ECE 333 – Green Electric Energy

13. Solar Insolation Components and Measurement

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THE IMPACTS OF THE ATMOSPHERE ON SOLAR IRRADIATION

- The incidence angle of the solar rays and the length of each ray’s path through the atmosphere depend on the sun’s position in the sky.

- As each beam passes through the atmosphere, a fraction is absorbed by atmospheric gases or scattered by air molecules or particulate matter.

- Another fraction of insolation is reflected by surfaces in front of the solar panel.
INSOLATION COMPONENTS ON A SOLAR PANEL

- Direct beam radiation
- Diffused radiation
- Reflected radiation

Source: http://www.inforse.org/europe/dieret/Solar/solar.html
INSOLATION COMPONENTS AT THE EARTH’S SURFACE

- Insolation received at a solar panel is a combination of three distinct components:
  - **direct beam radiation** that passes in a straight line through the atmosphere
  - **diffused radiation** that has been scattered by molecules and aerosols in the atmosphere
  - **reflected radiation** that is bounced off the ground or other surfaces in front of the solar panel
INSOLATION COMPONENTS AT THE EARTH’S SURFACE

- The direct beam portion of the insolation is, typically, the most significant since its rays arrive from a consistent direction.
- Over a year’s time, less than half of the extraterrestrial solar irradiation that hits the top of the atmosphere reaches the earth’s surface as direct beam radiation.
- On a clear day, however, direct beam radiation on the earth’s surface can exceed 70% of the extraterrestrial solar irradiation.
Since weather conditions are uncertain, we need to approximate the clear–sky direct beam radiation on the earth’s surface to provide practical means to predict the radiation on solar panels.

The approximation used for the clear–sky direct beam radiation explicitly accounts for the time-varying intensity of the sun and distance between the earth and the sun.
As the extraterrestrial irradiation is attenuated as a function of the distance that the beam travels through the atmosphere, an approximation of the clear–sky direct beam radiation on the earth’s surface is given by

\[
\left. i_b(h) \right|_d = a \left. e^{-k d r(h)} \right|_d \frac{W}{m^2}
\]
CLEAR – SKY DIRECT BEAM RADIATION APPROXIMATION

- \( a_d \) is the approximation of the “apparent” solar irradiation expressed in \( W/m^2 \)

\[
a_d = 1,160 + 75 \sin \left( \frac{2\pi}{365} (d - 275) \right)
\]

- The dimensionless factor optical depth \( k_d \) is

\[
k_d = 0.174 + 0.035 \sin \left( \frac{2\pi}{365} (d - 81) \right)
\]
The air mass ratio $r(h)|_{d}$ accounts for the time-varying sun ray path length through the atmosphere and the spherical nature of atmosphere.

$$r(h)|_{d} = \sqrt{\left[708 \sin\left(\beta(h)|_{d}\right)\right]^2 + 1,417 - 708 \sin\left(\beta(h)|_{d}\right)}$$
EXAMPLE: DIRECT BEAM RADIATION IN CHICAGO

- We approximate the total direct beam radiation at the solar noon on a clear May 21 in Chicago at latitude $\ell = 0.731$ radians.

- For May 21, $d = 141$, the “apparent” solar irradiation is

$$ a \bigg|_{141} = 1,160 + 75 \sin \left( \frac{2\pi}{365} \left( 141 - 275 \right) \right) = 1,104 \, \frac{W}{m^2} $$
EXAMPLE: DIRECT BEAM RADIATION AT CHICAGO

The solar declination angle is

\[ \delta \bigg|_{141} = 0.41 \sin \left( \frac{2\pi}{365} (141 - 81) \right) = 0.351 \text{ radians} \]

The solar altitude angle at solar noon is given by

\[ \beta (0) \bigg|_{141} = \frac{\pi}{2} - 0.731 + 0.351 = 1.19 \text{ radians} \]

Now, we compute the air mass ratio
EXAMPLE: DIRECT BEAM IRRADIATION AT CHICAGO

\[ r(0)\big|_{141} = \sqrt{(708 \cdot 0.933)^2 + 1417} - (708)(0.933) = 1.064 \]

- The optical depth is given by

\[ k\big|_{141} = 0.174 + 0.035 \sin \left( \frac{2\pi}{365} (141 - 81) \right) = 0.197 \]

- Therefore, the clear-sky direct beam radiation is

\[ i_b(0)\big|_{141} = 1,104 e^{-0.197}(1.064) = 895 \frac{W}{m^2} \]
SOLAR PANEL POSITION/ORIENTATION

- solar panel
- tilt angle $\alpha$
- horizontal surface
- panel azimuth angle $\psi$
- N
- S
Solar panel position is expressed in terms of the

- **tilt angle** $\alpha$, defined as the angle between the panel and a horizontal surface

- **panel azimuth angle** $\psi$, defined as the angular displacement, through which the panel needs to rotate in order to face due South

The convention is that $\psi$ is *positive* (negative) for the panel facing away from South to the East (West)
RADIATION ON THE SOLAR PANEL

- $\epsilon(h)\big|_d$
- incidence angle
- line perpendicular to the panel surface
- $\beta(h)\big|_d$
- $\phi(h)\big|_d$
- $\psi$
- $S$
- $N$
- solar panel
- horizontal surface

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DIRECT BEAM RADIATION ON THE SOLAR PANEL

- The approximation of the clear-sky direct beam radiation is the basis to estimate each component of the solar insolation that strikes a solar panel on the earth’s surface.

- Given the panel tilt angle $\alpha$ and azimuth angle $\psi$, we determine the incidence angle $\varepsilon(h)\big|_d$ between a
line drawn perpendicular to the solar panel surface and the sun’s rays using

\[
\cos\left(\varepsilon(h)\big|_d\right) = \cos\left(\beta(h)\big|_d\right) \cos\left(\phi(h)\big|_d - \psi\right) \sin(\alpha) + \\
\cos\left(\beta(h)\big|_d\right) \cos(\alpha)
\]

and so the direct beam radiation received at the solar panel is its projection on the panel
The projection of the clear–sky direct beam radiation \( i_b(h) \) to direct beam radiation under a clear sky that strikes the panel surface, denoted by \( i_{bp}(h) \), is given by

\[
i_{bp}(h) = i_b(h) \cos(\varepsilon(h)) \frac{W}{m^2}
\]
EXAMPLE: DIRECT BEAM RADIATION ON THE PANEL

In the example, at solar noon on May 21 in Chicago at $\ell = 0.731$ radians, the altitude angle of the sun is 1.221 radians and the clear–sky direct beam irradiation is 895 $W/m^2$.

We consider a solar panel with 0.907–radian tilt angle and 0.348–radian azimuth angle.
EXAMPLE: DIRECT BEAM RADIATION ON THE PANEL

- The incidence angle satisfies

$$\cos\left(\varepsilon(0)\bigg|_{141}\right) = \cos(1.221)\cos\left(0 - 0.348\right)\sin(0.907)$$

$$+ \sin(1.221)\cos(0.907)$$

$$= 0.833$$

- Thus, the beam radiation on the panel is

$$i_{bp}(0)\bigg|_{141} = (895)(0.833) = 745 \frac{W}{m^2}$$
DIFFUSED RADIATION
RELECTED RADIATION
DIFFUSED AND REFLECTED RADIATION ON THE SOLAR PANEL

- The indirect radiation components are subject to
  - the uncertain impacts of particles and molecules in the atmosphere
  - the irregularities of the terrain of the earth surface for the reflected radiation

and so the approximation of the diffused and reflected radiation components is complicated

- The approximation of the diffused and reflected radiation is outside the scope of the course
APPLICATION OF CLEAR–SKY RADIATION APPROXIMATION

- Various solar technologies use these 2 insolation components in specific ways and so approximation methods are used to assess the performance of the solar panels.

- The clear–sky radiation approximation may be tabulated into hourly, daily, monthly and annual values to provide the basis for the determination of the position/orientation of each panel.
ANNUAL CLEAR–SKY INSOLATION VARIATION BY TILT ANGLE

annual insolation (kWh/m²⋅y)

ψ = 0

South facing

East/West

ψ = π/2 / ψ = −π/2

Southeast/Southwest

ψ = π/4 / ψ = −π/4

ℓ = 0.7 radians

tilt angle (degree)
We can observe that the solar panel position has significant impacts on the insolation received by the solar panels.

As such, in many circumstances, the solar panels are equipped with tracking systems to allow the panels to track the movement of the sun across the sky and change panel positions to make better use of the insolation the panels receive.
Tracking systems are categorized as

- **two–axis trackers**, which can adjust the two panel angles – tilt and azimuth – to orient the panels to be perpendicular to the sun rays

- **single–axis trackers**, which can only change only one of the solar panel angles
TWO – AXIS TRACKERS

- **S**: solar panel
- **W**: flexible azimuth angle
- **N**: flexible tilt angle
SINGLE – AXIS TRACKERS

The panel has fixed tilt angle.

Solar panel

Flexible azimuth angle
SINGLE – AXIS TRACKERS

the panel has fixed azimuth angle

solar panel

flexible tilt angle
SINGLE – AXIS TRACKERS
TRACKER

CLEAR – SKY INSOLATION ON SOUTH – FACING PANELS

Average daily insolation for each month (kWh/m²-d)

\( \alpha = 0.7 \) radians, annual insolation: 2,410 kWh/m² – y

\( \alpha = 0.35 \) radians, annual insolation: 2,350 kWh/m² – y

\( \alpha = \frac{\pi}{3} \), annual insolation: 2,210 kWh/m² – y

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CLEAR – SKY INSOLATION WITH VARYING PANEL POSITIONING

insolation (W/m²)

solar time (hour)

fixed α

flexible ψ

flexible α, flexible ψ

flexible α, fixed ψ

flexible α, fixed ψ
However, since the weather conditions are highly uncertain, the assumption that the sky is clear need not always be satisfied and the insolation is uncertain and may be intermittent.

As such, we need specific devices to measure the actual insolation to perform the analysis.
INSOLATION MEASUREMENT DEVICES

There are two major types of devices used to measure the insolation on the earth’s surface:

- **pyranometer** which measures the total insolation of all the three components.
- **pyrheliometer** which only measures the direct beam radiation.
PYRANOMETER HOURLY INSOLATION MEASUREMENTS IN ABILENE, TX

Feb. 15

July. 15

hour

total insolation (kW/m²)

0 0.4 0.8 1.2

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
1-MIN DIRECT BEAM PYRHELIOMETER MEASUREMENTS: LAS VEGAS

Jan. 1

Aug. 1

direct beam radiation (kW/m²)

min

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SOLAR IRRADIATION DATA BASES

- **National Oceanic and Atmospheric Administration (NOAA)** constructed the first US solar data base, primarily for weather forecasts in the 1970s.


- In 1995, **National Renewable Energy Laboratory (NREL)** established the **National Solar Radiation Data Base (NSRDB)** with the **typical meteorological year (TMY)** data of **hourly solar measurements at over 1,000 stations**;

NSRDB STATIONS

Source: https://maps.nrel.gov/nsrdb-viewer/
NSRDB STATIONS

- The 239 Class I stations have a complete hourly data set
- The 1462 Class II stations have a complete hourly data set, but assembled from lower-quality input data
- The 1454 Class III stations contain gaps in the records but have data for at least 3-year period
- The 40 stations in the updated NSRDB include measured solar data supplied by non-NREL groups
Measurement and Instrumentation Data Center (MIDC) provides 1–minute solar and wind data base for the US sites shown below at http://www.nrel.gov/midc/
LIVE GRAPHICAL DISPLAY OF SOLAR MEASUREMENTS

Conditions at 10:42 MST on October 22, 2015 at the Solar Radiation Research Laboratory (BMS)

- Temperature
  - Dry Bulb: 41.3°F, 5.2°C
- Pressure
  - Station Pressure: 24.11 in Hg, 816.4 mBar
- Precipitation
  - Daily Total Rain: 0.46 in
  - Snow Depth: 0 in
- Wind Speed
  - Current: 0.0 mph
  - 1 Min Peak: 0.0 mph
- Wind Direction
  - Current: NW
  - 1 Min Peak: 308.8 degrees
- Humidity
  - Current: 100.0%
- Solar Light
  - Estimated: 501 A
- Turbidity
  - Estimated: 5.224
- Albedo
  - Estimated: 0.11

Source: http://www.nrel.gov/midc/srrl_bms/display/
SOLAR IRRADIATION DATA BASES

- National Climatic Data Center (NCDC) maintains the world's largest climate data archive and provides climatological services and data, ranging from centuries–old data to data less than an hour old.

- The Center's mission is to collect, store and provide access to these data to the public, business, industry, government, and researchers at http://www.ncdc.noaa.gov/