Solar Radiation - ESL 100 (2023-2024 First Semester)

Source: John Duffie and William Beckman, Solar Engineering of Thermal Processes, 3rd Edition, Wiley(2013)

Solar Energy : Radiation emitted by PHOTOSPHERE of the Sun; Solar Radiation travels with the speed of light : Change in intensity with variation in Sun – Earth Distance

Rotation of the earth on its axis – one rotation in approximately 24 hours and the same is day length, Once in about 24 hours a particular longitude on earth is likely to be in the line of the Sun

Revolution of earth around the Sun in an elliptical path, Variation in sun-earth distance on different days of the year, Change in the intensity of radiation available.

Earth is inclined at 23.45 degrees from the plane of its orbit around the sun, Seasonal variation in solar radiation availability.

Earth has its atmosphere surrounding it – radiation is affected during its passage through the atmosphere,

Extra-terrestrial Solar Radiation: solar radiation just outside the earth's atmosphere.

The intensity of EXTRATERRESTRIAL SOLAR RADIATION depends on (i) the distance between sun and earth and (ii) orientation of the receiving surface with respect to direction of incidence of solar radiation; Change in the value of extra-terrestrial solar radiation just outside the earth's atmosphere due to change in earth-sun distance;

day of year.

$$G_{on} = G_{sc} [\, 1 + 0.033 \cos (360\, n / 365)]$$

Solar. cons. = 1364 W/m².

Wavelength Range (µm)	0 – 0.38	0.38 – 0.78	0.78 -
Energy in the Wavelength Range (fraction)	0.07	0.47	0.46

Solar Constant: Extraterrestrial solar radiation received per unit time per unit area of a surface kept at mean sun-earth distance from the sun and facing the incident solar radiation normally (at 90 degrees), Current value of solar constant is 1367 W/m^2

Terrestrial Solar Radiation: solar radiation available on the surface of earth (after passage through its atmosphere) - Difference in intensity, spectral distribution as well as angle of incidence of a certain portion of incident solar radiation

Absorption of solar radiation by gases present in the atmosphere -reduction in intensity and change in spectral distribution -Selective absorption characteristics of different constituents of atmosphere - Ozone : ultraviolet radiation (short wavelength), almost complete absorption up to 0.29 µm; Carbon dioxide, Water vapour: Infra-red (long wavelength), almost complete absorption beyond 2.3 µm; Extent of reduction in intensity of solar radiation depends on the distance traversed through the atmosphere and the composition of air/atmosphere; Distance traversed depends on the angle of incidence of solar radiation

If it is assumed that the attenuation is proportional to the local intensity (I) in the medium and also to the incremental distance (dx) traversed, then

$-dI \propto I$ and also $-dI \propto dx$; Thus, $dI = -K\, I\, dx$ (where the constant of proportionality, K, is the EXTINCTION COEFFICIENT for the air /atmosphere); $dI/I = -K\, dx$; Upon integration $\log I = -K x + C$; Using the condition that at $x = 0$, $I = I(0)$ $C = \log I(0)$; Thus $\log I - \log I(0) = -K x$ which gives

$$I = I(0) \exp(-K x)$$

Scattering of solar radiation by air molecules, dust particles, water vapour present in the atmosphere – Radiation received DIRECTLY as a BEAM and that received after SCATTERING -Direct (beam) and Diffuse components in Terrestrial Solar Radiation incident on earth after passage through the atmosphere

$\cos\theta_z = \cos\phi \cos\delta \cos\omega + \sin\phi \sin\delta.$

Direct (Beam) Radiation: radiation reaching earth without any change in its direction; The angle of incidence of DIRECT (BEAM) component of solar radiation can be precisely determined with knowledge of sun-earth geometry and surface orientation;

Diffuse Radiation: radiation reaching earth after scattering in the atmosphere - Angle of incidence of DIFFUSE component of solar radiation is not known; Isotropic distribution of diffuse solar radiation is often assumed (all parts of sky contributing equal amount of diffuse radiation); Total solar radiation = Direct + Diffuse components of solar radiation; Optically sensitive surfaces (Mirrors and Lenses) and collection of diffuse component of solar radiation - Diffuse fraction in total solar radiation and feasibility of using mirrors and lenses for solar energy collection.

Air Mass: Air mass (m) is defined as the ratio of the optical thickness of the atmosphere through which the beam radiation passes to the optical thickness if the sun were at zenith ($m = \sec(\theta z)$ with θz representing zenith angle.

AM0 : Extraterrestrial Solar Radiation; AM1: Sun is overhead (at zenith); AM1.5: Specified as a condition for Peak Watt; AM2: Zenith angle is 60°

Incidence Angle of Direct (Beam) Solar Radiation on a surface on earth depends on:

Attribute	Name of Corresponding Angle	Definition of Angle
Location	Latitude (ϕ) (angle between the earth's equatorial plane and a line from the centre of the earth to the site/ location)	Angular location of the place (site) north (+ ve) or south (- ve) of equator
Day of the year	Declination (δ) $\delta = 23.45° \sin [\{360 (284 + n)\}/365]$ [Maximum value: 23.45° Minimum value: (-) 23.45°]	Angular position of the sun at solar noon with respect to plane of the equator (+ ve , north of equator)
Time of Day	Hour Angle (ω) [(-) ve in the morning and (+) ve in the afternoon]	Angular displacement of the sun, east or west of the local meridian due to rotation of earth on its axis (at 15° an hour)
Slope of Surface	Tilt with the horizontal (β)	Angle between the plane surface in question and the horizontal
Orientation of Surface	Surface Azimuth Angle (γ) [zero due south, (-) ve east and (+) west]	Deviation of the projection of the normal to the surface on a horizontal plane from the local meridian (due south line)

Hour Angle = (15) x (Number of Hours from Solar Noon);Solar Noon: The time when the sun is just above the local meridian (longitude)- Thus, the value of hour angle at solar noon would be zero; Solar Day: It is the interval of time from the moment the sun crosses the local meridian to the next time it crosses the same meridian- Essentially it is the period between two successive solar noons at a place.

The hour angle is based on **SOLAR TIME** and not the **LOCAL (standard/clock) TIME** -Need to convert LOCAL/STANDARD time to SOLAR time prior to the determination of hour angle

The Solar Noon could be different from the Standard Noon as indicated by the clocks as the standard times of a time zone are based on the Solar Noon at a specific location - Need to correct the standard time as defined by a clock for the difference in the longitudes of the location of interest and the standard time location.

Since the rate of rotation of earth on its axis is not uniform during the year (thus changing the length of the day and also the time of Solar Noon) a correction **EQUATION OF TIME** is used for the same.

Solar Time = Standard Time + Longitude Correction + Equation of Time

Thus, two corrections are required to convert standard time to solar time: (1) **Longitude Correction**: for the difference between the local (observer's) longitude and the Standard longitude (for the time zone) – this correction can be positive or negative, and (2) **Equation of Time**: for perturbation in the rate of rotation of earth, thus affecting the length of Solar Day

If the location is on the EAST of Standard longitude, the sun has already passed through the local longitude by the time solar noon occurs, whereas if the location is on the WEST of Standard longitude, the sun would reach the local longitude some time after the solar noon

The equation relating the angle of incidence (θ) of direct (beam) radiation on a flat surface (the angle between direct radiation on a surface and normal to the surface) is as follows:

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

$$+ \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega$$

with θz representing the Zenith Angle (angle between zenith and beam solar radiation); Also if α represents the Altitude Angle of the Sun then $\theta z = 90 - \alpha$

Angle of Incidence on a Horizontal Surface: For a horizontal surface $\beta = 0$ and $\gamma = 0$. The angle of incidence of direct solar radiation on a horizontal surface is the same as the Zenith Angle (θz). Thus

$$\cos\theta z = \sin\delta\sin\phi\,(1) - \sin\delta\cos\phi\,(0)(1) + \cos\delta\cos\phi\,(1)\cos\omega + \cos\delta\,(0)(0)\sin\omega + \cos\delta\sin\phi\,(0)(1)\cos\omega$$

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

Since Zenith Angle (θz) = 90 – Solar Altitude Angle (α), $\sin\alpha = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi$

Angle of Incidence on a Vertical Surface: For a vertical surface $\beta = 0$

$$\cos\theta vert = \sin\delta\sin\phi\,(0) - \sin\delta\cos\phi\,(1)\cos\gamma + \cos\delta\cos\phi\,(0)\cos\omega + \cos\delta\sin\gamma\,(1)\sin\omega$$

$$+ \cos\delta\sin\phi\,(1)\cos\gamma\cos\omega$$

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

Angle of Incidence (θT) on a South Facing Tilted Flat Surface: For a south facing tilted flat surface $\gamma = 0$, and thus

$$\cos\theta T = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\,(1) + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\,(0)\sin\beta\sin\omega$$

$$+ \cos\delta\sin\phi\sin\beta\,(1)\cos\omega$$

$$\cos\theta T = \sin\delta\,\{\sin\phi\cos\beta - \cos\phi\sin\beta\} + \cos\delta\cos\omega\{\cos\phi\cos\beta + \sin\phi\sin\beta\}$$

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

Sunset Hour Angle and Duration of Sunshine

On a horizontal surface sun rise or sun set occurs when $\theta z = 90°$ or $\alpha = 0$

If the sunset hour angle is ω_s, then $\cos 90 = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega_s$

$0 = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\omega_s$ or $\cos\omega_s = (-)\sin\delta\sin\phi / \cos\delta\cos\phi = (-)\tan\phi\tan\delta$

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

Number of daylight hours (one hour time duration is equivalent to an hour angle of 15° and number of hours from solar noon to sunset are the same as the number of hours from sun rise to solar noon)

$$= (2/15)\cos^{-1}\{(-)\tan\phi\tan\delta\}$$

Total Solar Radiation on (South Facing) Tilted Surfaces:

Solar radiation on a tilted surface consists of (a) Direct (beam) solar radiation, (b) Diffuse solar radiation from sky and, (c) Solar radiation diffusely reflected from the ground/surface in front of the collector

Direct (beam) solar radiation on the tilted surface: If Ib and Id respectively represent the beam (direct) and diffuse solar radiation incident on a horizontal surface, the direct (beam) solar radiation on a flat surface tilted at an angle β with the horizontal would be equal to= (Ib/ cos θz) (cos θT) = (Ib) (Rb) with Rb = (cos θT / cos θz)

Diffuse Radiation on a Tilted Surface: Of the entire diffuse radiation coming from the sky, the fraction that passes through the sky view portion of the tilted surface strikes it. If it is assumed that the sky is a uniform source of diffuse radiation (i.e. isotropic distribution of solar radiation) a surface tilted at slope β from the horizontal has a view factor to the sky given by $(1 + \cos \beta)/2$. Thus diffuse radiation on a tilted surface = Id $\{(1 + \cos \beta)/2\}$; If $\beta = 0$ (i.e. horizontal surface) the view factor has a value of unity and If $\beta = 90°$ (i.e. vertical surface) the view factor has a value of (1/2) as a vertical surface sees only half of the sky.

Reflected Solar Radiation from Ground Facing the Solar Collector: A surface tilted with a slope β with the horizontal has a view factor of the ground of $(1 - \cos \beta)/2$; If $\beta = 0$ (horizontal surface) the view factor is zero as a horizontal surface does not view any ground whereas for $\beta = 90°$, the view factor is ½. If the surroundings of the collector have a reflectance of ρg for total (Ib + Id) solar radiation, the reflected radiation from the surroundings on the surface of the collector is (Ib + Id) ρg $(1 - \cos \beta)/2$. The value of ρg is assumed 0.2 for normal ground and 0.7 for snow covered surfaces

Total Solar Radiation on (South Facing)Tilted Surfaces: The hourly value of total solar radiation (IT)on a tilted surface can be estimated from: IT = (Ib) (cos θT / cos θz) + Id $\{(1 + \cos \beta)/2\}$ + (Ib + Id) ρg $(1 - \cos \beta)/2$

with $\cos \theta_T = \sin \delta \sin (\phi - \beta) + \cos (\phi - \beta) \cos\delta \cos \omega$, and $\cos \theta_z = \sin \delta \sin \phi + \cos\delta \cos \phi \cos \omega$

Since solar process calculations are often undertaken on an hourly basis, the values of cos θT and cos θz are determined for the midpoints of the hours before or after solar noon

Solar Photovoltaics

Direct conversion of solar radiation to electricity - Need to Create Electrons (and holes) with Solar Radiation (after absorption)- Need to make electrons move (flow) in an external circuit (instead of recombining with holes)

No moving parts to wear out and make noise; inherent reliability challenges in a system with moving parts; Solar cells (so far most of them) are made from silicon, one of the most abundant /plentiful materials on earth (Thus such solar cells do not consume any precious energy and other materials as resources); Overall conversion efficiency of solar radiation to electricity in the range of 14-20%; The semiconductor industry is a well developed, high technology industry; Solar cells can be readily adapted to mass production techniques; Improvement in technology may lead to further increase in useful life of solar cells; Solar cells have a high power to weight ratio; Solar cells themselves do not represent a health hazard and do not contribute any harmful waste products; Both LEARNING and VOLUME effects have contributed to cost reduction; In general, good quality PV modules may be expected to have a useful life of 20 to 25 years; Solar photovoltaic installations can be built relatively quickly (often in 6-12 months) as compared to coal thermal plants (4-5 years), hydro power plants and nuclear power plants; Photovoltaic devices can be constructed as stand-alone systems to give outputs from microwatts to megawatts (calculators, watches,...space vehicles.....MW scale plants); Photovoltaic panels can also be made to form components of building skin such as roof shingles and wall panels; PV modules and inverters are all subject to certification, predominantly by the International Electrotechnical Commission (IEC);Photovoltaic power generation may be very attractive for rapidly growing emerging markets with a high unmet demand and urgent need for power;

A photon (a packet of light energy) entering a material can free an electron from a stable position in the materials' crystal structure and give it enough energy to move freely through the material; The minimum amount of energy required to free an electron from a fixed site is called the **BAND GAP** of the material; Some electrons are also freed from fixed sites by atomic motion resulting from heat but in a semi-conducting material such as silicon, relatively few electrons are freed by room temperature heat; A photovoltaic device to create a voltage inside a material that can direct electrons freed by photon collisions and produce useful current; This is accomplished by combining semiconductor materials with different characteristics to form a junction. Junctions typically combine an 'n-type' and a 'p-type' material

For a **band gap of 1.08 eV** the required wavelength can be determined as: $hc/\lambda = [(1.08)(1.6)(10^{-19})\ J]$
$\lambda = (6.626)(10^{-34})(3)(10^{8}) / [(1.08)(1.6)(10^{-19})\ J] = [(6.626)(3)/(1.08)(1.6)]\,(10^{-7}) = (1150)\,(10^{-9})\ m = 1150\ nm$
Solar spectrum has radiation of different wavelengths (some have less energy than the band gap and some have more than the band gap; For a practical solar cell it is necessary that the photons of the incident solar radiation be absorbed in solar material and liberate electrons in such a way that current will flow in an external circuit

Losses during Photovoltaic Conversion: Long wavelength photons not utilized (absorbed). Material dependent. In case of silicon approximately 23% of the insolation has wavelength greater than the critical (maximum) wavelength and hence can not contribute to electron current; Photons of wavelength shorter than the critical wavelength will free an electron and the remaining energy will eventually be dissipated as heat (about 43% of the absorbed energy in case of silicon); Reflection of solar radiation from the top surface of the solar cell (optical losses) - use of antireflection coatings made; Re-combination losses - annihilation of electron-hole pair; Self shading -the electrical contacts on the surface of the solar cell reflect light and shade parts of the cell material directly under them; Resistance losses -the base material of the cell, the surface layers of the cell and the circuit connection all provide a resistance to the current flow- lowering the voltage; Temperature losses - loss due to current-voltage characteristics of the solar cell

The most commonly used PV technologies are: Crystalline Silicon (c-Si): Modules are made from cells of either mono-crystalline or multi-crystalline silicon. Mono-c-Si cells are generally the most efficient but are also more costly than multi-c-Si; **Thin-film**: Modules are made with a thin-film deposition of a semiconductor onto a substrate. This class includes semiconductors made from (a) Amorphous Silicon (a-Si), (b) Cadmium Telluride (CdTe), (c) Copper Indium Selenide (CIS) and (d) Copper Indium (Gallium) Di-Selenide (CIGS/CIS); **Heterojunction with intrinsic thin-film layer (HIT):** Modules are composed of a mono-thin c-Si wafer surrounded by ultra-thin a-

Si layers; **Organic solar cells** (Dye-sensitized.., organic thin layer type.., perovskite....); Due to reduced manufacturing costs and maturity of the technology, wafer-based crystalline modules have maintained a market production share of above 90 percent in 2021.

The main electrical characteristics of solar (PV)/ module are summarized in the relationship between the current and voltage produced on typical **I-V characteristics of the solar cell/module**; These show the current and voltage (I-V) characteristics of a particular PV cell, module or array; Knowing the electrical I-V characteristics (more importantly Pmax) of a solar cell or panel is critical in determining the output performance of the device and also solar energy conversion efficiency reduces its voltage; I-V characteristics of a solar cell/module are a graphical representation of the operation of the solar cell/module summarizing the relationship between the current and voltage at the existing conditions of irradiance and temperature; The intensity of solar radiation incident on the solar cell directly affects the current while an increase in operating temperature of the solar cell/module reduces its voltage.

The current produced by a solar cell depends on its size and the intensity of solar radiation incident on it. The voltage, on the other hand, depends on the type of cell material; When a solar cell is open circuited (that it is not connected to any load), the current will be at its minimum (zero) and the voltage across the cell is at its maximum- this voltage of the solar cell is defined as the **OPEN CIRCUIT VOLTAGE (Voc)**;At the other extreme, when the solar cell is short circuited, (that is the positive and negative leads are connected together) the voltage across the cell is at its minimum (zero) but the current flowing out of the cell reaches at its maximum - this current is defined as the **SHORT CIRCUIT CURRENT (Isc).**

The I-V Characteristics of a solar cell/module span from Isc at zero output voltage to zero current at Voc -neither of these two extremes generate any electrical power; If for each point the product of voltage with the corresponding current is determined, it would define the power curve for the given radiation level and the operating temperature; For a particular combination of voltage and current the power reaches its maximum value - defined as the **Maximum Power Point** at which, a PV cell/module should operate; **Fill Factor (FF)** is defined as the ratio of the maximum power (Vmp x Imp) from the solar cell to the product of Voc and Isc.
Efficiency of a solar cell (η) = (Imp)(Vmp)/Pin; Terrestrial solar cells are characterized for performance (including efficiency) under AM1.5 conditions at a temperature of 25°C with an input power of $1kW/m^2$
Cell, Module, Panel, Array; **Series and Parallel combinations of cells/modules**
Energy delivered by a PV plant under field real conditions is affected by variability in : (a) operating temperature, (b) solar radiation intensity and its spectral distribution, (c) angle of incidence, (d) extent of soiling

Solar cell performance decreases with increase in its operating temperature – fundamentally owing to increased internal carrier recombination rates; As the operating temperature of a solar cell panel increases, its current output increases exponentially while the voltage output is reduced linearly (in fact the voltage reduction is so predictable that it can be used to accurately measure cell operating temperature); A term **temperature coefficient or power** is defined that represents the loss in power output of the solar cell module for 1°C increase in temperature above 25°C; For example, for crystalline solar cells, the power output is typically reduced by about 0.5% with each increase of 1°C in the operating temperature.
Performance Ratio: The Performance Ratio (PR) is a parameter commonly used to quantify PV plant performance - Usually expressed as a percentage, the PR provides a benchmark to compare plants over a given time independent of plant capacity or solar resource; A plant with a high PR is more efficient at converting solar irradiation into useful energy. The 'Performance Ratio' also called as the 'Quality Factor' is independent from the irradiation and therefore, useful to compare systems; The PR is defined as the ratio between the exported AC yield and the theoretical yield that would be generated by the plant if the modules converted the irradiation received into useful energy according to their rated capacity.
Capacity Factor: The capacity factor (or **Annual Capacity Utilization Factor** of a PV power plant (usually expressed as a percentage) is the ratio of the actual output over a period of a year and Its output if it had operated at nominal power the entire year.
Capacity Factor (in fraction) = (Annual electricity generation in kWh)/ [(365)(24)(Installed Capacity in Peak kW)

Thermal Utilization of Solar Energy

Basic process:
Solar radiation is converted to heat on the absorber leading to an increase in the temperature of the absorber, Heat collected by the absorber can be extracted from the absorber often using a heat transfer fluid, The extracted heat can be utilized for the specific end use, Heat losses occur from the absorber to the surroundings if it is operating at higher temperatures than that of its surroundings.

Important Issues:
To maximize the amount of solar radiation available to the collector (beam/ direct, diffuse, ground reflected); To maximize the fraction of incident solar radiation absorbed by the absorber surface? (How to determine the fraction of energy absorbed?); To minimize heat losses from the solar collector (absorber) to the surroundings? To maximize heat extraction from the solar collector; To obtain a desired delivery temperatures of heat transfer fluids?

Three possibilities when solar radiation is incident on a surface – **reflection, absorption, transmission**; For solar collection, absorption of solar radiation on the collection surface should be as high as possible and thus the reflection form the surface and transmission from the surface should be minimal; Absorbers of solar thermal collectors are often opaque and are designed for maximum absorptance (which colour??).

The temperature of the absorber surface increase and becomes higher than that of its surroundings upon absorption of solar radiation. It loses heat to the surroundings by conduction , convection and radiation
Conduction: Rate of heat loss (conduction) per unit absorber area for an absorber at Tabs = $(k/\Delta x)$ (Tabs – Ta) with k representing the thermal conductivity of the medium in contact with the absorber , Δx the thickness of the medium and Ta the ambient temperature
Convection: Rate of heat loss per unit absorber area = (convective heat transfer coefficient)(Tabs – Ta)
Radiation: Rate of radiative heat exchange between an absorber and surroundings (sky) per unit area can be estimated from = $\varepsilon\sigma$ ($Tabs^4$ – $Tsky^4$) with ε representing emittance of the absorber surface, σ the Stefan Boltzmann constant, and Tsky the sky temperature
Approaches to Reduce Thermal Losses from the Absorber of a flat plate solar collector: For heat loss by conduction, put suitable thickness of good quality insulation on the un-exposed portion(s) of the absorber; To reduce heat loss by convection, reduce wind speed over the absorber, preferably avoid contact of air with the absorber surface (How to do the same??), For reducing heat loss by radiation decrease emittance of the absorber surface without significantly compromising with the absorptance of the absorber for incident solar radiation (How to achieve the same??)
One of the possibilities to reduce heat losses from the top of a flat plate solar collector is to INCREASE the RESISTANCE TO HEAT TRANSFER from the ABSORBER to its SURROUNDINGS, The resistance to heat transfer from the absorber plate to its surroundings can be increased by inserting one or more transparent (for allowing solar radiation to pass through) cover(s) between the absorber plate and the surroundings; In such a case, wind is not in direct contact with the absorber plate (instead it now flows over a relatively lower temperature transparent cover/ glazing); Moreover, the energy radiated by the absorber could partially be absorbed by the transparent cover and a fraction of it re-radiated back to the absorber plate (Greenhouse Effect)

Radiative thermal loss from an absorber plate depend on its emittance (for the range of wavelengths being emitted)- It is possible to develop surface coatings for the absorber with lower emittance (without significantly compromising with its absorptance - **Spectrally Selective Coatings** (for solar collection); Incremental cost of selective absorber coating versus incremental monetary value of increased useful energy collection due to reduced radiative losses; Since radiative losses are usually low at low temperatures, selective coatings may not be very useful; At very high operating temperatures there could be an overlap between the wavelengths in incident solar radiation and those emitted by the absorber (thus absorption of incident solar radiation may be crucially affected)
Desirable characteristics of the material to be used as the cover glazing in a solar collector: (a) Transmittance (b) Impact strength (c) Resistance to abrasion (d) Absorption of long wavelength radiation (e) Cost (f) Thermal cycling tolerance

Number of transparent covers in a solar collector – while resistance to heat transfer from the top of the absorber would increase with an increase in the number of glazings, the same would also reduce the amount of energy reaching the absorber plate due to increased reflection and absorption losses; Since thermal losses would depend on the absorber temperature, the number of transparent covers should also depend on the absorber operating temperature

Use of transparent cover(s) may reduce both convective and radiative THERMAL losses; However, use of transparent covers (between the sun and the absorber plate) introduces new OPTICAL losses - reflection from each interface of glazing and absorption in the material of the glazing

Reflection at Glass-Air Interface: Fraction reflected from first interface ($\rho_{\theta i}$)

$= (0.5)\{[\sin^2(\theta i - \theta r)/\sin^2(\theta i + \theta r)] + [\tan^2(\theta i - \theta r)/\tan^2(\theta i + \theta r)]\}$

For $\theta i = \theta r = 0$ (normal incidence of solar radiation on the glass) the fraction reflected from the first interface (ρ_{ni}) $= [(n-1)^2/(n+1)^2]$ with n representing refractive index of the glass (for n = 1.5 its value is 0.04 i.e. even for normally incident solar radiation 4% will be reflected at the first air-glass interface), θi the angle of incidence of solar radiation on the glazing and θr the angle of refraction; For $\theta i = 60°$ and n = 1.5 ($\sin 60/\sin \theta r$) = 1.5 and thus $\Theta r = 35.26$, The fraction reflected from first interface at an angle of incidence of 60 degrees

(ρ_{60}) $= (0.5)\{[\sin^2(60 - 35.26)/\sin^2(60+ 35.26)] + [\tan^2(60 - 35.26)/\tan^{2(}60+ 35.26)]\}$

$= (0.5)\{(0.1751/0.9916) + (0.2123/117.9855)\} = (0.5)(0.1766 + 0.0018) = 0.0892$ (or 8.92 %);

Thus at larger angles of incidence the optical loss due to reflection at the interfaces INCREASES as compared to normal incidence

Absorption of Radiation in the Glass: $I = I(0) \exp(-K x)$, Thus fraction of incident solar radiation I(0) absorbed in the glass (α_g) $= [I(0) - I]/I(0) = 1 - \exp(-K x)$ with $x = t \sec \theta r$ (t is thickness of glass)

For $\theta i = 30°$, $\theta r = 19.47°$ and if $K = 20\ m^{-1}$ and t = 0.003m (3 mm) $\alpha_g = 0.0626$ (or 6.26%)

For $\theta i = \theta r = 0$, $\alpha_g = 0.0582$ (or 5.82%)

For non-normal incidence, actual path length (x) traversed by the solar radiation is more than the thickness (t) of the transparent cover (glazing); Larger the angle of incidence (larger the angle of refraction) larger the optical path length traversed for a given value of the thickness (t) of the glazing; The reflection from the glass as well as absorption in the glass increases with an increase in the angle of incidence of solar radiation; The transmittance of the glass cover is thus dependent on the angle of incidence of solar radiation; As the angle of incidence of solar radiation changes (during the day, during different seasons) amount of solar radiation transmitted through a glass cover all changes and consequently, the amount of solar energy absorbed; - Variation in the OPTICAL PERFORMANCE of a FIXED solar collector during the day

Optical Efficiency (η_o or $\tau\alpha$): Ratio of energy absorbed to the amount of solar radiation incident on the aperture of the solar collector and it takes into account the optical losses due to reflection from the glass cover (glazing), absorption in the glass cover and reflection from the absorber surface (only upon absorption by the absorber plate the solar radiation is converted to heat, till than OPTICAL losses only); For an unglazed flat plate solar collector the only optical loss is that of reflection from the absorber plate. On inserting a cover glazing over the absorber plate the optical losses also include reflection from the glazing and absorption in the glazing material.

Modalities of reducing heat losses from the solar collector (absorber) and also of extracting heat from the same vary depending on the design of the solar collector - **Examples of Flat Plate Solar Collector, Evacuated Tubular Solar Collector and concentrating solar collector**

Thermal applications of solar energy - water heating, air heating, process heating, cooking, distillation, drying, space heating, space cooling, refrigeration, electricity (power) generation, thermochemical steam reforming of methane/natural gas for hydrogen production; different operating temperature requirements; Variation of solar collection efficiency with operating temperature; Low and medium temperature requirements with year round demand at locations with good solar resource availability; Cost effectiveness of thermal energy storage as against electricity (battery) storage.