PV201e: Conversions & Formulas (Rev 2.0)

These are some of the conversions and formulas that are explained in our PV201e course and in the textbook “Photovoltaic Systems” by James P. Dunlop

Conversions

1 Meter = 3.28 Feet
1 Horsepower = 746 Watts
Solar Constant = 1366 W/m²
1 Peak Sun-Hour = 1kWh/m² = 3.6 MegaJoules/m²

Temperature conversion:

°F = (9/5 x °C) + 32
°C = (°F - 32) x 5/9

where
°F = temperature in Fahrenheit
°C = temperature in Celsius

Formulas

Electricity Basics: voltage, current, resistance, power

Ohm’s Law:

\[ V = I \times R \]
\[ I = \frac{V}{R} \]
\[ R = \frac{V}{I} \]

where

\( I \) = Current, the flow of electricity (in Amperes (A))
\( V \) (also written \( E \)) = Voltage, the potential or pressure to cause a flow of electricity (in Volts (V))
\( R \) = Resistance, resists the flow of electricity (larger diameter wire = less resistance) (in Ohms (Ω))

Maximum Power of Solar Module:

\( P_{mp} = V_{mp} \times I_{mp} \)

where

\( P_{mp} \) = maximum power (in W)
\( V_{mp} \) = maximum power voltage (in V)
\( I_{mp} \) = maximum power current (in A)
The Solar Resource & Site Assessment

Solar Irradiation:

\[ H = E \times t \]

where

- \( H \) = solar irradiation (in Wh/m\(^2\))
- \( E \) = average solar irradiance (in W/m\(^2\))
- \( T \) = time (in hr)

Solar Irradiance Response: The relationships between irradiance, current, and power can be expressed by the following ratios:

\[ \frac{E_2}{E_1} = \frac{I_2}{I_1} = \frac{P_2}{P_1} \]

where

- \( E_2 \) = solar irradiance 2 (in W/m\(^2\))
- \( E_1 \) = solar irradiance 1 (in W/m\(^2\))
- \( I_2 \) = current at irradiance 2 (in A)
- \( I_1 \) = current at irradiance 1 (in A)
- \( P_2 \) = power at irradiance 2 (in W)
- \( P_1 \) = power at irradiance 1 (in W)

This relationship can be used to estimate how changes in irradiance affect short-circuit current, maximum power current, or maximum power changes:

\[ I_{sc2} = I_{sc1} \times \left( \frac{E_2}{E_1} \right) \]
\[ I_{mp2} = I_{mp1} \times \left( \frac{E_2}{E_1} \right) \]
\[ P_{mp2} = P_{mp1} \times \left( \frac{E_2}{E_1} \right) \]

Array Area Estimate:

\[ A = \frac{P_{mp}}{(1 \text{ kW} / \text{m}^2 \times \eta_m)} \]

where

- \( A \) = estimated required array area (in m\(^2\))
- \( P_{mp} \) = desired peak array power (in kW DC)
- \( \eta_m \) = module efficiency
Roof Slope to Tilt Angle
Example: 4:12 rise to run roof slope
Arctan of 4/12 = 18.4 degrees
Arctan is also shown on some calculators as tan -1

Trigonometry
Sin β° = side opposite/hypotenuse (beta)
Cos ψ° = adjacent side/hypotenuse (sigh)
Tan α° = side opposite/side adjacent (alpha)

In terms of shade analysis:
\[ d_{\text{shadow}} = \text{height} / \tan \alpha° \]
\[ \tan \alpha° = \text{height} / d_{\text{shadow}} \]
Height = \( \tan \alpha° / d_{\text{shadow}} \)

Where height = the top of the modules in one row to the bottom of the modules in the next row to the north;
Where the angle α° (theta) is the sun’s elevation angle also called the sun’s altitude angle

Formula to account for the azimuth correction angle:
\[ d_{\text{min}} = d_{\text{shadow}} \times \cos \psi° \]

Where the angle \( \psi° \) (sigh) is the azimuth correction angle calculated from due south which is 180 degrees or is zero degrees depending on the type of sun path diagram;
Solar Cells, Modules, and Arrays

Efficiency of Solar Module:
\[ \eta = \frac{P_{mp}}{(E \times A)} \]

where
- \( \eta \) = efficiency
- \( P_{mp} \) = maximum power (in W)
- \( E \) = solar irradiance (in W/m²)
- \( A \) = area (in m²)

Resistance Required at Maximum Power Point:
\[ R_{mp} = \frac{V_{mp}}{I_{mp}} \]

where
- \( R_{mp} \) = resistance at maximum power point (in Ω)
- \( V_{mp} \) = maximum power voltage (in V)
- \( I_{mp} \) = maximum power current (in A)

Cell Temperature Estimate:
\[ T_{cell} = T_{amb} + (C_{T-rise} \times E) \]

where
- \( T_{cell} \) = cell temperature (in °C)
- \( T_{amb} \) = ambient temperature (in °C)
- \( C_{T-rise} \) = temperature-rise coefficient (in °C/kW/m²)
- \( E \) = solar irradiance (in kW/m²)

Module or Array Coefficients:

For Voltage:
\[ \frac{C_{V} = C_{V-cell} \times n_{s}}{ } \]

where
- \( C_{V} \) = module or array absolute temperature coefficient for voltage (in V/°C)
- \( C_{V-cell} \) = cell absolute temperature coefficient for voltage (in V/°C/cell)
- \( n_{s} \) = number of series-connected cells
For Current: \( C_i = C_{I\text{-cell}} \times n_P \times A \)

where
- \( C_i \) = module or array absolute temperature coefficient for current (in A/°C)
- \( C_{I\text{-cell}} \) = cell absolute temperature coefficient for current (in A/°C/cm²)
- \( n_P \) = number of parallel-connected cell strings
- \( A \) = individual cell area (in cm²)

**Temperature Coefficients:**

\[
C_V = V_{\text{ref}} \times C_{\%V} \\
C_i = I_{\text{ref}} \times C_{\%I} \\
C_P = P_{\text{ref}} \times C_{\%P}
\]

where
- \( C_V \) = absolute temperature coefficient for voltage (in V/°C)
- \( V_{\text{ref}} \) = reference (or rated) voltage (in V)
- \( C_{\%V} \) = relative temperature coefficient for voltage (in V/°C)
- \( C_i \) = absolute temperature coefficient for current (in A/°C)
- \( I_{\text{ref}} \) = reference (or rated) current (in A)
- \( C_{\%I} \) = relative temperature coefficient for current (in I/°C)
- \( C_P \) = absolute temperature coefficient for power (in W/°C)
- \( P_{\text{ref}} \) = reference (or rated) power (in W)
- \( C_{\%P} \) = relative temperature coefficient for power (in P/°C)

**Voltage and Power Translations:**

\[
V_{\text{trans}} = V_{\text{ref}} + ( [T_{\text{cell}} - T_{\text{ref}}] \times C_V ) \\
P_{\text{trans}} = P_{\text{ref}} + ( [T_{\text{cell}} - T_{\text{ref}}] \times C_P )
\]

Where,
- \( V_{\text{trans}} \) = translated voltage at cell temperature (in V)
- \( V_{\text{ref}} \) = reference (or rated) voltage corresponding to \( T_{\text{ref}} \) (in V)
- \( T_{\text{cell}} \) = cell temperature (in °C)
- \( T_{\text{ref}} \) = reference (or rated) temperature (in °C)
- \( C_V \) = absolute temperature coefficient of voltage (in V/°C)
- \( P_{\text{trans}} \) = translated power at cell temperature (in W)
- \( P_{\text{ref}} \) = reference (or rated) power corresponding to \( T_{\text{ref}} \) (in W)
- \( C_P \) = absolute temperature coefficient of power (in W/°C)
Performance Analysis

Annual PV System Performance (approximate) in annual kWhs:
(average peak sun hours) x (system de-rating factor) x (array total Watts dc-STC) x 365 x Acorr

where

Acorr = azimuth correction from due south
Therefore, Acorr = 1.0 if azimuth of PV array is due south
Charge Controllers

Voltage Regulation Hysteresis:
VRH = VR - ARV
where
VR = Voltage Regulation Setpoint (in V)
ARV = Array Reconnect Voltage Setpoint (in V)

Low-Voltage Disconnect Hysteresis:
LVDH = LVD - LRV
where
LVD = Low-Voltage Disconnect Setpoint (in V)
LRV = Load Reconnect Voltage Setpoint (in V)

Setpoint Voltage at Battery Temperatures other than 25°C:
V_{comp} = V_{set} - (C_{Vcell} \times [25 - T_{bat}] \times n_s)
where
V_{comp} = temperature-compensated setpoint voltage (in V)
V_{set} = nominal setpoint voltage at 25°C (in V)
C_{Vcell} = temperature compensation coefficient (in V/°C/cell)
T_{bat} = battery temperature (in °C)
n_s = number of battery cells in series
Inverters

Energy

\[ E = P_{\text{avg}} \times t \]

where
\( E \) = energy (Wh)
\( P_{\text{avg}} \) = average power (W)
\( t \) = time (hrs)

Ohm’s Law

\[ V = I \times R \]

\[ I = \frac{V}{R} \]

\[ R = \frac{V}{I} \]

where
\( V \) = voltage (V)
\( I \) = current (A)
\( R \) = resistance (Ω)

Power in DC Circuits

\[ P = V \times I \]

\[ P = I^2 \times R \]

\[ P = \frac{V^2}{R} \]

where
\( P \) = power (W)
\( V \) = voltage (V)
\( I \) = current (A)
\( R \) = resistance (Ω)
Real Power in AC Circuits

\[ P = V \times I \times \cos \theta \]
\[ P = V \times I \times PF \]

where
\( P \) = power (W)
\( V \) = voltage (V)
\( I \) = current (A)
\( \theta \) = phase angle (deg)
\( \cos \theta \) = power factor (0-1)

In 3-phase circuits:
\[ P = V \times I \times \cos \theta \times \sqrt{3} \]

Inverter Efficiency

\[ \eta_{inv} = \frac{P_{AC}}{P_{DC}} = \frac{5700}{6000} = 0.95 = 95\% \]

where
\( \eta_{inv} \) = inverter efficiency
\( P_{AC} \) = AC power output (W)
\( P_{DC} \) = DC power input (W)

Transformer Turns Ratio

\[ \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} \]

where
\( N_1 \) and \( N_2 \) = number of turns in primary and secondary windings
\( V_1 \) and \( V_2 \) = voltage in primary and secondary windings
\( I_1 \) and \( I_2 \) = voltage in primary and secondary windings
System Sizing

Weighted Average Operating Time:

$$t_{\text{op}} = \frac{[(E_1 \times t_1) + (E_2 \times t_2) + \ldots + (E_n \times t_n)]}{(E_1 + E_2 + \ldots + E_n)}$$

where
- \(t_{\text{op}}\) = weighted average operating time (in hr/day)
- \(E_1\) = DL energy required for load 1 (in Wh/day)
- \(t_1\) = operating time for load 1 (in hr/day)
- \(E_2\) = DL energy required for load 2 (in Wh/day)
- \(t_2\) = operating time for load 2 (in hr/day)
- \(E_n\) = DL energy required for nth load (in Wh/day)
- \(t_n\) = operating time for nth load (in hr/day)

Required Daily System DC Electrical Energy

$$E_{\text{SDC}} = (E_{\text{AC}}/\eta_{\text{inv}}) + E_{\text{DC}}$$

where
- \(E_{\text{SDC}}\) = required daily system DC electrical energy (in Wh/day)
- \(E_{\text{AC}}\) = AC energy consumed by loads (in Whr/day)
- \(\eta_{\text{inv}}\) = inverter efficiency
- \(E_{\text{DC}}\) = DC energy consumed by loads (in Whr/day)

Required Battery-Bank Output

$$B_{\text{out}} = \frac{(E_{\text{crit}} \times t_a)}{V_{\text{SDC}}}$$

where
- \(B_{\text{out}}\) = required battery-bank output (in Ah)
- \(E_{\text{crit}}\) = average daily electrical-energy consumption during critical design month (in Wh/day)
- \(t_a\) = autonomy (in days)
- \(V_{\text{SDC}}\) = nominal DC-system voltage (in V)

Average Discharge Rate

$$R_d = \frac{(t_{\text{op}} \times t_a)}{\text{DOD}_a}$$

where
- \(R_d\) = average discharge rate (in hr)
- \(t_{\text{op}}\) = weighted average operating time (in hr/day)
- \(t_a\) = autonomy (in days)
- \(\text{DOD}_a\) = allowable depth of discharge
Total Required Battery-Bank Rated Capacity

\[ B_{\text{rated}} = \frac{B_{\text{out}}}{(DOD_a \times C_{T,rd})} \]

where

- \( B_{\text{rated}} \) = battery-bank rated capacity (in Ah)
- \( B_{\text{out}} \) = battery-bank required output (in Ah)
- \( DOD_a \) = allowable depth of discharge
- \( C_{T,rd} \) = temperature and discharge-rate derating factor

Average Battery-Bank Daily Depth of Discharge

\[ DOD_{\text{avg}} = \frac{(LF \times E_{\text{day}})}{(B_{\text{actual}} \times V_{SDC})} \]

Where

- \( DOD_{\text{avg}} \) = average battery-bank daily depth of discharge
- \( LF \) = estimated load fraction
- \( E_{\text{day}} \) = average daily electrical-energy consumption (in Wh)
- \( B_{\text{actual}} \) = actual total rated battery-bank capacity (in Ah)
- \( V_{SDC} \) = DC-system voltage (in V)

Required Array Maximum-Power Current

\[ I_{\text{array}} = \frac{E_{\text{crit}}}{(\eta_{\text{batt}} \times V_{SDC} \times t_{PSH})} \]

where

- \( I_{\text{array}} \) = required array maximum-power current (in A)
- \( E_{\text{crit}} \) = daily electrical-energy consumption during critical design month (in Wh/day)
- \( \eta_{\text{batt}} \) = battery-system charging efficiency
- \( V_{SDC} \) = nominal DC-system voltage (in V)
- \( t_{PSH} \) = peak sun hours for critical design month (in hr/day)

Rated Array Maximum-Power Current

\[ I_{\text{rated}} = \frac{I_{\text{array}}}{C_s} \]

where

- \( I_{\text{rated}} \) = rated array maximum-power current (in A)
- \( I_{\text{array}} \) = required array maximum-power current (in A)
- \( C_s \) = soiling derating factor
Rated Array Maximum-Power Voltage

\[ V_{\text{rated}} = 1.2 \times \left( V_{\text{SDC}} - \left( V_{\text{SDC}} \times C\%_V \times (T_{\text{max}} - T_{\text{ref}}) \right) \right) \]

Where

\( V_{\text{rated}} \) = rated array maximum-power voltage (in V)

\( V_{\text{SDC}} \) = nominal DC-system voltage (in V)

\( C\%_V \) = temperature coefficient for voltage month (in \(^{\circ}\text{C}\))

\( T_{\text{max}} \) = maximum expected module temperature (in \(^{\circ}\text{C}\))

\( T_{\text{ref}} \) = reference or rating temperature (in \(^{\circ}\text{C}\))

**INTERACTIVE PV SYSTEM PERFORMANCE WORKSHEET**

<table>
<thead>
<tr>
<th>Estimating and Verifying System AC Energy Production</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV Array DC Power Rating at STC - 1000 W/m(^2), 25 (^{\circ}\text{C}) (kW)</td>
<td></td>
</tr>
<tr>
<td><strong>Derating Factors</strong></td>
<td></td>
</tr>
<tr>
<td>Nameplate Ratings</td>
<td>0.95</td>
</tr>
<tr>
<td>Inverter and Transformer</td>
<td>0.95</td>
</tr>
<tr>
<td>Module Mismatch</td>
<td>0.98</td>
</tr>
<tr>
<td>DC Wiring</td>
<td>0.98</td>
</tr>
<tr>
<td>AC Wiring</td>
<td>0.99</td>
</tr>
<tr>
<td>Soiling</td>
<td>1.00</td>
</tr>
<tr>
<td>Shading</td>
<td>0.85</td>
</tr>
<tr>
<td>Sun Tracking</td>
<td>1.00</td>
</tr>
<tr>
<td>Age</td>
<td>1.00</td>
</tr>
<tr>
<td>Combined Derating Factors</td>
<td>0.73</td>
</tr>
<tr>
<td>Estimated System AC Power Output at STC - 1000 W/m(^2), 25 (^{\circ}\text{C}) (kW)</td>
<td>7.3</td>
</tr>
<tr>
<td><strong>Temperature Adjustments</strong></td>
<td></td>
</tr>
<tr>
<td>Array Power-Temperature Coefficient (%/(^{\circ}\text{C}))</td>
<td>-0.5</td>
</tr>
<tr>
<td>Average Array Operating Temperature ((^{\circ}\text{C}))</td>
<td>45</td>
</tr>
<tr>
<td>Estimated System AC Power Output at 1000 W/m(^2) and Average Operating Temperature (kW)</td>
<td>6.6</td>
</tr>
<tr>
<td><strong>Solar Radiation Received</strong></td>
<td></td>
</tr>
<tr>
<td>Solar Irradiation in Plane of Array (kWh/m(^2)/day)</td>
<td>5</td>
</tr>
<tr>
<td><strong>Estimated System AC Energy Output at Average Operating Temperature (kWh/day)</strong></td>
<td>29.5</td>
</tr>
</tbody>
</table>
Electrical Integration

Maximum PV System Voltage

\[ V_{\text{max}} = V_{oc} \times n_m \times C_T \]

where

\( V_{\text{max}} \) = maximum system voltage (V)
\( V_{oc} \) = module rated open-circuit voltage at 25°C (V)
\( n_m \) = number of series-connected modules
\( C_T \) = low-temperature correction factor

Maximum Inverter Input Current

For stand-alone inverters operating from batteries, the maximum inverter input current must be evaluated at the lowest operating voltage when the inverter is producing rated power. \( P_{AC} \) is the rated inverter maximum continuous AC power output (in W).

\[ I_{\text{max}} = \frac{P_{AC}}{V_{\text{min}} \times \eta_{\text{inv}}} \]

where

\( I_{\text{max}} \) = maximum inverter input current (A)
\( P_{AC} \) = rated inverter maximum AC power output (W)
\( V_{\text{min}} \) = minimum inverter operating voltage (V)
\( \eta_{\text{inv}} \) = inverter efficiency

Conductor Nominal Ampacity

\[ I_{\text{nom}} = I_{\text{max}} / (C_{\text{temp}} \times C_{\text{conduit}}) \]

where

\( I_{\text{nom}} \) = conductor nominal ampacity (in A)
\( I_{\text{max}} \) = maximum circuit current (in A)
\( C_{\text{temp}} \) = correction factor for temperature
\( C_{\text{conduit}} \) = correction factor for number of current-carrying conductors in a conduit or cable
Voltage Drop

\[ V_{drop} = I_{op} \times R_C \times L \]

where

- \( V_{drop} \) = voltage drop (V)
- \( I_{op} \) = operating current (A)
- \( R_C \) = conductor resistance per unit length (\( \Omega/\text{kft.} \))
- \( L \) = total conductor round-trip length (kft)

Economic Analysis

Time Value of Money

\[ PV = \frac{FV}{(1+r)^t} \]

Where:

- \( PV \) = present value
- \( FV \) = future value
- \( r \) = discount rate
- \( t \) = time period

Life-Cycle Cost Analysis

\[ LCC = I + M_{PV} + E_{PV} + R_{PV} - S_{PV} \]

where

- \( LCC \) = life-cycle cost ($)
- \( I \) = initial cost ($)
- \( M_{PV} \) = present value of maintenance costs ($)
- \( E_{PV} \) = present value of energy costs ($)
- \( R_{PV} \) = present value of repair and replacements ($)
- \( S_{PV} \) = present value of salvage value ($)