Solar Pro Technical Documentation

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1 Calculation of Solar Irradiance

In Solar Pro, total irradiance is calculated using latitude and longitude of the area, and meteorological database as follows.

1.1 Meteorological Database

Solar Pro supports meteorological data from the following databases:

1) 1,600 Points(1
2) TMY3(2
3) MONSOLA-11(3
4) METPV-11(4
5) Meteonorm Meteo Monthly(5
6) NSRDB Hourly(6
7) SolarGIS TMY Hourly(7

1.2 Calculation of Solar Altitude and Azimuth

The solar altitude (H [rad]) is obtained from the Spencer equation.(8

- $\sin\psi = \dfrac{\cos\delta \sin\omega}{\cos H}$
- $\sin H = \cos\varphi \cos\delta \cos\omega + \sin\delta \sin\varphi$
- $\sin H_0 = \cos(\delta - \varphi)$
- $\delta = 0.006918 - 0.399912\cos\chi + 0.070257\sin\chi - 0.006758\cos 2\chi + 0.000908\sin 2\chi$
- $\chi = \dfrac{2\pi(n-1)}{365}$
- $\omega = \lambda + 15e$
- $e = \dfrac{0.0172 + 0.4281\cos\chi - 7.3515\sin\chi - 3.3495\cos 2\chi - 9.3619\sin 2\chi}{60}$

ψ : Solar Azimuth
H : Solar Altitude
H_0 : Culminating Solar Altitude
$\delta[rad]$: Declination of the Sun
$e[hour]$: Equation of Time
$\omega[deg]$: Hour Angle
$\chi[rad]$: Coefficient of Days
$n[day]$: Total Days of a Year
φ : Latitude
$\lambda[deg]$: Longitude

1.3 Calculation of Total Irradiance

1.3.1 Calculation of Theoretical Horizontal Irradiance

To calculate total irradiance, global horizontal irradiance is first separated into direct normal irradiance and diffuse horizontal irradiance.

$H > 0$

- $I = 0.42 \sin H + \dfrac{2.92 - \sin H_0}{2 \sin H_0} \sin^2 H - \dfrac{2.92 - \sin H_0}{4 \sin^2 H_0} \sin^3 H$
- $I_{DN} = \dfrac{1.323\, I}{\sin H} - 0.5466$
- $I_{SH} = I - I_{DN} \sin H$

If $H \leqq 0$, all irradiance equal to 0

$I\,[kW/m^2]$: Global Horizontal Irradiance
$I_{DN}\,[kW/m^2]$: Direct Normal Irradiance
$I_{SH}\,[kW/m^2]$: Diffuse Horizontal Irradiance
H : Solar Altitude
H_0 : Culminating Solar Altitude

1.3.2 Calculation of Plane of Array (POA) Irradiance using the Hay transposition model

The plane of array (POA) Irradiance is the total irradiance that is incident upon (or normal to) the surface of the array. It is calculated using the Hay transposition model.(9

- $I_{\beta\gamma} = I_{b\beta\gamma} + I_{s\beta\gamma} + I_{r\beta\gamma}$
- $I_{b\beta\gamma} = I_{DN} \cdot \cos\theta$
- $I_{s\beta\gamma} = I_{SH} \cdot \left[\dfrac{I - I_{SH}}{I_{oH}} \cdot \dfrac{\cos\theta}{\sin H} + \left(1 - \dfrac{I - I_{SH}}{I_{oH}}\right) \cdot \dfrac{1 + \cos\beta}{2} \right]$
- $I_{oH} = I_{SC} \cdot \left\{ 1 + 0.033 \cdot \cos\left((n-2) \cdot \dfrac{2\pi}{365}\right) \right\} \cdot \sin H$
- $\cos\theta = (\sin\varphi \cos\beta - \cos\varphi \sin\beta \cos\gamma) \sin\delta$
  $\quad + (\cos\varphi \cos\beta + \sin\varphi \sin\beta \cos\gamma) \cos\delta \cos\omega$
  $\quad + \sin\beta \sin\gamma \cos\delta \sin\omega$
- $I_{r\beta\gamma} = \rho I \cdot \dfrac{(1 - \cos\beta)}{2}$
- $\rho = 0.2(1 - ns) + 0.7\, ns$

$I_{\beta\gamma}$: Total (Solar) Irradiance
$I_{b\beta\gamma}$: Direct Component
$I_{s\beta\gamma}$: Diffuse Component
$I_{r\beta\gamma}$: Reflected Component
I_{SC} : Solar Constant $(= 1.382\,[kW/m^2])$
I_{oH} : Extraterrestrial Solar Irradiance
ρ : Albedo (Ground Reflectivity)
β : Tilt Angle of PV Module
γ : Azimuth Angle of PV Module

θ : Angle between Incident Light and PV Module
H : Solar Altitude
δ : Declination of the Sun
φ : Latitude
ω : Time Angle
$n[day]$: Total Days of a Year

1.4 Solar Irradiance Curve

[Sunny Day]

When you select [Sunny Day] as the pattern of calculating PV generation, the simulation is for a day of no cloud. In this case, the plane-of-array irradiance curve is calculated using 1.3, without using the meteorological database.

[Mean Day]

When you select [Mean Day] as the pattern of calculating PV generation, the simulation is for a day of average irradiance. In this case, the plane-of-array irradiance curve is calculated using irradiation values from the meteorological database.

1) Monthly averages of global horizontal irradiation and horizontal diffuse irradiation are obtained from the meteorological database.
2) Theoretical global horizontal irradiance and horizontal diffuse irradiance for a mean day of the month are calculated by using 1.3.1. Integration of these values then result in the total theoretical global horizontal irradiation and horizontal diffuse irradiation for a mean day of the month.
3) The coefficient factors for global horizontal irradiation and horizontal diffuse irradiation are calculated using the ratio of the value of 2) to the value of 1).
Both are 1.0 on a [Sunny Day].
4) The irradiance curve for the reference day is calculated from 1.3.1, and multiplied with the coefficient from 3).
5) The plain of array irradiance curve is then calculated using 1.3.2.

*Mean day of the month[(10]

Month	Mean day
1	17
2	16
3	16
4	15
5	15
6	11
7	17
8	16
9	15
10	15
11	14
12	10

2 Temperature Calculation

2.1 Calculation of Outside Air Temperature

The variation curve of outside air temperatures per hour is calculated from meteorological data (average, max. average, and min. average temperature).

2.2 Calculation of the Module Temperature

2.2.1 Without Wind Velocity

The PV temperature (without Wind Velocity) is obtained as follows.

・$T_c = b_1 \cdot T_{air} + b_2 \cdot G_\alpha + b_3$

T_c[℃] : PV Temperature
T_{air}[℃] : Outside Air Temperature
$G_\alpha[kW/m^2]$: Irradiance
b_1 : Air Temperature Regression Coefficient…Initial Value = 1
b_2 : Irradiance Regression Coefficient…Initial Value = 45
b_3 : Constant …Initial Value = 0
(This generally represents the influence of wind, so its value is normally ≦0.)

2.2.2 With Wind Velocity[11]

The PV temperature (with wind velocity) is obtained as follows. It is available when using the meteorological database including wind velocity.

・$T_c = G_a \cdot e^{(a + b \cdot V_w)} + T_{air}$

T_c[℃] : PV Temperature
T_{air}[℃] : Outside Air Temperature
$G_\alpha[W/m^2]$: Irradiance
$V_w[m/s]$: Wind Speed

3 PV Equivalent Circuit Analysis

3.1 Equivalent Circuit of PV Module[12]

The I-V characteristics of the PV module is based on the following equation.

・$I = I_{ph} - I_o\left[\exp\left\{C\left(V + IR_s\right)\right\} - 1\right] - \dfrac{\left(V + IR_s\right)}{R_p}$

・$C = \dfrac{q}{D_p k T_c}$

I_{ph} : Photovoltaic Current
I_o : Diode Saturation Current
R_s : Inner Series Resistance
R_p : Inner Parallel Resistance
q : Elementary Charge
k : Boltzmann Constant
$T_c[K]$: Module Temperature
D_p : Diode Factor (Number of Cell In-Series × Diode Efficiency Index)

3.2 Calculation of The Equivalent Circuit Constant

The equivalent circuit constants under standard test conditions are defined as follows:

P_{max} : Max Power
I_{pm} : Max Power Current
V_{pm} : Max Power Voltage
I_{sc} : Short -circuit Current
V_{oc} : Open-circuit Voltage
PV Temperature $= 25$ [℃] Irradiance $= 1.0\,[kW/m^2]$ Air Mass $= 1.5$
Standard Test Condition [STC]

3.3 Output Characteristic Equation(12

The effects of solar irradiance and module temperature are calculated as follows:

- $I_{ph} = I_{ph0}\left\{1 + 5.1029\cdot 10^{-4}(T_c - 298.16)\right\}\cdot\left[1.03\,H_\alpha - 0.03\left\{1 - \exp(-8H_\alpha)\right\}\right]$
- $I_o = I_{o0}\exp\left\{0.09672(T_c - 298.16)\right\}$
- $R_s = R_{s0}\left\{1 + 3.3717\cdot 10^{-3}(T_c - 298.16) + 9.7058\cdot 10^{-5}(T_c - 298.16)^2\right\}$
- $R_p = \dfrac{R_{p0}}{1 + 5.7987\cdot 10^{-3}(T_c - 298.16) + 1.6129\cdot 10^{-4}(T_c - 298.16)^2}$

I_{ph} : Photovoltaic Current
I_o : Diode Saturation Current
R_s : Inner Series Resistance
R_p : Inner Parallel Resistance
$T_c[K]$: Module Temperature
$H_\alpha[kW/m^2]$: Irradiance of Module Surface
I_{ph0} I_{o0} R_{s0} R_{p0} are the value under Standard Test Condition.

3.4 I-V Curve Calculation and The Search for the Max. Power Point

Solar Pro constructs the array equivalent circuit by "connecting" the module equivalent circuits in series or parallel, taking into account bypass diodes and blocking diodes. The total I-V curve is then calculated, as well as P_{max} , I_{pm} , and V_{pm} .

4 Influence of Shadow

4.1 Shadow Density

The effects of shadow density on the amount of direct irradiance received by each PV module is calculated as follows:

$$\text{Direct Irradiance of PV Module} = I_{b\beta\gamma} \cdot \frac{100 - \text{Shadow Density [\%]}}{100}$$

In the recommended setting, shaded modules receive no direct irradiance. The ratio of shaded area to the whole module can also be taken into consideration.

4.2 Conditions of Shading Calculation

For calculating shading influence, you can select one from the following conditions.

Center Point: When the Center of PV module is shaded, Solar Pro defines the whole PV module is shaded.

Area: It is configurable to set the relation between ratio of shadow on PV module and ratio of shadow effect.

5 Correction Coefficient

Solar Pro has the following corrections.

Horizontal Irradiation Correction

It is the result by multiplying Horizontal Irradiation and Horizontal Irradiation Correction.

Total Irradiation Correction

It is the result by multiplying Total Irradiation and Total Irradiation Correction.

Light Soaking Effect

It is the result by multiplying PV output current and Light Soaking Effect coefficient.

DC Loss

It is the result by PV output voltage and DC Coefficient.

AC Loss

It is the result by inverter output power and AC Coefficient.

6 Generation Curve

Solar Pro simulates PV generation taking into account the effects of shading from surrounding objects created in 3D CAD.

6.1 Calculation of PV Power (Array Output Power) Curve

Solar Pro calculates the direct current output of the PV array at any time, in any location and any environment. The reduction coefficient is applied before calculating the DC output.

6.2 Power Curve Calculation of System Generation

It calculates generated output as follows.

$$\text{Generated Output} = \text{PV Power} \times \text{Inverter Efficiency}$$

6.3 Generated Output per Simulation Period

Solar Pro calculates and integrates generated output at a specified interval (1 - 60min) in any simulation period (day, month, or year).

7 Reference

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4 METPV-11, New Energy and Industrial Technology Development Organization (2012)
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6 National Solar Radiation Data Base, NREL
7 SolarGIS, GeoModel Solar
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9 JAPAN SOLAR ENERGY SOCIETY, New Solar Energy Utilization Handbook. (2010)
10 New Energy and Industrial Technology Development Organization (2012)
11 Photovoltaic Array Performance Model, Sandia Report (2004)
12 New Energy and Industrial Technology Development Organization (1997)