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/m^2
1 Peak Sun-Hour = 1kWh/m^2 = 3.6 MegaJoules/m^2

Temperature conversion:
$°F = (9/5 \times °C) + 32$
$°C = (°F - 32) \times 5/9$
where
$°F$ = temperature in Fahrenheit
$°C$ = temperature in Celsius

Formulas

Electricity Basics: voltage, current, resistance, power

Ohm’s Law:
$V = I \times R$
$I = V / R$
$R = V / I$
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:

$H = E \text{ x } t$

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:

$E_2 / E_1 = I_2 / I_1 = P_2 / P_1$

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:

$I_{sc2} = I_{sc1} \text{ x } (E_2 / E_1)$

$I_{mp2} = I_{mp1} \text{ x } (E_2 / E_1)$

$P_{mp2} = P_{mp1} \text{ x } (E_2 / E_1)$

Array Area Estimate:

$A = P_{mp} / (1 \text{ kW/ m}^2 \text{ x } \eta_m)$

where

A = estimated required array area (in m^2)

P_{mp} = desired peak array power (in kW DC)

η_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_shadow = height/tan α°
Tan α° = height/d_shadow
Height = tan α°/d_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_min = d_shadow x cos ψ°

Where the angle ψ° (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:

$\eta = P_{mp} / (E \times A)$

where

η = efficiency

P_{mp} = maximum power (in W)

E = solar irradiance (in W/m^2)

A = area (in m^2)

Resistance Required at Maximum Power Point:

$R_{mp} = V_{mp} / I_{mp}$

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:

$T_{cell} = T_{amb} + (C_{T\text{-}rise} \times E)$

where

T_{cell} = cell temperature (in °C)

T_{amb} = ambient temperature (in °C)

$C_{T\text{-}rise}$ = temperature-rise coefficient (in °C/kW/m^2)

E = solar irradiance (in kW/m^2)

Module or Array Coefficients:

For Voltage:

$C_V = C_{V\text{-}cell} \times n_s$

where

C_V = module or array absolute temperature coefficient for voltage (in V/°C)

$C_{V\text{-}cell}$ = 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/cm^2)
n_P = number of parallel-connected cell strings
A = individual cell area (in cm^2)

Temperature Coefficients:
$C_V = V_{ref} \times C_{\%V}$
$C_I = I_{ref} \times C_{\%I}$
$C_P = P_{ref} \times C_{\%P}$

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

Voltage and Power Translations:
$V_{trans} = V_{ref} + ([T_{cell} – T_{ref}] \times C_V)$
$P_{trans} = P_{ref} + ([T_{cell} – T_{ref}] \times C_P)$
Where,
V_{trans} = translated voltage at cell temperature (in V)
V_{ref} = reference (or rated) voltage corresponding to T_{ref} (in V)
T_{cell} = cell temperature (in °C)
T_{ref} = reference (or rated) temperature (in °C)
C_V = absolute temperature coefficient of voltage (in V/°C)
P_{trans} = translated power at cell temperature (in W)
P_{ref} = reference (or rated) power corresponding to T_{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

$$E = P_{avg} \times t$$

where
E = energy (Wh)
P_{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)
θ = 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
η_{inv} = inverter efficiency
P_{AC} = AC power ouput (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:

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

where

t_{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_1 = operating time for nth load (in hr/day)

Required Daily System DC Electrical Energy

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

where

E_{SDC} = required daily system DC electrical energy (in Wh/day)

E_{AC} = AC energy consumed by loads (in Whr/day)

η_{inv} = inverter efficiency

E_{DC} = DC energy consumed by loads (in Whr/day)

Required Battery-Bank Output

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

where

B_{out} = required battery-bank output (in Ah)

E_{crit} = average daily electrical-energy consumption during critical design month (in Wh/day)

t_a = autonomy (in days)

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

Average Discharge Rate

$R_d = (t_{op} \times t_a)/DOD_a$

where

R_d = average discharge rate (in hr)

t_{op} = weighted average operating time (in hr/day)

t_a = autonomy (in days)

DOD_a = allowable depth of discharge

Total Required Battery-Bank Rated Capacity

$B_{rated} = B_{out} / (DOD_a \times C_{T,rd})$

where

B_{rated} = battery-bank rated capacity (in Ah)

B_{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

$DOD_{avg} = (\mathrm{LF} \times E_{day}) / (B_{actual} \times V_{SDC})$

Where

DOD_{avg} = average battery-bank daily depth of discharge

LF = estimated load fraction

E_{day} = average daily electrical-energy consumption (in Wh)

B_{actual} = actual total rated battery-bank capacity (in Ah)

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

Required Array Maximum-Power Current

$I_{array} = E_{crit} / (\eta_{batt} \times V_{SDC} \times t_{PSH})$

where

I_{array} = required array maximum-power current (in A)

E_{crit} = daily electrical-energy consumption during critical design month (in Wh/day)

η_{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

$I_{rated} = I_{array} / C_s$

where

I_{rated} = rated array maximum-power current (in A)

I_{array} = required array maximum-power current (in A)

C_s = soiling derating factor

Rated Array Maximum-Power Voltage

$V_{rated} = 1.2 \times \{V_{SDC} – [V_{SDC} \times C_{\%V} \times (T_{max} – T_{ref})]\}$

Where

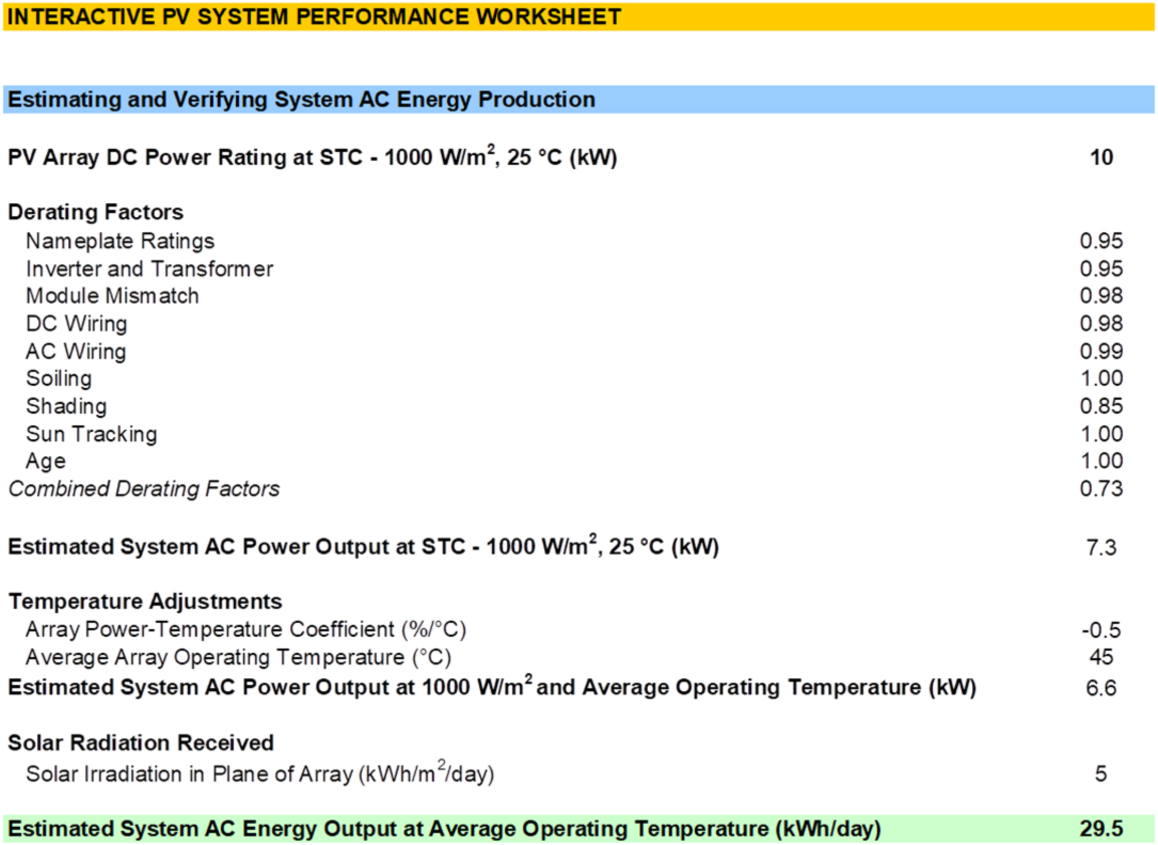
V_{rated} = rated array maximum-power voltage (in V)

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

$C_{\%V}$ = temperature coefficient for voltage month (in /°C)

T_{max} = maximum expected module temperature (in °C)

T_{ref} = reference or rating temperature (in °C)



INTERACTIVE PV SYSTEM PERFORMANCE WORKSHEET	
Estimating and Verifying System AC Energy Production	
PV Array DC Power Rating at STC - 1000 W/m^2, 25 °C (kW)	**10**
Derating Factors	
Nameplate Ratings	0.95
Inverter and Transformer	0.95
Module Mismatch	0.98
DC Wiring	0.98
AC Wiring	0.99
Soiling	1.00
Shading	0.85
Sun Tracking	1.00
Age	1.00
Combined Derating Factors	0.73
Estimated System AC Power Output at STC - 1000 W/m^2, 25 °C (kW)	7.3
Temperature Adjustments	
Array Power-Temperature Coefficient (%/°C)	-0.5
Average Array Operating Temperature (°C)	45
Estimated System AC Power Output at 1000 W/m^2 and Average Operating Temperature (kW)	6.6
Solar Radiation Received	
Solar Irradiation in Plane of Array (kWh/m^2/day)	5
Estimated System AC Energy Output at Average Operating Temperature (kWh/day)	**29.5**

Electrical Integration

Maximum PV System Voltage

$$V_{max} = V_{oc} \times n_m \times C_T$$

where
V_{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).

$$I_{max} = \frac{P_{AC}}{V_{min} \times \eta_{inv}}$$

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

Conductor Nominal Ampacity

$I_{nom} = I_{max}/(CF_{temp} \times CF_{conduit})$

where

I_{nom} = conductor nominal ampacity (in A)

I_{max} = maximum circuit current (in A)

CF_{temp} = correction factor for temperature

$CF_{conduit}$ = 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 (Ω/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

L_{CC} = 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 ($)