



UNIVERSITÉ DES
MASCAREIGNES

SAVOIR, C'EST POUVOIR

Session 1:

Solar Energy Fundamentals

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SESSION CONTENT

1. The Energy Context

2. Solar Radiation Basics

3. Solar Geometry

4. Solar Rooftop Design

Fundamentals of Solar Energy

Definition

Solar energy is radiation light and heat from the Sun that is harnessed using a range of technologies such as solar power to generate (1) electricity and (2) solar thermal energy (including solar water heating)

The Global Energy Context

Global energy security is a key endeavour in the current context:

- population expansion,
- rapid economic development,
- diminishing fossil fuel supply

This situation has been further exacerbated by the COVID pandemic, which left fossil fuel-reliant countries more exposed to economic shocks.

The global energy consumption is still dominated by fossil fuels, which accounted for about 84% (33.1% Oil; 27% Coal; 24.3% Gas) of the global energy mix in 2019

The release of large quantities of carbon dioxide in the atmosphere led to an increase in global temperature

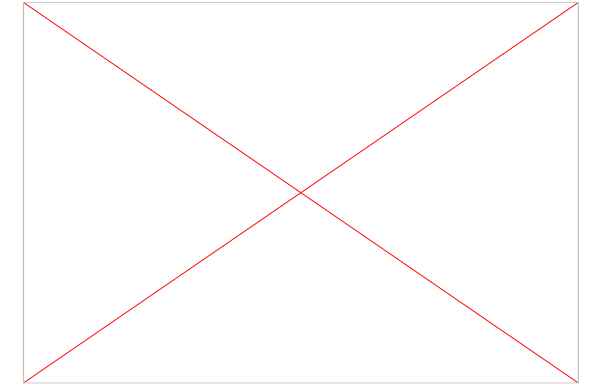


Renewables, The Solution?

Renewables accounted for 11.4% of global energy consumption in 2019, with hydropower contributing 6.4%, followed by wind (2.2%) and solar (1.1%)

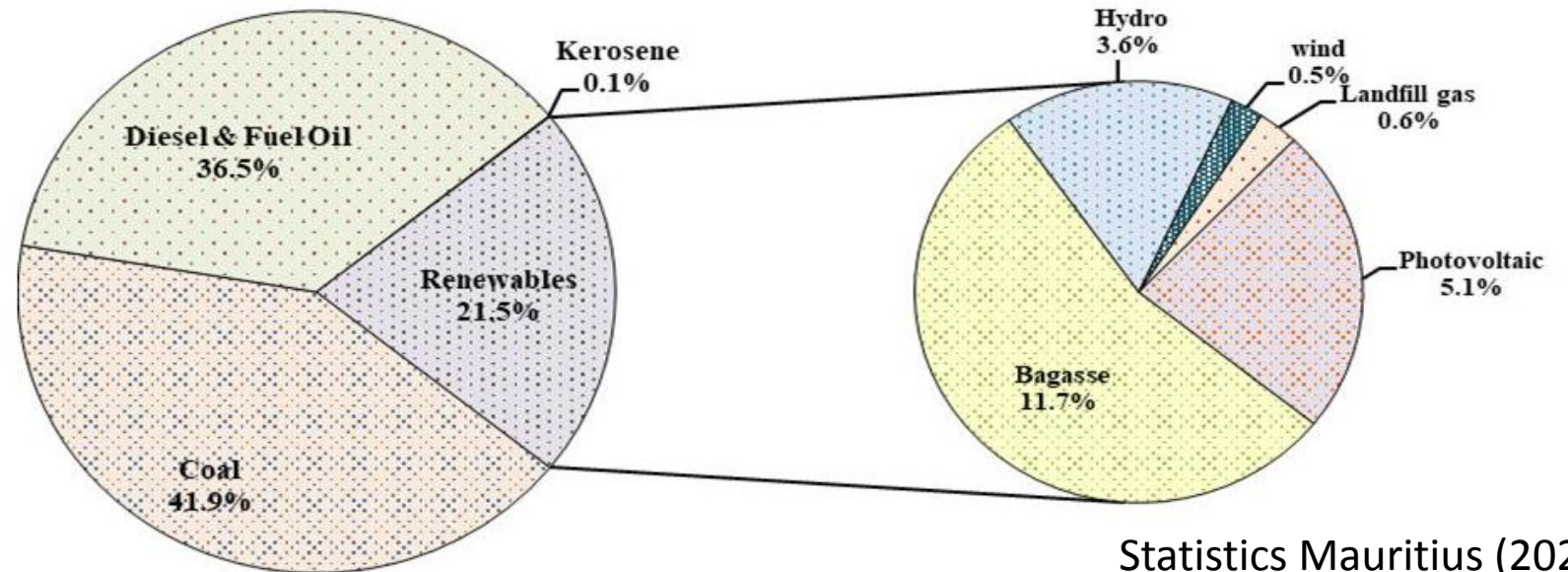
The rapidly decreasing cost of solar modules (2010-2016) is paving the way for a solar revolution. [Global average cost reductions of 69% in the electricity generated from utility-scale solar power plants from \$0.36/kWh to \$0.11/kWh]

It is expected that solar photovoltaic would generate 25% of the global electricity needs, becoming a major generation source by 2050



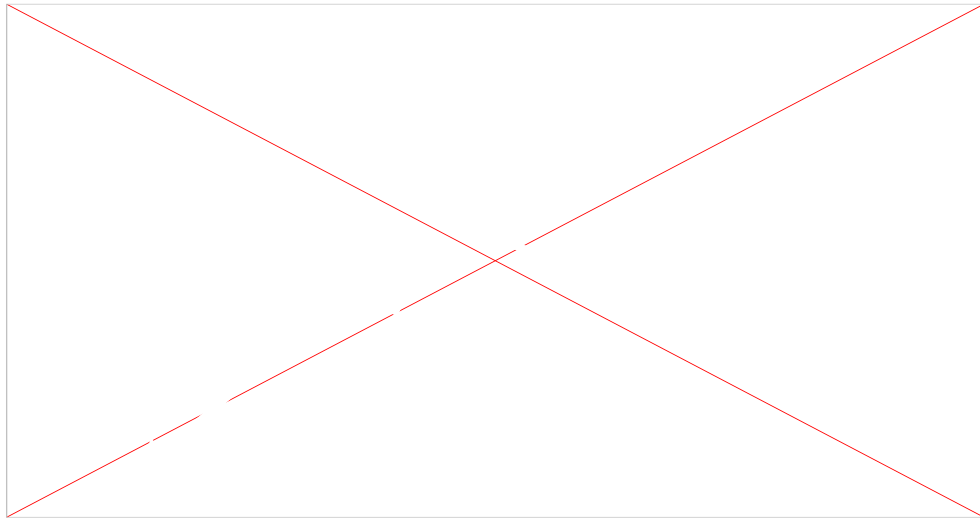
According to Statistics Mauritius (2021), a share of 5.1% of electricity generated is derived from PV solar

In 2017, Solar PV accounted for only 1.3% of electricity generated by energy mix



Solar Radiation

Solar radiation is the energy emitted by the Sun, which is sent in all directions through space (Power/Area)



Nuclear fusion reactions taking place in the core give rise to interior temperatures of 15 million degrees C

The rate of hydrogen fusion into helium is high owing to suitable temperatures of the core [Production of photons]

Photons are thereafter delivered to the convective layer through the radiative zone [170,000 years]

The outer layer has a temperature of 5,500 degrees C

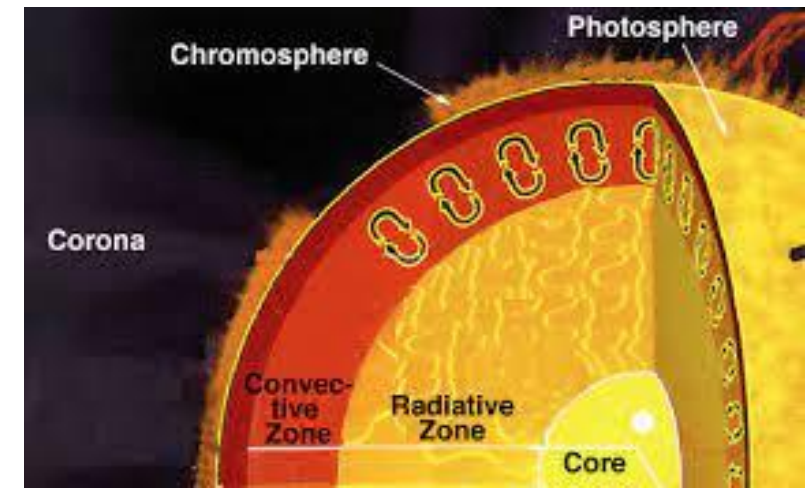
Radiation streams out of the Sun at a rate of 3.85×10^{26} W

Only $\frac{1}{2,000,000,000}$ of the outgoing solar radiation is intercepted by Earth

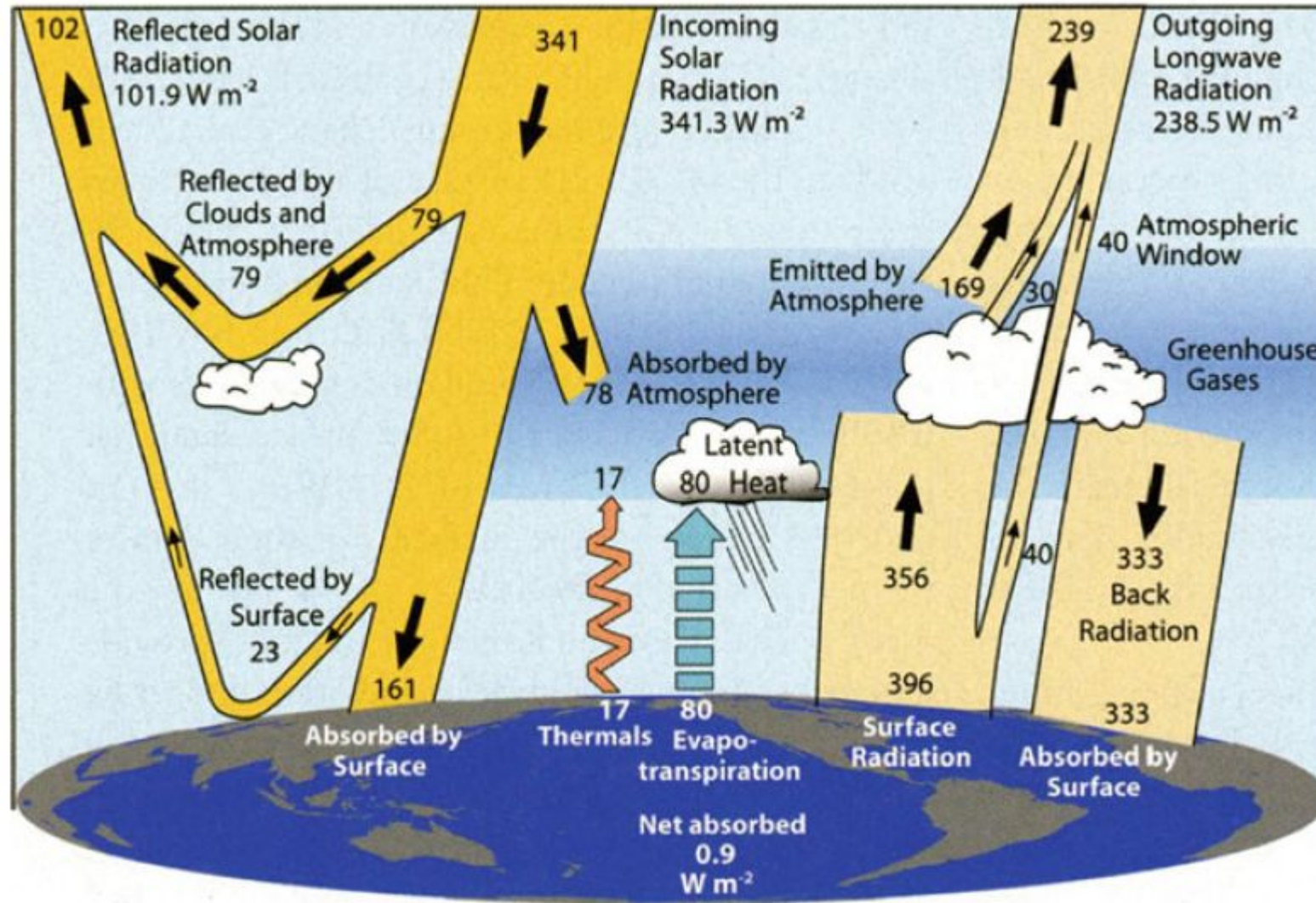
$$\frac{1}{2,000,000,000} \times 3.85 \times 10^{26} = 1.935 \times 10^{17} \text{ W (Intercepted)}$$

$$\text{Radiation at top atmosphere} = \frac{\text{Intercepted Radiation}}{\text{Surface Area Earth}} = \frac{1.935 \times 10^{17}}{5.1 \times 10^{14}} \sim 341 \text{ W/m}^2$$

Prior to entering atmosphere, radiation is $(342 \times 4 = 1370 \text{ W/m}^2) = \text{Solar Constant}$



Solar Radiation Budget



Incoming radiation at TOA = 341 W/m^2

- 79 W/m^2 is reflected by the presence of clouds, aerosol and constituents that make up the atmosphere
- 78 W/m^2 gets absorbed by the atmosphere
- An additional 161 W/m^2 is absorbed by the Earth's surface
- Reflection by the surface amounting to 23 W/m^2 due to Earth albedo (Ice sheet, Ocean, vegetation, ...)
- Balance of outgoing radiation ($102 \text{ W/m}^2 + 239 \text{ W/m}^2$) with incoming radiation (341 W/m^2) maintains the Earth's equilibrium temperature

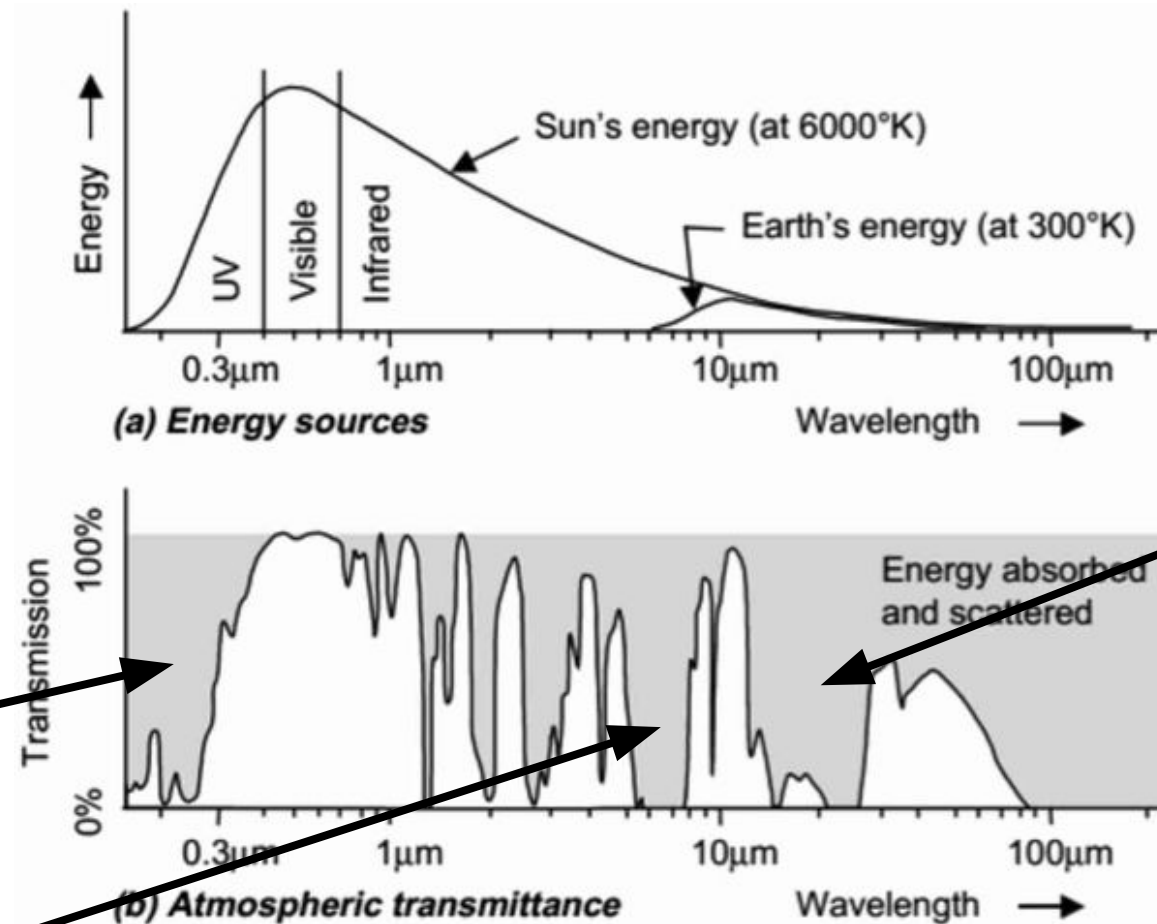
Solar Spectrum Theory & Atmospheric Interaction

The spectrum of radiation received on earth from the sun includes infrared, visible and ultraviolet radiation

These energies are transmitted by different extents (due to absorption and scattering processes)

Oxygen and ozone (absorb radiation less than $0.3\mu\text{m}$ in the uppermost layers of the atmosphere)

Water vapour is regarded as the most absorbing atmospheric gas with strong absorption around $6\mu\text{m}$



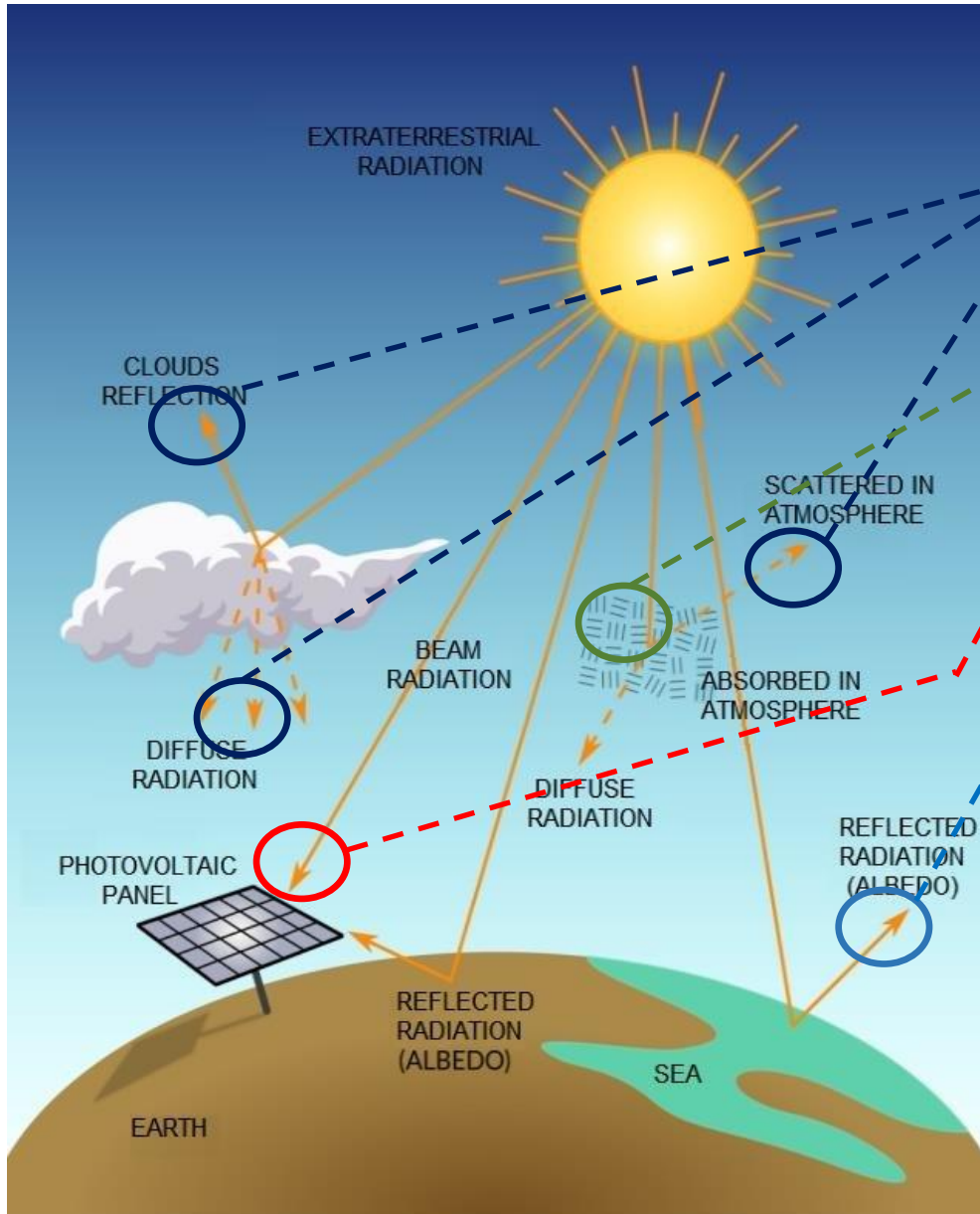
Carbon dioxide - with strong absorption band around $15\mu\text{m}$ is the main cause of attenuation in lower stratosphere

The solar radiation that reaches the earth consists of 55% infra-red radiation (IR), 42% visible light, 3% ultra-violet rays (UV)

While conventional solar panels use visible and infrared light to generate energy, recent developments are trying to tap into UV light

Solar Radiation Components

The combination of visible + IR +UV is termed radiation



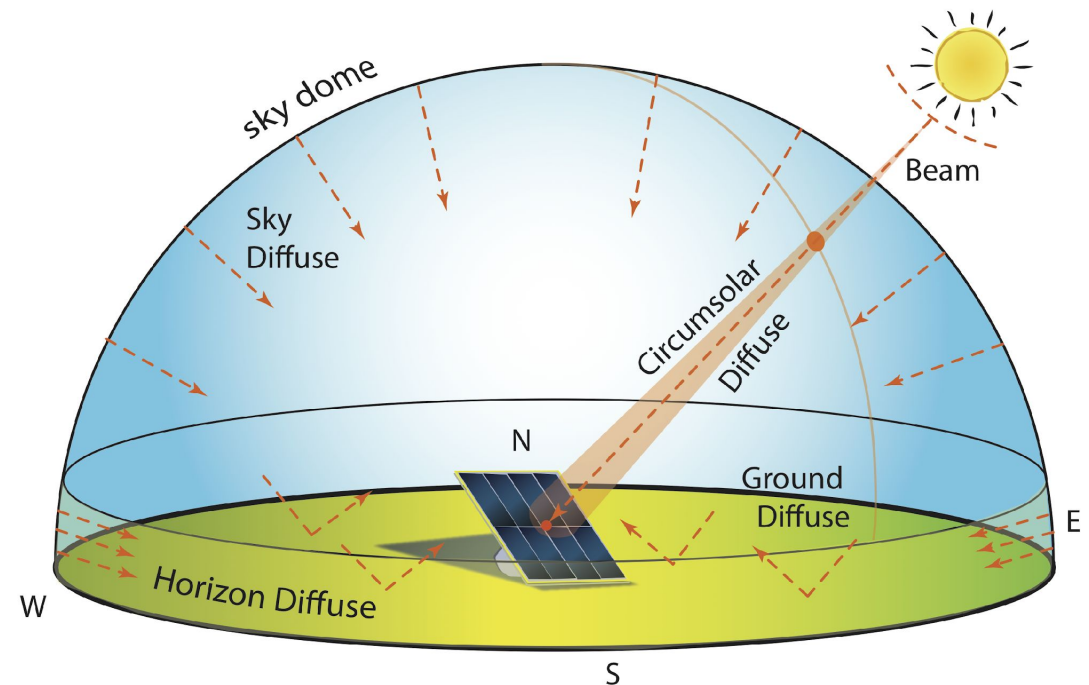
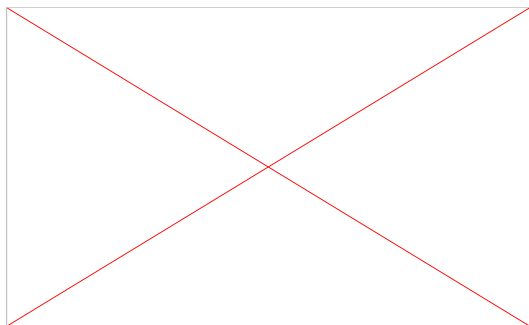
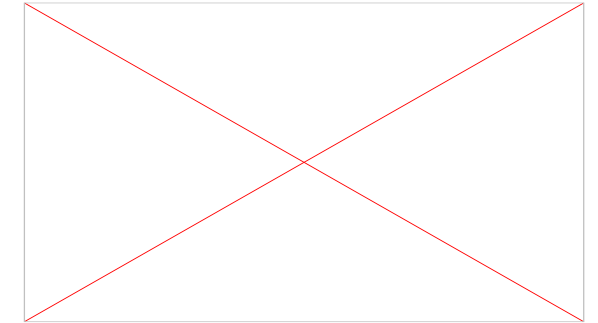
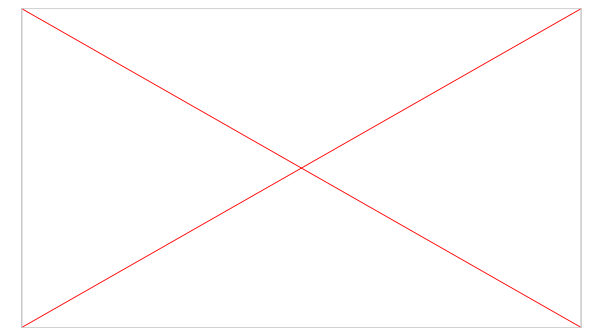
Extraterrestrial radiation from the Sun is split into several components upon encountering particles in the atmosphere

- Some radiation are back-scattered to the atmosphere due to clouds and particles in atmosphere. Others are diffused towards earth
- Some radiation are absorbed by the atmosphere
- Some radiation are non-scattered and unabsorbed and constitute the beam or direct radiation
- Some radiation are reflected by the earth surface (albedo)

Some of these radiations reach the PV panel in different directions and carry important information along different orientations

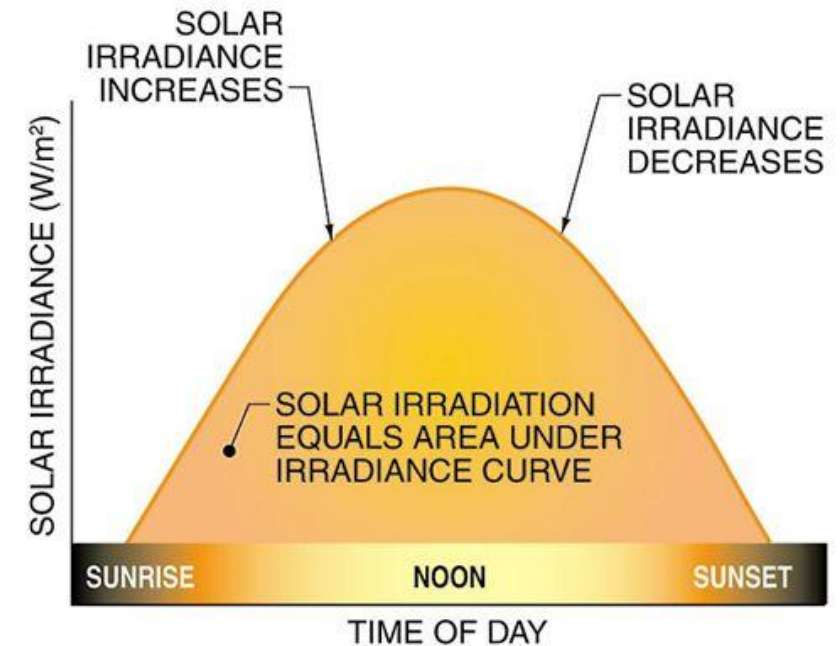
These information are important for measurement purposes but also to determine yield from PV panels

- **Global Horizontal Irradiation (GHI):** It is the total solar radiation incident per unit area on a horizontal surface. It is the sum of Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance, and ground-reflected radiation *[most vital and complete solar radiation component]*.
- **Direct Normal Irradiance (DNI):** Amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky *[No diffused or reflected components]*
- **Diffused Horizontal Irradiance (DHI):** Amount of radiation received per unit area by a horizontal surface that does not arrive on a direct path from the sun, but has been scattered by molecules and particles in the atmosphere *[No direct component]*



(Solar) irradiance - The power or instantaneous rate of energy received by a surface, originating from the sun, measured in W/m^2 .

(Solar) irradiation - The sum of the energy falling on a surface in a given time-period, originating from the sun, measured in MJ/m^2 .



Relationship:

$$\text{GHI} = \text{DNI} \cos(\text{Zenith Angle}) + \text{DHI}$$

Solar Parameter Measurements



The Kipp and Zonen pyranometer consists of a thermopile concealed in a glass hemisphere which uses the thermal property of solar radiation to generally measure the global horizontal irradiance and diffused component.

A pyr heliometer consists of a collimating tube that is able to measure direct radiation through an in-built mechanism (thermopile or thermocouple module).

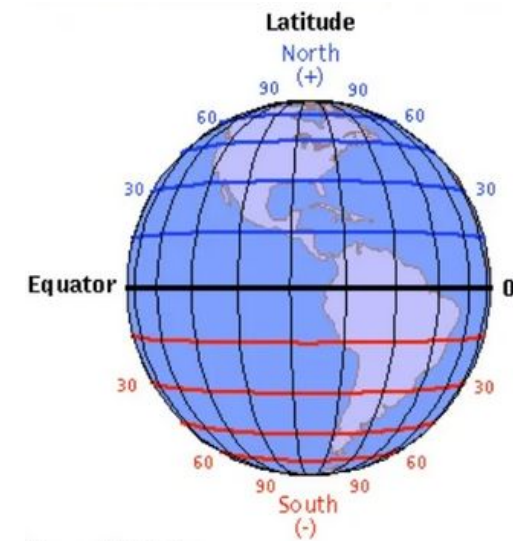
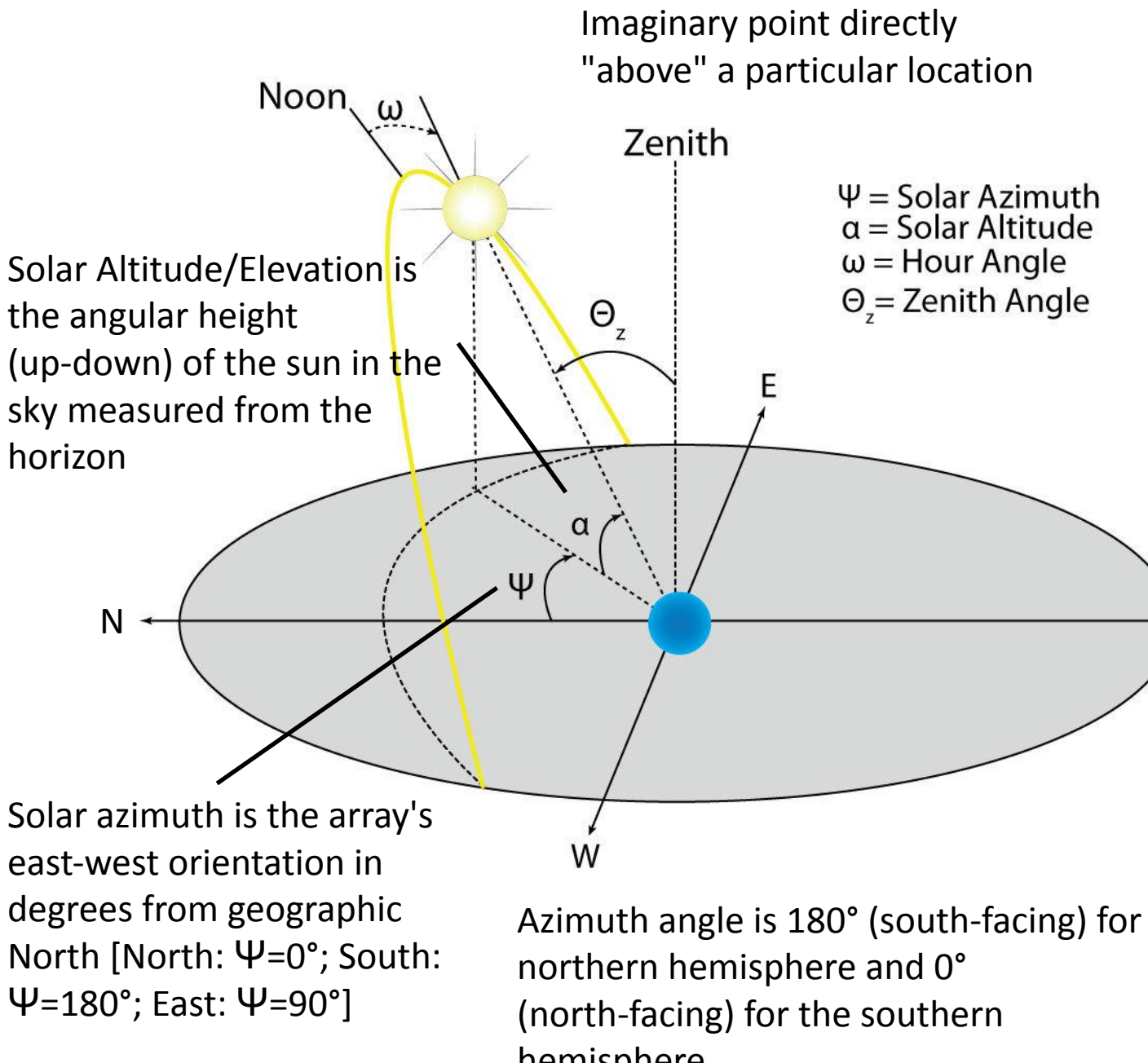


The sunshine duration parameter is generally measured using a Campbell-Stokes recorder which operates under the principle that light rays incident on a glass sphere would focus the radiation into a spot to burn a calibrated card.

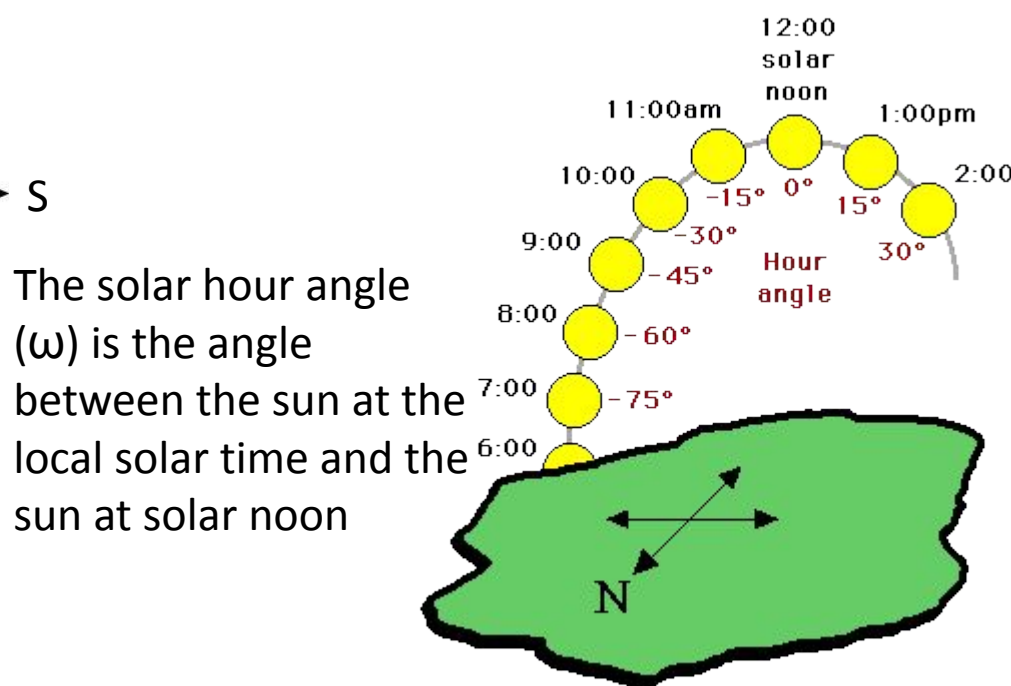
Climate monitoring satellite technology has matured significantly during the past decades and is capable of measuring high resolution solar radiation and sunshine duration parameters through mounted and calibrated sensors (e.g silicon photovoltaic detector).



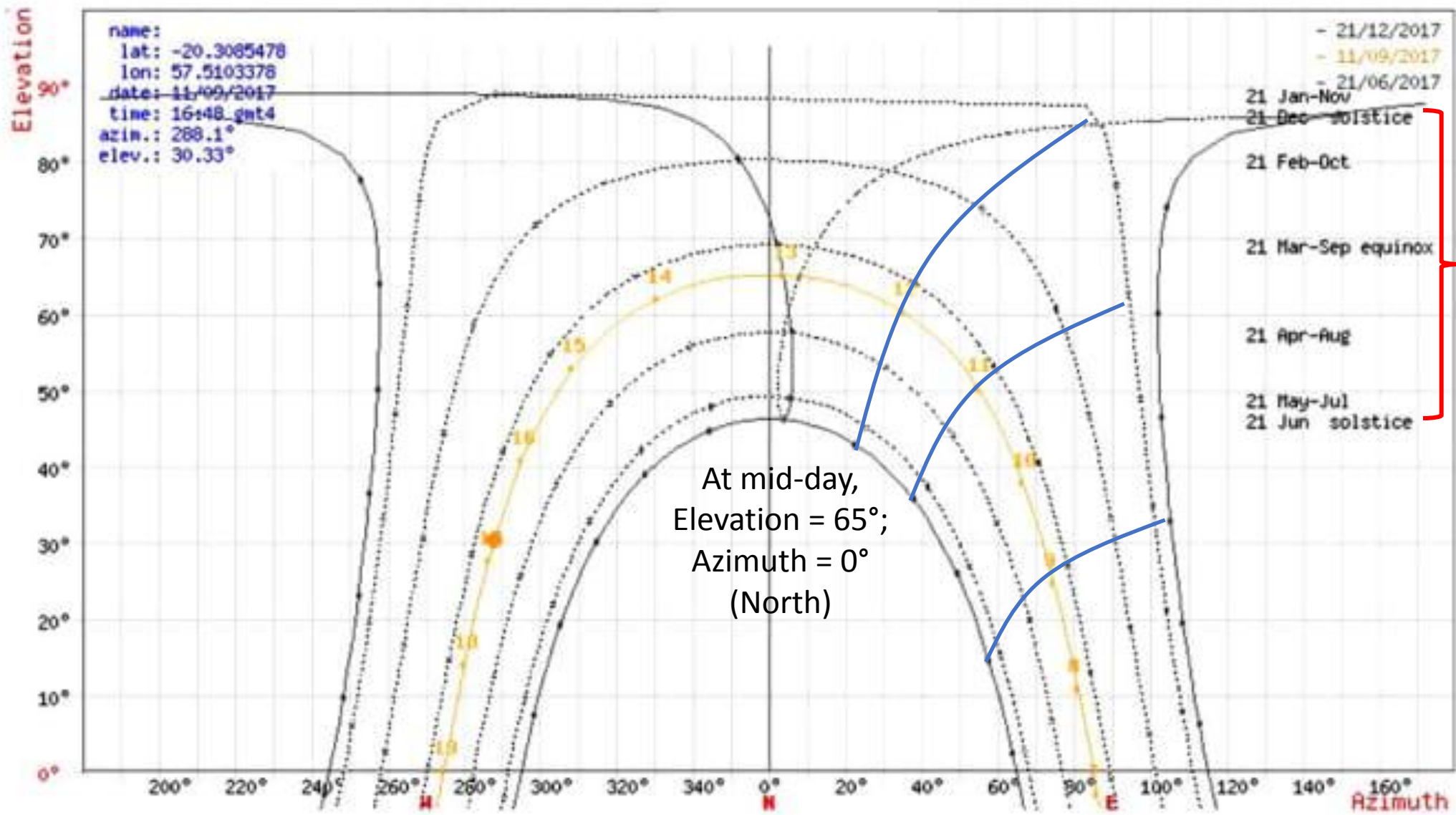
Solar Radiation Geometry



Latitude (ϕ) is a measurement on a globe north or south of the Equator



Sun Path Diagrams



Different sun path diagrams throughout the year due to different Sun position in the sky throughout the year

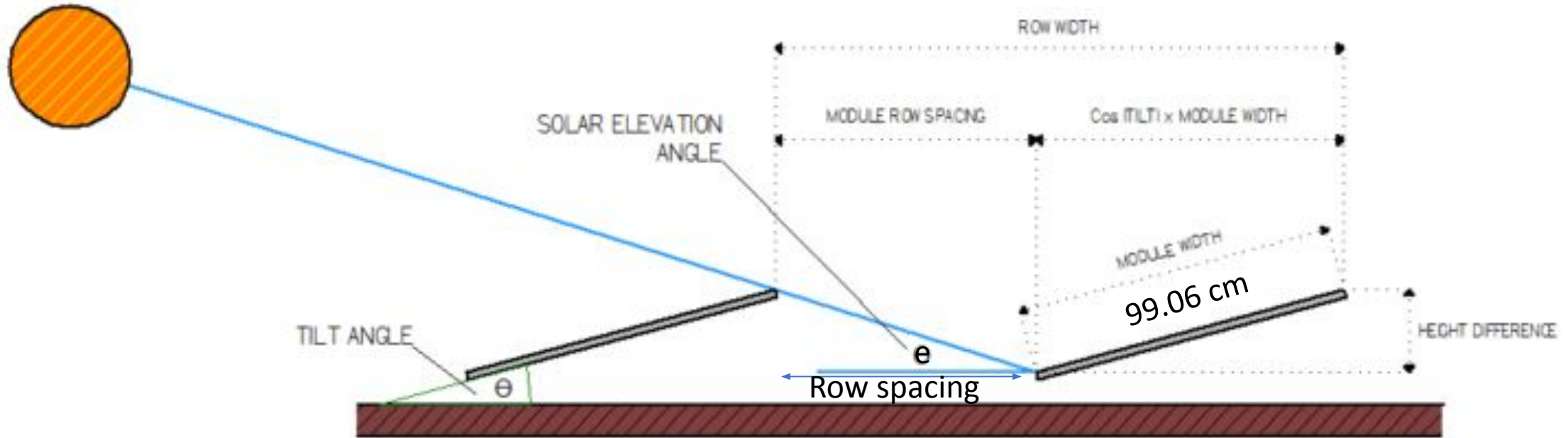
Sun's elevation is higher during summer than during winter

Change in azimuth angle is smaller during winter than summer, thus explaining the smaller sunshine hours and day length

At sunset, Elevation = 0°;
Azimuth = 270° (West)

At sunrise, Elevation = 0°;
Azimuth = 90° (East)

Row spacing and minimize inter-row shading



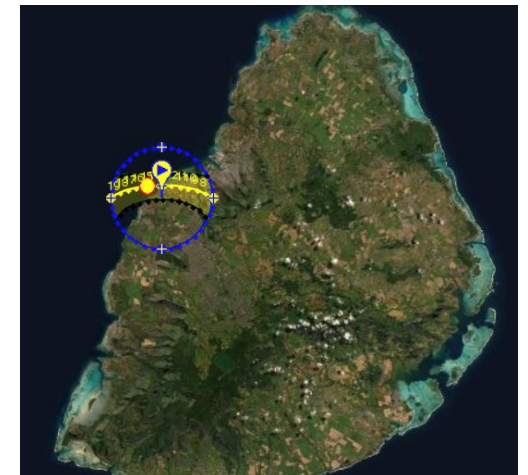
1) The first step in calculating the inter-row spacing for your modules is to calculate the height difference from the back of the module to the surface

Optimum tilt angle = 20.9°

$$\begin{aligned}\text{Height Difference} &= \sin(\text{Tilt Angle}) \times \text{Module Width} \\ &= \sin(20.9^\circ) \times 99.06 \\ &= 35.3 \text{ cm}\end{aligned}$$

2) Go to https://www.sunearthtools.com/dp/tools/pos_sun.php to determine what the Sun Elevation Angle is going to be. Select your location.

This will automatically generate a sun path diagram as follows



3) Picked a 9 AM to 5.30 PM window during the winter solstice for the worst case scenario. You may opt for a less stringent case to suit your needs. [Time window sometimes depend on rebates offered to customers]

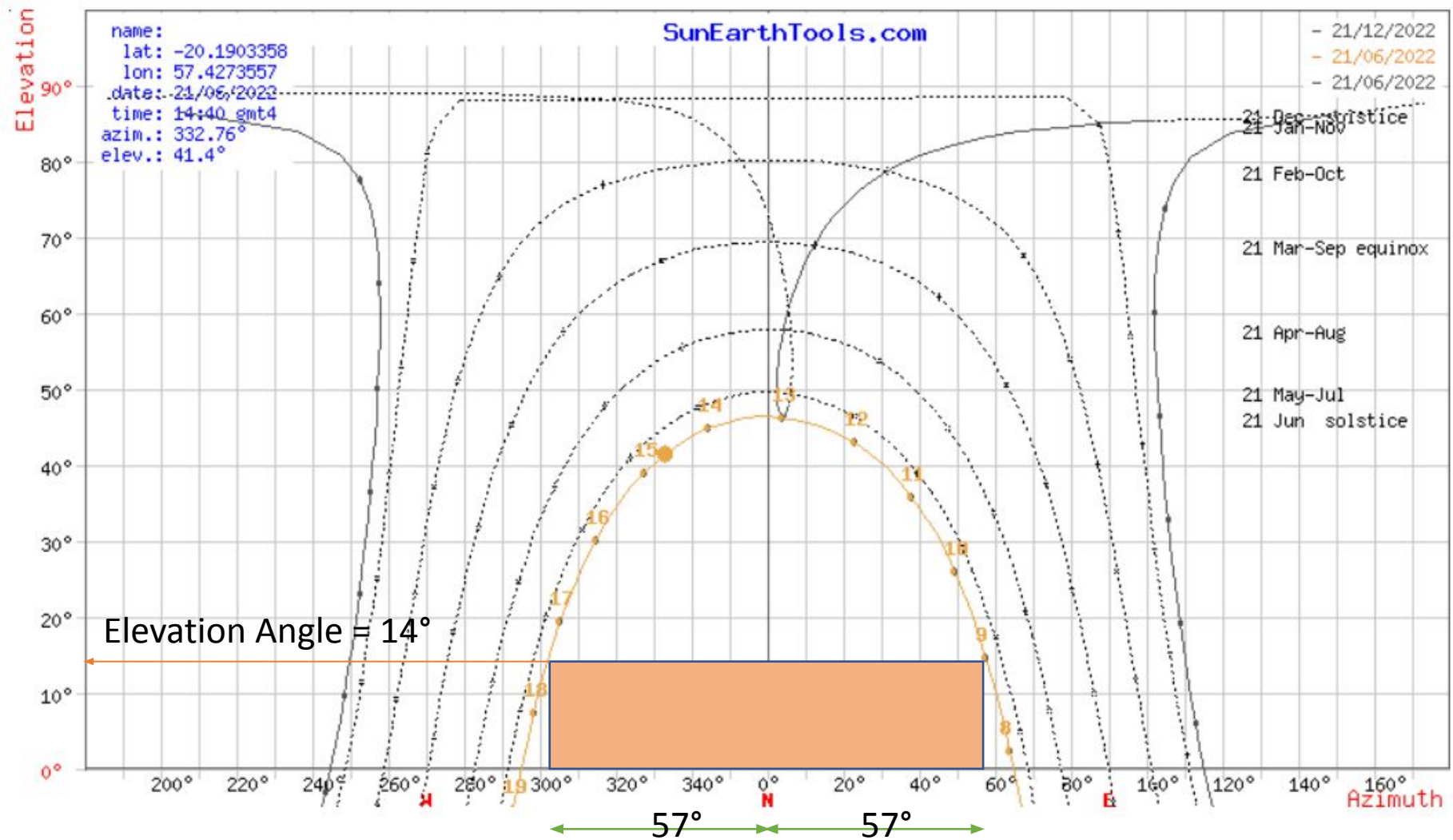
4) Read the corresponding Elevation Angle = 14°

5) The relationship between row spacing and height difference is:

$$\tan(14^\circ) = \frac{\text{Height}}{\text{Row s}}$$

$$\tan(14^\circ) = \frac{35.1}{\text{Row s}}$$

Module Row spacing = 141.6 cm



6) Account for the Azimuth angle (east-west orientation)

The difference with respect to North going from either directions is = 57°

Minimum Module Row Spacing = Module Row Spacing x Cos (Azimuth Correction Angle)

Minimum Module Row Spacing = 141.6 cm x Cos (57°) = 77.1 cm

Case Study

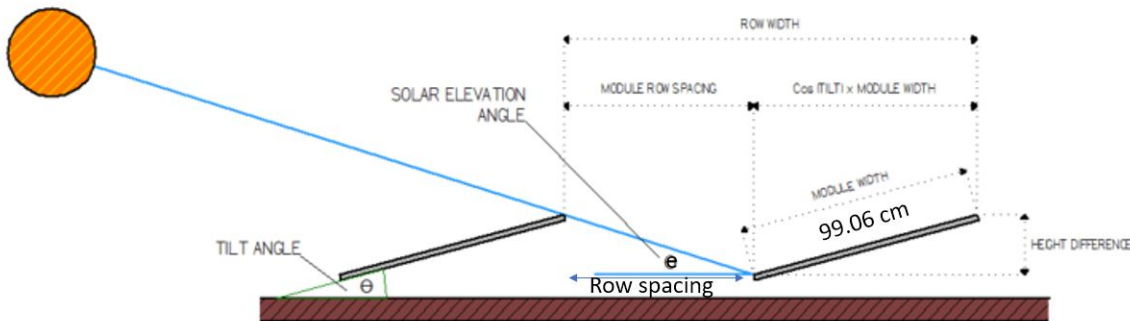
MAURITIUS:

A company located in the northern region of Mauritius wishes to install PV panels on the rooftop of one of its main buildings. Design the layout of the PV system so as to exploit the maximum possible rooftop space. [Assume PV panel size of 165.1 x 99.06 cm; Time Window from 8:30 AM to 18:00 PM]

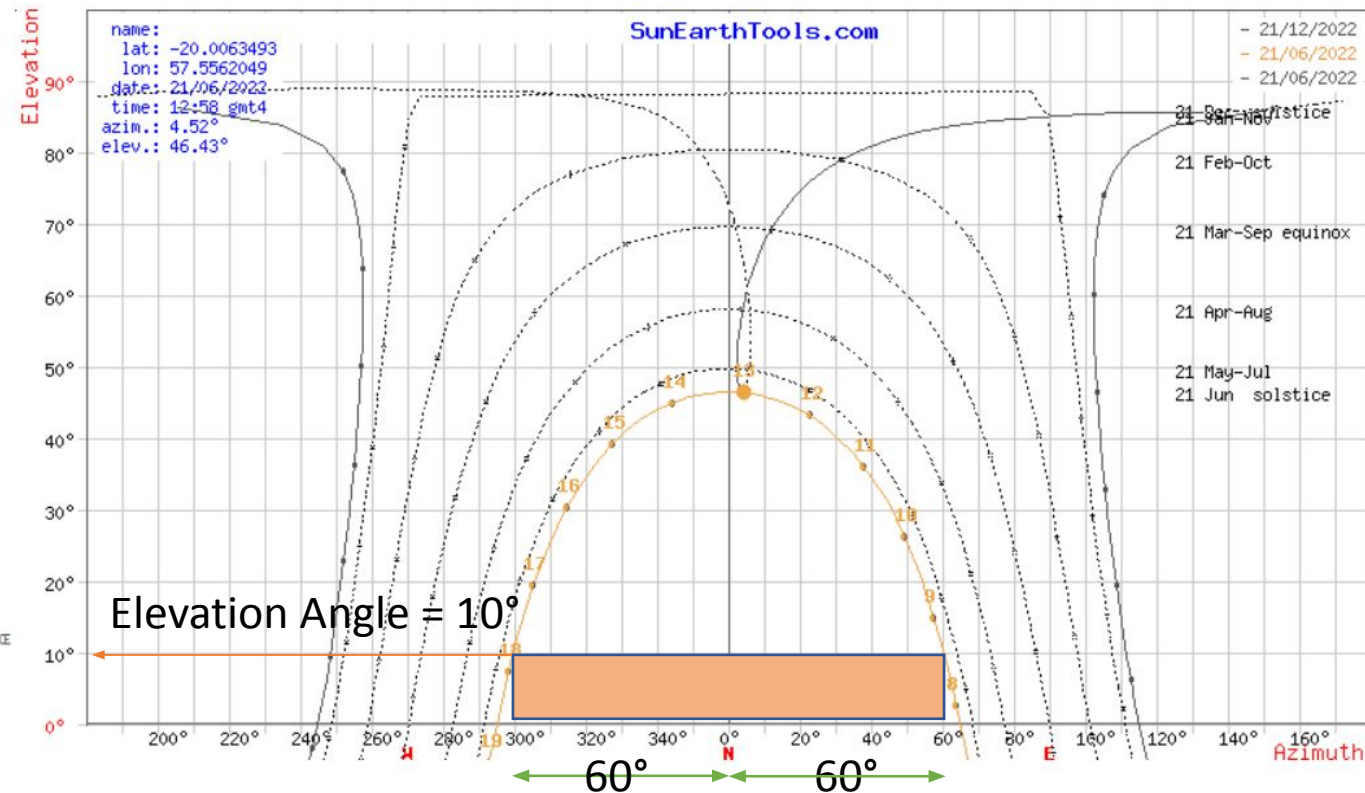


Optimum tilt angle = 20.9°

$$\begin{aligned} 1) \text{ Height Difference} &= \sin(\text{Tilt Angle}) \times \text{Module Width} \\ &= \sin(20.9^\circ) \times 99.06 \\ &= 35.3 \text{ cm} \end{aligned}$$



Elevation for winter solstice = 10°



2) The relationship between row spacing and height difference is:

$$\tan(10^\circ) = \frac{\text{Height}}{\text{Row s}}$$

$$\tan(10^\circ) = \frac{35.1}{\text{Row s}}$$

Module Row spacing = 200.2 cm

3) Account for the Azimuth angle
(east-west orientation)

The difference with respect to North
going from either directions is = 60°

Minimum Module Row Spacing =
Module Row Spacing x Cos (Azimuth
Correction Angle)

Minimum Module Row Spacing =
200.2 cm x Cos (60°) = 100.1 cm



4) Each module occupies a horizontal space of 99.06 Cos (20.9°)=92.54 cm