing a PV system– Site Analysis

Wind loading, weight loading, lag bolt and Ballast system.

- Wind could be a major issue in some location. This is quite dangerous if wind loading is not taken into consideration. It can rip off from the ground.
- The roof might get damaged. So, wind loading, weight loading, lag bolt, and ballast system all are interconnected.
- Always consider – the maximum weight handling capacity of the roof, the structure of the roof, wind speed, what support you need to prevent panels from ripping off?
- Calculate the force the solar panel can withstand. You need to find the uplift force, slide resistance (sitting on the roof), drag force (which can turn over the panel by wind).
- Drag force $F_d = \frac{1}{2}\rho v^2 A\, C_d$, where ρ = density of the wind, v = velocity of the wind, A = area of the panel, C_d = drag coefficient.
- When comes to weight loading, can the roof trusses/rafters handle the weight of the panels? The weight of a solar panel is between 15kg and 22kg.
- If there is snow, can the roof take this additional load?
- Some roofs have limitation and needs to be close to the beams.

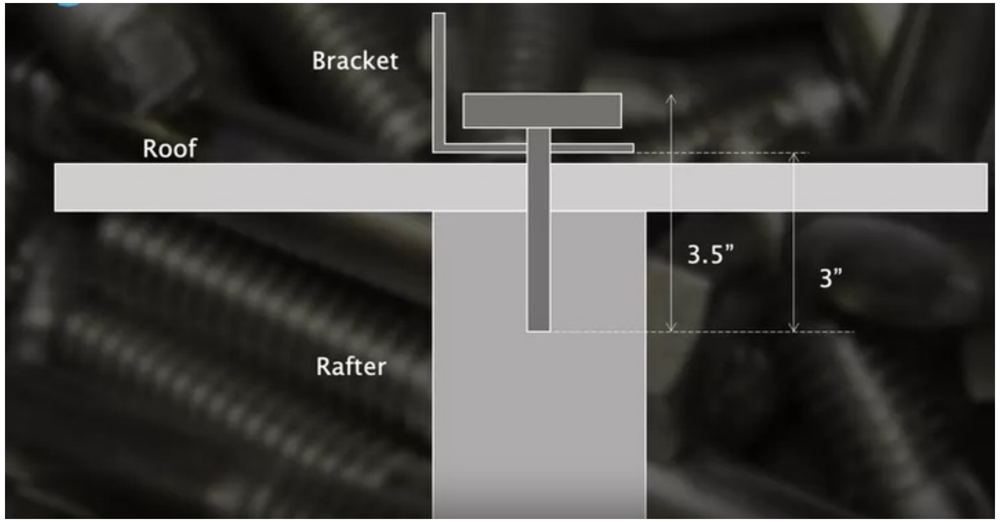


Designing a PV system– Site Analysis

- ❑ Truss – check the manufacturer of the truss and you might need to ask them about the truss.
- ❑ Measuring excess capacity – For steel beams, check if they have any post.
- ❑ Take pictures of the structure and consult with structural engineer to find if they can handle additional load.
- ❑ In some cases, solar rails are used. Consider the weight of them.
- ❑ Find the weight bearing capacity of the structure.
- ❑ Add up the additional items on the roof i.e. solar panels, solar rails, snow loads.
- ❑ Lag bolt- When using lag bolt, ask the manufacturer if you can put lag bolt or an engineer to make sure you can use lag bolt without any damage.
- ❑ In some cases, metal clamps are used to hold the panels (in case of metal roof)
- ❑ Ballast system is used to avoid wind damage.

The details of the calculation can be found in handbook.

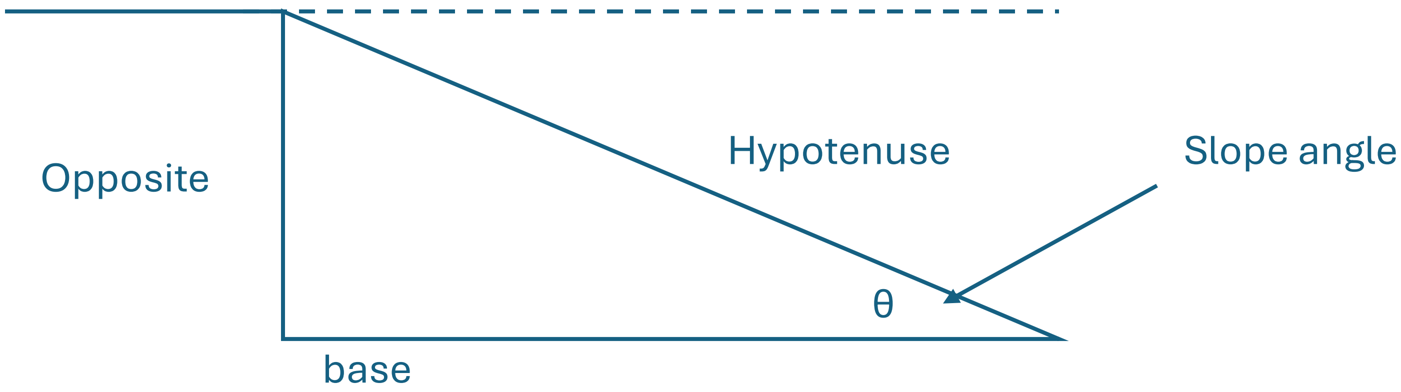
Consider snow and PV weight for weight loading. Check point loads.				
	weight, pounds, ea. Or per ft.	quantity	weight	
PV	51.80	45.00	2331.00	
rail	0.79	296.00	234.95	
Enphase inverter	4.40	45.00	198.00	
bolt	0.07	588.00	40.43	
feet	0.75	102.00	76.50	
TOTAL			2880.88	
Array size, sf	794.41			
snow load, sf	32.30			
snow load total	25659.53			
snow + array	28540.41			
Number of trusses	17.00	25.00	difference	percent
Weight per truss	1678.85	1141.62	537.23	47.06%



Designing a PV system– Roof assessment

While visiting the site, it is of utmost important to measure the space available for solar panels.

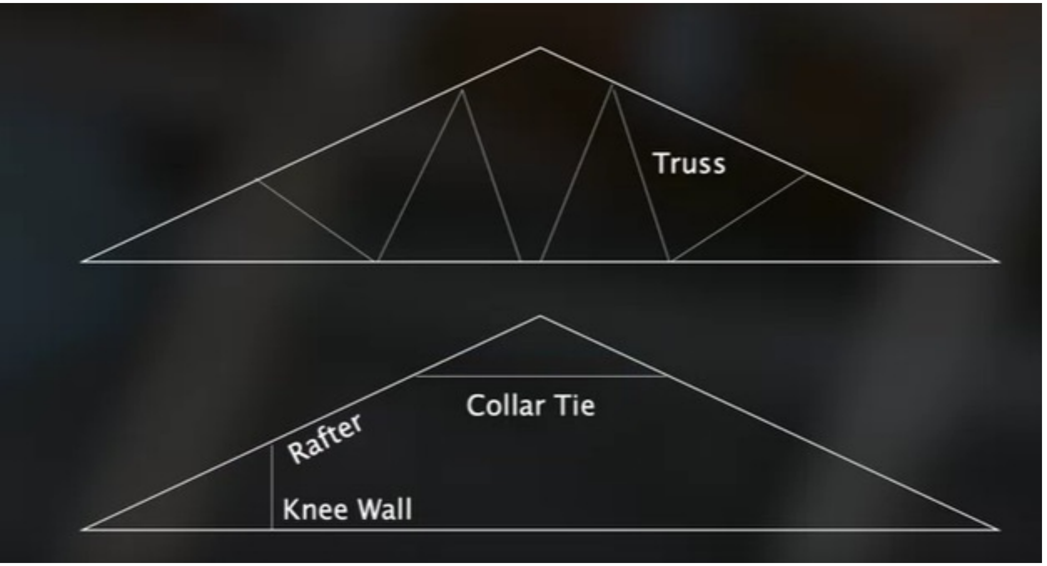
- ❑ Use the measuring tape to find the length and width of the roof.
- ❑ For sloped roof, take the measure from the side to find the slope angle by using trigonometry. This is important for tilting solar panel at an optimal angle and if any extra mechanical racks are needed.
- ❑ Also, helps to find the row gaps between the panels.
- ❑ For flat roof, for example in commercial building, there are plenty of open space. However, there could be air-conditioner, antennas etc which could be a possible obstacle for panel installation.
- ❑ It is also a must do job to find the height of the barriers and to find if they could possibly cause shading.



Designing a PV system– Roof assessment

Other important factors to be considered:

- If there are shingles on the roof, count the number of rows of shingles on a sloped roof (to find up-slope dimension)
- Take picture of the shingles.
- Check the structure of the roof.
- Check the structure of the roof (go to attic).
- Check the thickness of the rafters and spacing.
- Check if it has collar tie and has a knee wall (take pictures).
- Check the local authority guidelines on shingles layer.

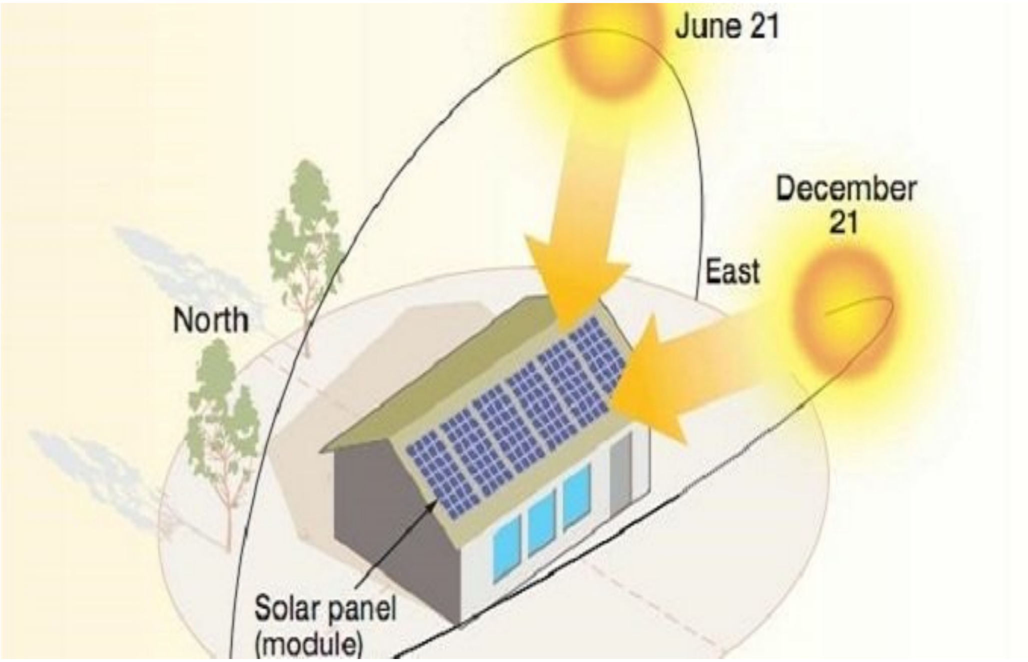


Panel location and Spacing

For roof top panels installation

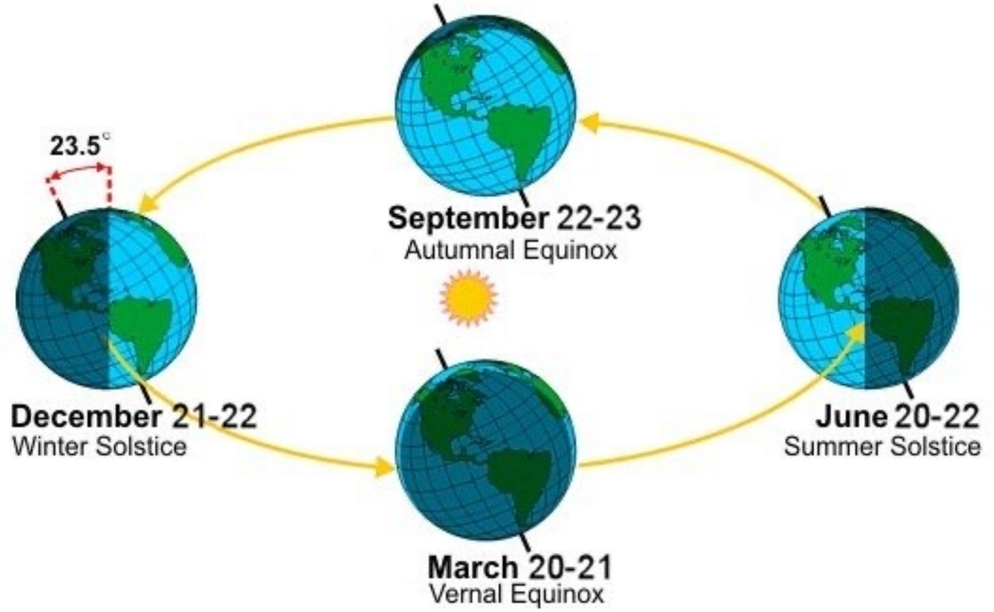
In previous lecturer, we learned about initial site inspection. In case of roof top panel installation, you need to check local authority (council or municipality) guidelines. You may require to provide an initial diagram that will show where you are putting the panels. Do the followings:

- ❑ Site inspection. (south facing ideally)
- ❑ Measure the availability of the space to check if the number of panels will fit.
- ❑ Check where the circuit box and meter is located and measure how far it is from the panels.
- ❑ Identify what will be the best tilt angle for the panels.
- ❑ Calculate the best row spacing of the panels if the customer's roof is not facing the south. This is done to avoid shading.
- ❑ Simulate sun's position during winter and summer to identify the best row spacing.



Panel location and Spacing

Sun's position is very important to calculate the row distance of the modules.



- ❑ The earth rotates about its own axis tilted at an angle 23.5^0.
- ❑ During summer, the North pole is tilted towards the sun.
- ❑ Around June 21st, tilted most towards the sun – Summer Solstice.
- ❑ For this reason, earth receives more sun light and heat. Longer day and shorter night in summer.
- ❑ Moving along its path, the North pole is tilted furthest making it colder, and shorter day and longer night in winter. (winter solstice)

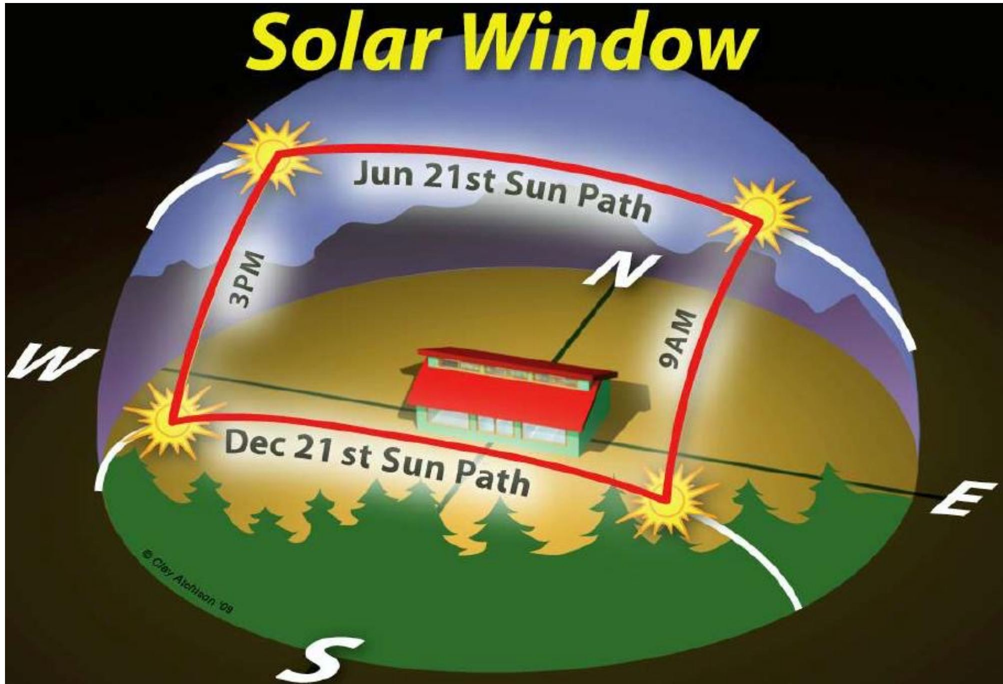
Solar window – Depends on the location

❑ On 21st December, the sun rise at 9am. However, on 21st June at the same Time the sun is in higher position.

❑ At 3 pm in December, the sun is at lowest and in June its height is higher.

❑ If the line is drawn for the sun's position on those dates and time, it forms a rectangle and area inside the rectangle is called the solar window for the given Location.

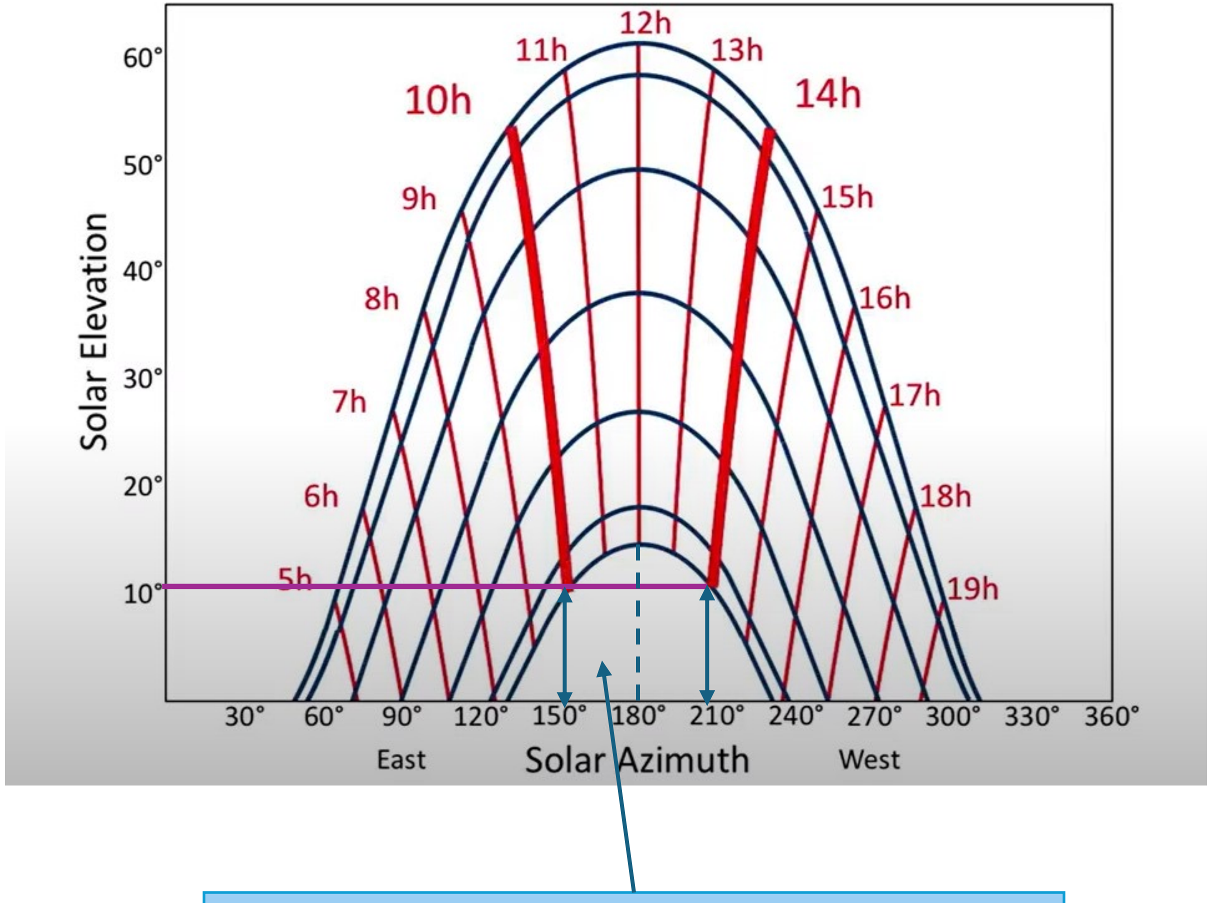
❑ This window is very important because earth receives the maximum energy From the sun and also crucial to calculate the minimum row spacing.



Panel location and Spacing

Sun's position is very important to calculate the row distance of the modules.

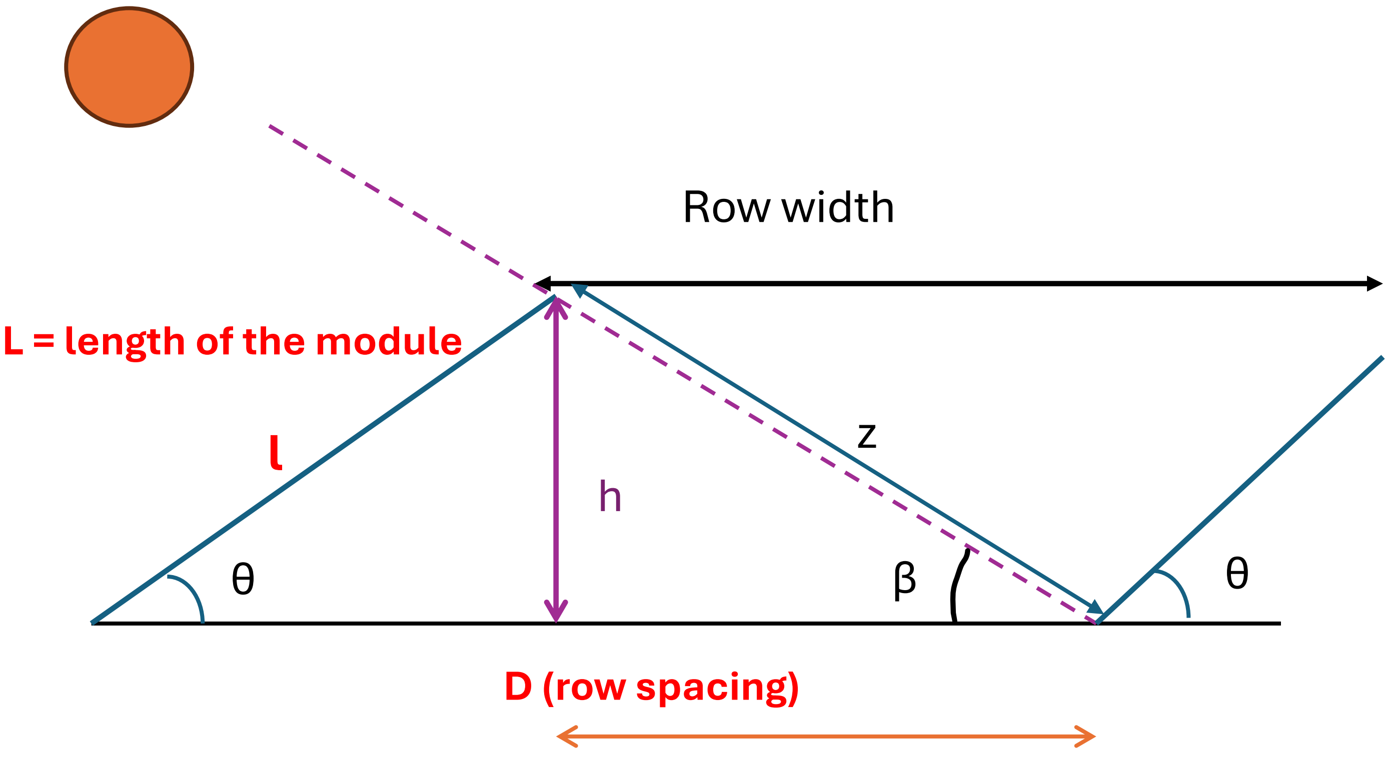
- ❑ Get the solar elevation chart for the selected location.
- ❑ This chart helps to ensure the rows are not shaded.
- ❑ From the solar chart, we see the solar window is between 10am and 2pm.
- ❑ Draw a horizontal line, to get the solar elevation angle. This will be used to determine the row spacing.
- ❑ Solar azimuth angle at 10am is 150^0 and 210^0 at 2pm.
- ❑ For most ground and roof mounted systems where row spacing is a concern, the height (h) of the obstruction can be directly obtained from the dimensions of the solar panel and the array tilt.
- ❑ The minimum inter-row spacing needed to avoid shade within your solar window. This is called the "Solar Azimuth Correction.

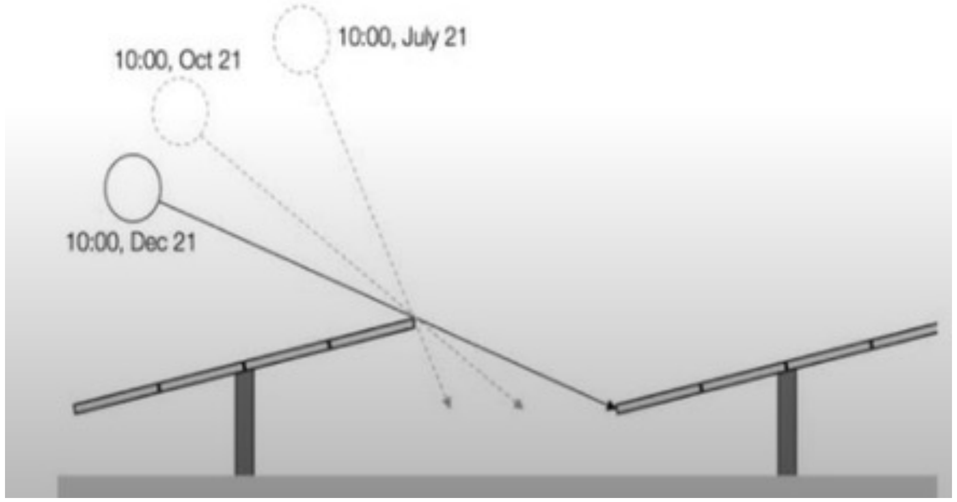


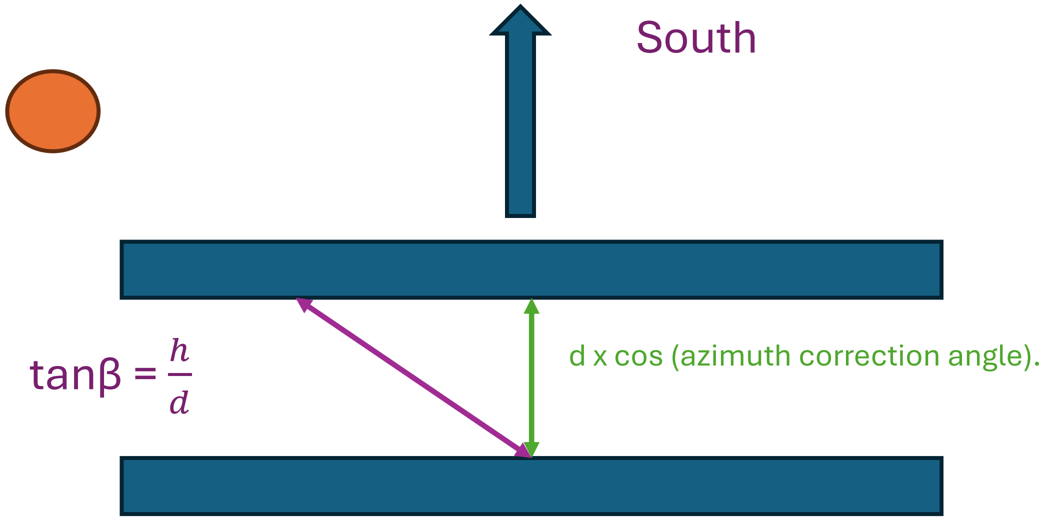
Azimuth Correction angle = (180 -150) = 30^0 (Before and after 12 noon)

Panel location and Spacing

Row spacing calculation







Z = distance between top edge of the module and the end of the shadow on the ground

Designing a PV system– Roof assessment

Row spacing calculation:

I. To find h, we use sinθ = $\frac{h}{l}$

II. To find module raw spacing d, tanβ = $\frac{h}{d}$ where d = module raw spacing, and β = solar elevation angle.

III. Azimuth needs to be considered, minimum d = d (from step ii) x cos (azimuth correction angle).

IV. Row width = step iii + (cos θ x l)

Example: Let's consider a solar module of length 160cm is tilted at an angle 15 degree. What should be the minimum module raw spacing and row width? Use the solar chart to find the solar elevation angle and azimuth angle.

Step 1: Finding h = sin 15 x 1.6m = 0.414 m

Step 2: Row spacing d = 0.414 / tan 10 = 2.35m

Step 3: minimum d = 2.35 x cos 30 = 2.03m

Step 4: Row width = 2.03 + (cos 15 x 1.6) = 2.03 + 1.55 = 3.58m ≈ 3.6m

Rule of thumb : 3 times the length of the module

Designing a PV system– Site Analysis

Flood plains Planning

- Sometimes it may be required to do commissioning of PV system on ground mount.
- Check if there is any possibility of being flooded.
- If there is a danger of flood, then the PV systems should have adequate space above the ground. However, there are rules imposed by local authority. So please check the allowable maximum height.
- The beam or support should be higher than the flood level.
- Geo engineer should visit the site and tells how deep the footers should go in the soil.
- This is because flood water can make the soil condition softer and as a result the panels won't be able to stand the ground.

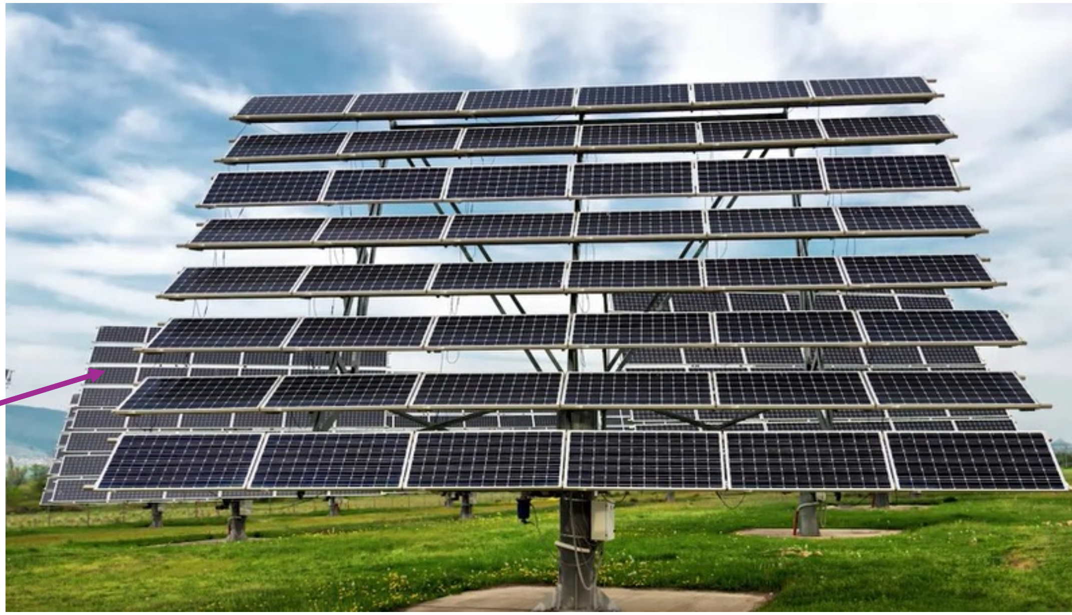
Good or bad plan?

Designing a PV system– Site Analysis

Ground mount

- ❑ No messing with the roof.
- ❑ Installed with optimum orientation and tilt.
- ❑ Not cost effective than roof mount.
- ❑ You need strong pilling to support – adding extra cost.
- ❑ You need to find a sunny spot and do shading analysis.
- ❑ Local authorities have rules on ground mount. Always check the rules.
- ❑ Increasing distance from the location means increasing the wire cost.
- ❑ If trackers are use, then it adds extra cost.
- ❑ Most of the roof mounted PV system use string inverters. We will go through about inverters in inverters section.

Ground mount PV system with trackers.



Designing a PV system– Site Analysis

Utility scale PV system

- On industrial or utility scale, there are plenty of open space.
- Size > 100kW.
- Solar car parking. Can be used for EV charging.
- The bigger the plant, the cheaper it gets.
- Utility scale cost less electricity bill than fossil-fuel fired power generation.
- Check Land-use requirements for solar power plants in your country.

Technology	Total Area			
	Projects	Capacity (MWac)	Capacity-weighted average area requirements (acres/MWac)	Generation-weighted average area requirements (acres/GWh/yr)
All	25	3,747	10	3.5
Trough	8	1,380	9.5	3.9
Tower	14	2,358	10	3.2
Dish Stirling	1	2	10	5.3
Linear Fresnel	1	8	4.7	4.0

An example of land requirements acres/MWac in the USA. Source NREL

Designing a PV system– Site Analysis

Inverters and Battery location

For utility scale, it is vital to check the followings:

- ❑ How far is the grid (if grid-connected is planned)?
- ❑ Can the grid be able to handle the power coming from the PV power plant?
- ❑ Phases of the power lines – single phase or three phase?
- ❑ What is the maximum capacity of the power lines?
- ❑ Inverters and battery should be place close to the PV system.
- ❑ Longer distance will increase cost i.e. wiring cost. In addition to that losses in the cable are involved.
- ❑ For residential, check the good location for batteries. The batteries are heavy, and attic not be able to support.
- ❑ Check the temperature of the place where you are putting the batteries. Colder place will downgrade the performance of the battery (optimal temperature is around 20^0).
- ❑ Inverters should be placed in a shaded region and not outside. The direct sunlight will impact its life span.
- ❑ A cooler location is good place for inverters.
- ❑ Place the inverter close to the meter to reduce line drops and efficiency.

Designing a PV system– Site Analysis

Summary

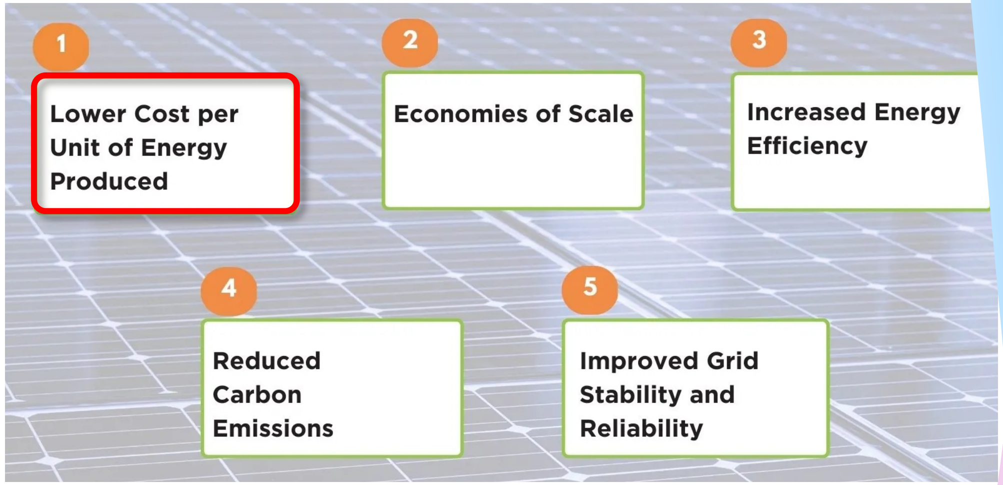
In this session we have learned

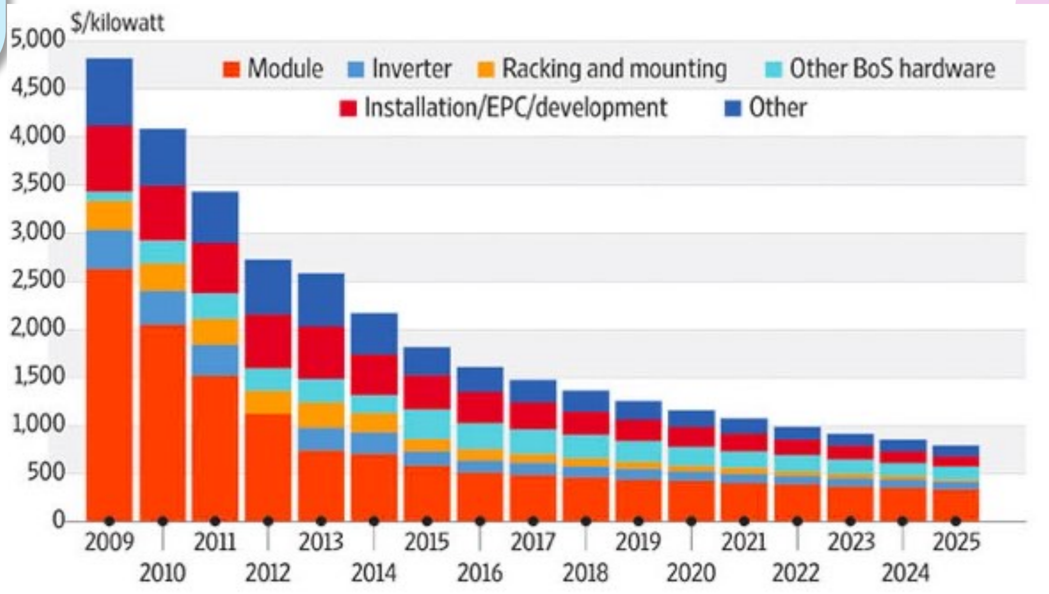
- Site selection criteria.
- Familiar with different solar kits and how to use them.
- Roof assessment – wind loading, weight loading, lag bolt.
- Solar window, solar elevation and azimuth.
- Optimal panel location calculation.
- Utility/industrial scale solar system.

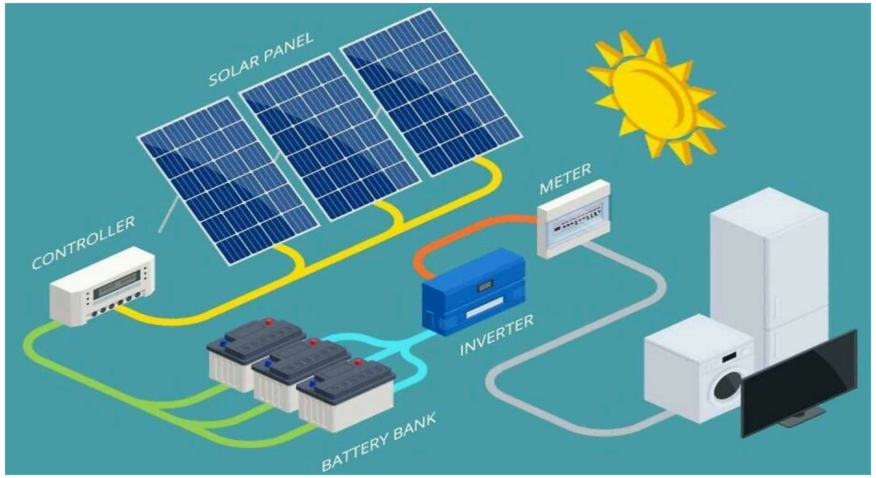
Benefits of Larger Solar Power Plants

Lower Cost per Unit Energy Produces

- One of the primary benefits of building larger solar power plants is the lower cost per unit of energy produced.
- This makes solar energy more competitive with traditional forms of energy, such as coal and oil, which can be expensive to produce.







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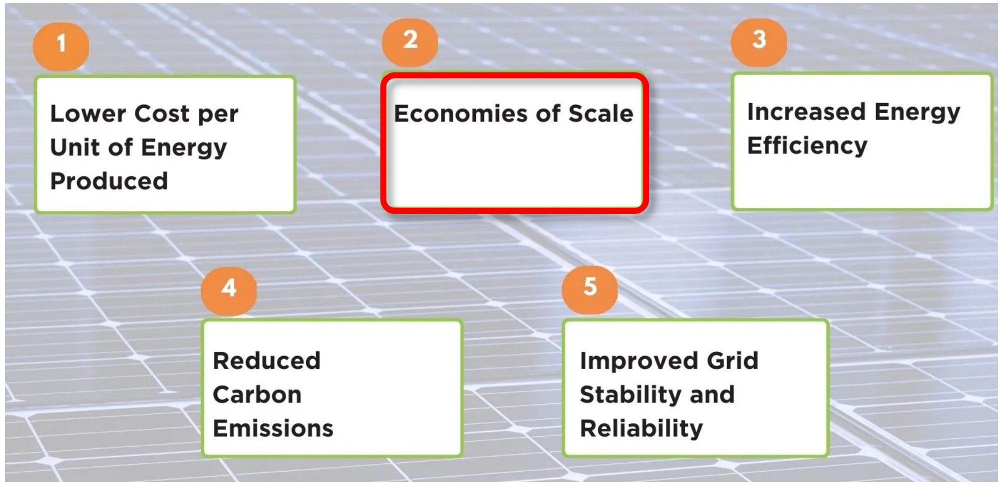
Benefits of larger solar Power plants. are:

Economies of Scale

- Land Efficiency: Larger plants need less land per unit of energy produced.

- Reduced Maintenance and Staffing Costs: Larger plants require less maintenance and fewer personnel, further lowering overall costs.



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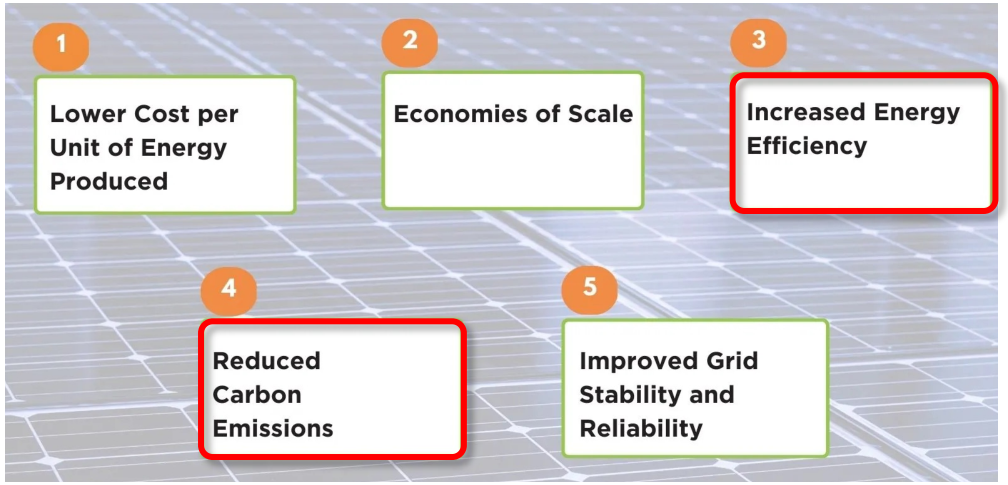
Benefits of larger solar Power plants. are:

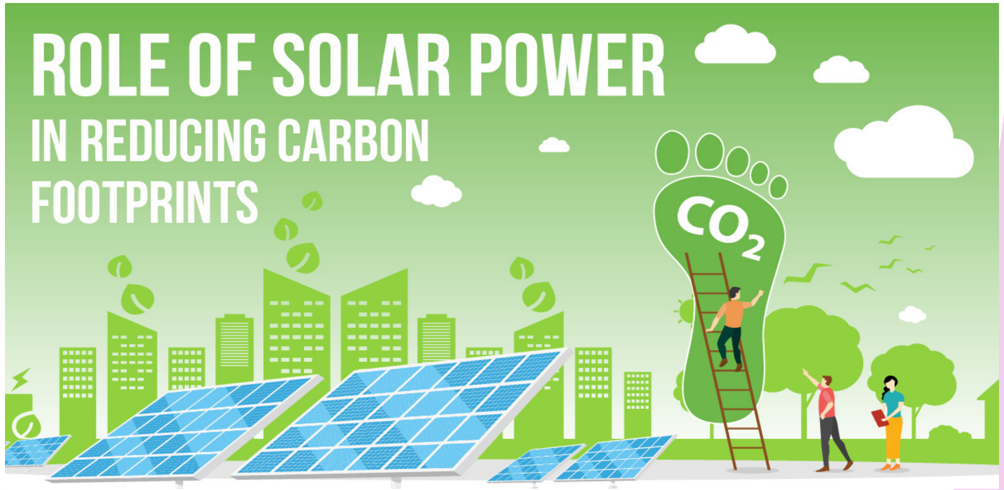
Increased Energy Efficiency

- This is because larger plants can use more efficient solar panel technologies and other equipment, which can improve the plant's overall efficiency.
- In addition, larger plants can be located in areas with better sunlight conditions, which can further increase efficiency.



Reduced Carbon Emissions

- By building large scale solar power plants, countries can reduce their dependence on fossil fuels and lower their carbon emissions, helping to combat climate change.



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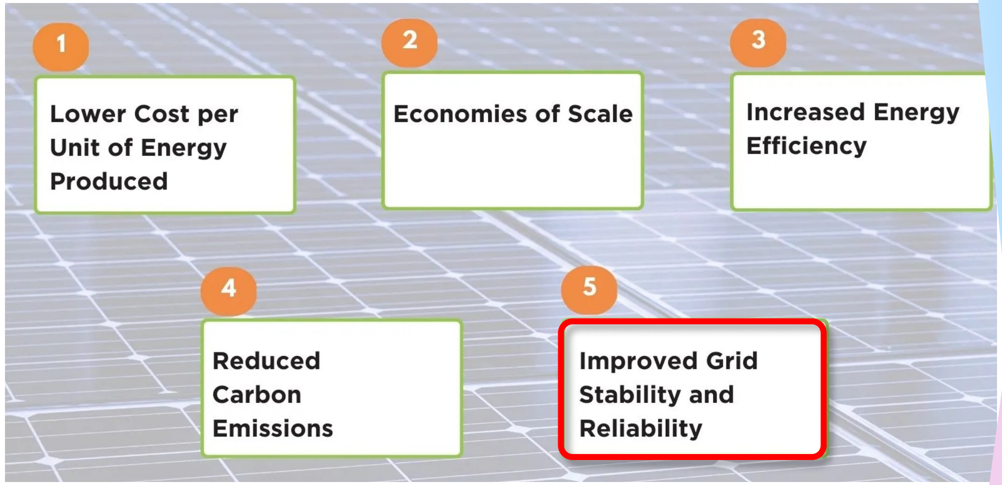
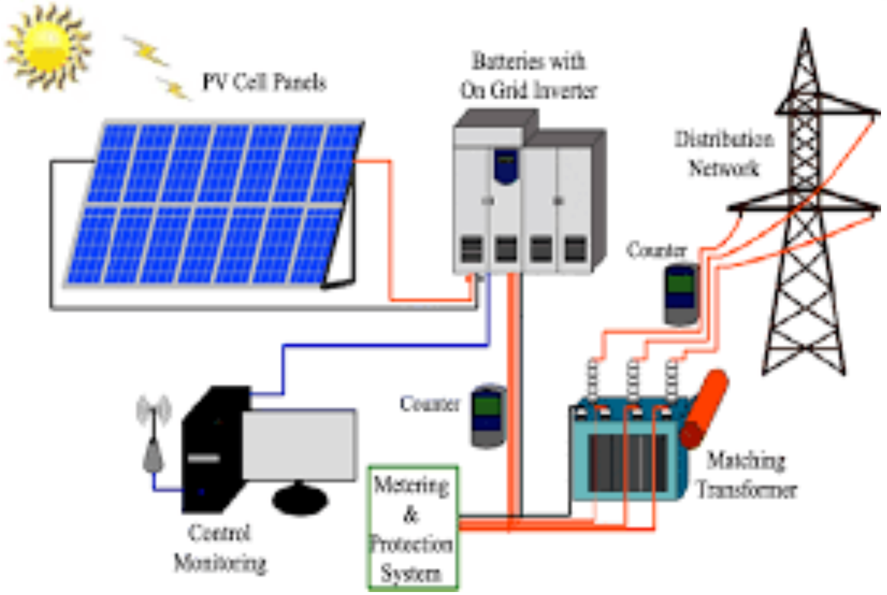
Benefits of larger solar Power plants. are:

Improved Grid Stability and Reliability

- According to researchers, building larger solar power plants can improve grid stability and reliability, overall capacity, which can help stabilize the grid and improve reliability.





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Load Calculation (Part2)

Learning objective

In this lecture we will learn load calculation which is one of the most crucial parts of PV system design. Here we will cover the followings:

- ❑ Key factors to consider before doing load calculations.
- ❑ Understanding sun-hours chart.
- ❑ Load calculations.
- ❑ Panel location and calculation of panel spacing.
- ❑ PV panel selection and calculation.
- ❑ Understanding PV and Inverter’s data sheet.
- ❑ Impact of temperature coefficients.

Key factors to consider before doing load calculations

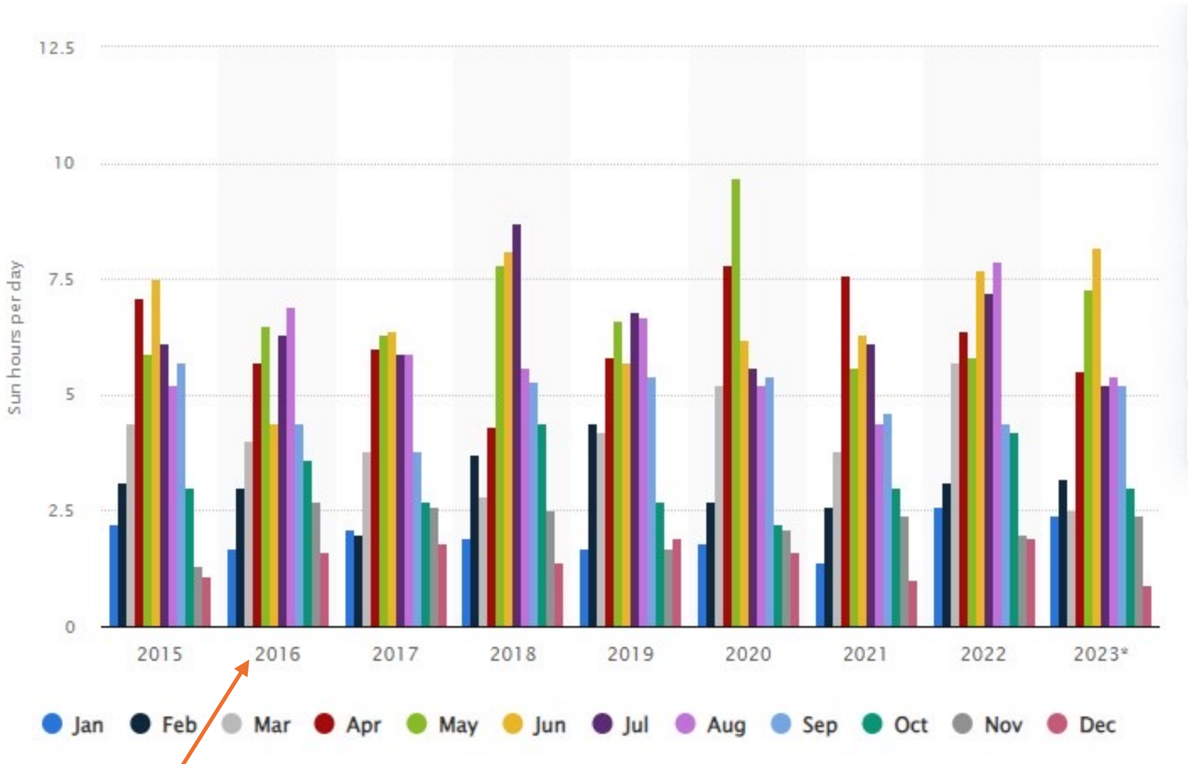
Before designing a PV system, it is paramount to consider the followings:

- ❑ Energy usage of the customer in kWhr/year.
  - ➢ One year usage from the customer's electric bill. Two years would be ideal.
  - ➢ Consider possible future load addition e.g. EV charging station.
- ❑ Sun-hours per year for the location.
- ❑ Assess the system efficiency.

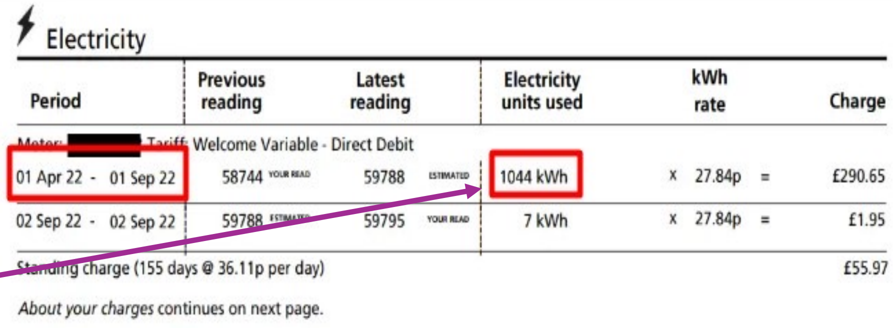
System efficiency, η_{system}

$$= \eta_{inverter} \times \eta_{battery} \times \eta_{other\ components}$$

Other components: MPPT, Cables etc.



Sun hours chart



Electricity

Period	Previous reading	Latest reading	Electricity units used	kWh rate	Charge
Meter: [redacted] Tariff: Welcome Variable - Direct Debit					
01 Apr 22 - 01 Sep 22	58744 YOUR READ	59788 ESTIMATED	1044 kWh	x 27.84p =	£290.65
02 Sep 22 - 02 Sep 22	59788 ESTIMATED	59795 YOUR READ	7 kWh	x 27.84p =	£1.95
Standing charge (155 days @ 36.11p per day)					£55.97

About your charges continues on next page.

Usage in kWhr

Monthly electric bill

Sun hours

Average daily sun hours in a year

Another example of sun hours chart

Tilt angle of the solar panels

Tilt angle = Panel's tilt angle

Tilt (deg)		Jan	Feb	Mar	Apr	May	Jun	Aug	Sep	Oct	Nov	Dec	Year
0	Average	1.6	2.4	3.4	4.5	5.5	6.1	6	5.2	2.6	1.6	1.3	3.7
	Minimum	1.4	2	3	3.6	4.3	5.1	5.4	4.6	2.2	1.3	1.1	3.4
	Maximum	1.8	2.8	4	5.2	6.5	6.9	6.7	5.9	3.3	1.9	1.5	4
Lat-15	Average	2.2	3.1	4.1	5	5.6	6	6	5.5	3.4	2.1	1.8	4.1
	Minimum	1.9	2.5	3.4	3.7	4.3	5	5.3	4.8	2.6	1.6	1.2	3.7
	Maximum	2.7	4	5.1	5.8	6.7	6.8	6.7	6.4	4.7	2.8	2.3	4.5
Lat	Average	2.4	3.3	4.2	4.8	5.2	5.5	5.5	5.3	3.6	2.3	1.9	4.1
	Minimum	2	2.7	3.4	3.6	4	4.6	4.9	4.7	2.7	1.7	1.2	3.6
	Maximum	3.1	4.4	5.3	5.7	6.3	6.2	6.2	6.2	5	3.1	2.6	4.5
Lat + 15	Average	2.5	3.4	4.1	4.5	4.6	4.8	4.8	4.8	3.6	2.3	2	3.8
	Minimum	2.1	2.7	3.3	3.3	3.5	4	4.3	4.2	2.6	1.7	1.2	3.4
	Maximum	3.3	4.6	5.2	5.3	5.6	5.4	5.4	5.7	5.1	3.2	2.8	4.3
90	Average	2.4	3	3.3	3	2.7	2.6	2.8	3	3	2	1.9	2.7
	Minimum	1.9	2.3	2.5	2.3	2.2	2.3	2.5	2.7	2.1	1.4	1	2.4
	Maximum	3.2	4.2	4.1	3.6	3.2	2.9	3	3.6	4.2	2.9	2.7	3.1

Effective sun hours calculation = Average daily sun hours in a year X number of days

Load Calculation

- To calculate power required from solar panel, we can use the formula below:

$$\text{PV power required} = \frac{Total\ energy\ usage\ of\ the\ customer\ in\ kWhr/year}{Effective\ sun{-}hours\ X\ System\ Efficiency}$$

Also, can be calculated per day or per month.

Example 1: In the UK, according to Ofgem, the average electricity consumption in a house is 2700kWhr/yr. If the system efficiency is assumed to be 90% (0.9), find the PV power required. Use the UK's sun-hours chart for the year 2023.

Solution:

Energy consumption – 2700kWhr/yr.

$$\text{Sun hours in 2023: -} \frac{\Sigma\ of\ 12\ months\ sun\ hours}{12} = \frac{2.4+3.2+2.5+5.5+7.3+8.2+5.2+5.4+5.2+3+2.4+09}{12} = 4.26 \text{ hours}$$

Effective sun hours calculation = Average daily sun hours in a year X number of days = 4.26 x 365 = 1555 sun hours in a year

$$\text{PV power required} = \frac{2700}{1555X\ 0.9} = \mathbf{1.929}\text{kW} \approx 2\text{kW or } 2000\text{W}$$

Therefore, 2kW of total solar power is required to deliver the energy for the customer.

Load Calculation

How to calculate a customer's load consumption ?

As earlier mentioned, the energy consumption is gettable from the customer's electric bill.

- ❑ Get the appliances data the customer is going to use (Number of loads and their respective power rating).
- ❑ Get the operating hours.
- ❑ Energy consumption = Power rating of a load x number of same load x operating hours.

Load Name	Power of Load in W	No of Load	Total Power in W	Operating Hours (hr)	Total Energy in Whr
LED bulb	4	6	24	6	144
CFL	6	3	18	6	108
Laptop	65	1	65	2	130
Smart TV	150	1	150	8	1200
Hoover	620	1	620	0.5	310
Microwave	800	1	800	0.25	200
Electric Kettle	2200	1	2200	0.1	220
Washing Machine	1000	1	1000	2	2000
Refrigerator	500	1	500	24	12000
Freezer	150	1	150	24	3600
Dishwasher	1500	1	1500	1	1500
Mobile charger	5	2	10	1	10
			7037		21422

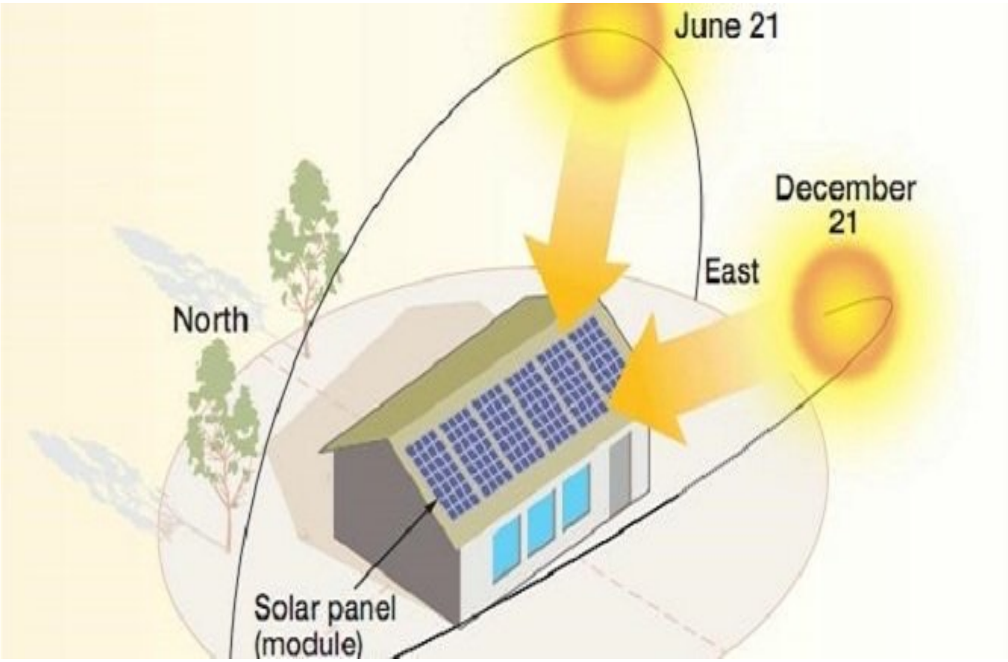
Total Energy required per day 21422Whr
Total Power required per day 7037W

Panel location and Spacing

For roof top panels installation

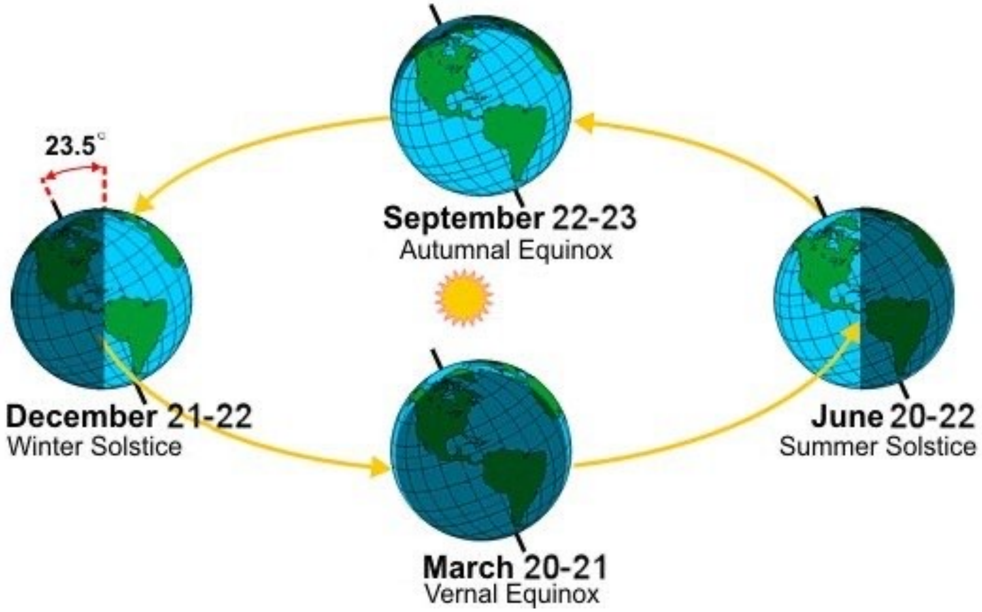
In previous lecturer, we learned about initial site inspection. In case of roof top panel installation, you need to check local authority (council or municipality) guidelines. You may require to provide an initial diagram that will show where you are putting the panels. Do the followings:

- ❑ Site inspection. (south facing ideally)
- ❑ Measure the availability of the space to check if the number of panels will fit.
- ❑ Check where the circuit box and meter is located and measure how far it is from the panels.
- ❑ Identify what will be the best tilt angle for the panels.
- ❑ Calculate the best row spacing of the panels if the customer's roof is not facing the south. This is done to avoid shading.
- ❑ Simulate sun's position during winter and summer to identify the best row spacing.



Panel location and Spacing

Sun's position is very important to calculate the row distance of the modules.



- ❑ The earth rotates about its own axis tilted at an angle 23.5^0.
- ❑ During summer, the North pole is tilted towards the sun.
- ❑ Around June 21st, tilted most towards the sun – Summer Solstice.
- ❑ For this reason, earth receives more sun light and heat. Longer day and shorter night in summer.
- ❑ Moving along its path, the North pole is tilted furthest making it colder, and shorter day and longer night in winter. (winter solstice)

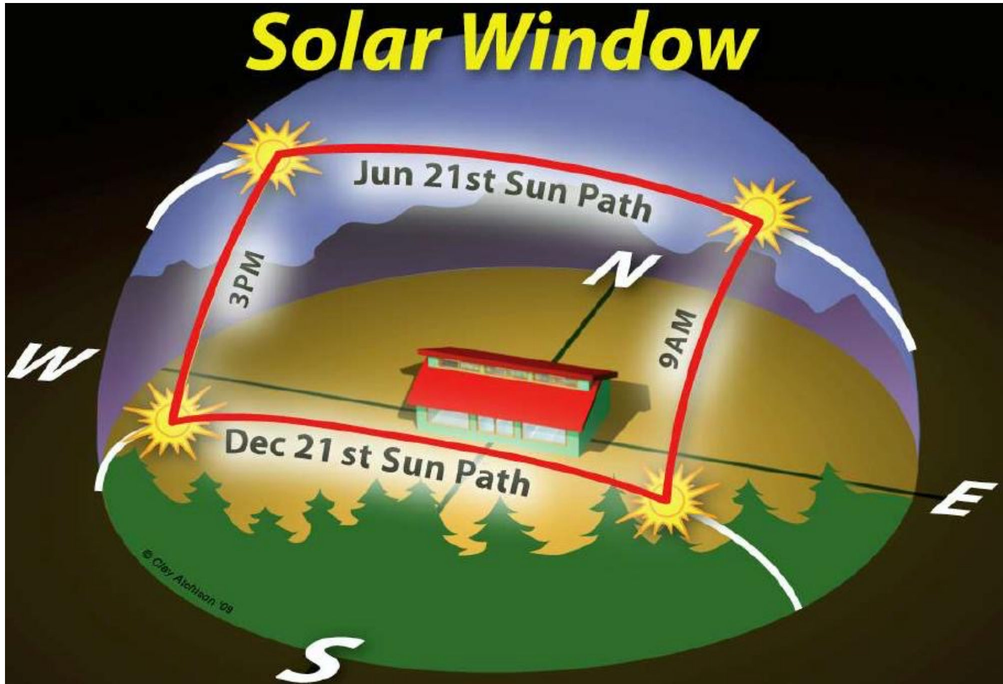
Solar window – Depends on the location

❑ On 21st December, the sun rise at 9am. However, on 21st June at the same Time the sun is in higher position.

❑ At 3 pm in December, the sun is at lowest and in June its height is higher.

❑ If the line is drawn for the sun's position on those dates and time, it forms a rectangle and area inside the rectangle is called the solar window for the given Location.

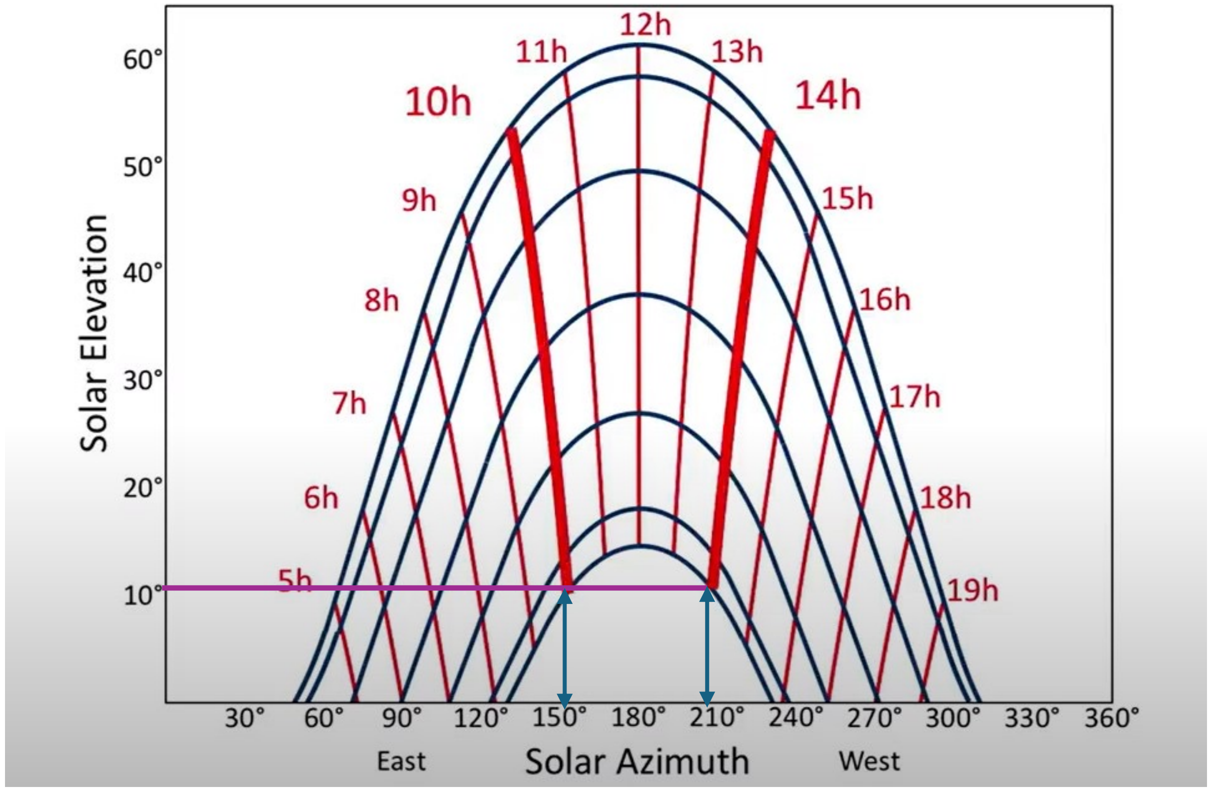
❑ This window is very important because earth receives the maximum energy From the sun and also crucial to calculate the minimum row spacing.



Panel location and Spacing

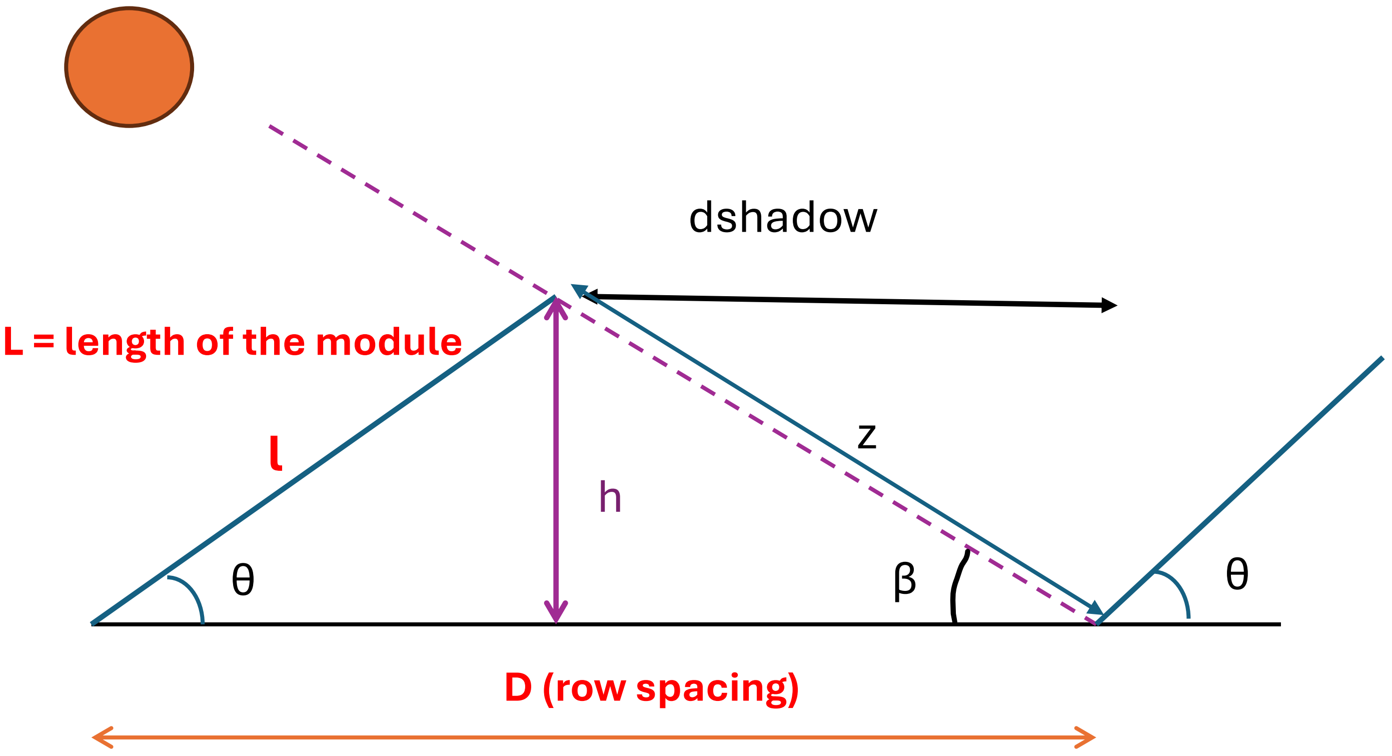
Sun's position is very important to calculate the row distance of the modules.

- ❑ Get the solar elevation chart for the selected location.
- ❑ This chart helps to ensure the rows are not shaded.
- ❑ From the solar chart, we see the solar window is between 10am and 2pm.
- ❑ Draw a horizontal line, to get the solar elevation angle. This will be used to determine the row spacing.
- ❑ Solar azimuth angle at 10am is 150^0 and 210^0 at 2pm.

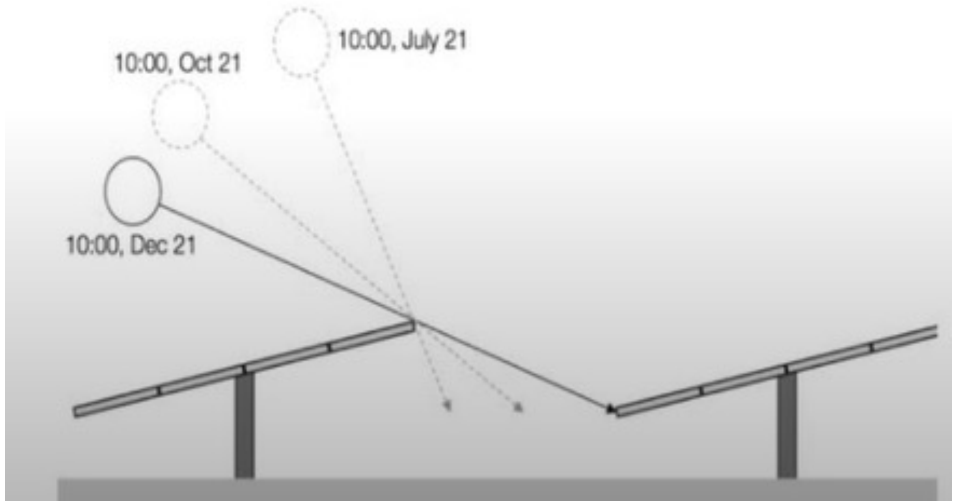


Panel location and Spacing

Row spacing calculation



Z = distance between top edge of the module and the end of the shadow on the ground



$$d = l\cos\theta + z\cos\beta = l\cos\theta + (h/\sin\beta)\cos\beta$$

$$d = l\cos\theta + \frac{l\sin\theta}{\tan\beta}$$

$$d = l\left[\cos\theta + \frac{\sin\theta}{\tan\beta}\right)$$

Rule of thumb : 3 times the length of the module

PV Panel selection and Calculation

From Example 1, it was found that the required PV power is 2kW or 2000W.

Number of Panels required = $\frac{Required\ PV\ power}{PV\ output\ power}$

Number of Panels required = $\frac{2000}{350}$ = 5.7 ≈ 6 panels required

The number of solar modules required for a particular location depends on the space availability. It is crucial to calculate the available area and the area of the module to check if the total number of modules fit in that allocated area or not.

Example 2: *A customer's yearly usage is 3575 kWhr per year and the full-sun-hours per year is 1426 and the system efficiency is 0.85. If 350W peak PV panels are used, then how many total modules you need?*
The roof size is 10 meter long by 5 meter up-slope. Each solar panel is 2280mm by 1136mm in size. Using your answer from the first part, will all the panels fit here in portrait? Does this leave a gap of about 0.40m both horizontally and vertically on the roof? The image below shows as example of portrait mounting but does not reflect the module configuration you would use.

PV Panel selection and Calculation

Solution:

PV power required = $\frac{3575}{1426 \ X \ 0.85}$ = 2.9494kW ≈ 2.95kW

Number of Panels required = $\frac{2950}{350}$ = 8.4 ≈ 9 Panels (rounding up 9 will provide sufficient power)

The length of the roof is 10m. So, depending on how you place the panel will determine if the panels leave some space. If we place the solar panel vertically, possible number of panels in horizontal direction of the roof = 10m/1.136m = 8.80 panels, so 8 panels.

The number of panels possible in vertical direction of the roof = 5/2.28 = 2.19, so 2 panels. But we need total 9 panels. So, 8 panels will cover in the horizontal direction, and 1 panel vertical.

The gap remains = 5m – (2.28mx2) = 0.44m vertically, and
10m – (1.136mX8) = 0.912m horizontally

All the calculations are at STC.

Solar module and Inverter Data sheet

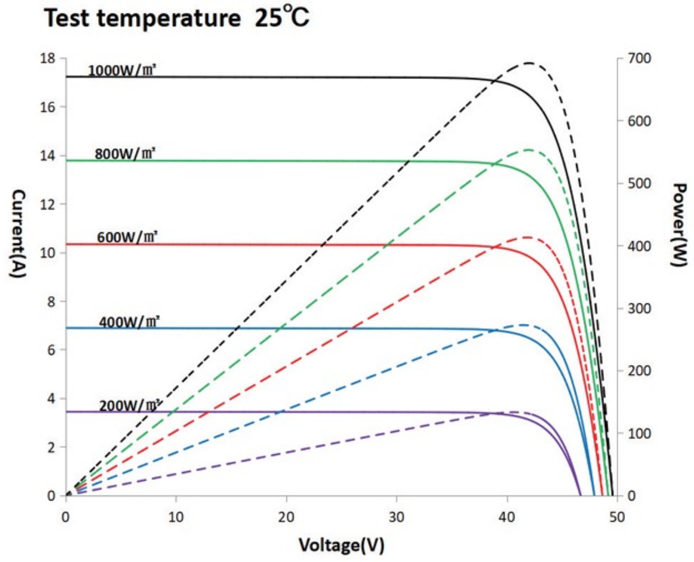
A solar panel data sheet is an important document that provides valuable information about the panel's maximum voltage and current at maximum power point, efficiency, open circuit voltage and short circuit current, mechanical parameters, temperature coefficients, IV curve etc.

ELECTRICAL PARAMETERS @ STC

Max. Power Output Pmax (W)	680 Front	577 Back	685 Front	580 Back	690 Front	585 Back	695 Front	589 Back	700 Front	593 Back
Power Tolerance	0~+3%		0~+3%		0~+3%		0~+3%		0~+3%	
Max. Power Voltage Vmp (V)	42.08	42.68	42.32	42.82	42.55	43.05	42.77	43.27	43.00	43.50
Max. Power Current Imp (A)	16.16	13.53	16.19	13.55	16.22	13.58	16.25	13.60	16.28	13.63
Open Circuit Voltage Voc (V)	49.20	48.60	49.40	48.90	49.60	49.10	49.80	49.30	50.00	49.50
Short Circuit Current Isc (A)	17.18	14.38	17.20	14.40	17.22	14.42	17.24	14.43	17.26	14.45
Module Efficiency (%)	21.90	18.60	22.10	18.70	22.20	18.80	22.40	19.00	22.50	19.10

*STC (Standard Test Condition): Irradiance 1000W/m², Cell Temperature 25℃, Air Mass 1.5
*Measurement Tolerance (±3.0%)

I-V CURVES



TEMPERATURE COEFFICIENTS

Temperature Coefficients of Pmp	-0.24%/ °C
Temperature Coefficients of Voc	-0.22%/ °C
Temperature Coefficients of Isc	+0.047%/ °C

Solar module and Inverter Data sheet

Depending on the location, we need to consider temperature coefficients of the module.

If the location is colder, then the voltage Voc will increase and Voc will decrease if the location is warmer.

Let's say the average temperature of the customer's location is 22^0 C, which is 3 degrees lower than the STC temperature. To calculate the new Voc, we use the following formula

TEMPERATURE COEFFICIENTS

Temperature Coefficients of Pmp	-0.24%/ °C
Temperature Coefficients of Voc	-0.22%/ °C
Temperature Coefficients of Isc	+0.047%/ °C

Voc (new) = V_{STC} + [Temp. coefficient of Voc X (temp of the location – 25^0C (STC temperature))

From the Data sheet, V_{STC} = 50V, Temp coefficient of Voc=-0.22%/C, Temp of the location = 22 degrees.

First, find the Temp. coefficient of Voc = 50 x -0.22%/C = -0.11V/C

Voc (new) = 50 + [-0.11 x (22-25)] = 50.33V [We see an increase in voltage by 0.33V]

For warmer location, let's say the temperature is 35^0 C,

Voc = 50 + [-0.11 x (35-25)] = 48.9V [Drop of 1.1V]

This calculation is also required to connect the modules to inverter DC input. Always check the input max DC voltage of the inverter from the inverter's Data sheet. If the Inverter's DC input voltage max range is 600V. So, the max number of modules you can connect to the inverter = 600/50.33 = 11.92 ≈ 11 series strings. If we select 12, this will be more than the input DC voltage capacity of the inverter.

It is vital to check the minimum and maximum temperature of the location and the maximum DC input voltage capability of the inverter.

Solar module and Inverter Data sheet

Inverter Data Sheet

Technical data	Sunny Boy 3.0-US		Sunny Boy 3.8-US		Sunny Boy 5.0-US	
	208 V	240 V	208 V	240 V	208 V	240 V
Input (DC)						
Max. PV power	4260 Wp		5396 Wp		7100 Wp	
Max. DC voltage	600 V					
Rated MPP voltage range	155 - 480 V		195 - 480 V		220 - 480 V	
MPPT operating voltage range	100 – 550 V					
Min. DC voltage / start voltage	100 V / 125 V					
Max. operating input current per MPPT	10 A					
Max. short circuit current per MPPT	18 A					
Number of MPPT tracker / string per MPPT tracker	2/1				3 / 1	
Output (AC)						
AC nominal power	3000 W	3000 W	3330 W	3800 W	5000 W	5000 W
Max. AC apparent power	3000 VA	3000 VA	3330 VA	3800 VA	5000 VA	5000 VA
Nominal voltage / adjustable	208 V / ●	240 V / ●	208 V / ●	240 V / ●	208 V / ●	240 V / ●
AC voltage range	183 – 229 V	211 – 264 V	183 – 229 V	211 – 264 V	183 – 229 V	211 – 264 V
AC grid frequency	60 Hz / 50 Hz					
Max. output current	14.5 A	12.5 A	16.0 A	16.0 A	24.0 A	24.0 A
Power factor (cos φ)	1					
Output phases / line connections	1 / 2					
Harmonics	< 4 %					
Efficiency						
Max. efficiency	97.2 %	97.6 %	97.2 %	97.5 %	97.2 %	97.5 %
CEC efficiency	96 %	96.5 %	96.5 %	96.5 %	96.5 %	97 %

Max DC input Voltage

Impact of temperature coefficient in module calculation

***For the same Example 2, if the AKCOME 700W module is used we need 5 modules to provide sufficient power to meet the customer's demand. The temperature of the location is 22 degrees Celsius. How many modules the customer can connect to the inverter? Use the data sheet given above for the calculations*.**

Solution:

Voc (new) = V_{STC} + [Temp. coefficient of Voc X (temp of the location – 25^0C (STC temperature))

From the Data sheet, V_{STC} = 50V, Temp coefficient of Voc=-0.22%/C, Temp of the location = 22 degrees.

First, find the Temp. coefficient of Voc = 50 x -0.22%/C = -0.11V/C

Voc (new) = 50 + [-0.11 x (22-25)] = 50.33V

The inverters max DC input voltage is 600V so, 600/53.33 = 11.9. Therefore, maximum 11 modules in series can be connected to the inverter.

The customer's power requirement is 2950W and we need 5 modules of 700W Akcome module. The new Voc is 50.33V so 5 modules will have total 251.65V which is well within the Inverter's DC input voltage. So, yes, we can connect the 5 series strings to the Inverter's DC input.

Summary

In this lecture we learned

- ❑ Factors to be considered before solar modules installation.
- ❑ Importance of sun-hours.
- ❑ Use of solar elevation chart.
- ❑ Distance calculation to avoid shading affect.
- ❑ Roof space calculation.
- ❑ Solar panel and Inverter’s data sheet.
- ❑ How to use data sheet to calculate panel sizing.

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