Energy Center, AAiT - AAU

Semester II, 2017/18 A.Y.

ECEG-6442:

Photovoltaic Systems Engineering

Instructor: Frehiwot Woldehanna, PhD

ECEG-6442 [Course Outline]

1. Review of Solar Radiation
   - The Solar Radiation Process
   - Characteristics of Solar Radiation
   - Effect of the Atmosphere
   - Solar Energy Resource Assessment

2. PV System Components
   - The Basic PV Generator - The PV Cell
   - PV Modules, Strings, and Array
   - Energy Storage and Charge Controllers
   - Power Electronic Interface Circuits,

ECEG-6442 [Course Outline]

3. PV System Sizing and Simulation
    - PV System Configurations
    - PV System Sizing
    - PV System Simulation
4. Economic and Environmental Aspects
    - Introduction
    - Life Cycle Costing
    - Environmental Impact Assessment
5. PV Manufacturing Technology
    - Cell Production
    - Module Production

Course Reference

1. Duffie J.A. and Beckman, W.A., Solar Engineering of Thermal Processes, Wiley, New York, 1991.
2. J. Twidell, T. Wier, Renewable Energy Resources, Spon Press London
3. Roger Messenger, Jerry Ventre, Photovoltaic Systems Engineering, CRC Press, 2000
4. Websites: A number of useful websites are available that will serve as helpful supplements to the basic reference materials.

Possible Evaluation Components

- Assignments
- Survey Projects with Presentations
- Mid-Semester Examination
- Final Examination

ECEG-6442 Photovoltaic Systems Engineering

Semester II, 2017/18 A.Y.

1. Review of Solar Radiation Concepts

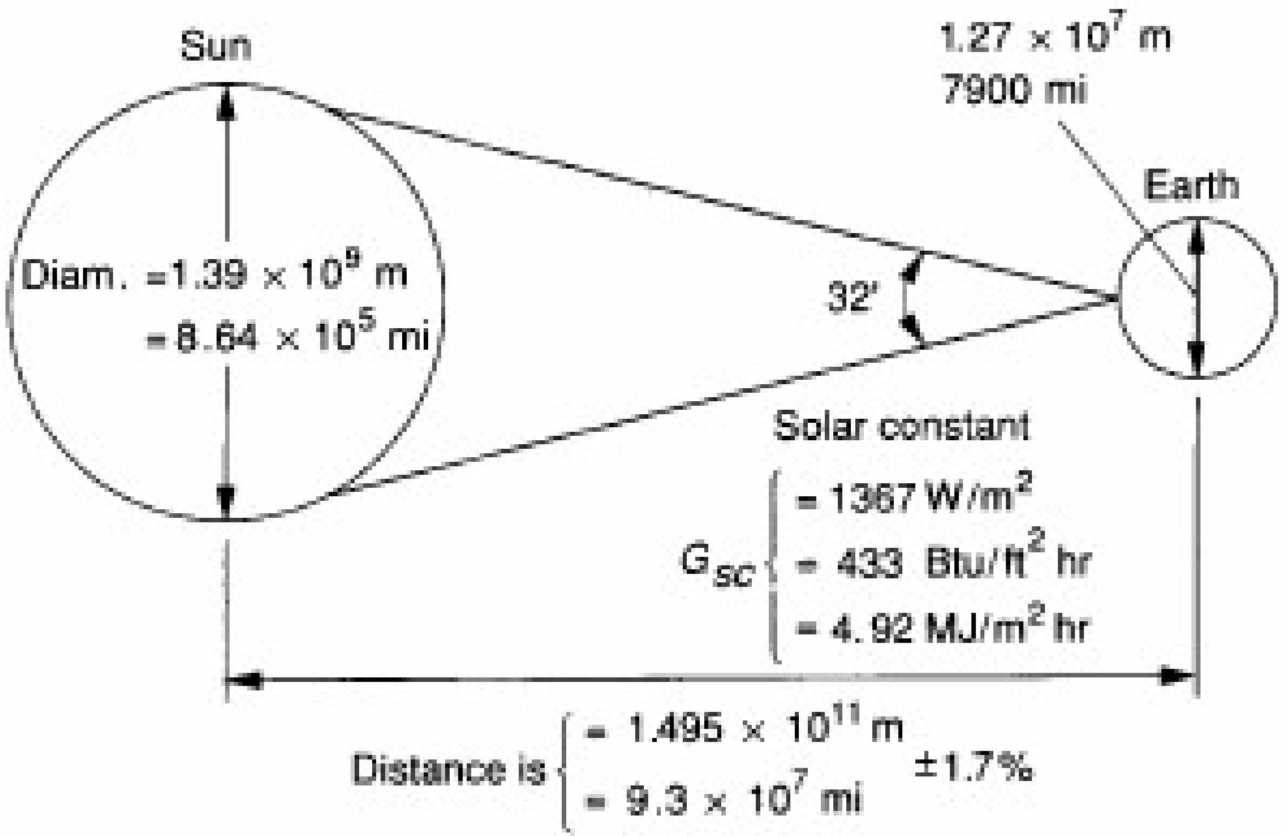
Basic Terminologies

- The major source of renewable energy, apart from geothermal, is the sun which is converted into different forms, e.g., solar radiation, wind, wave, etc.

- Solar energy originates with the thermonuclear fusion reaction occurring at the center of the sun and represents the entire electromagnetic radiation (visible light, infrared, ultraviolet, x-rays, and radio waves).

Solar Parameters

- The sun, the source of solar radiation, is a sphere of intensely hot gaseous matter with a diameter of about 1.39×10^9 m, a total mass of 1.99×10^{30} kg, and on the average 1.50×10^{11}m away from the earth.



Solar Parameters

- The intensity of solar radiation incident per unit area exposed normally to the sun's rays at the average sun-earth distance (about 1.5×10^{11}m), measured outside the earth's atmosphere is called the **solar constant, G_{sc}** the value of which is determined experimentally.
- Early measurements resulted in a value of 1353 W/m^2. But, recent estimation techniques now favour a value of **1367 W/m^2** and this is the current accepted value.
- The solar constant is not a true constant but changes over time, by not more than a few tenths of 1% in several years.

Solar Parameters …

- One of the reasons for the small variation of the solar constant is the earth's orbit, which is slightly elliptical.
- The intensity of radiation received outside the earth's atmosphere varies as the inverse square of the earth-sun distance, resulting in a maximum intensity at perihelion and a minimum at aphelion.
- The variation amounts to ±3.4% over the year, and is very nearly sinusoidal.

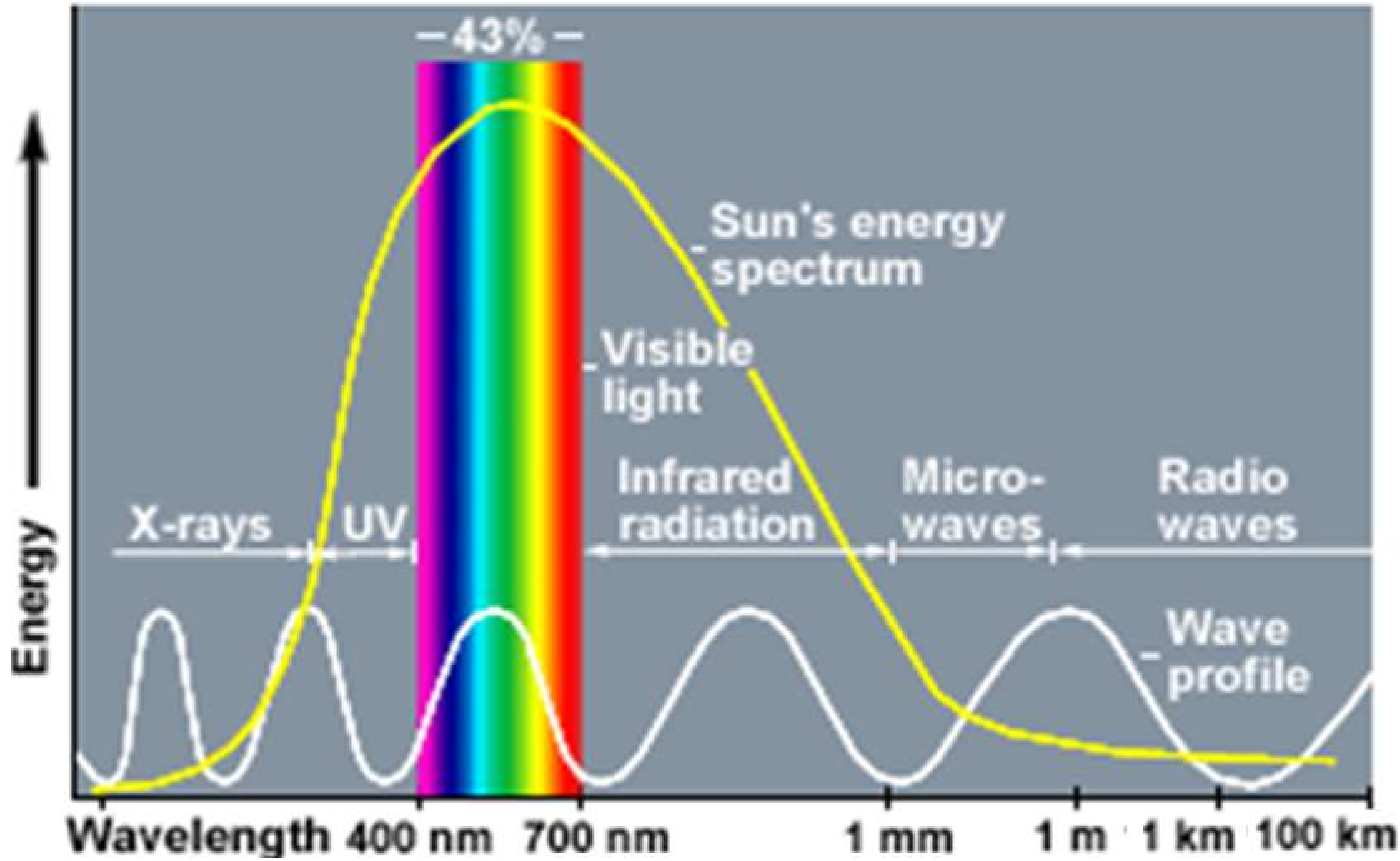
Radiation Inside and Outside ..

- **Extraterrestrial radiation (XTR) is the solar radiation outside the Earth's atmosphere which becomes Terrestrial radiation (TR) and when it crosses the atmospheric boundary.**
- **The extraterrestrial irradiance on a surface at normal incidence (G_{on}) may be expressed as:**

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

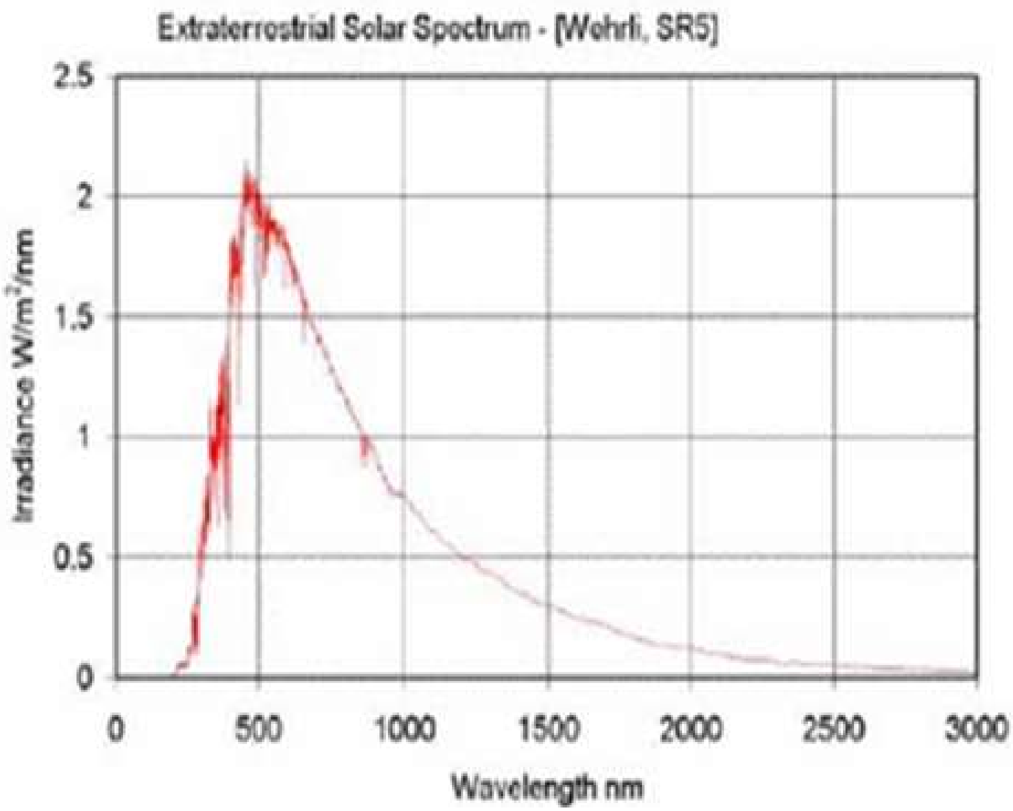
- **where m is the number of the day in the year with January 1st representing a value of 1 and December 31 a value of 365.**

Solar Energy Spectrum



XTR Solar Radiation Spectrum

Visible light has a wavelength of between 0.40 to 0.71 micrometers (μm). The sun emits only a portion (44%) of its radiation in this range. Solar radiation spans a spectrum from approximately 0.1 to 4.0 micrometers. About 7% of the sun's emission is in 0.1 to 0.4 micrometers wavelength band (UV). About 48% of the sun's radiation falls in the region between 0.71 to 4.0 micrometers (near infrared : 0.71 to 1.5 micrometers; far infrared: 1.5 to 4.0 micrometers).



Solar radiation incident outside the earth's atmosphere is called extraterrestrial radiation. On average the extraterrestrial irradiance is 1367 W/m².

XTR ...

- **The extraterrestrial irradiance incident on a horizontal plane at an arbitrary angle of incidence is also of interest and is given by,**

$$G_o = G_{on} \cos(\theta_z)$$

- **where θ_z is the zenith angle, the angle between the sun and the vertical line from a point on the surface of the earth.**

TR

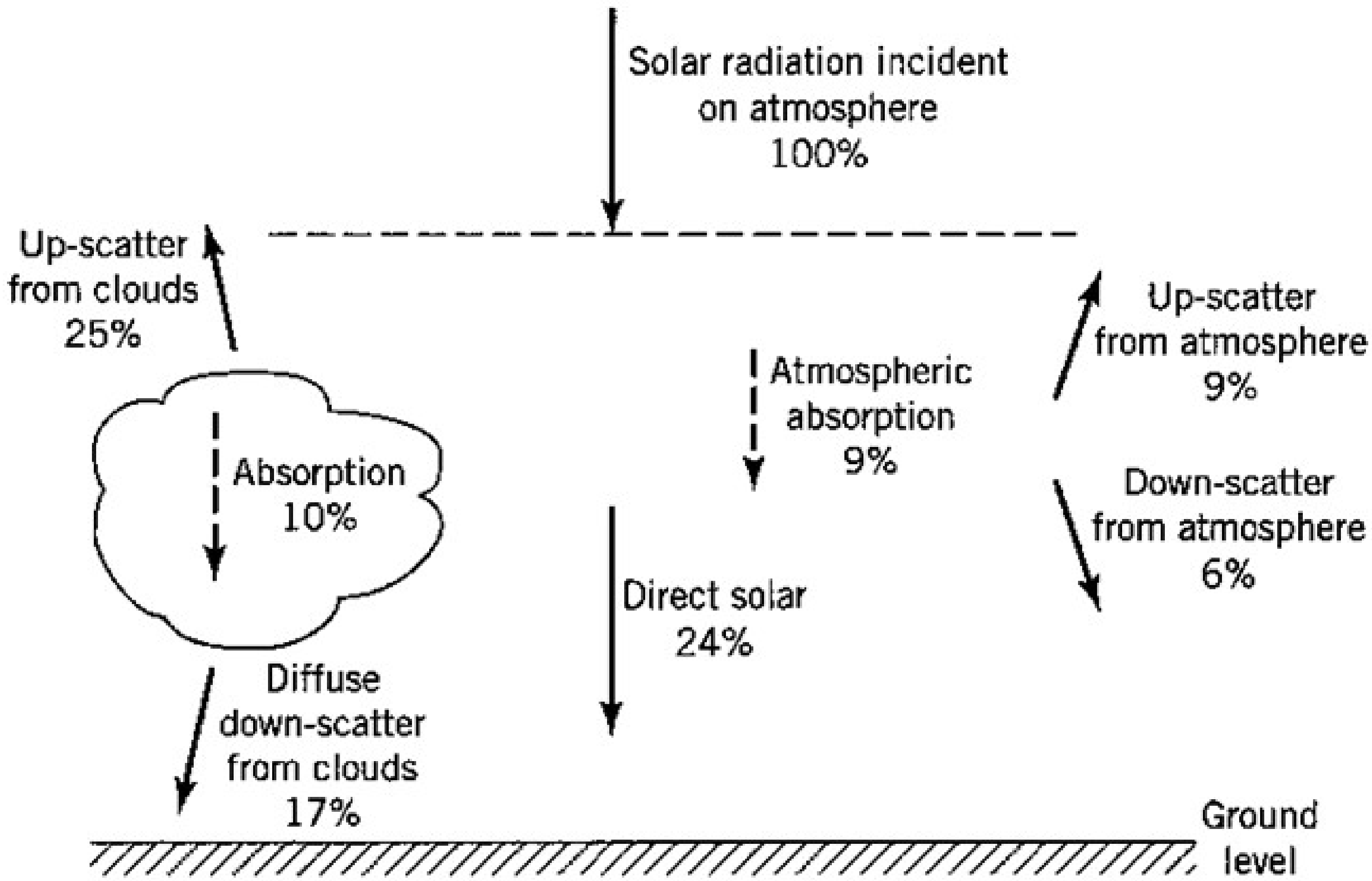
- **When the extraterrestrial radiation enters the earth's atmosphere, part of the incident energy is removed by scattering and absorption by several elements, aerosols, water vapour, ozone, clouds, etc.**
- **The extent of energy removal depends upon the thickness of the atmosphere and the term air mass is introduced to represent the relative thickness.**
- **By definition, an air mass is the path traversed by the radiation expressed as multiples of the path traversed at sea level with the sun directly overhead.**

TR Components

Sunlight reaching the Earth's surface unmodified by any of the atmospheric processes is termed direct solar radiation. Solar radiation that reaches the Earth's surface after it was altered by the process of scattering is called diffused solar radiation. Not all of the direct and diffused radiation is available at the Earth's surface. Some of the radiation received at the Earth's surface is redirected back to space by reflection.

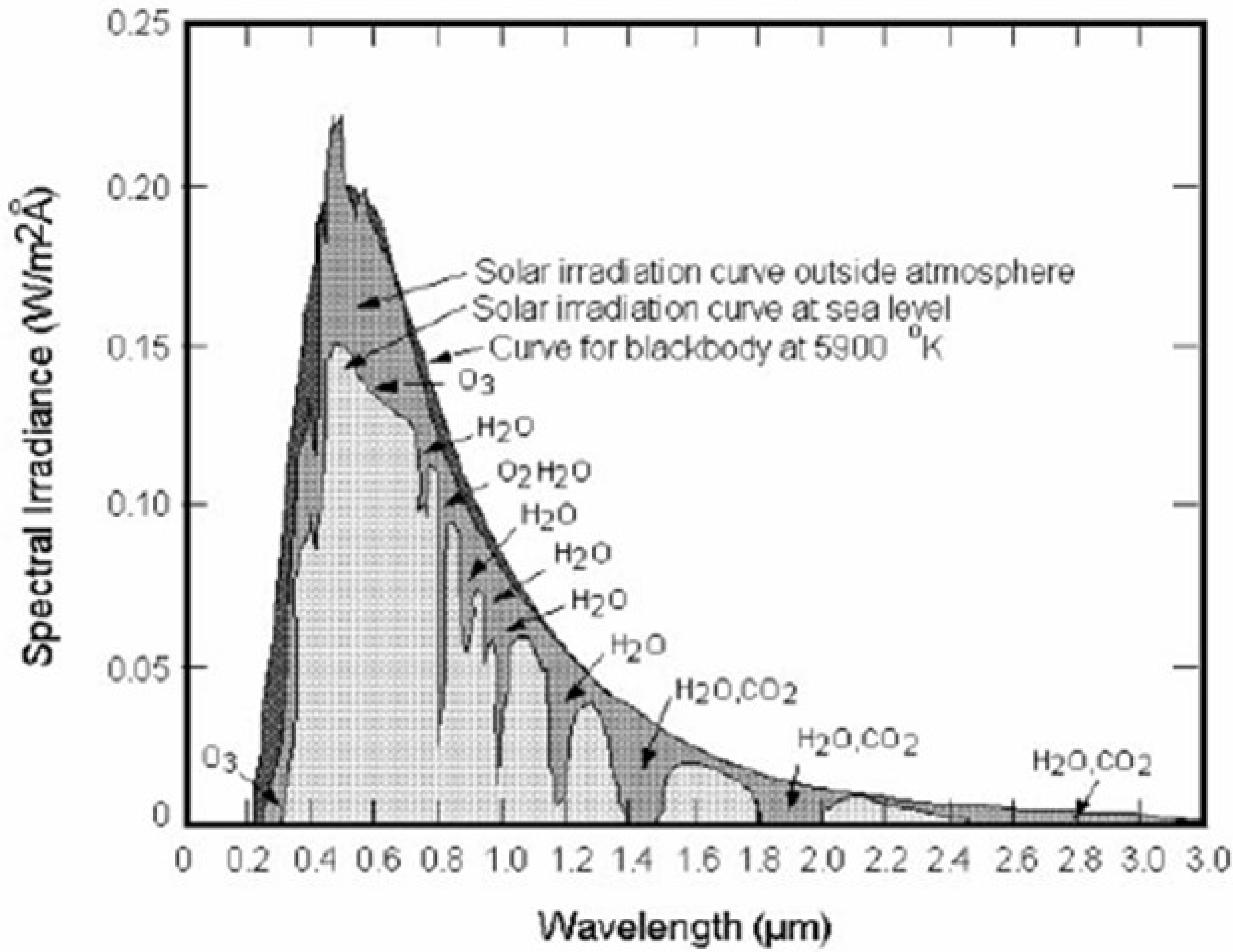
Of all the sunlight that passes through the atmosphere annually, only 51 % is available at the Earth's surface; to heat the Earth's surface and lower atmosphere, evaporate water, and run photosynthesis in plants. Of the other 49 %, 4 % is reflected back to space by the Earth's surface, 26 % is scattered or reflected to space by clouds and atmospheric particles, and 19 % is absorbed by atmospheric gases, particles, and clouds.

TR Components …

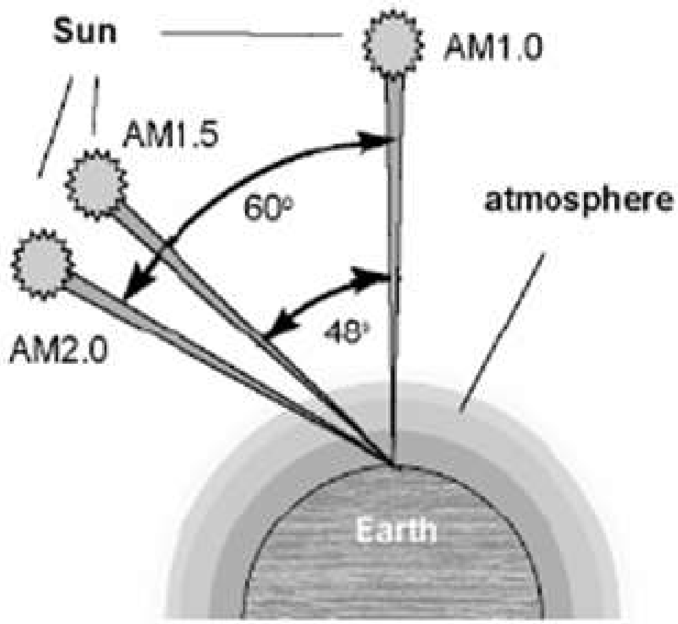


Absorption and scattering of solar radiation in the atmosphere. The values shown are for average weather, and are averaged over all seasons and latitudes.

XTR and TR Spectra



Air Mass, Measure of Thickness



The path length of the solar radiation through the Earth's atmosphere in units of Air Mass (*AM*) increases with the angle from the zenith. The AM 1.5 spectrum is the preferred standard spectrum for solar cell efficiency measurements.

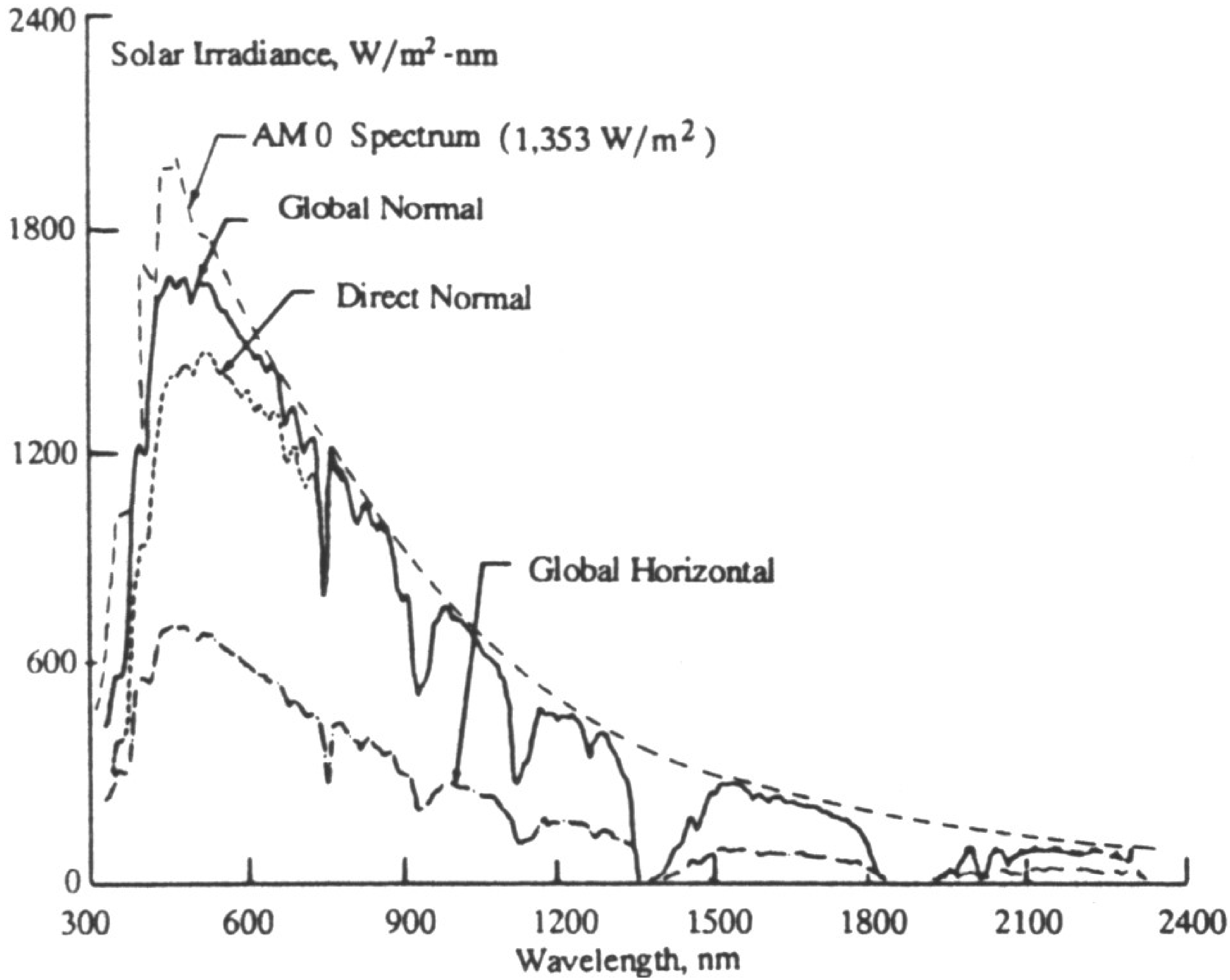
The easiest way to estimate the air mass in practice is to measure the length of the shadow *s* cast by a vertical structure of height *h* using

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

Air Mass *AM*: The ratio of the mass of atmosphere through which beam radiation passes to the mass it would pass through if the sun were at zenith (directly overhead).

At sea level, AM =1 when the sun is at zenith; *AM* = 2 for a zenith angle θ_z of 60°.

For $0 < \theta_z < 70°$ AM= $1/\cos\theta_z$



Solar Irradiance, W/m² -nm
AM 0 Spectrum (1,353 W/m²)
Global Normal
Direct Normal
Global Horizontal
2400
1800
1200
600
0
300
600
900
1200
1500
1800
2100
2400
Wavelength, nm

Estimation of Air Mass …

- **The Air Mass is also given by:**

$$AM_n = \sec(\theta_z)$$

where θ_z = sec-1(n) and AM_0 denotes the extraterrestrial path. AM_1 is the path at sea level with sun in its zenith position, AM_2 the path corresponding to zenith angle of 60^0, and so on. .

Solar Geometry

- A model of any solar radiation based system begins with evaluation of a series of geometrical factors that deal with the complex nature of diffuse and reflected radiation.
- The most important factors are the position of the sun in the sky, the slope and orientation of a collecting surface, and obstruction and reflection properties of neighbouring structures.

Solar Altitude and Azimuth

- Location of the sun in the sky, relative to a point on the ground, can be defined in terms of two angles, the **solar altitude** α_s (or its complement the solar zenith angle, θ_z) and the **solar azimuth** γ_s.
- At a given point on earth, the solar altitude is the angle between the line passing through the point and the sun and the line passing through the point tangent to the earth and passing below the sun. Solar azimuth is the angle between the line under the sun and the local meridian pointing to the equator.

Solar Geometry …

- **Solar altitude and solar azimuth angles are then given by the next equations.**

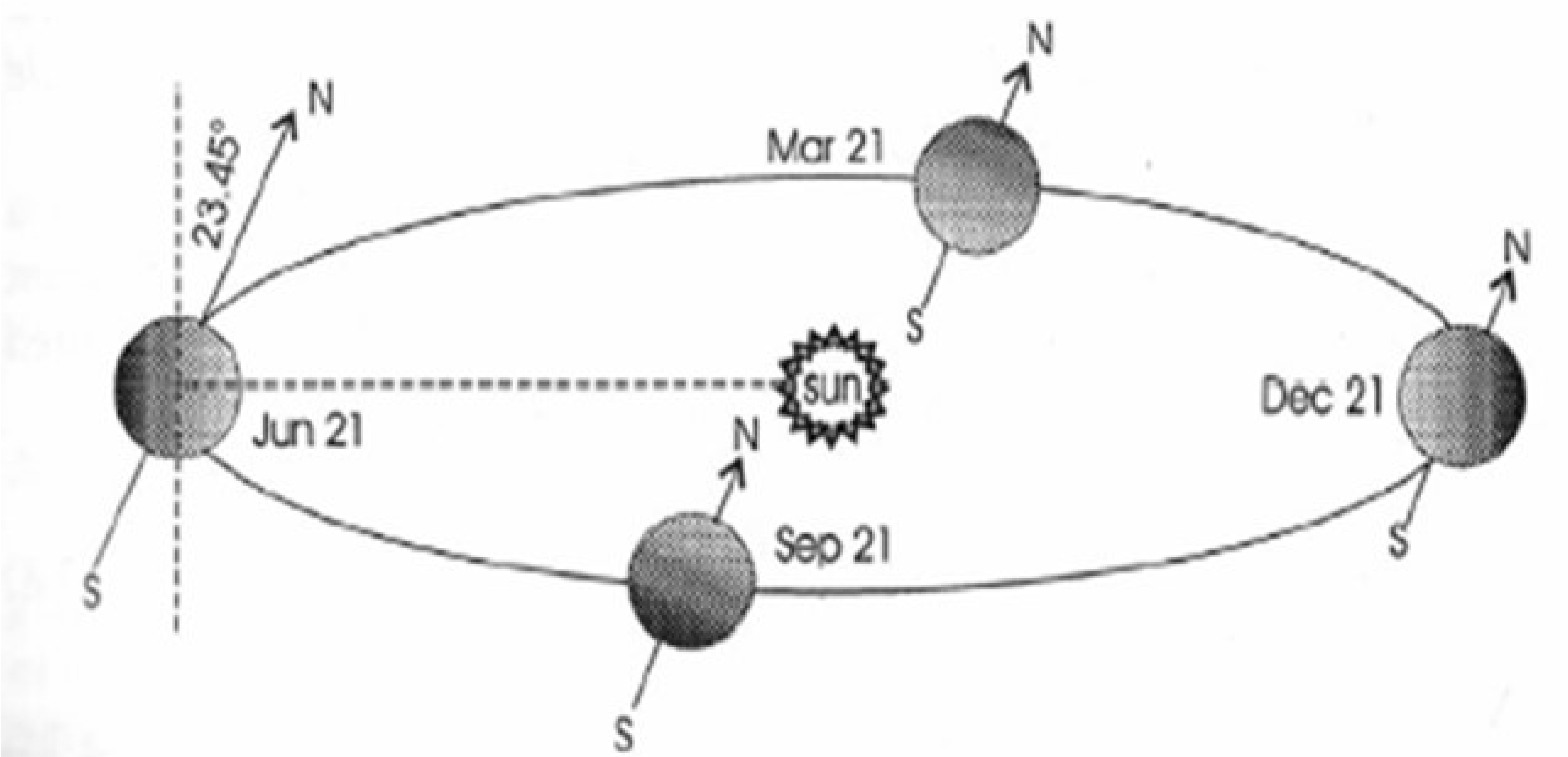
$$\sin(\alpha_s) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(\omega)$$

$$\sin(\gamma_s) = \frac{\cos(\delta)\sin(\omega)}{\cos(\alpha_s)}$$

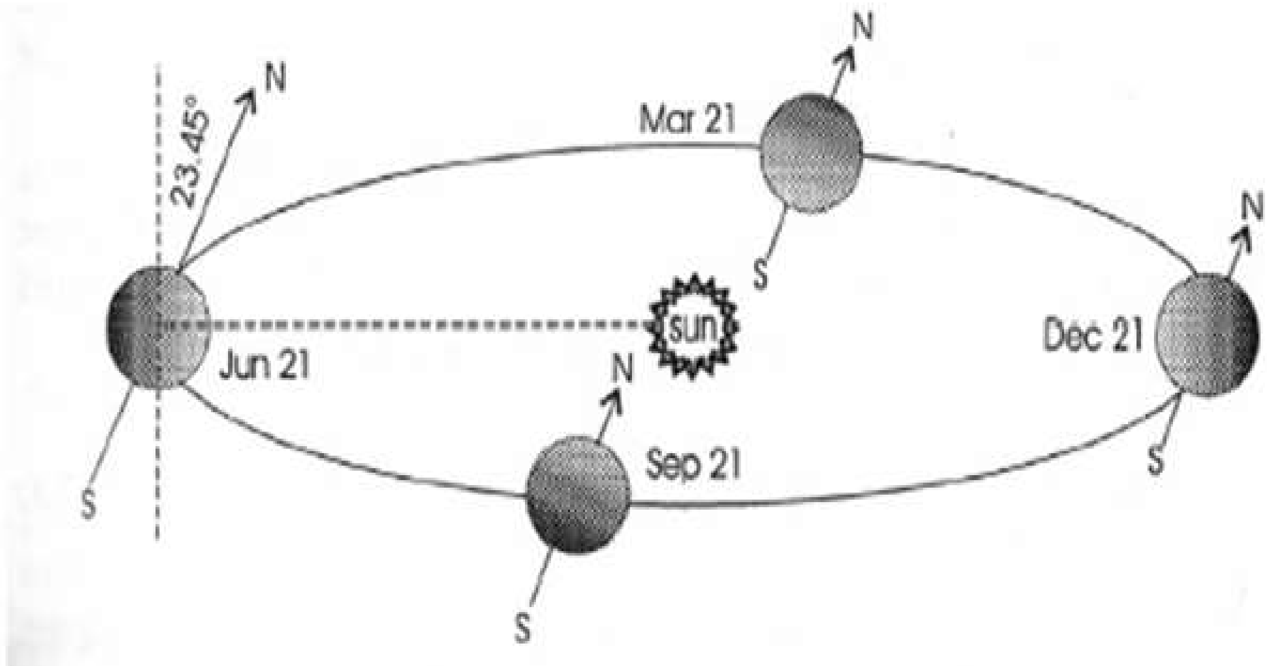
Latitude and Declination Angle

- The solar altitude angle and the solar azimuth angle are functions of the location on the earth, the time of the year, and the day.
- The location is specified by the **latitude ϕ,** which is zero at the equator, conventionally positive to the north and negative to the south.
- The time of the year is represented by the **solar declination angle δ**, which is defined as the angle between the earth's equatorial plane and the earth sun line.

Declination Angle



Solstice and Equinox Days



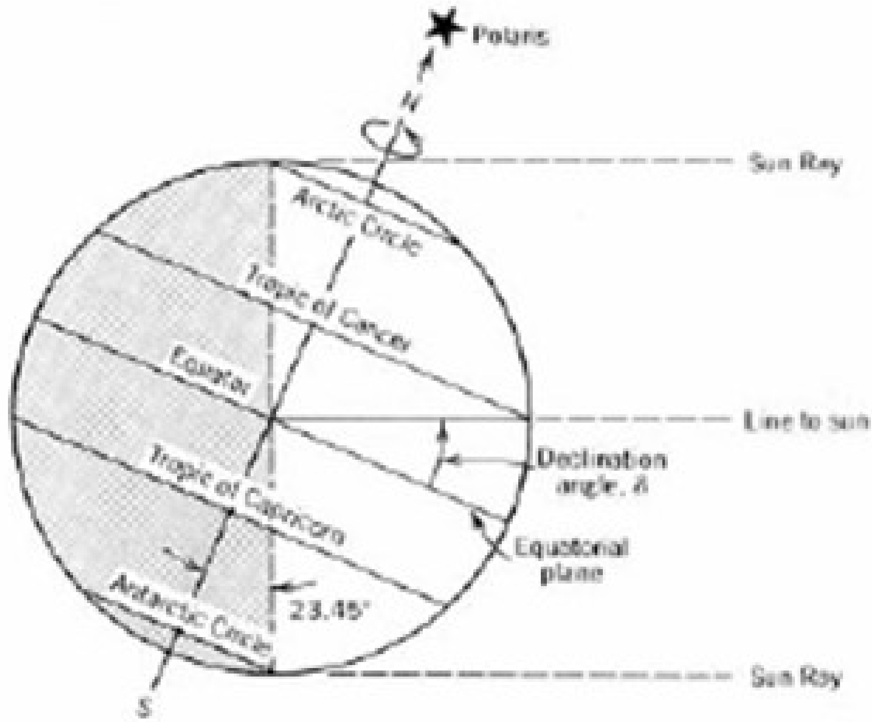
At about June 21, we observe that the noontime time sun is at its highest point in the sky and the declination angle (δ) = +23.45°. We call this condition *summer solstice* and it marks the beginning of Summer in the northern hemisphere. The *winter solstice* occurs on about December 22 - the northern hemisphere is tilted away from the sun. The noontime sun at its lowest point in the sky, i.e the declination angle (δ) = -23.45°. In between, on about September 23 (autumnal equinox) and March 22 (vernal equinox) , the line from the earth to the sun lies on the equatorial plane and δ = 0°

Declination Angle

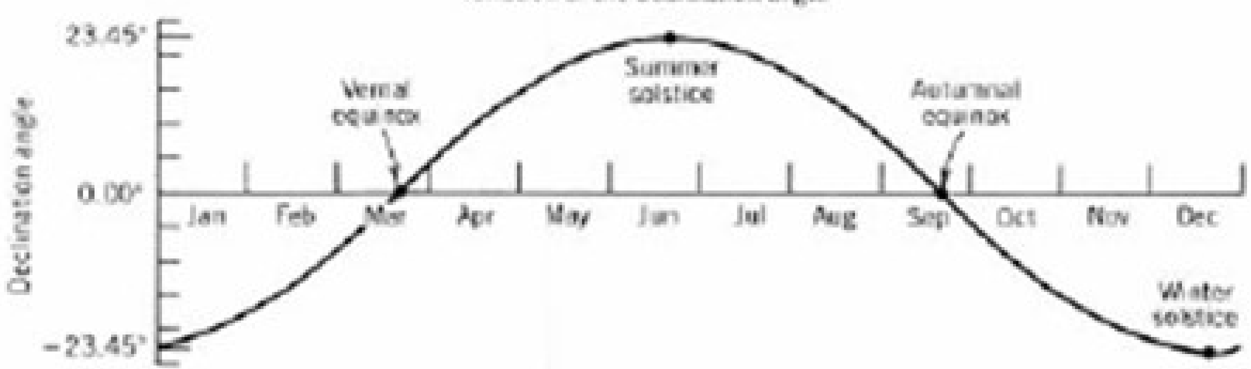
- Because of the earth's elliptic orbit around the sun and the variation in the sun-earth distance, the solar declination angle varies from positive 23.45^0 north equator on the 21st June to negative 23.45^0 south of equator on the 21st December. The simplest approximation is given by,

$$\delta = 23.45 \sin\left(2\pi \frac{284 + m}{365.25}\right)$$

where m is the number of the day in the year as defined earlier.



Variation of the declination angle



$$\delta = (0.006918 - 0.399912\cos b + 0.070257\sin b - 0.006758\cos 2b + 0.000907\sin 2b - 0.002697\cos 3b + 0.00148\sin 3b) * (180/\pi).$$

Hour Angle

- **The time of the day is expressed in terms of the hour angle, w. It is taken to be zero at local solar noon, increases by 15^0 for each hour before local solar noon and decreases at the same rate after solar noon.**

$$\omega = (12 - t_L)15^0$$

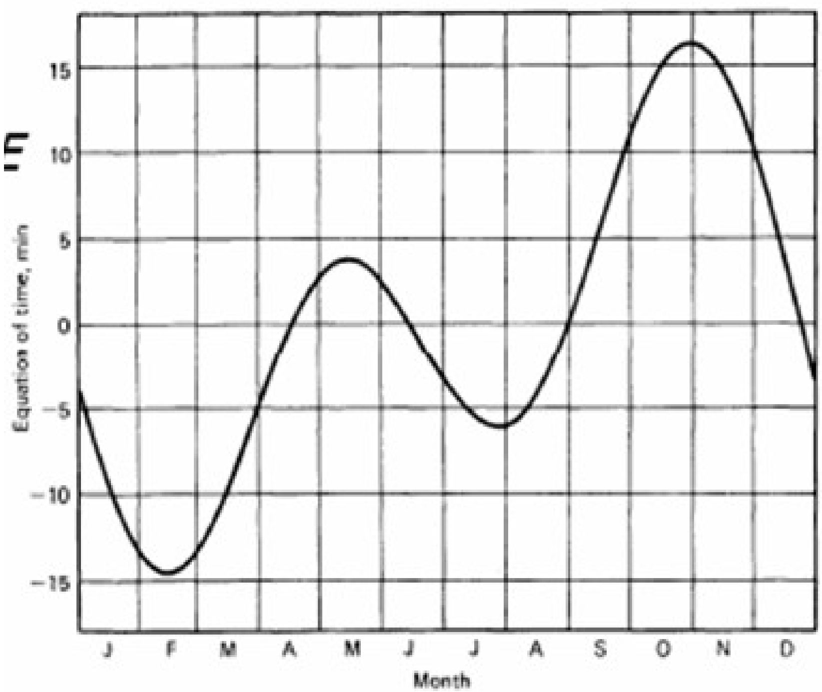
where t_L is the local solar time in hours.

Solar Time & Equation of Time

Time based on the apparent angular motion of the sun across sky, with solar noon the time the sun crosses the meridian of the observer.

$$\text{Solar time - standard time} = 4(L_{st} - L_{loc}) + E$$

Where L_{st} is the standard meridian for local time zone. L_{loc} is the longitude of the location in question in degrees west. The time E is determined from the following figure.



Tallahassee, FL
Latitude: 30.438N
Longitude: 84.28W
Time zone: Eastern Daylight Saving

$$E = 229.2(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B)$$

$$B = (n-1)\frac{360}{365}$$

Where n is the day of the year

Sun Set Angle and Day Length

- The **sunrise (sunset) angle** and the day length can be determined using the previous equation under the condition $\alpha s = 0$. The result is,

$$\omega_s = \cos^{-1}(-\tan(\phi)\tan(\delta))$$

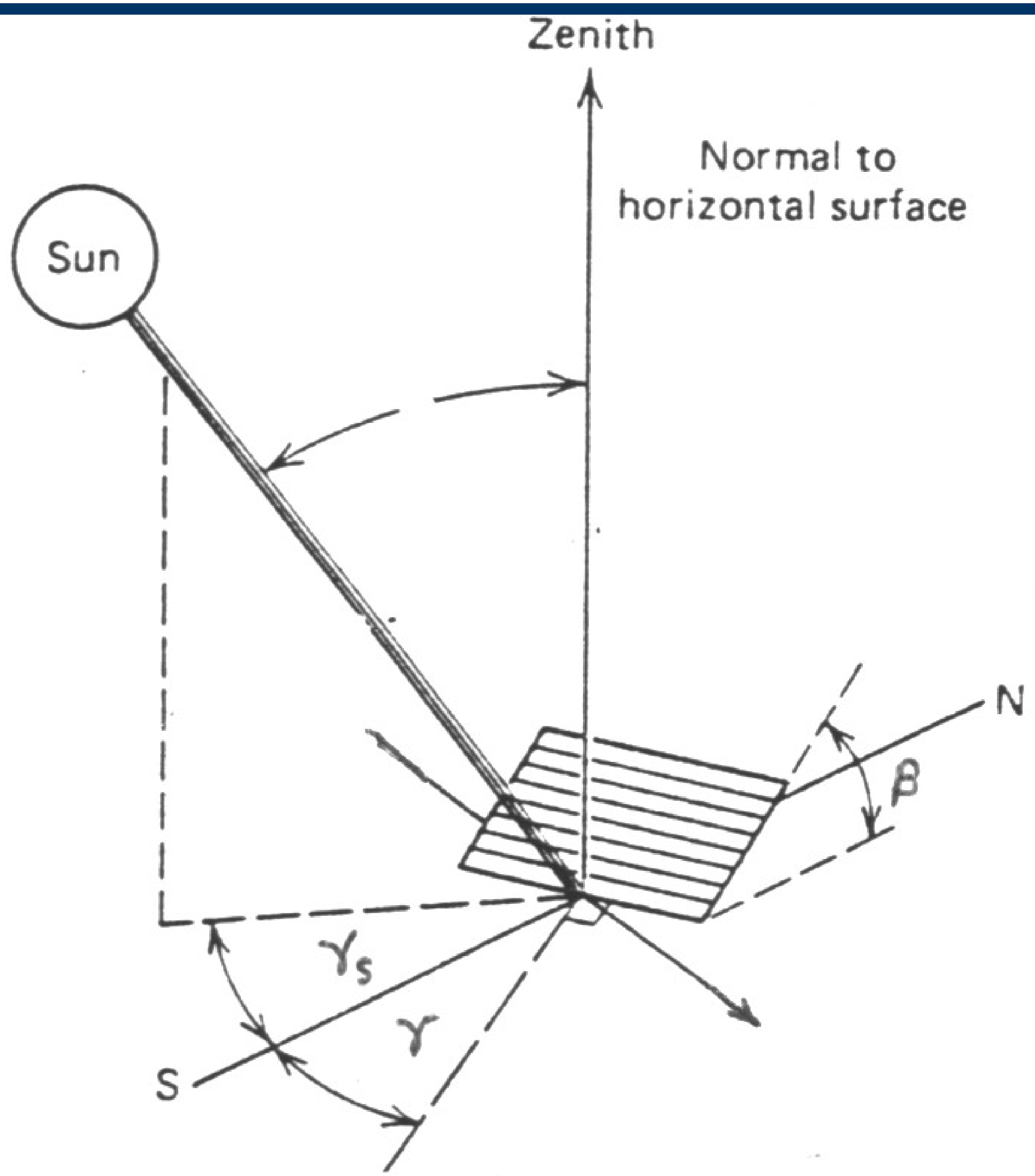
$$N_d = \frac{2\omega_s}{15}$$

Collector Surface Angles

- The orientation of the collector surface is defined by its **azimuth γ** measured from the local meridian toward the equator (positive to the east and negative to the west) and a **tilt angle β** measured relative to the horizontal as shown in the figure.

- The **angle of incidence θ_i**, which is the angle between the normal to the collector surface and the beam radiation, is computed by the equation.

Collector Angles



Collector Incidence Angle

$$\cos(\theta_i) = \sin(\delta)\sin(\phi)\cos(\beta) - \sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma)$$
$$+\cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega)$$
$$+\cos(\delta)\sin(\phi)\sin(\beta)\cos(\gamma)\cos(\omega)$$
$$+\cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega)$$

- **The expression can be simplified for specific conditions. For instance, for a collector surface facing to the equator γ is zero so that,**

$$\cos(\theta_i)=\sin(\delta)\sin(\phi)\cos(\beta)-\sin(\delta)\cos(\phi)\sin(\beta)$$
$$+\cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega)$$
$$+\cos(\delta)\sin(\phi)\sin(\beta)\cos(\omega)$$

- **which can further be simplified to,**

$$\cos(\theta_i)=\cos(\delta)\cos(\phi-\beta)\cos(\omega)+\sin(\delta)\sin(\phi-\beta)$$

- **For a vertical collector ($\beta=90^0$) facing the equator the expression will even become simpler:**

$$\cos(\theta_i)=\cos(\delta)\sin(\phi)\cos(\omega)-\sin(\delta)\cos(\phi)$$

- **The expression for horizontal surface will result in the expression identical to that of zenith angle, which effectively means the angle of incidence is exactly the zenith angle.**
- **All of the above equations will be very useful for computation of the various components of the incident radiation on a solar collector be it a PV panel or thermal collector.**

Solar Energy Measurement

- The annual, monthly, daily and hourly records of the solar radiation received at any given location over the earth's surface are essential for the design of solar energy systems. Therefore, solar radiation measurements are made continuously at many monitoring stations.
- Measurements mainly include, direct component at normal incidence, diffuse component at a horizontal surface, global radiation on a horizontal surface.
- Additional variables such as total radiation on an inclined surface, ground reflected radiation, and spectral distribution over certain wavelength bands can be estimated using constants and empirical relationships.

Pyranometers

- Pyranometers are used to measure the global (total) radiation, incident on a horizontal surface from the entire sky. They can also measure the diffuse component if covered by an appropriate shade band.

Pyranometers

- The operation of pyranometer is based on measurement of temperature difference between black and white elements using a thermopile. Low cost, low sensitivity to tilt and temperature, pyranometers are built with silicon photovoltaic cell.

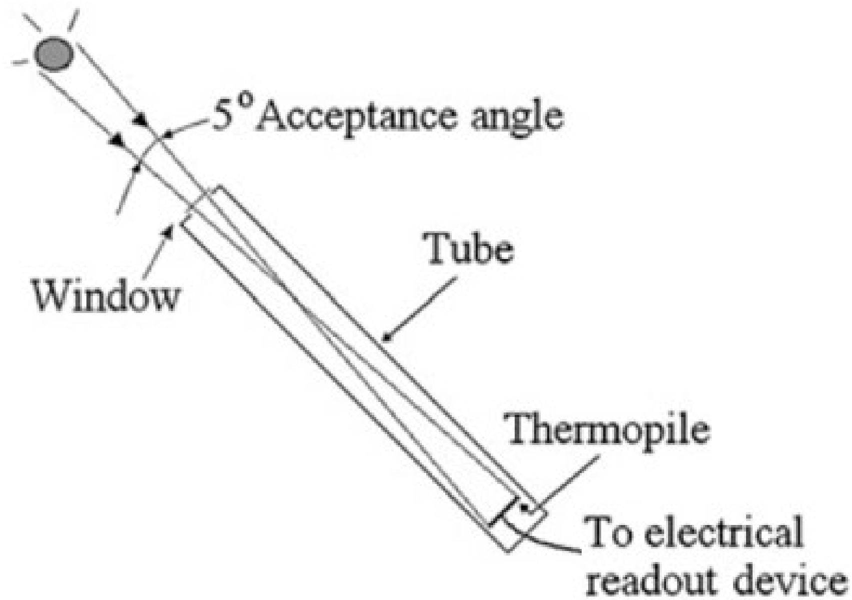
Pyrheliometers

- Pyrheliometers measure the intensity of the direct solar radiation at normal incidence. Most pyrheliometers used for routine measurements operate on the thermopile effect so are similar to pyranometers in this respect.

- Pyrheliometers differ from pyranometers in that they must mechanically follow (track) the sun to measure the direct sunlight only and avoid the diffuse component.

Pyrheliometer…

- In practice, direct solar radiation is measured by attaching the pyrheliometer to an electrically driven equatorial mount for tracking the sun. The diffuse component is avoided by installing a collimator tube over the sensor with a circular cone angle of about 50.

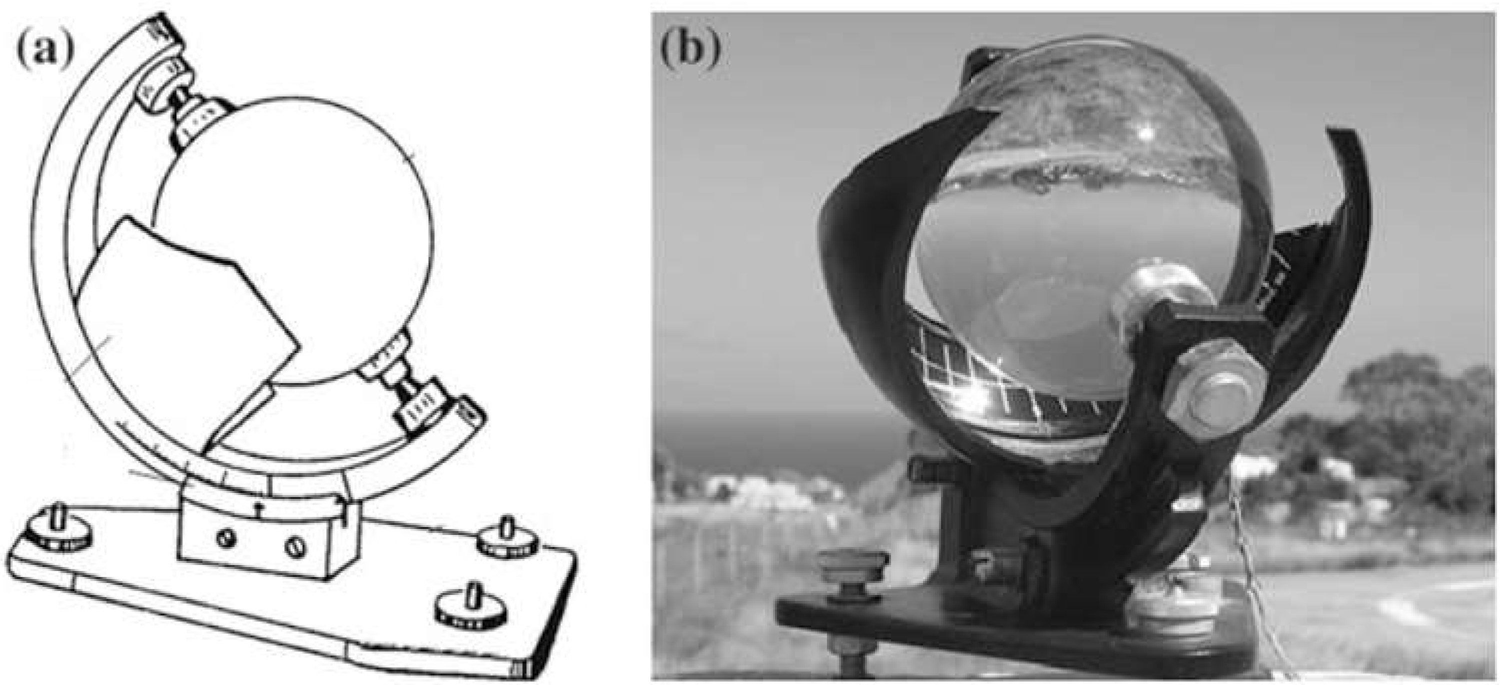


Sunshine Recorders

- Apart from the direct solar radiation records, there may be records of bright sunshine hours and approximate cloud cover for the location under interest.
- Sunshine recorders are devices that measure hours of bright sunshine, not energy. These devices are sensitive only to the direct component of solar radiation when it is above some imprecise threshold.

Sunshine Recorders …

- The Campbell sunshine recorder is the classic recorder widely used throughout the world.



a Schematic **b** Photo of a typical Campbell-Stokes sunshine recorder

Modern Weather Data Logging

Modern Weather Data Logging …

Anemometer

Temperature/Relative humidity sensor with radiant shield

Pyranometer

Datalogger with remote data transmission device (GSM/GPRS modem)

Indipendent power supply system

Solar Energy Estimation

- Since measurements of radiation components requires expensive equipment that is costly to operate as well as maintain, reliable measurements are undertaken at only a limited number of stations. Empirical formulas are therefore required for estimation of radiation, for locations at which insufficient or no measurements are available.
- Various climatological parameters such as humidity, temperature, rainfall, number of sunshine hours and total amount of cloud coverage have been used in developing empirical relations as substitutes for the direct measurement.

Solar Energy Estimation …

- It is also necessary to predict both the demand and the likely solar energy available, together with their variability before installing a solar energy system. Knowing this and the projected pattern of energy usage from the device, it is possible to calculate the size of collector and storage.
- Ideally, the data required to predict the solar input are several years of measurements of irradiance on the proposed collector plane. These are very rarely available, so the required (statistical) measures have to be estimated from meteorological data available.

Solar Energy Estimation …

- The meteorological data can be obtained either (i) from the site, or (ii) (more likely) from some ‘nearby’ site having similar irradiance, or (iii) (most likely) from an official solar atlas or database. All such data have systematic error and uncertainty, and natural climatic variability

Solar Energy Estimation …

Three basic problems can be clearly identified as most relevant when estimation radiation components arriving on a collector surface:

1. evaluation of the global radiation from other meteorological variables such as percent sunshine hours, extent of cloud cover, relative humidity, etc.
2. conversion of daily radiation components into hourly values.
3. conversion of the horizontal components of the radiation into equivalent inclined components.

Solar Energy Estimation …

The original Angstrom type equation relates the mean global irradiation to clear day irradiation and mean fraction of possible sunshine hours: conversion of daily radiation components into hourly values.

$$H_g = H_g^c \left(a_0 + b_0 \frac{n}{N} \right)$$

Where

- H_g is monthly average daily global irradiation,
- Hgc is clear day global irradiation for the same period
- n is monthly average daily bright sunshine hours,
- N is the maximum daily hours of bright sunshine
- a, b are regression constants.

Solar Energy Estimation …

As noted earlier, the proportion of incoming radiation that is focusable (beam component) depends on the cloudiness and dustiness of the atmosphere. These factors can be measured by the clearness index KT, which is the ratio of radiation received on a horizontal surface in a period (usually one day) to the radiation that would have been received on a parallel extraterrestrial surface in the same period:

$$K_{\mathrm{T}} = H_{\mathrm{h}} / H_{\mathrm{oh}}$$

Solar Energy Estimation …

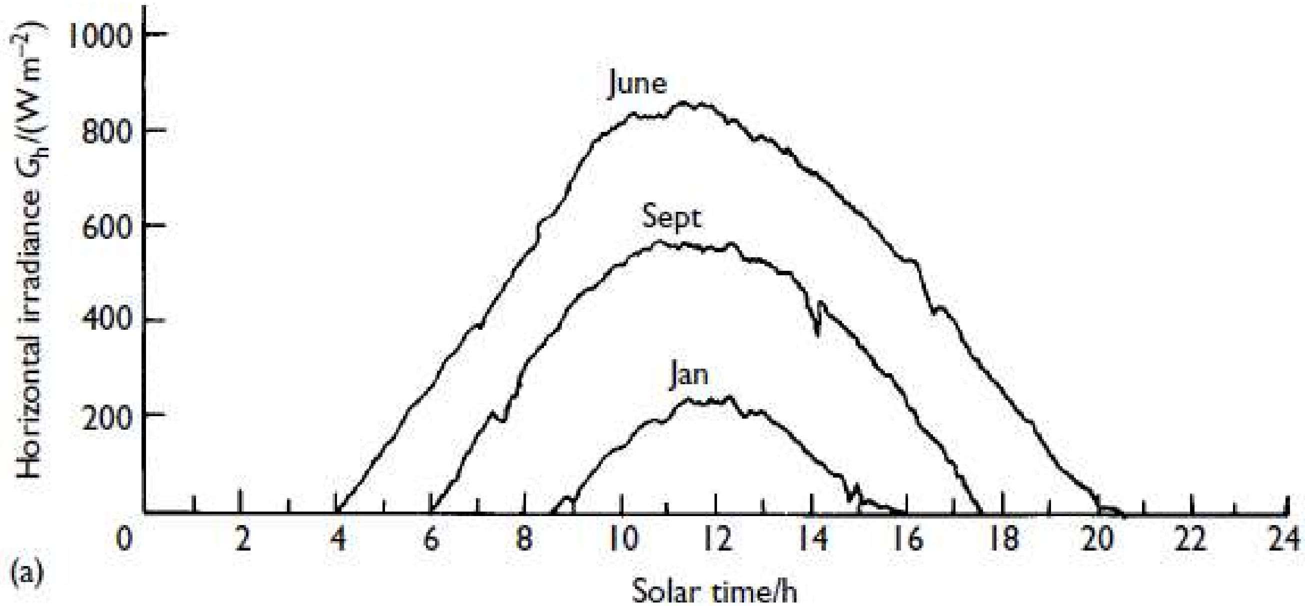
A clear day may have air-mass-ratio $m = 1$ and therefore $K_T \approx 0.8$. For such days the diffuse fraction is about 0.2; it increases to 1.0 on completely overcast days $K_T = 0$. On a sunny day with significant aerosol or thin cloud, the diffuse fraction can be as large as 0.5.

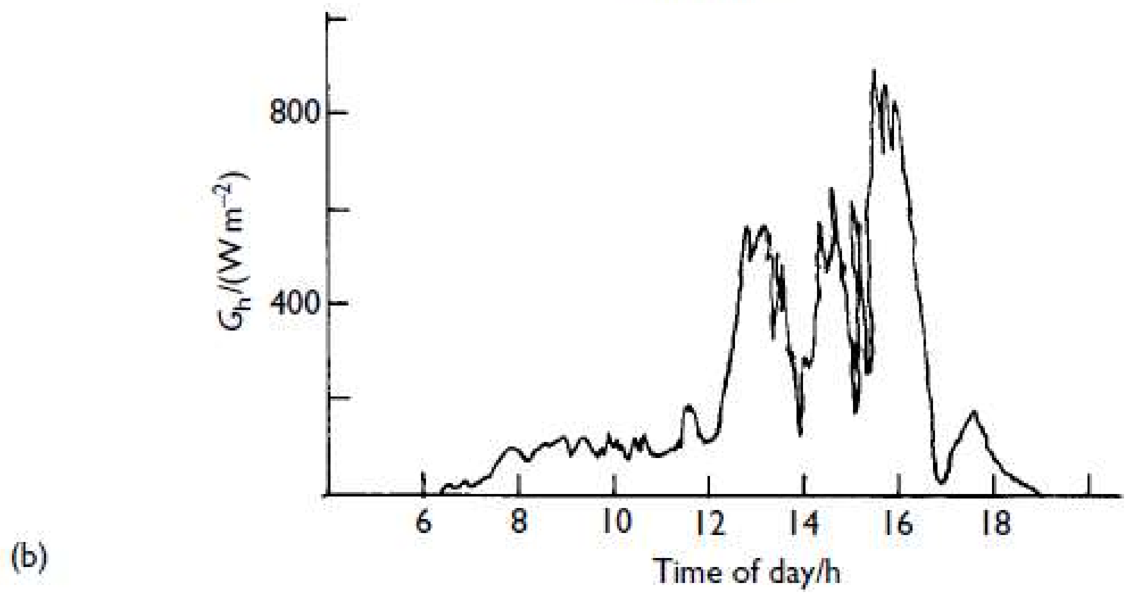
Hourly Radiation Data

- Radiation data on hourly basis may be estimated from daily records although such computation may not be accurate and may even be completely misleading. The reason is that different combinations of cloudy periods and sunny hours may result in the same daily total radiation.
- The hourly solar radiation on a horizontal surface is found to be dependent on the sunset hour angle. The ratio of hourly total to daily total is given by the following relation:

$$\frac{I_g}{H_g}=\frac{\pi}{24}[A+B\cos(\omega)]\frac{\cos(\omega)-\cos(\omega_s)}{\sin(\omega_s)-\frac{\pi\omega_s}{180}\cos(\omega_s)}$$

Hourly Radiation Data …





Radiation on Inclined Surface

Once the horizontal components of radiation are determined, it would be easy to combine them to get the total radiation on the inclined surface using various types empirical formulas on the basis of different assumptions

The daily total irradiation on the inclined surface, the horizontal beam irradiation and horizontal diffuse irradiation (H_β, H_b and H_d , respectively) as well as the corresponding hourly valued (I_β, I_b and I_d) can be related a simple constant *Tb* or *tb:*

$$H_\beta = T_b \,(H_b + H_d)$$

$$I_\beta = t_b (I_b + I_d)$$

Radiation on Inclined Surface

The above approximation works well on clear days only but less useful for the general sky conditions. Another assumption is that the diffuse component is uniformly distributed over the sky. The diffuse radiation will then be independent of the collector orientation and the radiation on the inclined surface. Thus,

$$H_{\beta} = T_b \; H_b + H_d$$

$$I_{\beta} = t_b \; I_b + I_d$$

Solar Energy Estimation …

- An improvement on this model has been made by Liu and Jordan

$$H_{\beta} = T_b H_b + \frac{1+\cos(\beta)}{2} H_d + \frac{1-\cos(\beta)}{2} \rho (H_b + H_d)$$

$$I_{\beta} = t_b I_b + \frac{1+\cos(\beta)}{2} I_d + \frac{1-\cos(\beta)}{2} \rho (I_b + I_d)$$

- where ρ is the albedo (ground reflection) factor and B is the angle of inclination of the surface from the horizontal. The cosine factors are known as the view factors of the tilted surface to the sky and to the ground respectively. The model is called isotropic model and it results in better approximations

Hourly Radiation Data

- The tilt factor, can be determined for various orientations of the collector. The daily ratio T_b , or the hourly ratio t_b, of the beam component can be easily determined using the relations:

$$T_b = \frac{\cos(\phi - \beta)\cos(\delta)\sin(\omega_s) + \frac{\pi\omega_s}{180}\sin(\phi - \beta)\sin(\delta)}{\cos(\phi)\cos(\delta)\sin(\omega_s) + \frac{\pi\omega_s}{180}\sin(\phi)\sin(\delta)}$$

$$t_b = \frac{\cos(\phi - \beta)\cos(\delta)\cos(\omega_s) + \sin(\phi - \beta)\sin(\delta)}{\cos(\phi)\cos(\delta)\cos(\omega_s) + \sin(\phi)\sin(\delta)}$$

Summary

- Utilization of renewable energy resources is becoming more and more critical in view of environmental damage by the conventional fuels, rising cost of the limited fossil reserve, and political pressures.

- The major source of renewable energy is the solar radiation and detailed study of the characteristics of solar radiation including measurement and estimation on the horizontal as well as inclined surfaces is the starting point for study of application of renewable energy technologies,

Summary …

- Analysis and design of solar energy systems requires measurement data over sufficiently long period and/or estimation of various radiation components.
- Pyranometers, Pyrheiometers, and Sunshine Recorders are the basic measuring devices for the most important radiation components.
- In the absence of all or some measuring instruments, it is possible to use crude data available from satellite records or estimate radiation components using standard empirical formulas applicable to the location of interest.

Summary …

- Typical computations include total radiation on the inclined collector based on one or more radiation components (global, diffuse, beam).
- In addition to radiation calculations, analytical and computational methods can be used to solve heat transfer, and fluid mechanics equations to get a complete analysis of renewable energy systems.

End of Lecture