3.4 Calculates the Radiation Incident on the Solar Array

In the solar resource total amount of solar radiation striking the horizontal surface on the Earth surface. But the power output of the solar array depends on the amount of radiation striking the surface of the solar array, which in general is not horizontal. So in each time step, calculate the global solar radiation incident on the surface of the solar array. The orientation of the PV array using two parameters, a slope and an azimuth angle. The slope is the angle formed between the surface of the panel and the horizontal, so a slope of zero indicates a horizontal orientation, whereas a 90° slope indicates a vertical orientation. The azimuth is the direction towards which the surface faces. The convention where by zero azimuth corresponds to due south, and positive values refer to west-facing orientations. So an azimuth of -45° corresponds to a southeast-facing orientation, and an azimuth of 90° corresponds to a west-facing orientation.

The other factors relevant to the geometry of the situation are the latitude, the time and the time of day. The time of year affects the solar declination, which is the latitude the Sun's rays are perpendicular to the Earth's surface at solar noon. The following equ calculate the solar declination:

$$\delta = 23.45^{\circ} \sin\left(360^{\circ} C \frac{284+n}{265}\right) h$$

Where

n is t... day of the year [a number 1 through 365]

The time of day ...fects the location of the Sun in the sky, which we can describe by angle. The convention whe...by the hour angle is zero at solar noon (the time of day at w Sun is at its highest point in the sky), negative before solar noon, and positive after sol The following equation to calculate the hour angle:

$$\omega = (t_s - 12h_r).15^{\circ}/h_r$$

where : t_s is the solar time [hr]

The value of Ist is 12hr at solar noon, and 13.5hr ninety minutes later. The above follows from the fact that the Sun moves across the sky at 15 degrees per hour. That dependent data, such as solar radiation data and electric load data, are specified not in sc but in civil time, also called local standard time. Calculates solar time from civil time following equation:

$$t_s = t_c + \frac{\lambda}{15^{\circ}/h_r} - Z_c + E$$

where:

t_c	is the civil time in hours corresponding to the midpoint of the time
λ	is the longitude [°]
Z_c	is the time zone in hours east of GMT [hr]
E	is the equation of time [hr]

Note : that west longitudes are negative, and time zones west of GMT are negative

The equation of time accounts for the effects of obliquity (the tilt of the Earth rotation relative to the plane of the ecliptic) and the eccentricity of the Earth's orbit. The of time as follows:

$$E = 3.82\ (.000075 + .001868.\cos B - 0.032077.\sin B - 0.014615.\cos 2B - 0.0408$$

where B is given by:

$$B = 360^{\circ} \left(\frac{n-1}{365}\right).$$

where n is the day of the year. starting with 1 for January 1st.

Now. for a surface with any orientation, we can define the angle of incidence, meaning the angle between the Sun's beam radiation and the normal to the surface, using the following equation:

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

where:

θ is the angle of incidence [º]

β is the slope of the surface [º]

γ is the azimuth of the surface [º]

$\varnothing$ is the latitude [º]

δ is the solar declination [º]

ω is the hour angle [º]

An incidence angle of particular importance, which we will need shortly, is the zenith angle, meaning the angle between a vertical line and the line to the Sun. The zenith angle is zero when the Sun is directly overhead, and 90º when the Sun is at the horizon. Because a horizontal surface has a slope of zero, we can find a equation for the zenith angle by setting b = 0º in the above equation, which yields:

$$\cos\theta_z = \cos\varnothing\cos\delta\cos\omega + \sin\varnothing\sin\gamma$$

θ_z is the zenith angle [º]

Now we turn to the issue of the amount of solar radiation arriving at the top of the atmosphere over a particular point on the Earth's surface. We assume the output of the Sun is constant in time. But the amount of Sunlight striking the top of the Earth's atmosphere varies over the year because the distance between the Sun and the Earth varies over the year due to the eccentricity of Earth's orbit. To calculate the extraterrestrial normal radiation, defined as the amount of solar radiation striking a surface normal (perpendicular) to the Sun's rays at the top of the Earth's atmosphere, The following equation:

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

$$G_0 = G_{on}\cos\theta_z$$

where :

G_{on} is the extraterrestrial normal radiation [kW/m^2]

G_{sc} is the solar constant [1.367 kW/m^2]

n is the day of the year [a number between 1 and 365]

The average extraterrestrial horizontal radiation over the time step:

$$G_0^- = \frac{12}{\pi} G_{on} \left[\cos\varphi\cos\delta(\sin\omega 2 - \sin\omega 1) + \frac{\pi\left(\omega^2 - \omega\right)}{180^\circ}\sin\varphi\sin\delta\right]$$

where:

G_0^- is the extraterrestrial horizontal radiation averaged over the time step [kW

G_{on} is the extraterrestrial normal radiation [kW/m²]

ω_1 is the hour angle at the beginning of the time step [°]

ω_2 is the hour angle at the end of the time step [°]

The above equation gives the average amount of solar radiation striking a horizontal su at the top of the atmosphere in any time step. The solar resource data give the average am of solar radiation striking a horizontal surface at the bottom of the atmosphere (the surface o Earth) in every time step. The ratio of the surface radiation to the extraterrestrial radiation is c the clearness index. The following equation defines the clearness index:

$$K_T = G^-/G_0^-$$

where:

G^- is the global horizontal radiation on the Earth's surface averaged over the time step [kW

G_0^- is the extraterrestrial horizontal radiation averaged over the time step [kW/m²]

Now let us look more closely at the solar radiation on the Earth's surface. Some of radiation is "**beam radiation**", defined as solar radiation that travels from the Sun to the Ea surface without any scattering by the atmosphere. Beam radiation (sometimes called direct radiat casts a shadow. The rest of the radiation is "**diffuse radiation**", defined as solar radiation wh direction has been changed by the Earth's atmosphere. Diffuse radiation comes from all parts the sky and does not cast a shadow. The sum of beam and diffuse radiation is called global s radiation, a relation expressed by the following equation:

$$G^- = G_b^- + G_d^-$$

where:

G_b^- is the beam radiation [kW/m²]

G_d^- is the diffuse radiation [kW/m²]

The distinction between beam and diffuse radiation is important when calculating the amo of radiation incident on an inclined surface. The orientation of the surface has a stronger ef on the beam radiation, which comes from only one part of the sky, than it does on the dif radiation, which comes from all parts of the sky.

However, in most cases, we measure only the global horizontal radiation, not its beam diffuse components. That means in every time step, the global horizontal radiation into its be and diffuse components to find the radiation incident on the solar array. For this purpose **diffuse fraction** as a function of the clearness index as follows:

$$\frac{\bar{G}_d}{\bar{G}} = \begin{cases} 1-0.09K_T & K_T \le 0.22 \\ 0.9511-0.1604K_T+4.388K_T^2 & 0.22 < K_T \le 0.80 \\ 0.165 & K_T > 0.80 \end{cases}$$

The following equation defines R_b, the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface:

$$R_b = \cos\theta/\cos\theta_z$$

The anisotropy index, with symbol A_i, is a measure of the atmospheric transmittance of eam radiation. This factor is used to estimate the amount of circumsolar diffuse radiation, also alled forward scattered radiation. The anisotropy index is given by the following equation:

$$A_i = \frac{\bar{G}_b}{\bar{G}_d}$$

The final factor, we need to define is a factor used to account for 'horizon brightening', or e fact that more diffuse radiation comes from the horizon than from the rest of the sky. This term related to the cloudiness and is given by the following equation:

$$f = \sqrt{\frac{\bar{G}_d}{\bar{G}}}$$

Following equation to calculate the output of the PV array:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) [1 + \alpha_P (T_C - T_{C,STC})]$$

where:

Y_{PV} is the rated capacity of the PV array, meaning its power output under standard test nditions [kW]

f_{PV} is the PV derating factor [%]

G_T is the solar radiation incident on the PV array in the current time step [kW/m^2]

$G_{T,STC}$ is the incident radiation at standard test conditions [1 kW/m^2]

α_P is the temperature coefficient of power [%/°C]

T_c is the PV cell temperature in the current time step [°C]

$T_{c,STC}$ is the PV cell temperature under standard test conditions [25°C]