RENEWABLE ENERGY SYSTEMS

COURSE CODE: ME 4026D
SLOT: F

COURSE FACULTY: DR. ARUN P
ASSOCIATE PROFESSOR,
DEPARTMENT OF MECHANICAL ENGINEERING

COURSE OUTLINE

- Module 1: Energy Scenario, Role of renewables, Solar Energy and its applications
- Module 2: Wind energy conversion, Small hydro power, Ocean Thermal Energy Conversion, Geothermal energy
- Module 3: Biomass energy conversion, Economic analysis, Integrated energy systems

COURSE OUTCOMES

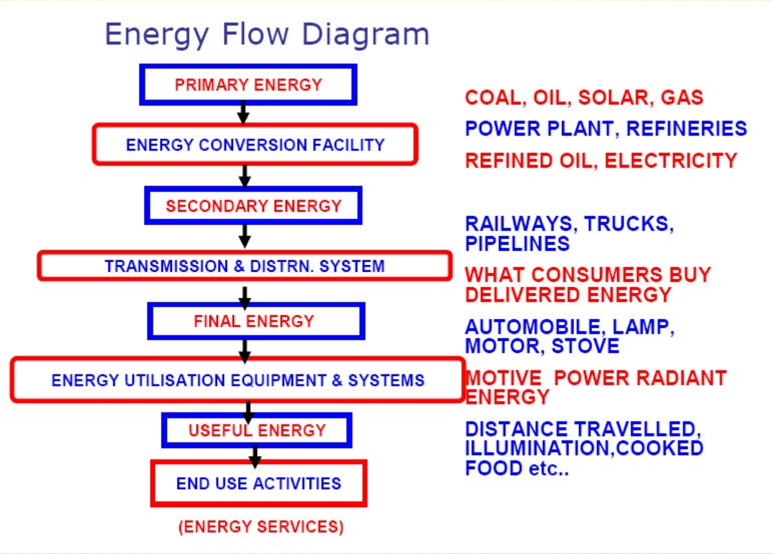
- CO1: Estimate the renewable energy potential for a specified location
- CO2: Illustrate the applications of various renewable energy systems
- CO3: Compute the energy conversion efficiencies of typical renewable energy systems
- CO4: Assess the techno-economic viability of representative renewable energy systems

REFERENCES

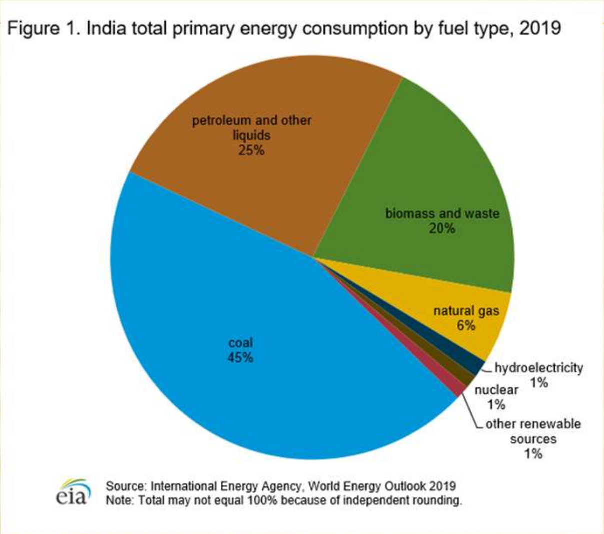
- Sukhatme, S.P., and Nayak, J.K., *Solar Energy-Principles of Thermal Collection and Storage*, 3rd ed., Tata McGraw Hill, 2008.
- Twidell, J. and Weir T., *Renewable Energy Resources*, 2nd ed., Taylor and Francis, 2006.
- Boyle, G. (Ed.), *Renewable Energy*, 2nd ed., Oxford University Press, 2004.
- Cengel, Y. and Cimbala J., *Fundamentals and Applications of Renewable Energy*, 1st ed., Tata McGraw Hill, 2020.

EVALUATION POLICY

- Mid-sem Test: 30 Marks
- Assignments: 20 Marks
- End Semester Exam: 50 Marks

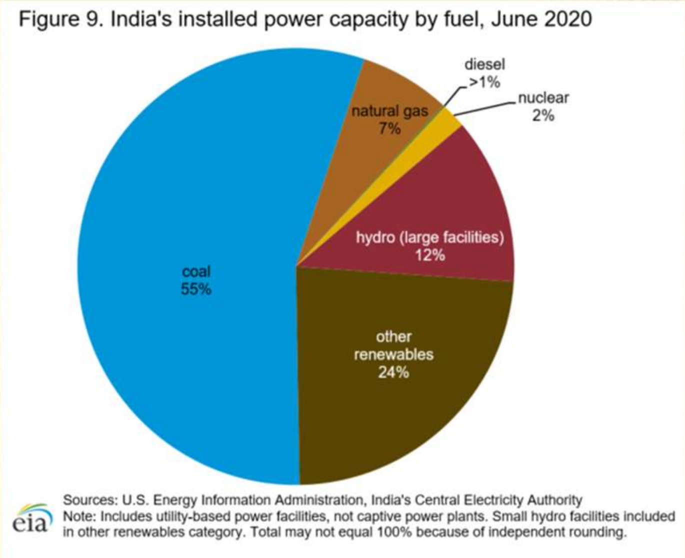


INDIA: PRIMARY ENERGY MIX



Renewable fuel sources make up a small portion of primary energy consumption, although the capacity potential is significant for several of these resources such as solar, wind, and hydroelectricity. .

INDIA: INSTALLED POWER CAPACITY



RENEWABLE ENERGY

- Renewable energy. ‘Energy obtained from natural and persistent flows of energy occurring in the immediate environment’
- An obvious example is solar (sunshine) energy, where ‘repetitive’ refers to the 24-hour major period
- The energy is already passing through the environment as a current or flow, irrespective of there being a device to intercept and harness this power
- Such energy may also be called Green Energy or Sustainable Energy

NON-RENEWABLE ENERGY

- Energy obtained from static stores of energy that remain underground unless released by human interaction
- Examples are nuclear fuels and fossil fuels of coal, oil and natural gas
- The energy is initially an isolated energy potential, external action is required to initiate the supply of energy for practical purposes

NEED FOR RENEWABLE ENERGY

- the finite nature of fossil and nuclear fuel materials
- the harm of emissions
- ecological sustainability
- promote self reliance and reduce foreign dependence

essential to expand renewable energy supplies and to use energy more efficiently

COMPARISON OF RENEWABLE AND CONVENTIONAL SOURCES

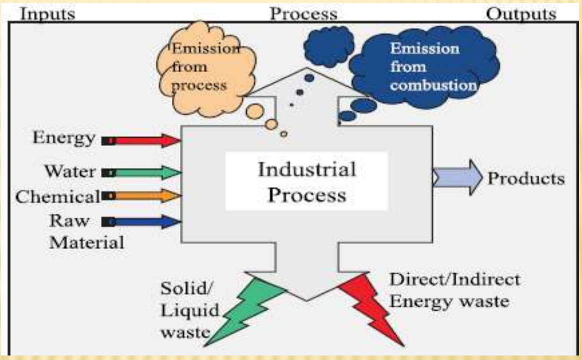
	Renewable	Conventional
Source	Natural local environment	Concentrated stock
Normal state	A current or flow	Static source
Intensity	Low and dispersed, <300 W/m^2	Released at > 100 kW/m^2
Lifetime of supply	Infinite	Finite
Variation and control	Fluctuating, best controlled by change of load	Steady, best controlled by adjusting source with feedback control
Environmental impact	Less	Pollution from resource extraction and utilization

RENEWABLE ENERGY BREAKUP IN POWER GENERATION

TYPE	CAPACITY (in GW)
Large Hydro	156
Small Hydro	9.4
Solar	50.1
Wind	64.6
Biomass	13.9
Other	0.4
TOTAL	294.4

As on 2019

ENERGY AND ENVIRONMENT



GLOBAL WARMING

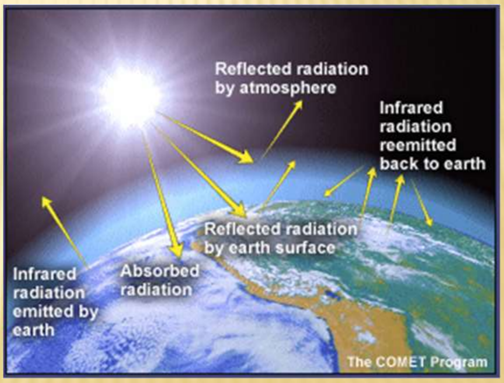
- ❖ Global warming is a significant increase in the Earth's climatic temperature over a relatively short period of time as a result of human activities
- ❖ An increase of 1 or more degrees Celsius in a period of one hundred to two hundred years would be considered global warming!
- ❖ The scientists determined that the Earth has warmed 0.6 degrees Celsius between 1901 and 2000.

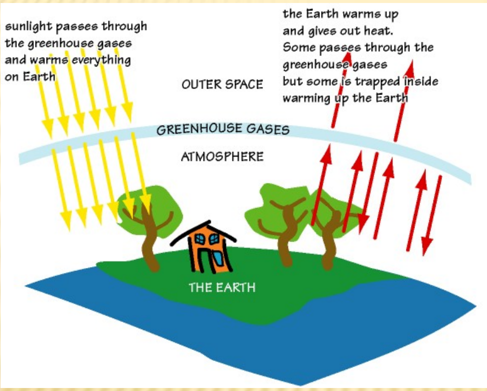
ENERGY AND SUSTAINABLE DEVELOPMENT

- Sustainable development can be broadly defined as living, producing and consuming in a manner that meets the needs of the present without compromising the ability of future generations to meet their own needs.

The Greenhouse Effect

- Sun's energy gets trapped in the troposphere
  - Some radiation that reaches Earth's surface is absorbed.
  - Some energy is reflected.





- Reflected heat might get trapped by carbon dioxide, water vapor, or other gases.
- Trapped heat makes atmosphere warmer.
- Warm atmosphere reflects heat to Earth's surface *again!*

Consider a simple numerical model:

- *R = EN*

R is the total yearly energy requirement for a population of N people

E is the per capita energy use

- *S = f E*

S is the per capita gross national product

$$R = \frac{(SN)}{f}$$

$$\frac{\Delta R}{R} = \frac{\Delta S}{S} + \frac{\Delta N}{N} - \frac{\Delta f}{f}$$

N: increase of approximately 2–3% per year

S: exponential growth at 2–5% per year

RENEWABLE ENERGY

- How much energy is available in the immediate environment – what is the resource?
- What technologies can harness these resources?
- How can the energy be used efficiently? What is the end use?
- What is the environmental impact of the technology? Is it sustainable?
- What is the cost-effectiveness of the energy supply as compared to other supplies?

PRINCIPLES OF RENEWABLE ENERGY

- Appropriate identification of energy currents
- Dynamic characteristics
- Quality of supply

RENEWABLE ENERGY SUPPLY

- Mechanical Supplies

- *Examples: hydro, wind, wave and tidal power*
- Usually transformed into electricity at high efficiency
- The proportion of power in the environment extracted: determined by the mechanics of the process and the variability of the source
- Wind: 35%, hydro 70–90%, wave 50% and tidal 75%.

Heat Supplies

- Examples: biomass combustion, solar collectors etc.
- The maximum proportion of energy extractable as mechanical work, and hence electricity, governed by the second law of thermodynamics and the Carnot Theorem
- Maximum mechanical power produced in a dynamic process is about half that predicted by the Carnot criteria

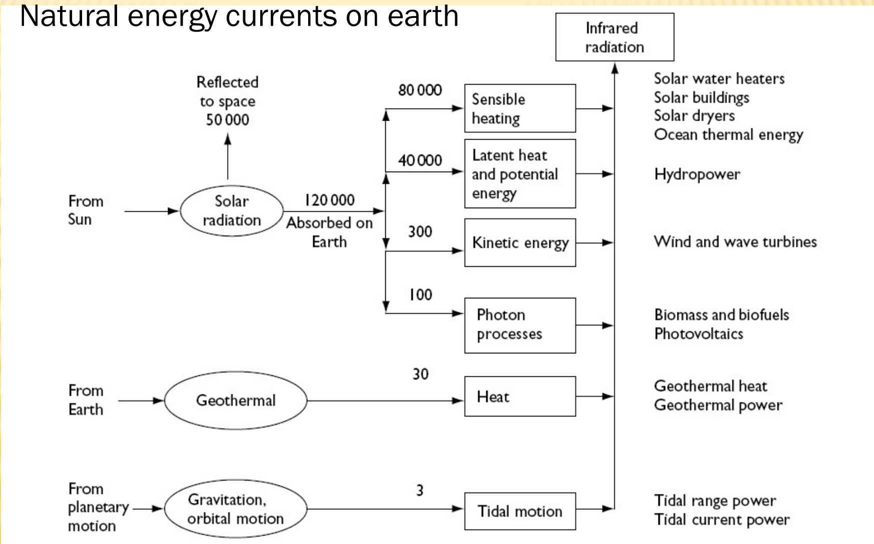
ENERGY SOURCES

- The Sun
- The motion and gravitational potential of the Sun, Moon and Earth
- Geothermal energy from cooling, chemical reactions and radioactive decay in the Earth
- Human-induced nuclear reactions
- Chemical reactions from mineral sources

Photon processes

- Photosynthesis and photovoltaic conversion
- Solar photons of a single frequency may be transformed into mechanical work via electricity using a solar cell

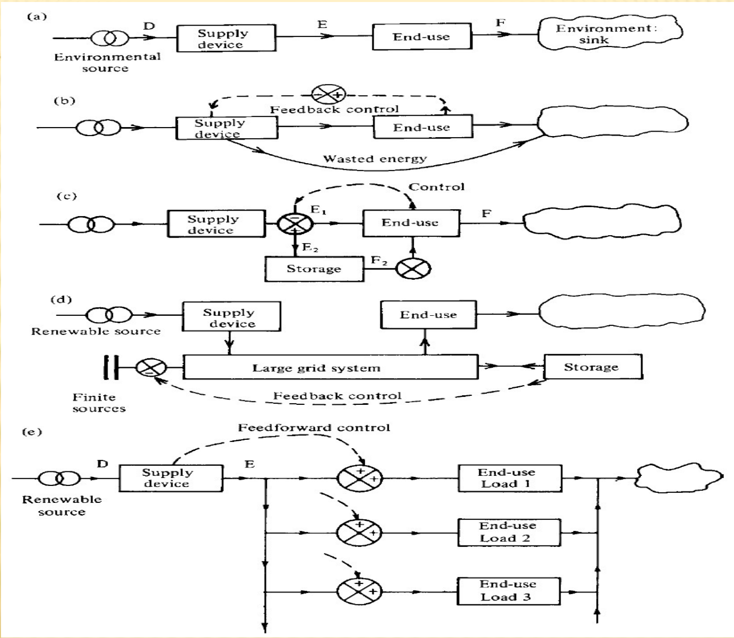
Natural energy currents on earth



Units: terawatts, 10^{12} W

TECHNICAL IMPLICATIONS

- Prospecting the environment
- End-use requirements and efficiency
- Matching supply and demand



ENERGY PLANNING

- Analysis of the complete energy systems
- System efficiency
- Energy management

COST EFFECTIVENESS

- Appreciating the *distinctive scientific principles of renewable energy*
- Making each stage of the energy supply process *efficient in terms of* both minimising losses and maximising economic, social and environmental benefits
- Like-for-like *comparisons, including externalities, with fossil fuel and* nuclear power

DISPERSED VERSUS CENTRALISED ENERGY

- Renewable energy commonly arrives at about 1 kWm^{-2}

Compared with:

- boiler tubes in gas furnaces easily transfer $100kWm^{-2}$
- in nuclear reactors, the first wall heat exchanger must transmit several MWm^{-2}
- *Finite energy is most easily produced centrally and is expensive to distribute.*
- *Renewable energy is most easily produced in dispersed locations and is expensive to concentrate*

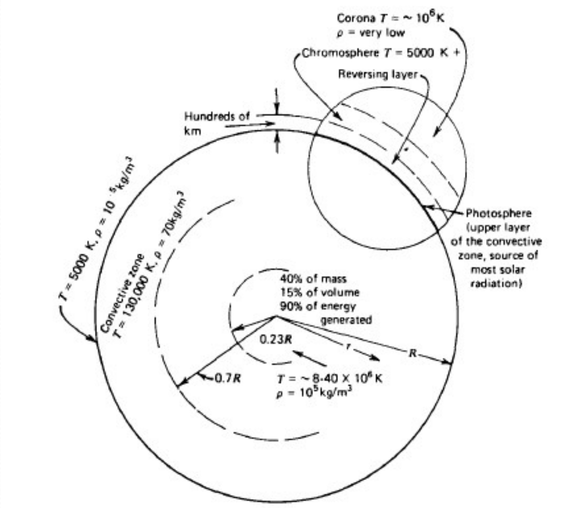
MEETING THE ENERGY DEMAND

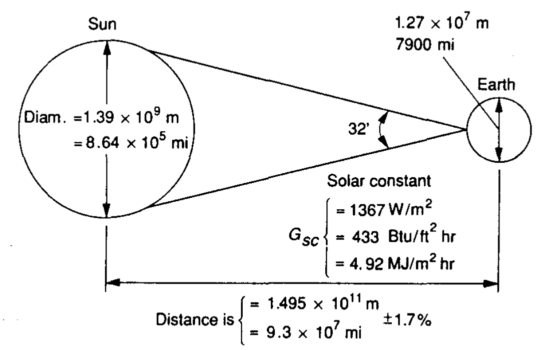
- India: peak demand shortage of around 14% and energy deficit: 8.4%
- Increased power generation capacity through conventional sources of energy
- Present energy systems: unsustainable
- Harnessing new and unexplored sources of energy

SOLAR ENERGY ESTIMATION

Solar Radiation

- Sun: A sphere of intensely hot gaseous matter with a diameter of 1.39×10^{9} m and is on the average at a distance of 1.5×10^{11} m from the earth





Radiation

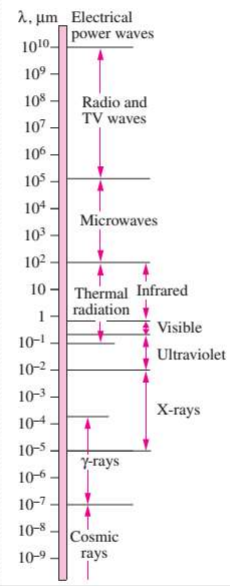
Electromagnetic waves transport energy just like other waves, and all electromagnetic waves travel at the *speed of light* in vacuum
2.9979 x 10^8 m/s.

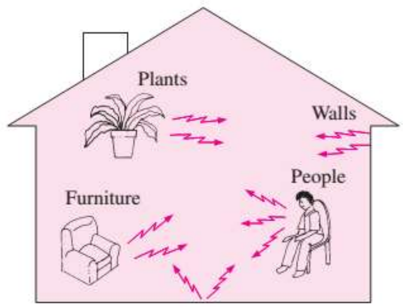
$$\lambda = \frac{c}{\nu}$$

$$e = h\nu = \frac{hc}{\lambda}$$

$$h = 6.6256 \times 10^{-34}\ \mathrm{J \cdot s}$$

Electromagnetic wave spectrum





Thermal radiation is also defined as the portion of the electromagnetic spectrum that extends from about 0.1 to 100 μm

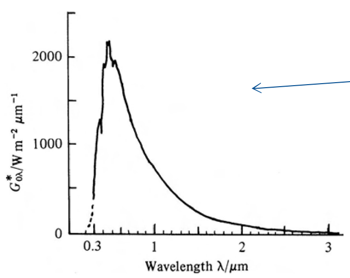
Thus, thermal radiation includes the entire visible and infrared (IR) radiation as well as a portion of the ultraviolet (UV) radiation

Light is simply the *visible* portion of the electromagnetic spectrum that lies between 0.40 and 0.76 μm

The electromagnetic radiation emitted by the sun is known as **solar radiation,** and nearly all of it falls into the wavelength band 0.3 to 3 μm

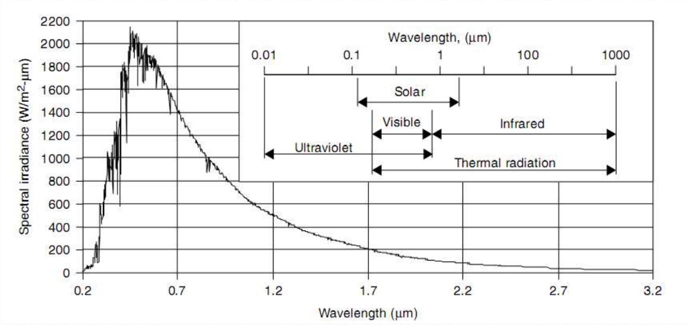
Extraterrestrial Solar radiation

The amount of solar energy per unit time, at the mean distance of the earth from the sun, received on a unit area of a surface normal to the sun (perpendicular to the direction of propagation of the radiation) outside the atmosphere is called the solar constant, G_{sc} (1367 W/m^2)



Black body radiation corresponding to 5800 K

▪ Solar radiation reaches the Earth's surface at a maximum flux density of about 1 kWm^{-2} in a wavelength band between 0.3 and 2.5 µm
▪ The radiant flux from the Sun at the Earth's distance varies through the year by ± 4%



Spectral distribution of the solar irradiance at the Earth's mean distance, uninfluenced by any atmosphere

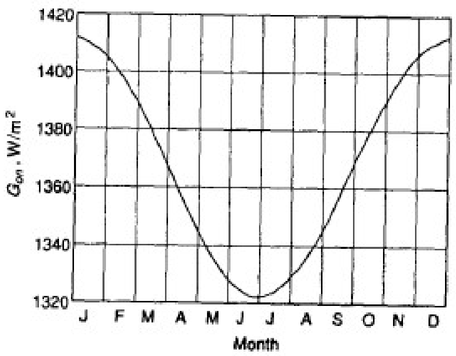
The solar spectrum:

The proportions as received at the Earth's surface with the Sun incident at about 45°

Ultraviolet region ($\lambda < 0.4\,\mu m$)	~5% of the irradiance
Visible region ($0.4\,\mu m < \lambda < 0.7\,\mu m$)	~43% of the irradiance
Infrared region ($\lambda > 0.7\,\mu m$)	~52% of the irradiance.

the range from 0.3 to 2.5 µm corresponds to photon energies of 4.1 - 0.50 eV.

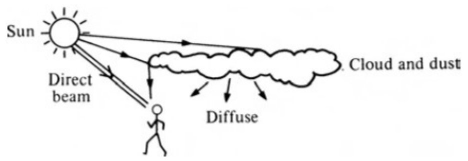
Variation of extraterrestrial solar radiation with time of the year



$$G_{on} = G_{sc}\left(1 + 0.033 \cos \frac{360\, n}{365}\right)$$

Definitions

- Air mass: The ratio of the mass of the atmosphere through which the beam radiation passes to the mass it would pass through if the sun were at the zenith (directly over head)
- Beam radiation (direct solar radiation): The solar radiation received from the sun without having been scattered by the atmosphere
- Diffuse radiation: The solar radiation received from the sun after its direction has been changed by scattering by the atmosphere



Definitions

- Total solar radiation (global radiation): The sum of the beam and diffuse solar radiation on a surface
- Irradiance: The rate at which incident energy is received on a surface, per unit area of the surface (W/m^2, symbol G is used for the solar irradiance with appropriate subscripts)
- Irradiation: The incident energy per unit area on a surface, found by integration of irradiance over a specified time interval, a hour or a day. Insolation is applied to solar energy irradiation (H-insolation for a day, I-insolation for a hour)

Incident solar radiation depends on

- Location
- Orientation of the surface
- Day of the year
- Time of the day

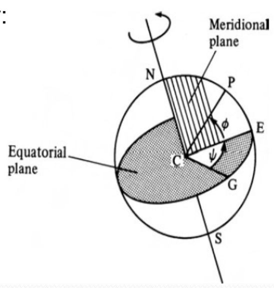
Geometry of the Earth and Sun

Geometry of the Earth and Sun

❖ The point P on the Earth's surface is determined by: latitude (φ) and longitude (ψ)
11.25°N, 75.77°E

❖ Latitude is defined positive for points north of the equator, negative for south of the equator

❖ By international agreement longitude is measured positive eastwards from Greenwich, England



❖ The vertical north-south plane through P is the local meridional plane

❖ Noon solar time occurs once every 24 h when the meridional plane CEP includes the Sun, as for all points having that longitude

❖ Civil time is defined so that large parts of a country, covering up to 15° of longitude cover the same official time zone

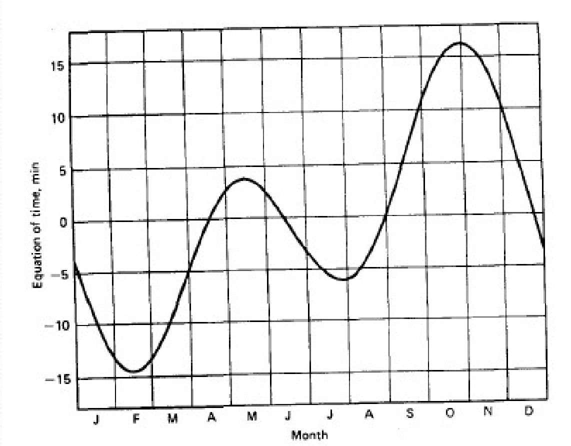
Solar time

- Time based on the apparent angular motion of the sun across the sky, with the solar noon the time sun crosses the meridian of the observer
- Local Apparent Time = Standard time ± 4'(Standard time longitude-longitude of location) + E
- \- sign for eastern hemisphere

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

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

Equation of time

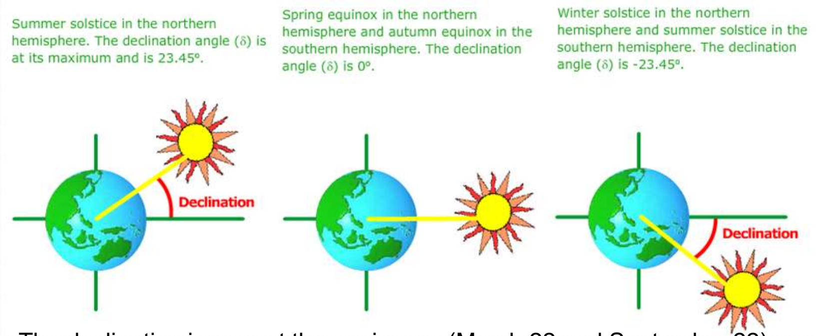


Hour angle (ω)

- It is an angular measure of time
- Equivalent to 15° per hour
- The angle through which the Earth has rotated since solar noon.
- Measured from noon based on LAT, being positive in the morning and negative in the afternoon

DECLINATION (δ)

The declination is the angle made by the line joining the centers of the sun and the earth with the projection of this line on the equatorial plane



The declination is zero at the equinoxes (March 22 and September 22), positive during the northern hemisphere summer and negative during the northern hemisphere winter

The declination reaches a maximum of 23.45° on June 22 (summer solstice in the northern hemisphere) and a minimum of -23.45° on December 22 (winter solstice in the northern hemisphere).

DECLINATION (δ)

Cooper Equation

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365}\right)$$

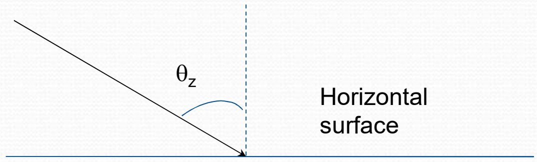
where n is the day in the year ($n = 1$ on 1 January). The error for a leap year is insignificant in practice.

Zenith (θ_z)

This is defined as the angle between the Sun's ray and the line perpendicular to the horizontal plane

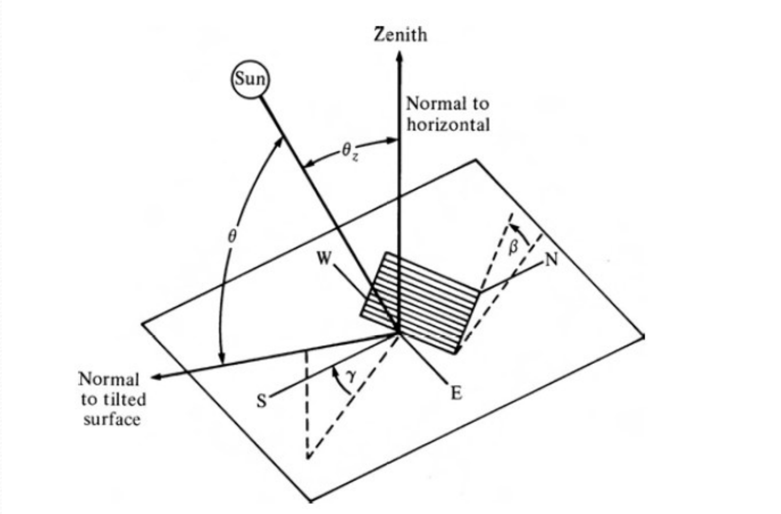
Altitude or solar altitude angle (α)

This is defined as the angle between line Sun's rays and a horizontal plane



Surface Azimuth Angle (γ)

- Angle made in the horizontal plane between the line due south and the projection of the normal to the surface on the horizontal plane.
- Varies from -180^o to 180^o
- Angle is positive if the normal is east of south and negative if west of south



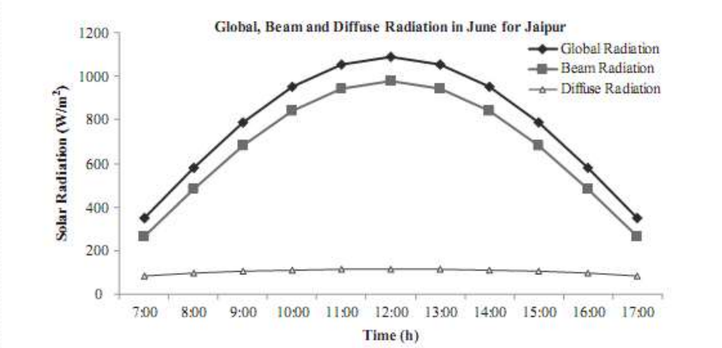
Solar Azimuth Angle (γ_s)

- Angle made in the horizontal plane between the line due south and the projection of the line of sight of the sun on the horizontal plane.
- Angle is positive if the projection of the line of sight is east of south and negative if west of south
- Gives the direction of the shadow cast in the horizontal plane by a vertical rod

$$\cos\gamma_s = \frac{\cos\theta_z \sin\phi - \sin\delta}{\sin\theta_z \cos\phi}$$

$$\cos\theta = \cos\theta_z \cos\beta + \sin\theta_z \sin\beta \cos(\gamma_s - \gamma)$$

Hourly variation of solar radiation



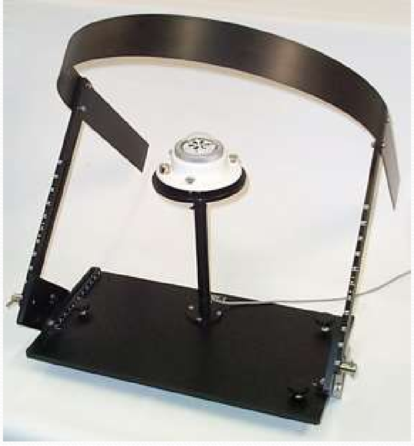
For a typical day of June

SOLAR RADIATION MEASUREMENT

PYRANOMETER

For measuring global radiation

PYRANOMETER WITH SHADING RING



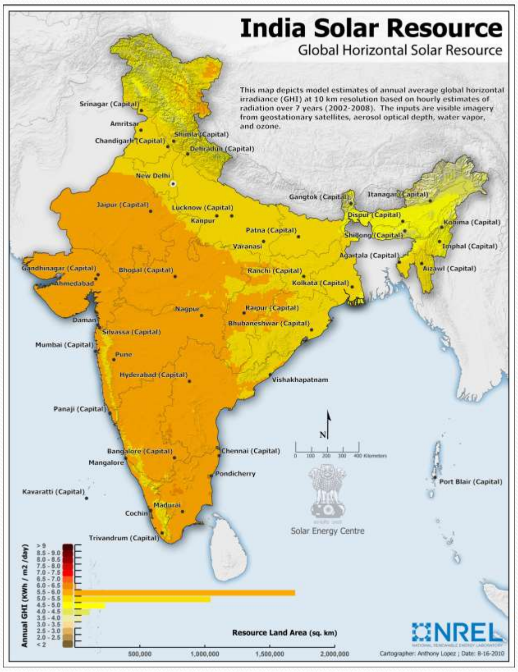
For measuring diffuse radiation

PYRHELIOMETER

For measuring beam radiation

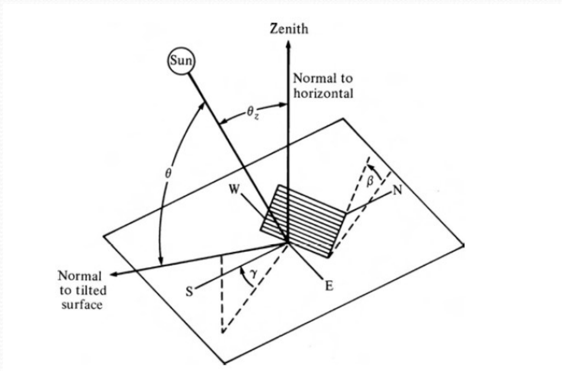
SUNSHINE RECORDER

For measuring duration of bright sun shine in a day



Solar angle relation

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



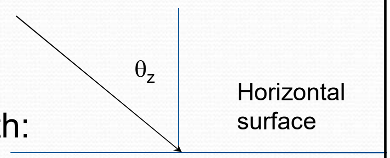
Solar angle relations

- Vertical surface:

$$\cos\theta = \sin\phi\cos\delta\cos\gamma\cos\omega - \cos\varphi\sin\delta\cos\gamma + \cos\delta\sin\gamma\sin\omega$$

- Horizontal surface:

$$\cos\theta = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$



- Inclined surface facing due south:

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

- Vertical surface facing due south:

$$\cos\theta = \sin\phi\cos\delta\cos\omega - \cos\phi\sin\delta$$

Empirical Equations

- Monthly Average Daily Global radiation

$$\frac{\overline{H_g}}{\overline{H_0}} = a + b\left(\frac{\bar{S}}{\overline{S_{max}}}\right)$$

$$H_0 = \frac{24}{\pi} I_{sc}\left(1 + 0.033cos\frac{360n}{365}\right)(\omega_s sin\phi sin\delta + cos\phi cos\delta sin\omega_s)$$

Monthly average of the daily extraterrestrial radiation which would fall on a horizontal surface at the location under consideration

$\omega_s = \cos^{-1}(-\tan\phi\ \tan\delta)$ Hour angle corresponding to sunrise/sunset on a horizontal surface

$S_{max} = (2/15)\ \omega_s$ Day length (in hours)

For Kozhikode: $a = 0.27$, $b = 0.43$ Constants for the location

- Monthly Average Daily Diffuse radiation

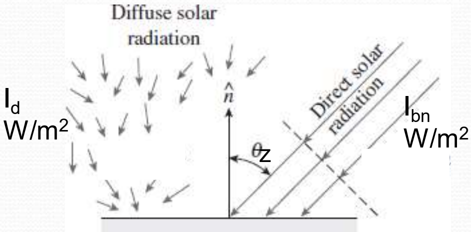
$$\frac{\overline{H}_D}{\overline{H}_g} = 1.390 - 4.027\overline{K}_T + 5.531\overline{K}_T^2 - 3.108\overline{K}_T^3$$

$$\overline{K}_T = \frac{\overline{H}_g}{\overline{H}_o}$$

Monthly average clearness index

Hourly Global, Beam and Diffuse Radiation Under Cloudless Skies

- $I_g = I_b + I_d$
- $I_g = I_{bn} \cos\theta_z + I_d$



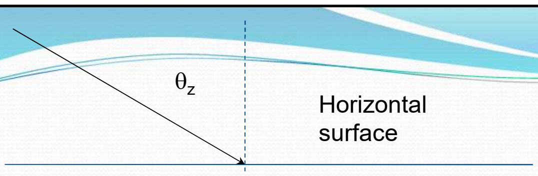
$$I_{bn} = \mathbf{A}\exp\{-\mathbf{B}/\cos\theta_z\}$$

$$I_d = \mathbf{C}I_{bn.}$$

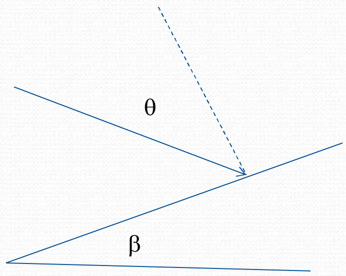
$\mathbf{A} = 1136$ W/m^2, $\mathbf{B} = 0.165$, $\mathbf{C} = 0.121$ for September

Calculation of incident flux on tilted surface

- Measuring instruments give the value of solar radiation falling on a horizontal surface
- But solar collectors are placed tilted to the horizontal plane
- We use tilt factor for the estimation of flux on tilted surfaces
- Beam radiation tilt factor: The ratio of beam radiation flux falling on a tilted surface to that falling on a horizontal surface



$I_b = I_{bn} \cos\theta_z$



Beam radiation tilt factor
$r_b = \cos\theta/\cos\theta_z$

$I_{bT} = I_{bn} \cos\theta$

Diffuse radiation tilt factor
$r_d = (1+\cos\beta)/2$

Reflected radiation tilt factor, $r_r = \rho(1-\cos\beta)/2$

Flux on tilted surface, $I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r$