
1

MODELING OF THE SOLAR SOURCE

1.1 INTRODUCTION

Solar energy is the portion of the Sun's radiant heat and light, which is available at the Earth's surface for various applications of generating energy, that is, converting the energy form of the Sun into energy for useful applications. This is done, for example, by exciting electrons in a photovoltaic cell, supplying energy to natural processes like photosynthesis, or by heating objects. This energy is free, clean, and abundant in most places throughout the year and is important especially at the time of high fossil fuel costs and degradation of the atmosphere by the use of these fossil fuels. Solar energy is carried on the solar radiation, which consists of two parts: extraterrestrial solar radiation, which is above the atmosphere, and global solar radiation, which is at surface level below the atmosphere. The components of global solar radiation are usually measured by pyranometers, solarimeters, actinography, or pyrheliometers. These measuring devices are usually installed at selected sites in specific regions. Due to high cost of these devices, it is not feasible to install them at many sites. In addition, these measuring devices have notable tolerances and accuracy deficiencies, and consequently wrong/missing records may occur in a measured data set. Thus, there is a need for modeling of the solar source considering solar astronomy and geometry principles. Moreover, the measured solar radiation values can be used for developing solar radiation models that describe the mathematical relations between the solar radiation and the meteorological variables such as ambient temperature,

humidity, and sunshine ratio. These models can be later be used to predict solar radiation at places where there is no solar energy measuring device installed.

1.2 MODELING OF THE SUN POSITION

As a fact, the Earth rotates around the Sun in an elliptical orbit. Figure 1.1 shows the Earth rotation orbit around the Sun. The length of each rotation the Earth makes around the Sun is about 8766 h, which approximately stands for 365.242 days.

From the figure, it can be seen that there are some unique points at this orbit. The winter solstice occurs on December 21, at which the Earth is about 147 million km away from the Sun. On the other hand, at the summer solstice, which occurs on June 21, the Earth is about 152 million km from the Sun. However, to provide more accurate points, the Earth is closest to the Sun (147 million km) on January 2, and this point is called perihelion. The point where the Earth is furthest from the Sun (152 million km) is called aphelion and occurs on July 3.

For an observer standing at specific point on the Earth, the Sun position can be determined by two main angles, namely, *altitude angle* (α) and *azimuth angle* (θ_s), as seen in Figure 1.2.

From Figure 1.2 the altitude angle is the angular height of the Sun in the sky measured from the horizontal. The altitude angle can be given by

$$\sin \alpha = \sin L \sin \delta + \cos L \cos \delta \cos \omega \quad (1.1)$$

where L is the latitude of the location, δ is the angle of declination, and ω is the hour angle.

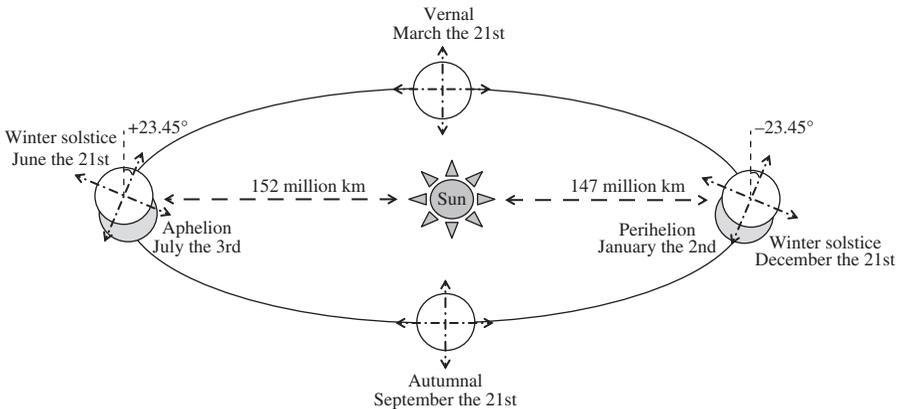


FIGURE 1.1 Earth rotation orbit around the Sun.

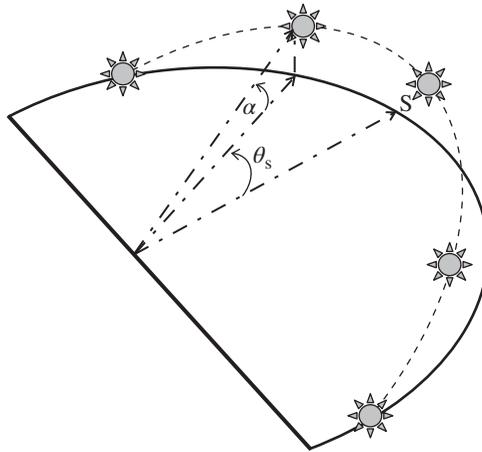


FIGURE 1.2 The Sun's altitude and azimuth angles.

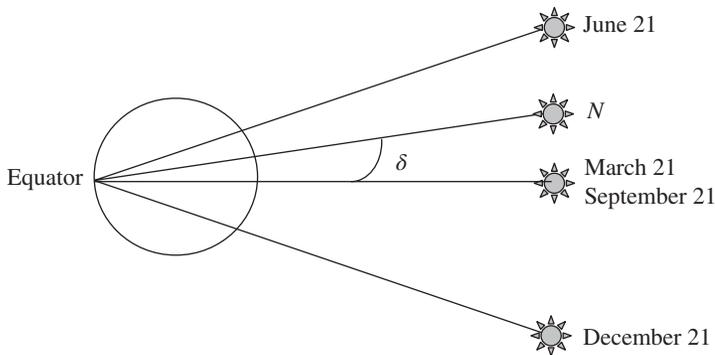


FIGURE 1.3 Solar declination angle.

The angle of declination is the angle between the Earth–Sun vector and the equatorial plane (see Fig. 1.3) and is calculated as follows (results in degree, arguments to trigonomic functions are expected to be in radian):

$$\sigma_s = 23.45^\circ \sin \left[\frac{2\pi(N - 81)}{365} \right] \tag{1.2}$$

The hour angle, ω , is the angular displacement of the Sun from the local point, and it is given by

$$\omega = 15^\circ(\text{AST} - 12 \text{ h}) \tag{1.3}$$

where AST is apparent or true solar time and is given by the daily apparent motion of the true or observed Sun. AST is based on the apparent solar day, which is the interval

between two successive returns of the Sun to the local meridian. Apparent solar time is given by

$$\text{AST} = \text{LMT} + \text{EoT} \pm 4^\circ / (\text{LSMT} - \text{LOD}) \quad (1.4)$$

where LMT is the local meridian time, LOD is the longitude, LSMT is the local standard meridian time, and EoT is the equation of time.

The LSMT is a reference meridian used for a particular time zone and is similar to the prime meridian, used for Greenwich Mean Time. LSMT is given by

$$\text{LMST} = 15^\circ T_{\text{GMT}} \quad (1.5)$$

The EoT is the difference between apparent and mean solar times, both taken at a given longitude at the same real instant of time. EoT is given by

$$\text{EoT} = 9.87 \sin(2B) - 7.53 \cos B - 1.5 \sin B \quad (1.6)$$

where B can be calculated by

$$B = \frac{2\pi}{365}(N - 81) \quad (1.7)$$

where N is the day number defined as the number of days elapsed in a given year up to a particular date (e.g., the 2nd of February corresponds to 33).

On the other hand, the azimuth angle as can be seen in Figure 1.2 is an angular displacement of the Sun reference line from the source axis. The azimuth angle can be calculated by

$$\sin \theta = \frac{\cos \delta \sin \omega}{\cos \alpha} \quad (1.8)$$

Example 1.1: Develop a program in MATLAB® that calculates the altitude and azimuth angles at 13:12 on July 2, for the city of Kuala Lumpur.

Solution

The main parts of the program's structure are described as follows:

- Insert location coordinates (latitude and longitude), day number, and local mean time.
- Calculate angle of declination, equation of time, and LMST.
- Calculate AST and hour angle.
- Calculate altitude angle.
- Calculate azimuth angle.
- Plot results.

Modeling of PV systems using MATLAB

%Chapter I

%Example 1.1

```

%-----
%date 2/7/2015 (N=183)
%location Kuala Lumpur, Malaysia, L =(3.12), LOD = (101.7)
L=3.12; %Latitude
LOD=101.7; %longitude
N=183; %Day Number
T_GMT=8; %Time difference with reference to GMT
LMT_minutes=792; %LMT in minutes
Ds=23.45*sin((360*(N-81)/365)*(pi/180)); % angle of
  declination
B=(360*(N-81))/364; %Equation of Time
EoT=(9.87*sin(2*B*pi/180)) - (7.53*cos(B*pi/180)) -
  (1.5*sin(B*pi/180)); % Equation of Time
Lzt= 15* T_GMT; %LMST
if LOD>=0
Ts_correction= (-4*(Lzt-LOD))+EoT; %solar time correction
else
Ts_correction= (4*(Lzt-LOD))+EoT; %solar time correction
end
Ts= LMT_minutes + Ts_correction; %solar time
Hs=(15 *(Ts - (12*60)))/60; %Hour angle degree
sin_Alpha= (sin (L*pi/180) * sin (Ds*pi/180) ) +
  (cos(L*pi/180)*cos(Ds*pi/180)* cos(Hs*pi/180)); %altitude
  angle
Alpha=asind(sin_Alpha) %altitude angle
Sin_Theta= (cos(Ds*pi/180)*sin (Hs*pi/180)) ./cos(Alpha_i.
  *pi/180); %Azimuth angle
Theta=asind(Sin_Theta) %Azimuth angle

```

ANS: Alpha = 70.04°; theta = -1.13°

Example 1.2: Modify the developed MATLAB code in Example 1.1 to calculate the altitude and azimuth angle profile (every 5 min) for the whole solar day of the 2nd of July for the city of Kuala Lumpur.

Solution

The solar day is defined as the duration from sunrise to sunset. Thus, the altitude and azimuth angles are required to be calculated for each hour from sunrise to sunset. The sunrise and sunset hour angles can be considered equal and calculated as

$$\omega_{ss,sr} = \cos^{-1}(-\tan L \tan \delta) \quad (1.9)$$

In the meanwhile, the solar time of each hour angle can be calculated by rewriting Equations 1.3 as follows:

$$\frac{\omega_{sr,ss}}{15^\circ} \pm 12 \text{ h} = \text{AST}_{sr,ss} \quad (1.10)$$

The sign of Equation 1.10 must be minus if we want to calculate the sunrise time, while it must be plus if we are calculating the sunset time. Following that the main parts of the program's structure can be described as follows:

- Insert location coordinates (latitude and longitude) and day number.
- Calculate angle of declination.
- Calculate sunrise and sunset hour angles.
- Calculate AST of the sunrise and sunset.
- Calculate equation of time and LMST.
- Calculate the actual sunrise and sunset times.
- Set for a loop starting from the sunrise and terminating by the sunset with a step size of 5 min.
- Calculate the solar time and hour angle at each step.
- Calculate altitude angle at each step.
- Calculate azimuth angle at each step.
- Store the calculated altitude and azimuth angles in arrays.
- Plot the results.

```
%Modeling of PV systems using MATLAB
%Chapter I
%Example 1.2
%-----
%Date 2/7/2015 (N=183)
%Location Kuala Lumpur, Malaysia, L=(3.12), LOD=(101.7)
%Actual solar day time 07:11 to 19:22
L=3.12; %altitude
LOD=101.7; %longitude
N=183; %Day Number
T_GMT=8; %Time difference with reference to GMT
Step=5;
Ds=23.45*sin((360*(N-81)/365)*(pi/180)); % angle of
      declination
```

```

Lzt= 15* T_GMT; %LMST
B=(360*(N-81))/364; %Equation of Time
EoT=(9.87*sin(2*B*pi/180))- (7.53*cos(B*pi/180))- (1.5*sin
(B*pi/180)); %Equation of Time
if LOD>=0
Ts_correction= (-4*(Lzt-LOD))+EoT; %solar time correction
else
Ts_correction= (4*(Lzt-LOD))+EoT; %solar time correction
end
Wsr_ssi=- tan(Ds*pi/180)*tan(L*pi/180);%Sunrise/Sunset
hour angle
Wsr_r_ss=acosd(Wsr_ssi);% Sunrise/Sunset hour angle
ASTsr=abs((((Wsr_r_ss/15)-12)*60));%Sunrise solar time
ASTss=(((Wsr_r_ss/15)+12)*60);%Sunset solar time
Tsr=ASTsr+abs(Ts_correction); %Sunrise local time
Tss=ASTss+abs(Ts_correction); %Sunset local time
Alpha=[];
Theta=[];
for LMT=Tsr:Step:Tss %for loop for the day time
Ts= LMT + Ts_correction; % solar time at each step
Hs=(15 *(Ts - (12*60)))/60; % Hour angle degree at each
step
sin_Alpha = (sin(L*pi/180)*sin(Ds*pi/180)) +
(cos(L*pi/180)*cos(Ds*pi/180)*cos(Hs*pi/180)); %altitude
angle
Alpha_i=asind(sin_Alpha) ; %altitude angle
Alpha=[Alpha;Alpha_i];%store altitude angle in array
Sin_Theta=(cos(Ds*pi/180)*sin(Hs*pi/180))./cos(Alpha_i.*pi/
180);%Azimuth angle
Theta_i=asind(Sin_Theta);%Azimuth angle
Theta=[Theta;Theta_i];% store azimuth angle in array
end
Alpha;
Theta;
subplot(2,1,1)%plot results
plot(Alpha)
subplot(2,1,2)
plot(Theta, 'red')

```

ANS

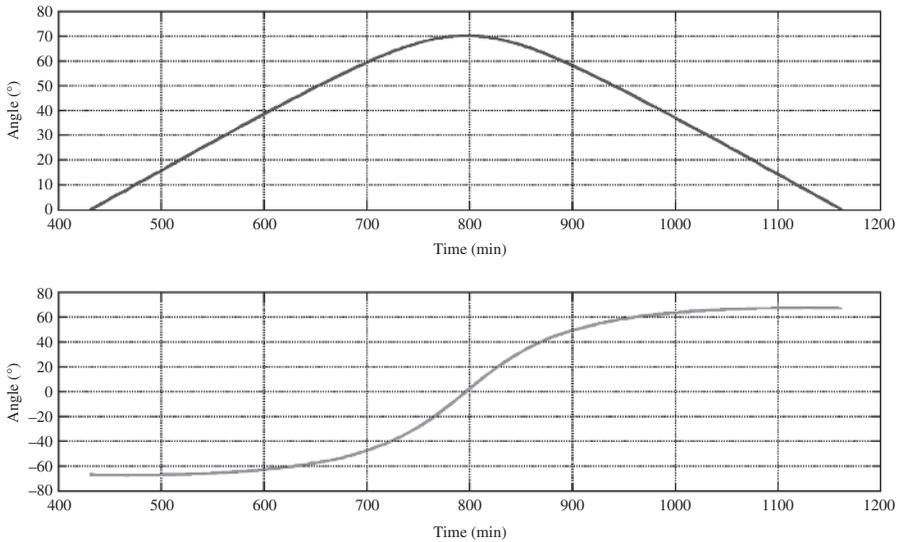


FIGURE 1.4 A day's profile of the Sun's altitude and azimuth angles (Example 1.2).

1.3 MODELING OF EXTRATERRESTRIAL SOLAR RADIATION

The first step in modeling the solar source is to estimate the emitted radiation from the Sun. As a fact, the radiant energy of any emitting object can be described as a function of its temperature. The usual practice to estimate the radiant energy by an object is to compare it to a blackbody. A blackbody is defined as a perfect emitter and absorber. A perfect absorber can absorb all of the received energy with any reflections, while a perfect emitter emits energy more than any other object. Planck's law describes the wavelengths emitted by a blackbody at a specific temperature as follows:

$$E_{\lambda} = \frac{3.74 \times 10^8}{\lambda^5 \left[\exp \frac{14,400}{\lambda T} \right] - 1} \quad (1.11)$$

where E_{λ} is the total emissive per unit area of blackbody emission rate ($\text{W}/\text{m}^2 \mu\text{m}$), T is the absolute temperature of the blackbody (K), and λ is the wavelength (μm).

Example 1.3: Develop a MATLAB code that calculates the spectral emissive power of a 288 K blackbody, for wavelengths in the range of (1–60) μm . After that calculate the power emitted between the wavelength of 20 and 30 μm .

Solution

The first part of the example can be solved by simply implementing Equation 1.11 and calculating its value for the requested wavelength range as follows:

```
%Modeling of PV systems using MATLAB
%Chapter I
%Example 1.3
```

```

%-----
T=288;
E_lambda=[];
for lamda=1:1:60;
E_lambda_i= (3.74*10e8)/(lamda^5*(exp(14400/(lamda*T))-1));
E_lambda=[E_lambda; E_lambda_i];
end
E_lambda
lamda=1:1:60;
plot(lamda,E_lambda)
    
```

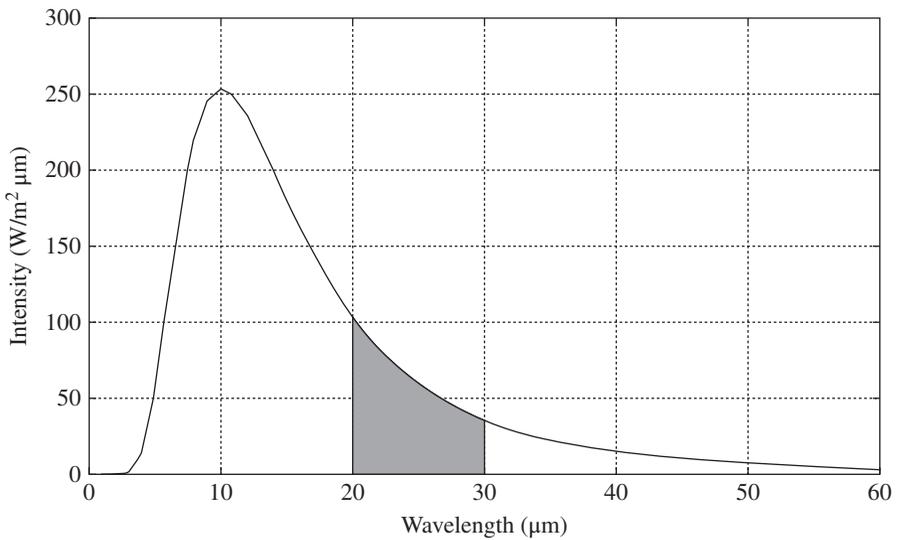


FIGURE 1.5 Spectral emissive power of a 288 K blackbody, for wavelengths in the range of (1–60) μm (Example 1.3).

In order to calculate the emitted power between the wavelength value of 20 and 30 μm, the shaded area in Figure 1.5 can be calculated as follows:

$$\sum_{\lambda=20}^{\lambda=30} E_{\lambda} = \sum_{\lambda=20}^{\lambda=30} \frac{3.74 \times 10^8}{\lambda^5 \left[\exp \frac{14,400}{\lambda T} \right] - 1} \tag{1.12}$$

which can be implemented in MATLAB as follows:

```

T=288;
E_lambda=[];
for lamda=20:1:30;
    
```

```

E_lambda_i = (3.74 * 10e8) / (lambda^5 * (exp(14400 /
(lambda*T)) - 1));
E_lambda = [E_lambda; E_lambda_i];
end
E_lambda;
Power = sum(E_lambda)

```

ANS = 704.0801 W/m²

The interior of the Sun is estimated to have a temperature of around 15 million Kelvin, while the surface temperature is, relatively speaking, much cooler and lies approximately at 5778 K (5505°C). Thus, the radiation that is emitted from the Sun's surface has a spectral distribution matching the prediction by Planck's law for a 5800 K blackbody. The total area under the blackbody curve has been scaled to equal to (1307–1393) W/m², which is the solar radiation amount just outside Earth's atmosphere. This amount of radiation is called *solar constant* (G_o), although it is not exactly constant due to the elliptical orbit of Earth, Earth's diameter, and changing conditions in solar activity. A recommended value of solar constant by many researchers is 1367 W/m².

Solar radiation value outside the atmosphere varies as the Earth orbits the Sun. Therefore, the distance between the Sun and the Earth must be considered in modeling the extraterrestrial solar radiation. Thus, the extraterrestrial radiation (G_{ex}) is given by

$$G_{ex} = G_o \left(\frac{R_{av}}{R} \right)^2 \quad (1.13)$$

where R_{av} is the mean distance between the Sun and the Earth and R is the instantaneous distance between the Sun and the Earth. The instantaneous distance between the Sun and the Earth depends on the day of the year or *day number*. In fact there are different approximations for the factor (R_{av}/R) in the literature. A recommended approximation can be given by

$$\left(\frac{R_{av}}{R} \right) = 1 + 0.0333 \cos \left(\frac{2\pi N}{365} \right) \quad (1.14)$$

By substituting Equation 1.14 in Equation 1.13, the extraterrestrial solar radiation unit of time falling at a right on square meter of a surface can be given by

$$G_{ex} = G_o \left(1 + 0.0333 \cos \left(\frac{2\pi N}{365} \right) \right)^2 \quad (1.15)$$

However, an instructional concept, and one often used in solar radiation models, is that of the extraterrestrial solar irradiance *falling on a horizontal surface*. Consider a flat surface just outside the Earth's atmosphere and parallel to the Earth's surface

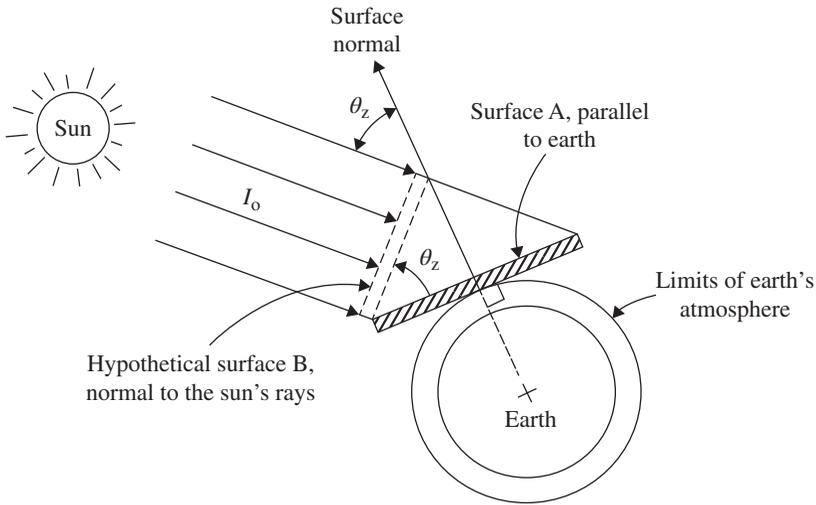


FIGURE 1.6 Calculation of extraterrestrial solar radiation on a horizontal surface.

below. When this surface faces the Sun (normal to a central ray), the solar irradiance falling on it will be G_{ex} , the maximum possible solar radiation at that distance. If the surface is not normal to the Sun, the solar radiation falling on it will be reduced by the cosine of the angle between the surface normal and a central ray from the Sun. This concept is described in Figure 1.6. From the figure it can be seen that the rate of solar energy falling on both surfaces is the same. However, the area of surface A is greater than its projection, hypothetical surface B, making the rate of solar energy per unit area falling on surface A less than on surface B.

Thus, the extraterrestrial solar radiation on a horizontal surface located in a specific location (G_{exH}) can be calculated by

$$G_{exH} = G_{ex} \cos \varphi \tag{1.16}$$

where φ is the solar zenith angle, which is measured from directly overhead to the geometric center of the Sun's disc. The solar zenith angle value is equal to the altitude value, and thus Equation 1.16 can be rewritten as follows:

$$G_{exH} = G_o \left(1 + 0.0333 \cos \left(\frac{360N}{365} \right) \right) \sin L \sin \delta + \cos L \cos \delta \cos \omega \tag{1.17}$$

Finally, the total extraterrestrial solar energy (E_{ex}) (Wh/m^2) is calculated as follows:

$$E_{ex} = \int_{T_{sr}}^{T_{ss}} G_{exH} dt \tag{1.18}$$

Example 1.4: Develop a MATLAB program that predicts the hourly extraterrestrial solar radiation profile for Nablus city, Palestine, on the 31st of March.

Solution

According to Equation 1.17, the hourly values of the altitude angle of the selected location must be calculated first (see Example 1.2). After that the value of the hourly solar radiation can be generated using Equation 1.17 as follows:

```
%Modeling of PV systems using MATLAB
%Chapter I
%Example 1.4
%-----
%Date 31/3/2015 (N=90)
%Location Nablus, Palestine, L =(32.22), LOD = (35.27)
L=32.22; %Latitude
LOD=35.27; %Longitude
N=90; %day number
T_GMT=+3; %Time difference with reference to GMT
Step=60; %step each hour
Ds=23.45*sin((360*(N-81)/365)*(pi/180)); % angle of
    declination
B=(360*(N-81))/364; %Equation of time
EoT=(9.87*sin(2*B*pi/180))- (7.53*cos(B*pi/180))- (1.5*sin
    (B*pi/180)); %Equation of time
Lzt= 15* T_GMT; %LMST
if LOD>=0
Ts_correction= (-4*(Lzt-LOD))+EoT; %solar time correction
else
Ts_correction= (4*(Lzt-LOD))+EoT; %solar time correction
end
Wsr_ssi=- tan(Ds*pi/180)*tan(L*pi/180); %Sunrise/Sunset
    hour angle
Wrsr_ss=acosd(Wsr_ssi); %Sunrise/Sunset hour angle
ASTsr=abs(((Wrsr_ss/15)-12)*60); %Sunrise solar time
ASTss=(((Wrsr_ss/15)+12)*60); %Sunset solar time Tsr=ASTsr+
    abs(Ts_correction) %Actual Sunrise time
Tss=ASTss+abs(Ts_correction) %Actual Sunset time
sin_Alpha=[];
for LMT=Tsr:Step:Tss %for loop for the day time
Ts= LMT + Ts_correction; %solar time at each step
Hs=(15 *(Ts - (12*60)))/60; %hour angle at each step
sin_Alpha_i=(sin(L*pi/180)*sin(Ds*pi/180))+
    (cos(L*pi/180)*cos(Ds*pi/180)*cos(Hs*pi/180)); %altitude
    angle
```

```

sin_Alpha=[sin_Alpha;sin_Alpha_i];    % store altitude
angle results
end
LMT=Tsr:Step:Tss
sin_Alpha;
Go=1367; %solar constant
Gext=Go*(1+(0.0333*cos(360*N/365))); %available Gext
GextH=Gext*sin_Alpha; %Gex on horizontal surface
plot(LMT,GextH) %plot results
    
```

ANS

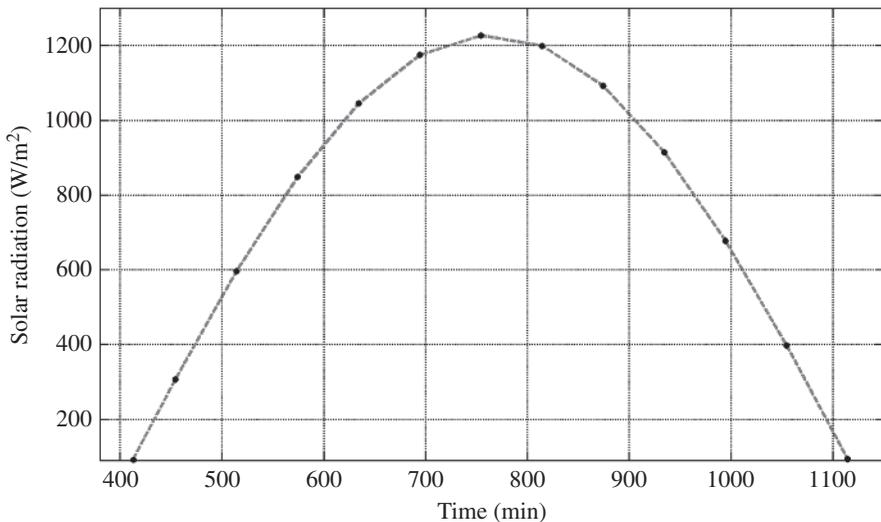


FIGURE 1.7 Daily extraterrestrial solar radiation for Nablus city (Example 1.4).

1.4 MODELING OF GLOBAL SOLAR RADIATION ON A HORIZONTAL SURFACE

The global solar radiation (terrestrial solar radiation) (G_T) is the available solar radiation at sea level below the Earth’s atmosphere. The global solar radiation that falls on a horizontal surface is consisted of two components, namely, direct (beam) and diffuse solar radiation. Figure 1.8 illustrates the component of solar radiation on a horizontal surface. The direct solar radiation (G_B) is the beam that falls directly from the Sun, while the diffuse solar radiation (G_D) is the radiation that is being scattered by clouds and other particles in the sky.

Based on that the G_T can be described as

$$G_T = G_B + G_D \tag{1.19}$$

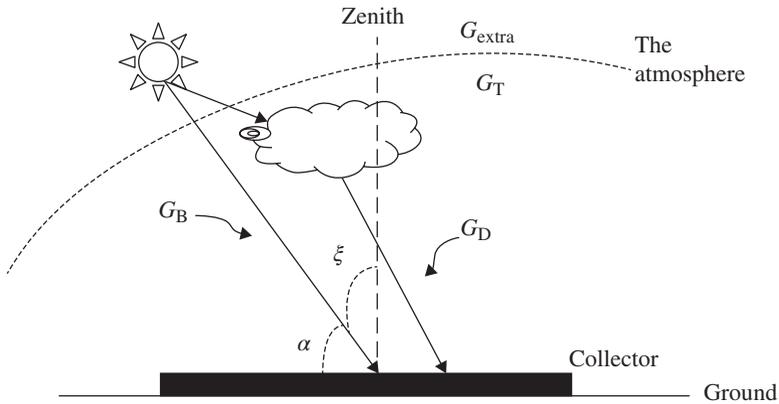


FIGURE 1.8 Components of global solar radiation on a horizontal surface.

As the extraterrestrial solar radiation beam passes through the atmosphere, many components of this beam is absorbed, attenuated, and scattered by sky gases or air molecules. For a clear sky day, 70% of the global solar radiation is direct solar radiation. The attenuation of this beam due to dust, air pollution, water vapor, clouds, and turbidity can be modeled relatively easily. However there are many attempts to model this attenuation as a function of day number. One of these models is the ASHRAE model or clear sky model, as it is called sometimes. According to this model, the direct solar radiation reaching the Earth surface ($G_{B, \text{norm}}$) can be expressed as

$$G_{B, \text{norm}} = A e^{\frac{-K}{\sin \alpha}} \quad (1.20)$$

where A is an apparent extraterrestrial flux and K is a dimensionless factor called optical depth. A and K factors can be expressed as functions of day number as follows:

$$A = 1160 + 75 \sin \left[\frac{360}{365} (N - 275) \right] \quad (1.21)$$

$$K = 0.174 + 0.035 \sin \left[\frac{360}{365} (N - 100) \right] \quad (1.22)$$

Now the direct solar radiation collected by a horizontal surface G_B can be expressed by

$$G_B = G_{B, \text{norm}} \sin \alpha \quad (1.23)$$

On the other hand, the calculation of diffuse radiation falling on a horizontal surface collector is more difficult as compared to the calculation of direct solar radiation. Incoming radiation can be scattered from atmospheric particles and water vapor, and it can be reflected by clouds. Some radiation is reflected from the surface back into the sky and scattered again back to the ground. The simplest models of diffuse radiation assume it arrives at a site with equal intensity from all directions; that is, the sky is considered to be isotropic. Obviously, on hazy or overcast days, the sky is considerably brighter in the vicinity of the Sun, and measurements show a similar phenomenon on clear days as well, but these complications are often ignored. Following that, the diffuse solar radiation can be approximated by

$$G_D = 0.095 + 0.04 \sin \left[\frac{360}{365} (N - 100) \right] G_{B, \text{norm}} \quad (1.24)$$

Example 1.5: Develop a MATLAB code that predicts hourly global and diffuse solar radiation profile on a horizontal surface for Kuwait City, Kuwait, on the 2nd of May from sunrise time to sunset time.

Solution

The program required is divided into two parts: the calculation of the altitude angle and then the calculation of the solar radiation component. The first part is illustrated in previous examples like Example 1.2. In the meanwhile in the second part, equations from 1.19 to 1.24 are coded as follows:

```
%Modeling of PV systems using MATLAB
%Chapter I
%Example 1.5
%-----
%Date 02/05/2015 (N=122)
%Location Kuwait City, Kuwait, L =(29.36), LOD = (47.97)
L=29.36; %latitude
LOD=47.97; %longitude
N=122; %day number
T_GMT=+3; %time difference with reference to GMT
Step=60; %time step
Ds=23.45*(sind((360*(N-81)/365))); % angle of declination
%=====
B=(360*(N-81))/364; %Equation of time
EoT=(9.87*sin(2*B*pi/180)) - (7.53*cos(B*pi/180)) - (1.5*sin
(B*pi/180)); %Equation of time
Lzt= 15* T_GMT; %LMST
if LOD>=0
```

```

Ts_correction= (-4*(Lzt-LOD))+EoT; %solar time correction
else
Ts_correction= (4*(Lzt-LOD))+EoT; %solar time correction
end
Wsr_ssi=- tan(Ds*pi/180)*tan(L*pi/180); %Sunrise/Sunset
hour angle
Wsrssr_ss=acosd(Wsr_ssi); %Sunrise/Sunset hour angle
ASTsr=abs(((Wsrssr_ss/15)-12)*60)); %Sunrise solar time
ASTss=(((Wsrssr_ss/15)+12)*60); %Sunset solar time
Tsr=ASTsr+abs(Ts_correction) %Actual Sunrise time
Tss=ASTss+abs(Ts_correction) %Actual Sunset time
sin_Alpha=[];
for LMT=Tsr:Step:Tss %for loop for the day time
Ts= LMT + Ts_correction; %solar time
Hs=(15 *(Ts - (12*60)))/60; %Hour angle degree
sin_Alpha_i=(sin(L*pi/180)*sin(Ds*pi/180))+
(cos(L*pi/180)*cos(Ds*pi/180)*cos(Hs*pi/180)); %altitude
angle
sin_Alpha=[sin_Alpha;sin_Alpha_i]; % Store altitude
angle
end
sin_Alpha
%=====solar radiation calculation=====
A=1160+(75*sind((360/365)*(N-275))); %extraterrestrial
solar energy flux
k= 0.174+ (0.035*sind((360/365)*(N-100))); %k is a
factor
C= 0.095+ (0.04*sind((360/365)*(N-100))); %C is a
factor
G_B_norm=A*exp(-k./sin_Alpha) % available beam radiation
in the sky
G_B=G_B_norm.*sin_Alpha; %collected beam solar radiation
by the collector on a horizontal surface
G_D=C*G_B_norm; %diffuse on horizontal surface
G_T= G_B+G_D
%--actual global solar radiation data for Kuwait city
*10e3----
G_A=[000 0.2431 0.4422 0.5966 0.865 0.976 1.031 1.016
0.936 0.788 0.5904 0.3541 0.1439];
LMT=Tsr:Step:Tss
plot(LMT,G_T)
holdon
plot(LMT,G_A*1e3, 'red')

```

ANS

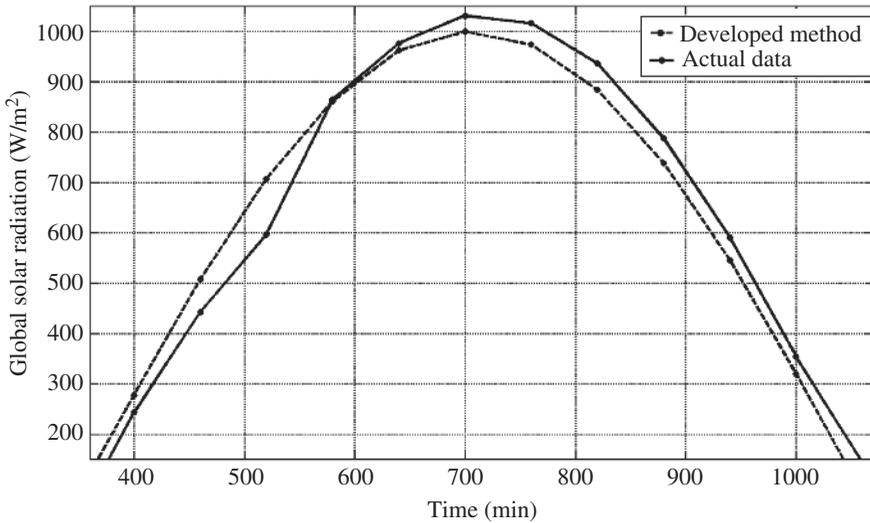


FIGURE 1.9 Global solar radiation for Kuwait City (Example 1.5).

1.5 MODELING OF GLOBAL SOLAR RADIATION ON A TILT SURFACE

In the case of the tilted collector, the components of incident global solar radiation on a tilted surface are shown in Figure 1.10. In addition to the direct ($G_{B,\beta}$) and diffuse ($G_{D,\beta}$) solar radiation, a new component called reflected solar radiation (G_R) is added to form the global solar radiation incident on a tilted surface.

These components can be expressed by

$$G_{T,\beta} = G_{B,\beta} + G_{D,\beta} + G_R \tag{1.25}$$

Equation 1.25 can be rewritten in terms of solar energy components on a horizontal surface as follows:

$$G_{T,\beta} = G_B R_B + G_D R_D + G_T \rho R_R \tag{1.26}$$

where R_B , R_D , and R_R are coefficients and ρ is ground Albedo. R_B is the ratio between global solar energy on a horizontal surface and global solar energy on a tilted surface. R_D is the ratio between diffuse solar energy on a horizontal surface and diffuse solar energy on a tilted surface, and R_R is the factor of reflected solar energy on a tilted surface.

From Equation 1.26 it is clear that the key of finding solar energy components on a tilted surface is to estimate the coefficients R_B , R_D , and R_R . The most often used model for calculating R_B is the Liu and Jordan model, which defines R_B as

$$R_B = \frac{\cos(L - \beta) \cos \delta \sin \omega_{ss} + \omega_{ss} \sin(L - \beta) \sin \delta}{\cos L \cos \delta \sin \omega_{ss} + \omega_{ss} \sin L \sin \delta} \tag{1.27}$$

On the other hand, anisotropy is the property of being directionally dependent, as opposed to isotropy, which implies identical properties in all directions. It can be defined as a difference, when measured along different axes, of a material’s physical property (absorbance, refractive index, density, etc.). Therefore, anisotropic solar models are based on the hypothesis that anisotropic radiation has a different intensity depending on the direction of measurement, and it radiates nonuniformly in all directions. Some of the anisotropic moles presented for R_D are the following:

$$R_D = \frac{G_B}{G_T} R_D + \left(1 - \frac{G_B}{G_T}\right) \left(\frac{1 + \cos \beta}{2}\right) \tag{1.34}$$

$$R_D = 0.51R_B + \frac{1 + \cos TLT}{2} - \frac{1.74}{1.26\pi} \left[\sin \beta = \left(\beta \frac{\pi}{180}\right) \cos \beta - \pi \sin^2 \left(\frac{\beta}{2}\right) \right] \tag{1.35}$$

$$R_D = \frac{G_B}{G_T} R_B + \left(1 - \frac{G_B}{G_T}\right) \left(\frac{1 + \cos \beta}{2}\right) \left(1 + \sqrt{\frac{G_B}{G_T}} \sin^3 \left(\frac{\beta}{2}\right)\right) \tag{1.36}$$

Example 1.6: Develop a MATLAB program that predicts the hourly global and diffuse solar radiation on a tilted surface for Kuwait City, Kuwait, on the 31st of March from sunrise time to sunset time. Assume that tilt angle is equal to latitude angle.

Solution

```
%Modeling of PV systems using MATLAB
%Chapter I
%Example 1.6
%-----31/03/2015 (N=90)
%Location Kuwait, Kuwait, L =(29.36), LOD = (47.97)
L=29.36; %latitude
LOD=47.97; %longitude
N=90; %day number
T_GMT=+3; %time difference with reference to GMT
Step=60; %time step
Ds=23.45*(sind((360*(N-81)/365))); % angle of
declination
%=====
B=(360*(N-81))/364; %Equation of time
EoT=(9.87*sin(2*B*pi/180)) - (7.53*cos(B*pi/180)) - (1.5*sin
(B*pi/180)); %Equation of time
Lzt= 15* T_GMT; %LMST
if LOD>=0
```

```

Ts_correction= (-4*(Lzt-LOD))+EoT; %solar time correction
else
Ts_correction= (4*(Lzt-LOD))+EoT; %solar time correction
end
Wsr_ssi=- tan(Ds*pi/180)*tan(L*pi/180); %Sunrise/Sunset
hour angle time
Wsrssr_ss=acosd(Wsr_ssi) %Sunrise/Sunset hour angle time
ASTsr=abs(((Wsrssr_ss/15)-12)*60)); %Sunrise solar time
ASTss=((Wsrssr_ss/15)+12)*60 %Sunset solar time
Tsr=ASTsr+abs(Ts_correction); Sunrise time
Tss=ASTss+abs(Ts_correction); Sunset time
sin_Alpha=[];
for LMT=Tsr:Step:Tss-60
Ts= LMT + Ts_correction; % solar time
Hs=(15 *(Ts - (12*60)))/60; % Hour angle degree
sin_Alpha_i=(sin(L*pi/180)*sin(Ds*pi/180))+
(cos(L*pi/180)*cos(Ds*pi/180)*cos(Hs*pi/180)); %altitude
angle
sin_Alpha=[sin_Alpha;sin_Alpha_i];
end
sin_Alpha;
%=====
A=1160+(75*sind((360/365)*(N-275))); %extraterrestrial
solar energy flux
k= 0.174+ (0.035*sind((360/365)*(N-100))); %k is a factor
C= 0.095+ (0.04*sind((360/365)*(N-100))); %C is a factor
%-----calculation of solar radiation on horizontal surface
-----
G_B_norm=A*exp(-k./sin_Alpha) % available beam radiation
in the sky
G_B=G_B_norm.*sin_Alpha; %collected beam solar radiation
by the collector on a horizontal surface
G_D=C*G_B_norm; %diffuse on horizontal surface
G_T= G_B+G_D;
%-----calculation of solar radiation on tilt surface
-----
Beta=L; %tilt angle
Rb=((cos((L-Beta).*(pi/180)).*cos(Ds.*(pi/180)).*sin(Ws
rsr_ss.*(pi/180))+ ...
... (Wsrssr_ss.*(pi/180)).*sin((L-Beta).*(pi/180)).*sin(Ds.
*(pi/180))))./...
... (((cos(L*(pi/180)).*cos(Ds.*(pi/180)).*sin(Wsrssr_ss.
*(pi/180)))+...
... ((Wsrssr_ss.*(pi/180)).*sin(L*(pi/180)).*sin(Ds.*(pi/
180))))));

```

```

Rd= (1+cos (Beta* (pi/180))) ./2;
Rr= (0.3*(1-cos (Beta* (pi/180)))) ./2;
G_B_Beta=(G_B.*Rb) ;
G_D_Beta=(G_D.*Rd) ;
G_R=(G_T.*Rr) ;
G_T_Beta=G_B_Beta+G_D_Beta+G_R;
LMT=Tsr:Step:Tss-60;
plot (LMT,G_T)
holdon
plot (LMT,G_T_Beta, 'k')
    
```

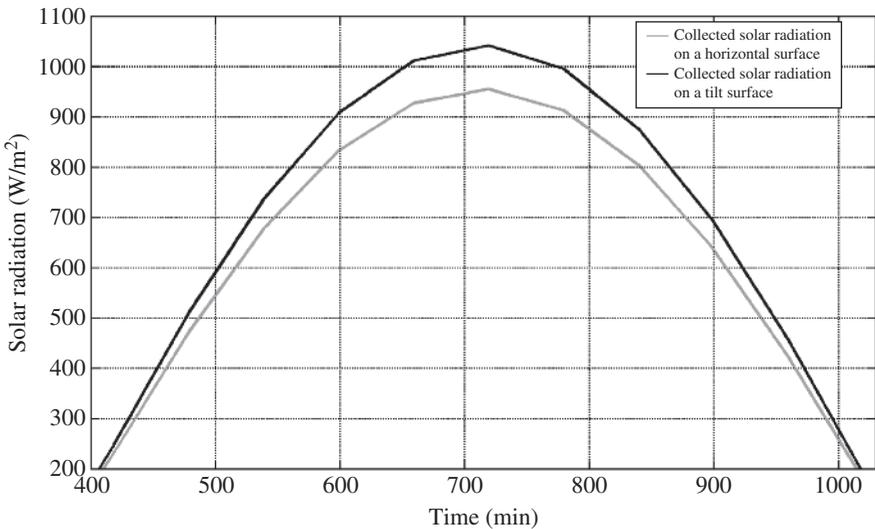


FIGURE 1.11 Global solar radiation on horizontal and tilted surfaces for Kuwait City (Example 1.6).

1.6 MODELING OF SOLAR RADIATION BASED ON GROUND MEASUREMENTS

The commonly used input variables are the sunshine ratio, ambient temperature, and relative humidity to predict global solar energy at different locations.

The global solar energy on a horizontal surface is the average of global solar radiation multiplied by the length of the solar day. The solar day length (S_o) is calculated by

$$S_o = \frac{2}{15} \cos^{-1}(-\tan L \tan \delta) \tag{1.37}$$

The global solar energy strongly depends on a factor called the sunshine ratio. High sunshine ratio means high solar energy and vice versa. The sunshine ratio is given by

$$\frac{S}{S_o} = \frac{(10-1.25C)}{10} 0.0 < \frac{S}{S_o} < 1.0 \quad (1.38)$$

where S_c is the number of shining hours in a solar day and C is the measured daily mean cloud cover with values from 0 for clear sky to 10 for being fully overcast.

1.6.1 Modeling of Global Solar Radiation

Many models have been presented in the literature for modeling global solar energy on a horizontal surface. In general, there are four kinds of global solar energy models, namely, linear, nonlinear, fuzzy logic, and AI-based models. The global solar radiation has a linear relation with the sunshine hours. Therefore, a linear model can be developed to calculate the global solar energy based on the sunshine hours. One of the most often used models for this purpose is given in the following:

$$\frac{G_T}{G_{ex}} = a + b \frac{S}{S_o} \quad (1.39)$$

As for the determination of the coefficients a and b , there are different possibilities to calculate the optimum value of these coefficients. The first global solar energy estimation model known as the Angström model derived from sunshine duration data defines the values of a and b as follows:

$$b = \frac{\sum_{i=1}^n \left[\left(\frac{G_T}{G_{ex}} \right)_i - \left(\frac{S}{S_o} \right)_i \right] \left[\left(\frac{G_T}{G_{ex}} \right)_{i-1} - \left(\frac{S}{S_o} \right)_{i-1} \right]}{\sqrt{\sum_{i=1}^n \left[\left(\frac{G_T}{G_{ex}} \right)_i - \left(\frac{S}{S_o} \right)_{i-1} \right]^2 \left[\left(\frac{G_T}{G_{ex}} \right)_{i-1} - \left(\frac{S}{S_o} \right)_{i-1} \right]^2}} \quad (1.40)$$

$$a = \left(\frac{G_T}{G_{ex}} \right) - b \left(\frac{S}{S_o} \right) \quad (1.41)$$

Example 1.7: Develop a linear model for a monthly average of daily solar radiation based on the data in the following table using MATLAB. Assume that the solar time is equal to the local time.

Solution

```
%Modeling of PV systems using MATLAB
%Chapter I
%Example 1.7
```

```

fileName = 'PV Modeling Book Data Source.xls';
sheetName = 'Source 1' ;
L=3.11;
LOD=101.6;
Go=1367;
%-----
G_T=xlsread(fileName, sheetName , 'E5:E3640');
S_So=xlsread(fileName, sheetName , 'I5:I3640');
N=xlsread(fileName, sheetName , 'C5:C3640');
LMT= xlsread(fileName, sheetName , 'D5:D3640');
Ts=LMT; %assumption
%-----calculation of Gext-----
Ds=23.45*sin((360*(N-81)/365)*(pi/180));% angle of
declination
Hs=15 *(Ts - 12); % Hour angle degree
sin_Alpha=(sin(L*pi/180).*sin(Ds.*pi/180))+ (cos(L*pi/18
0)*cos(Ds.*pi/180).* cos(Hs.*pi/180)); %altitude angle
Gext=Go*(1+(0.0333*cos(360*N/365)));
GextH=Gext.*sin_Alpha;
G_T_G_ext=G_T./GextH;
%-----Modeling of global solar energy-----
-----
N_Liner=1;%order of the model ex nonlinear model (Eq.28),
N_Liner=2
P_Liner=polyfit(S_So,G_T_G_ext,N_Liner)
X_Liner=S_So;
Y_Liner=0;
fori=1:N_Liner+1 %constant calculation
Y_Liner=Y_Liner+P_Liner(i)*X_Liner.^(N_Liner-i+1);
end
plot(S_So,G_T_G_ext)
holdon
plot(X_Liner,Y_Liner, '-red')

```

ANS

$$\frac{G_T}{G_{ex}} = 0.2743 + 0.2772 \frac{S}{S_0} \quad (1.42)$$

On the other hand, some authors have suggested changing the model by adding a nonlinear term to the Angström model as follows:

$$\frac{G_T}{G_{ex}} = a + b \frac{S}{S_0} + c \left(\frac{S}{S_0} \right)^2 \quad (1.43)$$

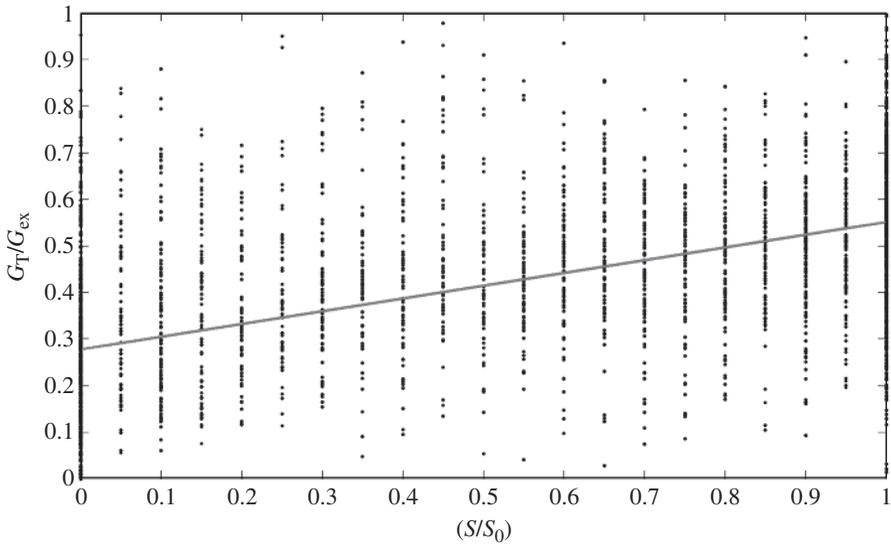


FIGURE 1.12 Modeling of global solar radiation on a horizontal surface using linear model. (See insert for color representation of the figure.)

A number of theoretical studies have shown the sensitivity of cloud irradiative properties to their spatial structure affecting the sunshine duration and, subsequently, the global solar energy amounts. It is, therefore, important to preserve in any estimation procedure the third- or higher-order statistical moments. One way of incorporating these moments in the model is the inclusion of a third power of the sunshine duration variable given as

$$\frac{G_T}{G_{ex}} = a + b \frac{S}{S_0} + c \left(\frac{S}{S_0} \right)^2 + d \left(\frac{S}{S_0} \right)^3 \quad (1.44)$$

In addition to that, there are ambiguities and vagueness in solar energy and sunshine duration records during a day. A fuzzy logic algorithm can be devised for tackling these uncertainties and estimating the amount of solar radiation. The main advantage of the fuzzy logic model is the ability to describe the knowledge in a descriptive humanlike manner in the form of simple logical rules using linguistic variables only. The fuzzy logical propositions in the forms of IF–THEN statements are, for example:

IF sunshine duration is “long,” THEN the solar energy amount is “high.”
IF sunshine duration is “short,” THEN the solar energy amount is “small.”

In these two propositions solar energy variables of sunshine duration and solar energy are described in terms of linguistic variables such as “long,” “high,” “short,” and “small.” Indeed, these two propositions are satisfied logically by a simple Angström model.

1.6.2 Modeling of Diffuse Solar Radiation

Many linear models described the relation between G_D/G_T and the clearness index K_T , which equals to G_T/G_{ex} . The general equation of a linear model that calculates the diffuse solar energy can be expressed as follows:

$$\frac{G_D}{G_T} = a + bK_T \tag{1.45}$$

where a and b are the coefficients of the model.

In the meanwhile, the same relationship between G_D/G_T and the clearness index K_T can be described by the following nonlinear model:

$$\frac{G_D}{G_T} = a + bK_T + cK_T^2 + dK_T^3 \tag{1.46}$$

Example 1.8: Red o Example 1.7 for diffuse solar radiation.

Solution

```
%Modeling of PV systems using MATLAB
%Chapter I
%Example 1.7
fileName1 = 'PV Modeling Book Data Source.xls';
sheetName = 'Source 1' ;
L=3.11;
LOD=101.6;
Go=1367;
%-----
G_T=xlsread(fileName1, sheetName , 'E5:E3640');
G_D=xlsread(fileName1, sheetName , 'F5:F3640');
N=xlsread(fileName1, sheetName , 'C5:C3640');
LMT= xlsread(fileName1, sheetName , 'D5:D3640');
Ts=LMT; %assumption
%-----calculation of Gext-----
Ds=23.45*sin((360*(N-81)/365)*(pi/180));% angle of
declination
Hs=15 *(Ts - 12); Hour angle degree
sin_Alpha=(sin(L*pi/180).*sin(Ds.*pi/180))+ (cos(L*pi/180)
*cos(Ds.*pi/180).* cos(Hs.*pi/180)); %altitude angle
Gext=Go*(1+(0.0333*cos(360*N/365)));
GextH=Gext.*sin_Alpha;
G_T_G_ext=G_T./GextH;
G_D_G_T=G_D./G_T;
%-----Modeling of diffuse solar energy-----
-----
```

```

N_Liner=1;
P_Liner=polyfit(G_T_G_ext,G_D_G_T,N_Liner)
X_Liner=G_T_G_ext;
Y_Liner=0;
fori=1:N_Liner+1
Y_Liner=Y_Liner+P_Liner(i)*X_Liner.^(N_Liner-i+1);
end
plot(G_T_G_ext,G_D_G_T)
hold on
plot(X_Liner,Y_Liner,'-red')

```

ANS

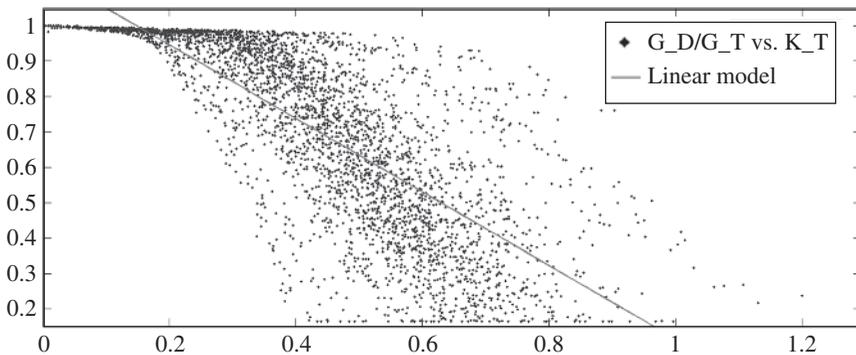


FIGURE 1.13 Modeling of diffuse solar radiation on a horizontal surface using linear model. (See insert for color representation of the figure.)

1.7 AI TECHNIQUES FOR MODELING OF SOLAR RADIATION

Artificial neural networks (ANNs) are information processing systems that are non-algorithmic and intensely parallel and learn the relationship between the input and output variables by examples, for example, from previously recorded data. In ANNs, the neurons are connected by a large number of weighted links, over which signals can pass. A neuron receives inputs over its incoming connections, combines the inputs, generally performs a nonlinear operation, and outputs the final results. We used a MATLAB program to train and develop ANNs for modeling of the global solar energy. We used a feedforward, multilayer perceptron (FFMLP) network because it is the most commonly used ANN that learns from examples, and it is suitable for the task. A schematic diagram of the basic ANN architecture is shown in Figure 1.14. The network has three layers: the input, hidden, and output layer. Each layer is interconnected by connections of different strengths, called weights.

Four geographical and climatic variables are used as input features of the FFMLP. These variables are the day number, latitude, longitude, and daily sunshine hour ratio (measured sunshine duration over daily maximum possible sunshine duration). There is

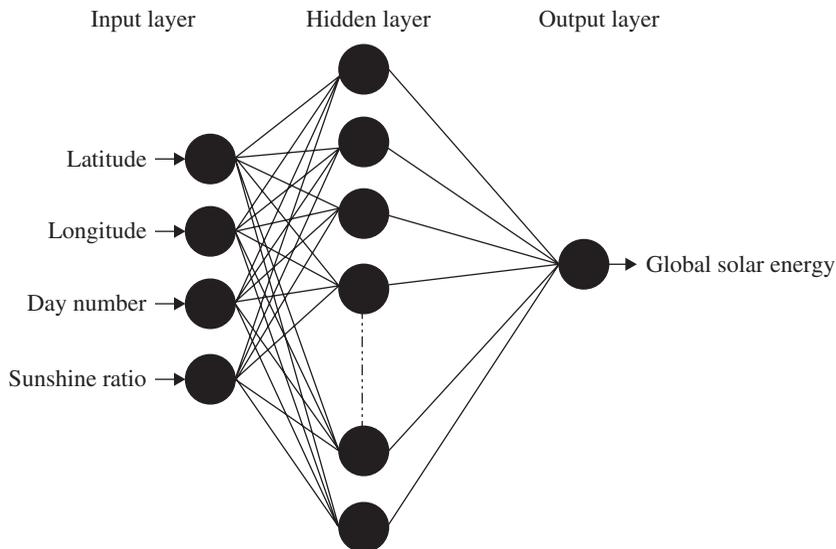


FIGURE 1.14 Topology of the ANN used to model the global solar energy.

a single output node to represent the estimated daily clearness index prediction as the output. The transfer function adopted for the neurons is a logistic sigmoid function $f(z_i)$,

$$f(z_i) = \frac{1}{1 + e^{-z_i}} \quad (1.47)$$

$$z_i = \sum_{j=1}^4 w_{ij} x_j + \beta_i \quad (1.48)$$

where z_i is the weighted sum of the inputs, x_j is the incoming signal from the j th neuron of the input layer, w_{ij} is the weight on the connection from neuron j to neuron i at the hidden layer, and β_i is the bias of neuron i .

Neural networks learn to solve a problem rather than being programmed to do so. Learning is achieved through training. In other words, training is the procedure by which the networks learn to minimize the error between its output value and a reference value. In FFMLP, the error is propagated backward using the so-called backpropagation training algorithm, from the output layer, via the hidden layer, to the input layer, and the weights on the interconnections between the neurons are updated as the error is backpropagated. A multilayer network can mathematically approximate any continuous multivariate function to any degree of accuracy, provided that a sufficient number of hidden neurons are available. A possible problem can be that instead of learning and generalizing the basic structure of the data, the network may learn irrelevant details of individual cases.

The same ANN topology, which has been used in modeling the global solar energy, is also used in modeling the diffuse solar energy. Figure 1.15 shows the ANN for the diffuse solar energy prediction. The network has four inputs comprising of latitude, longitude, clearness index, and day number and one output variable, which is the diffuse solar energy. Figure 1.16 shows the performance of such an ANN model.

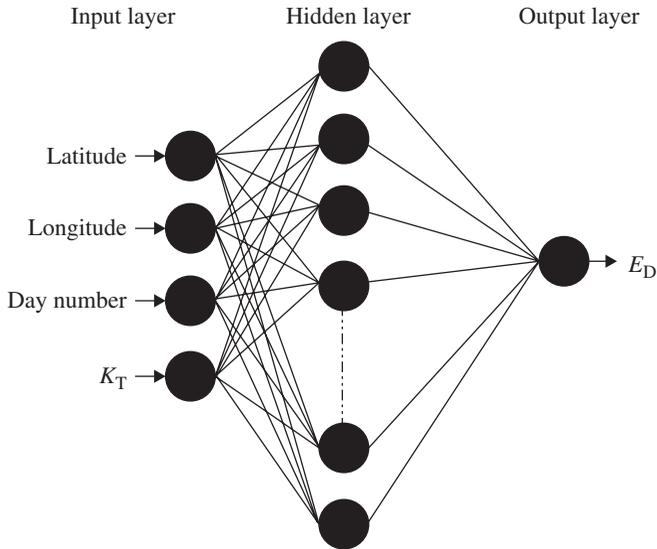


FIGURE 1.15 ANN model for diffuse solar energy prediction.

Example 1.9: Develop an FFMLP ANN model that predicts hourly global solar radiation and diffuse solar radiation as illustrated in Figure 1.16 based on the data provided in file 1.

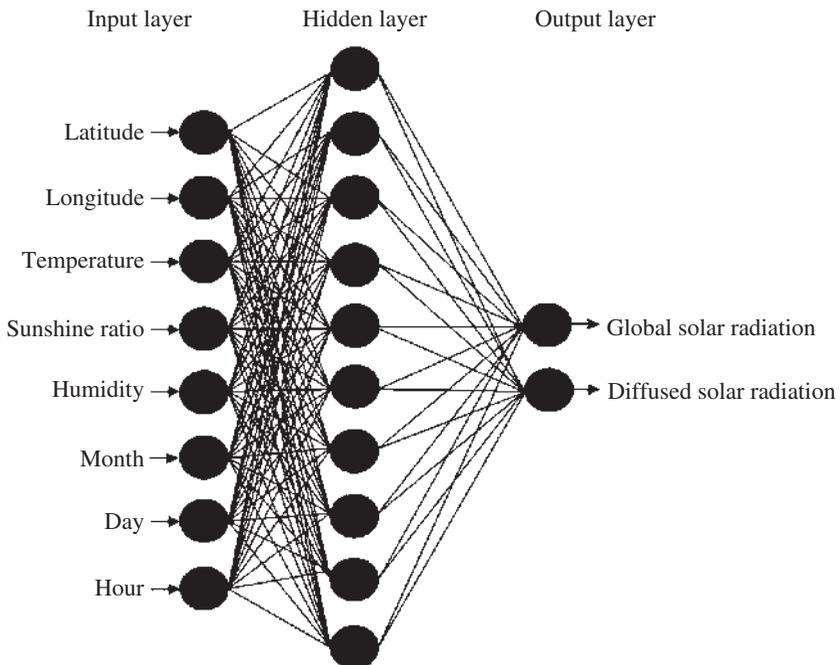


FIGURE 1.16 Hybrid ANN model for global and diffuse solar radiation prediction.

Solution

```

%Modeling of PV systems using MATLAB
%Chapter I
%Example 1.9
fileName = 'PV Modeling Book Data Source.xls';
sheetName = 'Source 1' ;
G_T=xlsread(fileName, sheetName , 'E5:E2997');
G_D=xlsread(fileName, sheetName , 'F5:F2997');
Hum=xlsread(fileName, sheetName , 'H5:H2997');
T=xlsread(fileName, sheetName , 'J5:J2997');
S=xlsread(fileName, sheetName , 'I5:I2997');
M=xlsread(fileName, sheetName , 'A5:A2997');
D=xlsread(fileName, sheetName , 'B5:B2997');
H=xlsread(fileName, sheetName , 'D5:D2997');
G_T_Test=xlsread(fileName, sheetName , 'E2998:E3640');
G_D_Test=xlsread(fileName, sheetName , 'F2998:F3640');
Hum_Test=xlsread(fileName, sheetName , 'H2998:H3640');
T_Test=xlsread(fileName, sheetName , 'J2998:J3640');
S_Test=xlsread(fileName, sheetName , 'I2998:I3640');
M_Test=xlsread(fileName, sheetName , 'A2998:A3640');
D_Test=xlsread(fileName, sheetName , 'B2998:B3640');
H_Test=xlsread(fileName, sheetName , 'D2998:D3640');
%-----
inputs = [M,D,H,T,H,S];
I=inputs';
targets= [G_T, G_D];
T=targets';
%-----ann Model development and training
net = newff(I,T,5);
Y = sim(net,I);
net.trainParam.epochs = 100;
net = train(net,I,T);
%-----testing the developed model-----
test=[M_Test,D_Test,H_Test,T_Test,H_Test,S_Test];
Test1=test';
G_Mi = sim(net,Test1);
G_M= G_Mi';
%-----
G_Tp= [];
G_Dp= [];
for i=1:1:length(G_M)
    G_Tp=[G_Tp;G_M(i,1)];
    G_Dp=[G_Dp;G_M(i,2)];
end
G_Tp;

```

```

G_Dp;
subplot(2,1,1)
plot(G_T_Test)
hold on
plot(G_Tp,'red')
subplot(2,1,2)
plot(G_D_Test)
hold on
plot(G_Dp,'red')

```

ANS

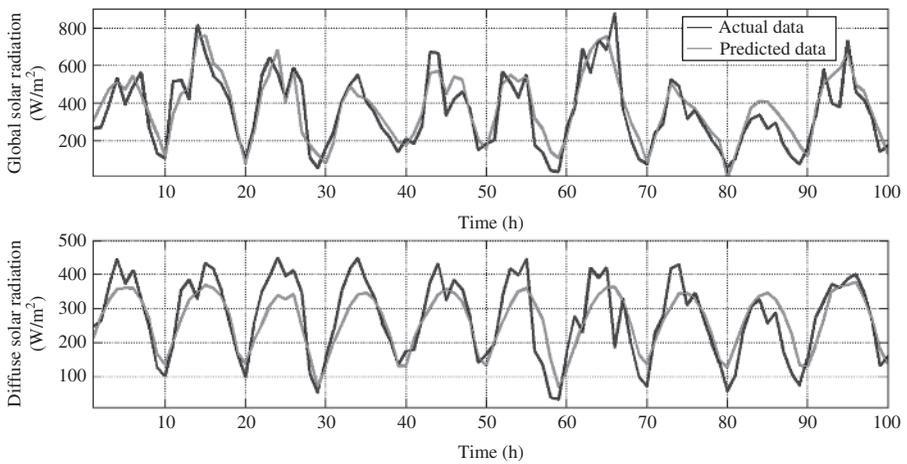


FIGURE 1.17 Prediction results of ANN model in Example 1.8. (See insert for color representation of the figure.)

The generalized regression neural network (GRNN) is a probabilistic-based network. This network makes classification where the target variable is definite, while GRNNs make regression where the target variable is continuous. Figure 1.18 shows the GRNN diagram for hourly solar radiation prediction.

The network consists of input, hidden, and output layers. The input layer has one neuron for each predictor variable. The input neurons standardize the range of values by subtracting the median and dividing by the interquartile range. The input neurons then feed the values to each of the neurons in the hidden layer. In the hidden layer, there is one neuron for each case in the training data set. The neuron stores the values of the predictor variables for each case along with the target value. When presented with the vector of input values from the input layer, a hidden neuron computes the

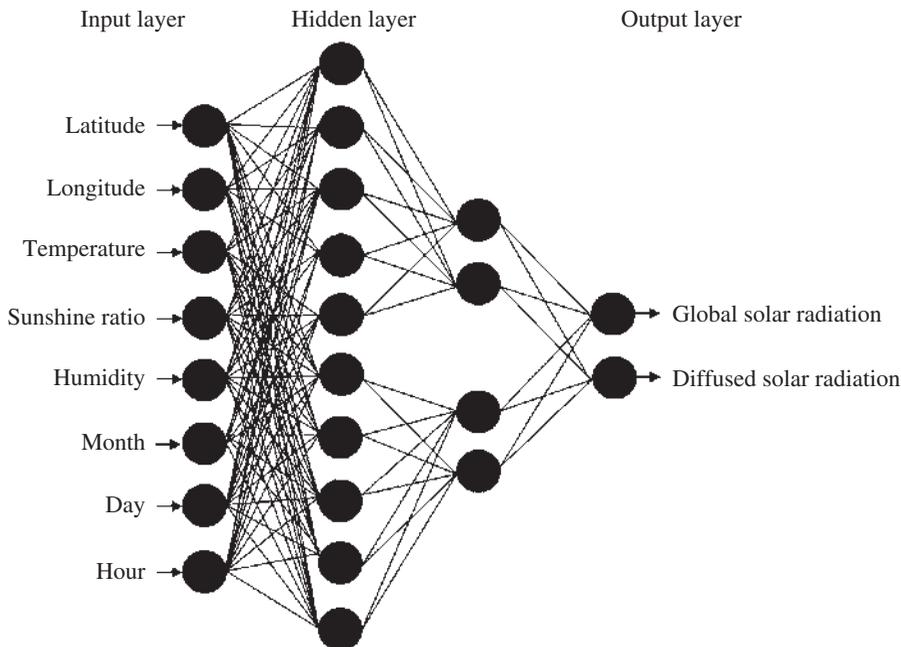


FIGURE 1.18 GRNN model for solar radiation prediction.

Euclidean distance of the test case from the neuron's center point and then applies the RBF kernel function using the sigma value(s). The resulting value is passed to the neurons in the pattern layer. However, the pattern layer (summation layer) has two neurons: one is the denominator summation unit and the other is the numerator summation unit. The denominator summation unit adds up the weights of the values coming from each of the hidden neurons. Meanwhile, the numerator summation unit adds up the weights of the values multiplied by the actual target value for each hidden neuron. Finally, the decision layer divides the value accumulated in the numerator summation unit by the value in the denominator summation unit and uses the result as the predicted target value.

In addition to that cascade correlation neural networks are “self-organizing” networks. The network begins with only input and output neurons. It is called a cascade because the output from all of the neurons is already in the network that feeds into new neurons. As new neurons are added to the hidden layer, the learning algorithm attempts to maximize the magnitude of the correlation between the new neuron's output and the residual error of the network that we are trying to minimize. A cascade neural network has three layers: input, hidden, and output. The input layer is a vector of predictor variable values. The input neurons do not perform any action on the values other than distributing them to the neurons in the hidden and output layers. In addition to the predictor variables, there is a constant input of

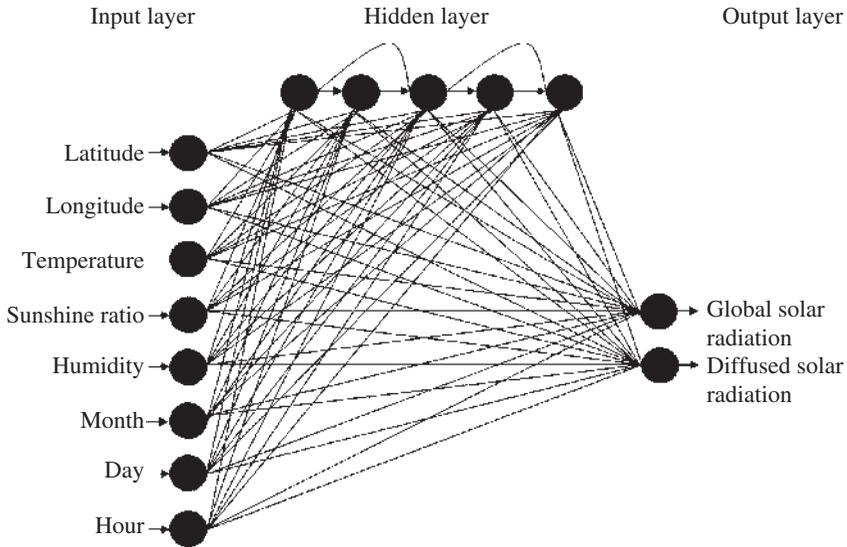


FIGURE 1.19 CFNN model for solar radiation prediction.

1.0, called the bias that is fed into each of the hidden and output neurons; the bias is multiplied by a weight and added to the sum going into the neuron. In the hidden layer, each input neuron is multiplied by a weight, and the resulting weighted values are added together to produce a combined value. The weighted sum is fed into a transfer function, which then outputs a value. The outputs from the hidden layer are distributed to the output layer that receives values from all of the input neurons (including the bias) and all of the hidden layer neurons. Each value presented to an output neuron is multiplied by a weight, and the resulting weighted values are added together again to produce a combined value. The weighted sum is fed into a transfer function, which then outputs the final value. Figure 1.19 shows the CFNN diagram for solar radiation prediction.

1.8 MODELING OF SUN TRACKERS

If a PV system tracks the Sun, that is, moving its panels to orient them toward the Sun, the energy yield increases. On days with high irradiation and a large proportion of direct radiation, relatively high radiation gains can be obtained by tracking mechanisms. In summer, these gains can reach about 50% on clear days, and in winter, 300% as compared with systems with a static horizontal PV array. The predominant part of the increase in yield due to tracking can be obtained in summer. The gains are typically lower in winter, where the proportion of hazy days is significantly greater. In general, there are two types of tracking devices: dual axis and single axis. The dual axis system is more capable than the single axis

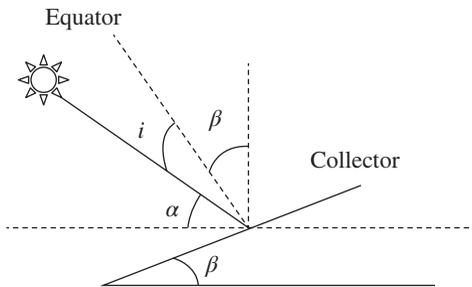


FIGURE 1.20 Geometrical angles of the Sun’s projection.

since it can focus on the optimum point. However, the dual axis system is technically more complex than the single axis system. In central Europe, systems using dual axis increase the achieved yield by 30–40% over nontracker systems. In comparison, one axis system has a yield of approximately 20% more than comparable nontracker systems.

Figure 1.20 shows the principle of dual axis Sun tracker. The perpendicular path between the Sun projection and the collector is called the equator. The angle between the collector and the reference line is called tilt angle (β), and the angle between the Sun projection and the collector is called altitude angle (α). The incidence angle (i) is the angle between the Sun projection and the equator.

From the Earth’s perspective, the Sun is moving across the sky during the day. In the case of fixed solar collectors, the projection of the collector area on the plane, which is perpendicular to the radiation direction, is given by cosine function of the angle of incidence. The higher the angle of incidence (i), the lower is the power.

As shown in Figure 1.20 the maximum power can be achieved at a tilt angle, which investigates a zero incidence angle. The relationships of the tilt, altitude, and incidence angles are given in the following:

At AM time,

$$\beta + \alpha - i = 90 \tag{1.49}$$

and at PM time,

$$\beta + \alpha + i = 90 \tag{1.50}$$

To achieve the maximum radiation by the collector, the incidence angle (i) must be zero, and so the optimum tilt angle can be determined as follows:

$$\beta = 90^\circ - \alpha \tag{1.51}$$

A schematic diagram of the proposed Sun tracker is shown in Figure 1.21. It consists of two parts: a stepper motor driven by a microcontroller and a gear system in order to step up the motor torque to drive the collector.

The stepper motor and microcontroller technologies can be combined to form an accurate controller that can tilt the solar collectors as close as possible to the Sun angle.

Example 1.10: Develop a single axis Sun tracker model using MATLAB that tracks the Sun every 5 min.

Solution

```
%Modeling of PV systems using MATLAB
%Chapter I
Example 1.10
%
%-----
%Date 01.01 to 4.01 2015 (four days)
%Location Kuala Lumpur, Malaysia, L =(3.12), LOD = (101.7)
L=3.12; %(A1.1)
LOD=101.7; %(A1.2)
BetaT= [];
for N=1:1:4 %Day number
T_GMT=8; %(A1.3)
Step=5;
Ds=23.45*sin((360*(N-81)/365)*(pi/180)); % angle of declination
%(A.2)
B=(360*(N-81))/364; %(A3.1)
EoT=(9.87*sin(2*B*pi/180))- (7.53*cos(B*pi/180))-
(1.5*sin(B*pi/180)); %(A3.1)
Lzt= 15* T_GMT; %(A3.2)
if LOD>=0
Ts_correction= (-4*(Lzt-LOD))+EoT; %(A3.3) solar time
correction
else
Ts_correction= (4*(Lzt-LOD))+EoT; %(A3.3) solar time
correction
end
Wsr_ssi=- tan(Ds*pi/180)*tan(L*pi/180);
Wsr_r_ss=acosd(Wsr_ssi);
ASTsr=abs(((Wsr_r_ss/15)-12)*60);
ASTss=(((Wsr_r_ss/15)+12)*60);
Tsr=ASTsr+abs(Ts_correction);
Tss=ASTss+abs(Ts_correction);
Alpha= [];
Theta= [];
```

```

for LMT=Tsr:Step:Tss
Ts= LMT + Ts_correction; %(A3.3) solar time
Hs=(15 *(Ts - (12*60)))/60; % (A4) Hour angle degree
sin_Alpha = ( sin (L*pi / 180) * sin (Ds*pi / 180) ) +
            (cos(L*pi/180)*cos(Ds*pi/180)*          cos(Hs*pi/180));
            %(A5.1)
Alpha_i=asind(sin_Alpha) ;    %altitude angle (A5.1)
Alpha=[Alpha;Alpha_i];
end
Alpha;
Beta=[];
for i=1:length(Alpha)
Betai=90-Alpha(i);
Beta=[Beta;Betai];
end
Beta;
BetaT=[BetaT,Beta];
end
BetaT
Beta1=[];
Beta2=[];
Beta3=[];
Beta4=[];
for i=1:1:142;
Beta1=[Beta1;BetaT(i,1)];
Beta2=[Beta2;BetaT(i,2)];
Beta3=[Beta3;BetaT(i,3)];
Beta4=[Beta4;BetaT(i,4)];
end
Beta1;
Beta2;
Beta3;
Beta4;
subplot(2,2,1)
plot(Beta1)
subplot(2,2,2)
plot(Beta2)
subplot(2,2,3)
plot(Beta3)
subplot(2,2,4)
plot(Beta4)

```

ANS

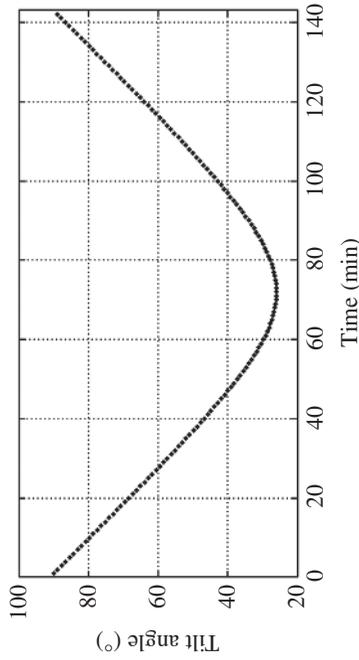
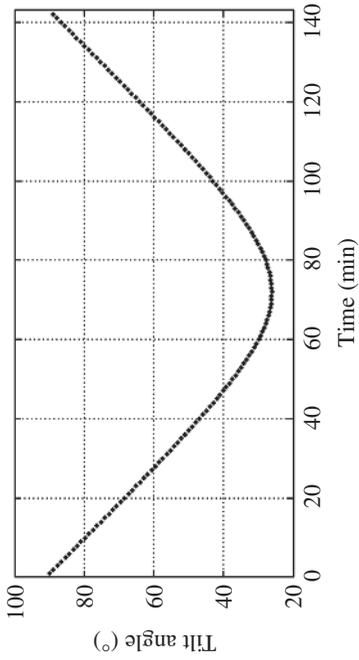
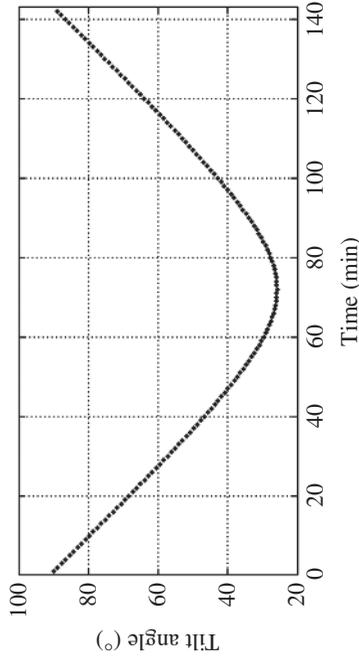
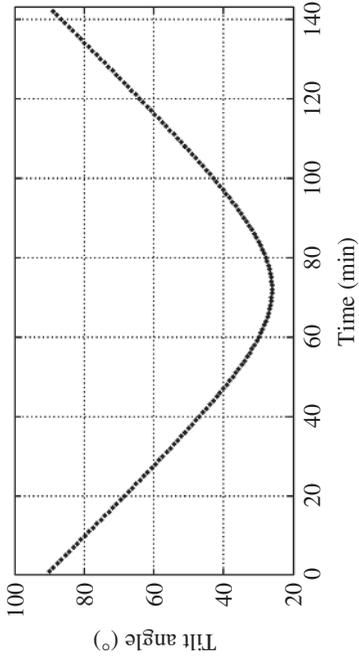


FIGURE 1.21 Optimum tilt angle results (Example 1.9).

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