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PVPerformance
MODELING COLLABORATIVE

Tutorial on Photovoltaic System Performance

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WCPEC-6

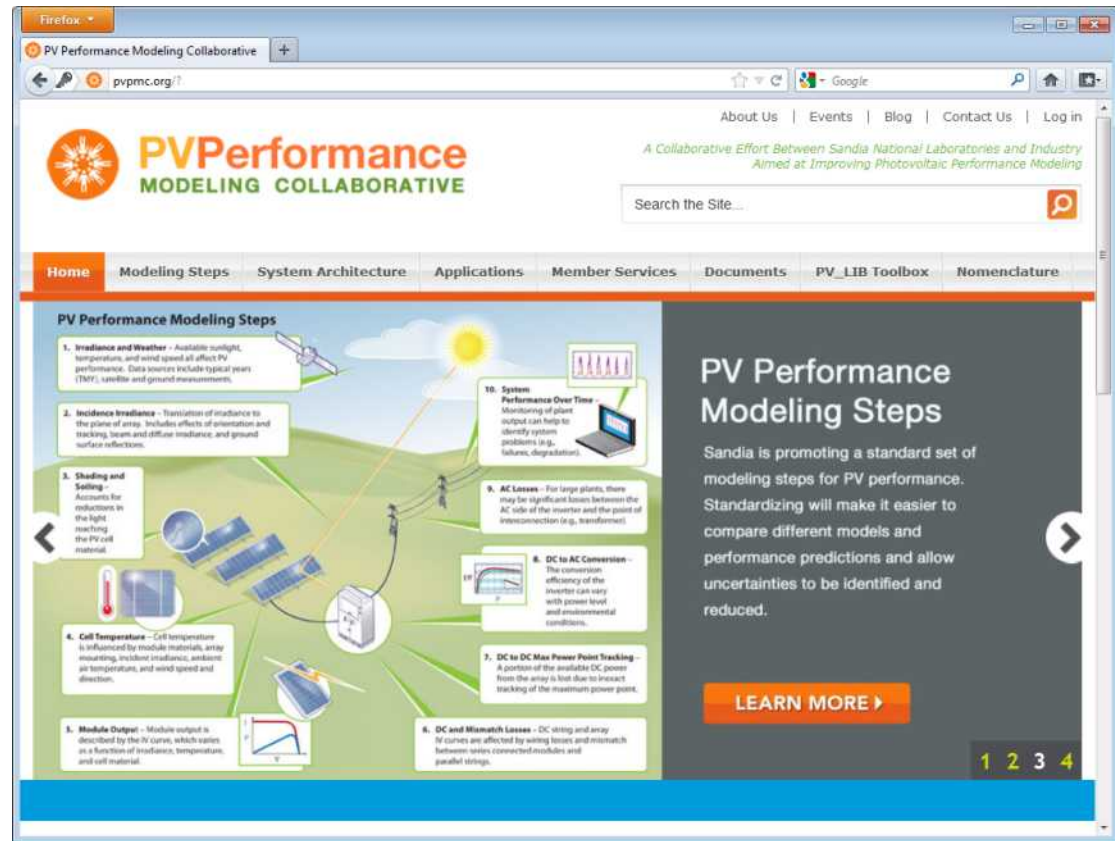
November 23, 2014 Kyoto, Japan

PV Performance Modeling Collaborative Sandia National Laboratories

- Started after 1st PV Performance Modeling Workshop (Albuquerque, NM, Sept. 2010)
- PV performance modeling lacked organization.
 - Accurate information about algorithms, validation data, best practices difficult to find and access.
- PVPMC.org started to provide an information hub on PV performance modeling
 - Model agnostic, focus on algorithms, methods, data, etc.
 - Detailed Modeling Steps (online textbook)
 - Modeling function library in Matlab and Python (PV_LIB)
 - Member contact list, document library, bibliography, glossary, blog, events, ...
- 2nd PV Performance Modeling Workshop (Santa Clara, CA, May 2013)
- 3rd PV Performance Modeling Workshop (Santa Clara, CA, May 2014)

Website: <http://pvpmc.sandia.gov>

- 1600+ Members (and growing)
- 10,000 to 15,000 visits per month
- ~218 web pages published



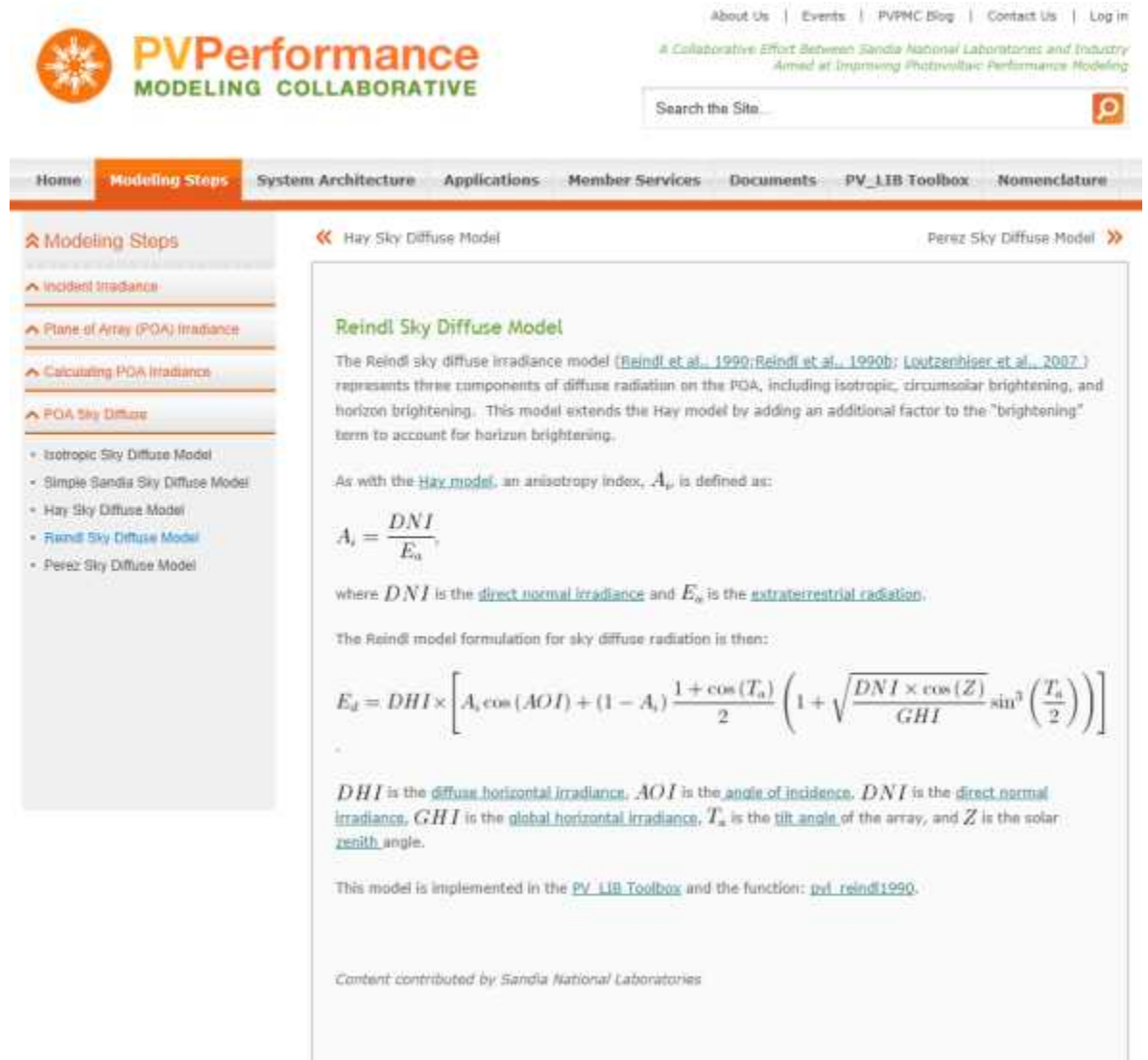
When you join you will set up a *username* and *password*
-Sign up for weekly email updates separately

Standard Modeling Steps (PVPMC)

- Irradiance and Weather
 - Definitions and Overview
 - Sun Position
 - Solar Position Algorithm (SPA)
 - Simple models
 - Sandia's code
 - Irradiance and Insolation
 - Extraterrestrial radiation
 - Air Mass
 - DISC Model
 - DIRINT Model
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 - Global Horizontal Irradiance
 - Diffuse Horizontal Irradiance
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 - AM 1.5 Standard Spectrum
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 - Short-term variability
 - Spatial variability
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 - Incident Irradiance
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 - 1-Axis Tilted Roll
 - 1-Axis Equatorial
 - Two-Axis Tracking
 - 2-Axis Azimuth-Elevation
 - 2-Axis Polar
 - 2-Axis Tilt-Roll
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 - Effect of Array Tilt Errors
 - Effect of Array Azimuth Errors
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 - Calculating POA Irradiance
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 - Angle of Incidence
 - POA Ground Reflected
 - Albedo
 - POA Sky Diffuse
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 - Near Shading
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 - Single Diode Equivalent Circuit Models
 - De Soto "Five-Parameter" Module Model
 - PVsyst Module Model
 - Point-value models
 - Sandia PV Array Performance Model
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 - PVWatts
 - Improvements to PVWatts
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 - String IV Curves
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 - Array IV Curves
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- Simple Sandia Sky Diffuse Model
- Hay Sky Diffuse Model
- Reindl Sky Diffuse Model
- Perez Sky Diffuse Model
- Concentrators
- POA Irradiance Uncertainty and Validation
- Uncertainty and Validation Studies
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 - Uncertainty and Validation
- DC to AC Conversion
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 - Sandia Inverter Model
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 - AC Wiring Losses
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 - Data Filtering
 - Data Filling
 - PV Performance Metrics
 - Performance Ratio
 - Performance Index
 - Annual Yield
 - PV Systems Operations and Maintenance
 - Definitions and Overview
 - Availability
 - Failure Mode and Rates
- References

Example Model Description

- Brief description
 - Equation support
 - Hyperlinking
 - Link to PV_LIB functions
 - References
 - Contributor info
-
- We are looking for additional models and process descriptions



The screenshot shows the PVPerformance Modeling Collaborative website. The header includes the logo, navigation links (About Us, Events, PVPNC Blog, Contact Us, Log in), and a search bar. The main navigation bar highlights 'Modeling Steps'. The left sidebar lists the modeling steps: Incident Irradiance, Plane of Array (POA) Irradiance, Calculating POA Irradiance, and POA Sky Diffuse. Under POA Sky Diffuse, several models are listed, with 'Reindl Sky Diffuse Model' selected. The main content area displays the 'Reindl Sky Diffuse Model' page, which includes a brief description, the mathematical formula for A_i , and the formula for E_d . The page also mentions that the model is implemented in the PV_LIB Toolbox and provides a link to the function `pyl_reindl1990`.

PVPerformance MODELING COLLABORATIVE

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A Collaborative Effort Between Sandia National Laboratories and Industry Aimed at Improving Photovoltaic Performance Modeling

Search the Site

Home | **Modeling Steps** | System Architecture | Applications | Member Services | Documents | PV_LIB Toolbox | Nomenclature

Modeling Steps

- Incident Irradiance
- Plane of Array (POA) Irradiance
- Calculating POA Irradiance
- POA Sky Diffuse
 - Isotropic Sky Diffuse Model
 - Simple Sandia Sky Diffuse Model
 - Hay Sky Diffuse Model
 - Reindl Sky Diffuse Model**
 - Perez Sky Diffuse Model

Hay Sky Diffuse Model

Perez Sky Diffuse Model

Reindl Sky Diffuse Model

The Reindl sky diffuse irradiance model (Reindl et al., 1999; Reindl et al., 1990b; Loutzenhiser et al., 2007) represents three components of diffuse radiation on the POA, including isotropic, circumsolar brightening, and horizon brightening. This model extends the Hay model by adding an additional factor to the "brightening" term to account for horizon brightening.

As with the Hay model, an anisotropy index, A_i , is defined as:

$$A_i = \frac{DNI}{E_a}$$

where DNI is the direct normal irradiance and E_a is the extraterrestrial radiation.

The Reindl model formulation for sky diffuse radiation is then:

$$E_d = DHI \times \left[A_i \cos(AOI) + (1 - A_i) \frac{1 + \cos(T_a)}{2} \left(1 + \sqrt{\frac{DNI \times \cos(Z)}{GHI}} \sin^3\left(\frac{T_a}{2}\right) \right) \right]$$

DHI is the diffuse horizontal irradiance, AOI is the angle of incidence, DNI is the direct normal irradiance, GHI is the global horizontal irradiance, T_a is the tilt angle of the array, and Z is the solar zenith angle.

This model is implemented in the PV_LIB Toolbox and the function: `pyl_reindl1990`.

Content contributed by Sandia National Laboratories

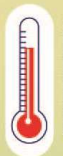
PV Performance Modeling Steps

1. Irradiance and Weather – Available sunlight, temperature, and wind speed all affect PV performance. Data sources include typical years (TMY), satellite and ground measurements.



2. Incidence Irradiance – Translation of irradiance to the plane of array. Includes effects of orientation and tracking, beam and diffuse irradiance, and ground surface reflections.

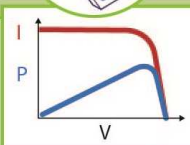
3. Shading and Soiling – Accounts for reductions in the light reaching the PV cell material.



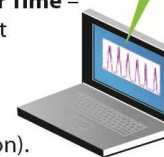
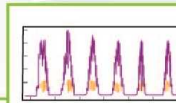
4. Cell Temperature – Cell temperature is influenced by module materials, array mounting, incident irradiance, ambient air temperature, and wind speed and direction.



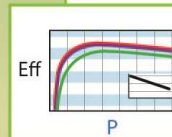
5. Module Output – Module output is described by the IV curve, which varies as a function of irradiance, temperature, and cell material.



10. System Performance Over Time – Monitoring of plant output can help to identify system problems (e.g., failures, degradation).



9. AC Losses – For large plants, there may be significant losses between the AC side of the inverter and the point of interconnection (e.g., transformer).



8. DC to AC Conversion – The conversion efficiency of the inverter can vary with power level and environmental conditions.

7. DC to DC Max Power Point Tracking – A portion of the available DC power from the array is lost due to inexact tracking of the maximum power point.

6. DC and Mismatch Losses – DC string and array IV curves are affected by wiring losses and mismatch between series connected modules and parallel strings.

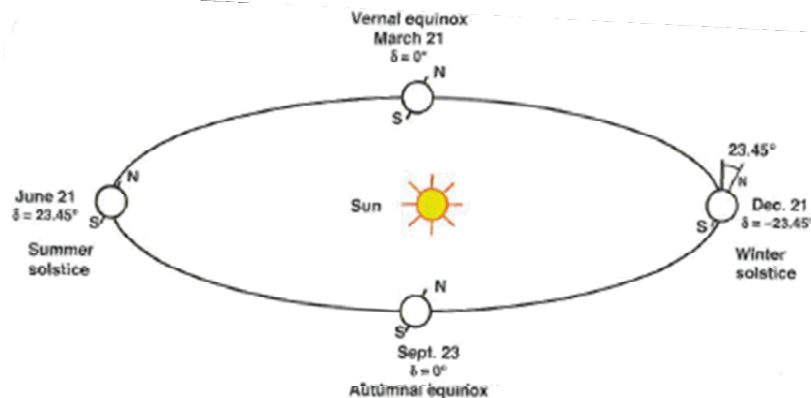
1. Irradiance and Weather

- One of the primary inputs for a PV performance model
 - e.g., 8760 hourly values of irradiance, temperature, precipitation, wind speed, etc.
 - Three options to choose from:
 - Typical years (Irradiance is mostly modeled from other measurements)
 - Satellite modeled data (everywhere, indirect measurement)
 - Ground measurements from site (short time period, accurate)
 - Varies with time and location (and instruments used for measurements). Data quality is important
 - Largest source of uncertainty in PV performance modeling

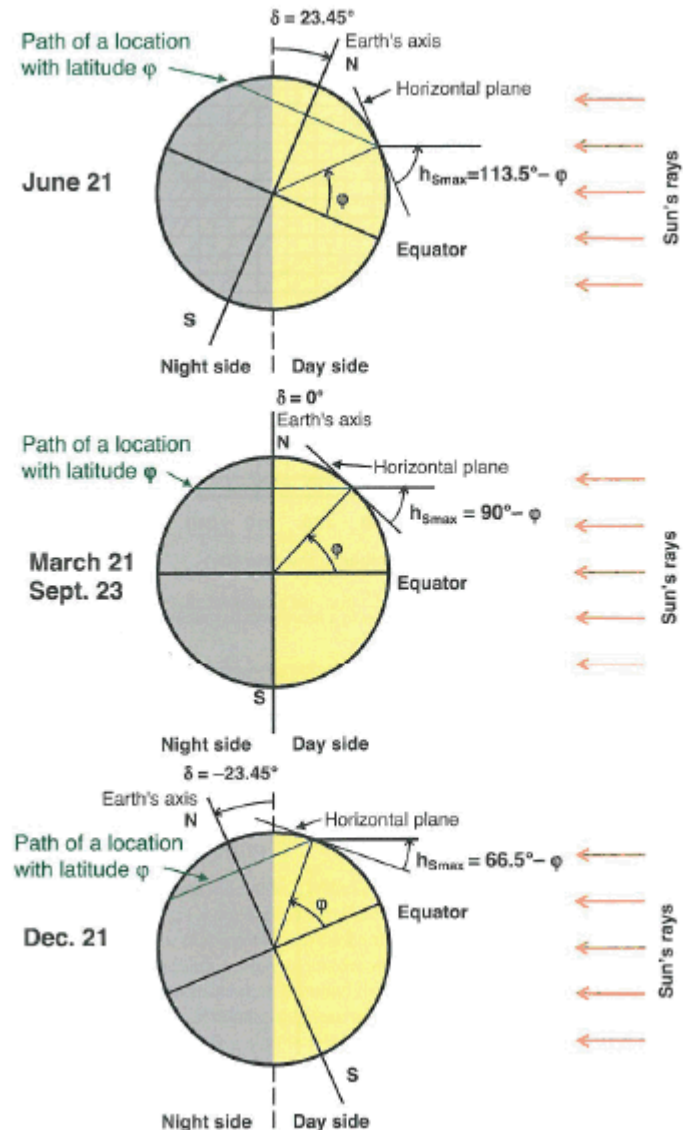
Earth-Sun System

Two Important Facts

- Earth's axis is tilted (23.45° deg) relative to Earth's orbital plane
 - Seasons!
- Orbit is elliptical (closest on Jan 4)
 - Affects extraterrestrial irradiance (6-7%)
($1,415\text{--}1,322\text{ W/m}^2$)



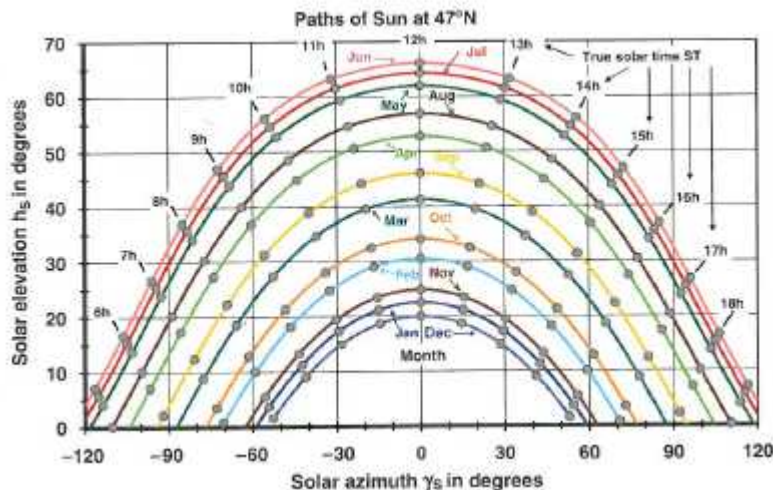
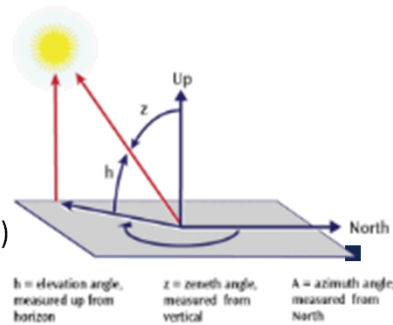
Source: Häberlin, 2012



Source: Häberlin, 2012

Solar Position

- Solar position relative to an observer on Earth is a critical input to PV performance models.
- Imbedded in PV simulation programs
- Described with:
 - Sun Elevation Angle
 - Zenith = 90-elevation angle)
 - Sun Azimuth Angle



Example Algorithms

- Various online calculators
 - <http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html>
 - <http://solardat.uoregon.edu/SolarPositionCalculator.html>
 - <http://www.pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator>
 - <http://www.suncalc.net>
 - http://www.sunearthtools.com/dp/tools/pos_sun.php

NREL Solar Position Algorithm (SPA) (also available in PV_LIB)

- “Gold Standard” (Most Accurate)
- Sandia “ephemeris” algorithm (available in PV_LIB)

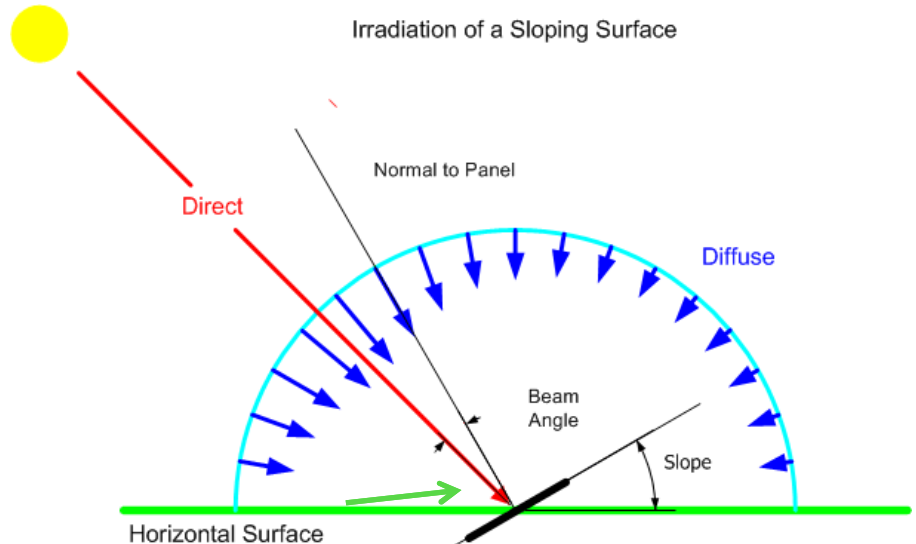
PV_LIB functions

- pvl_spa
- pvl_ephemeris

Irradiance Components

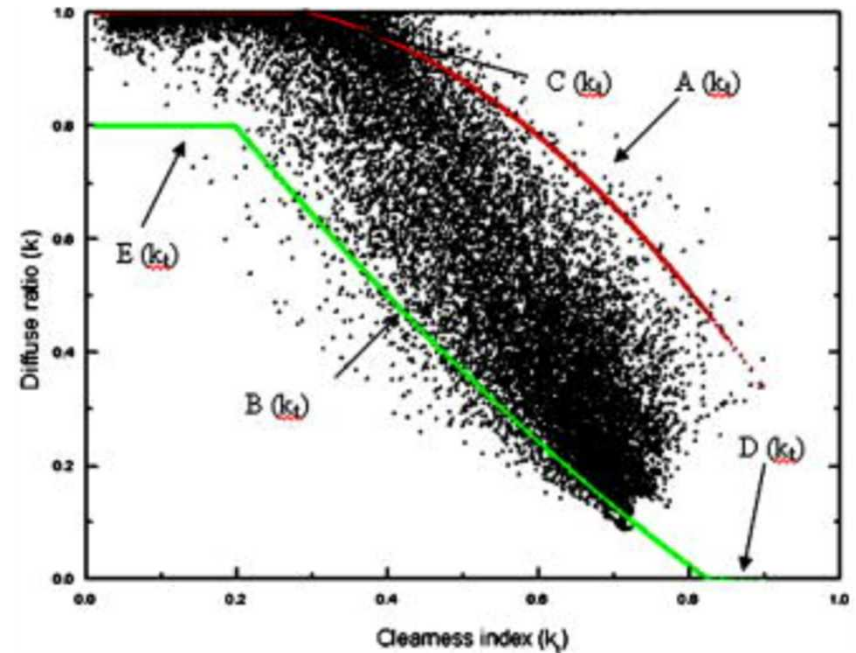
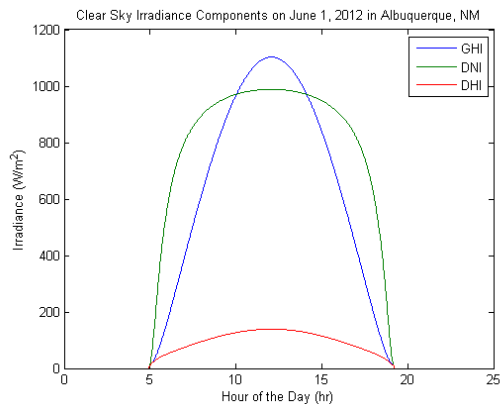
Reference Quantities

- Direct Normal Irradiance (DNI)
 - Light hitting a plane normal to the sun's rays that comes directly from the sun.
- Global Horizontal Irradiance (GHI)
 - All light hitting a horizontal plane
 - Horizontal beam irradiance = $\text{DNI} \cdot \cos(\text{Zenith Angle})$
- Diffuse Horizontal Irradiance (DHI)
 - Light hitting a horizontal plane that does NOT come directly from the sun
- Albedo
 - Relative reflectivity of the ground surface (usually ~ 0.2 , which means about 20% of the light hitting the ground is reflected)



More Irradiance Concepts

- Decomposition models
 - Timescale matters (1-min, 1-hr, 1-day)
 - Estimate DNI from GHI
 - Erbs model
 - DISC model
 - DIRINT model
 - Many more...
- Extraterrestrial radiation
 - Irradiance outside atmosphere
- Clear Sky Irradiance Models
 - Assumes atmosphere but no clouds



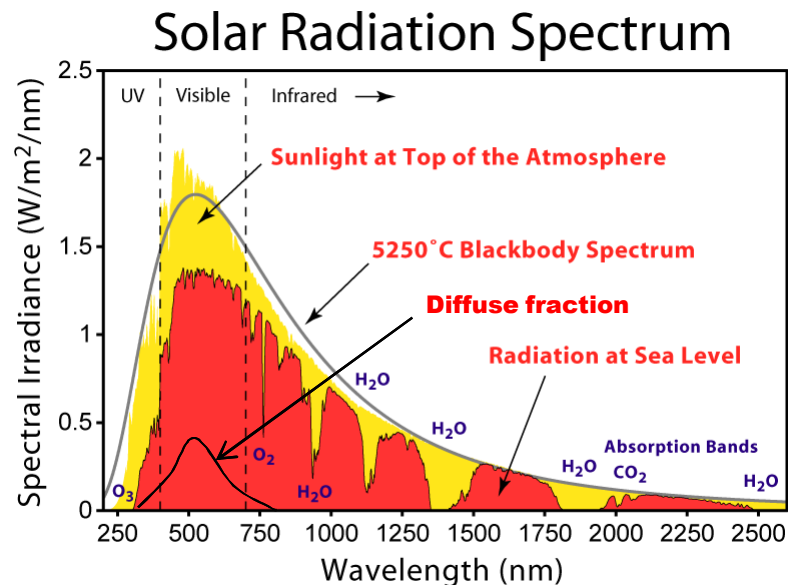
Source: J. Sol. Energy Eng.. 2005;128(1):104-117. doi:10.1115/1.2148972

PV_LIB functions

- pvl_disc
- pvl_dirint
- pvl_extraradiation
- pvl_clearsky_haurwitz
- pvl_ineichen

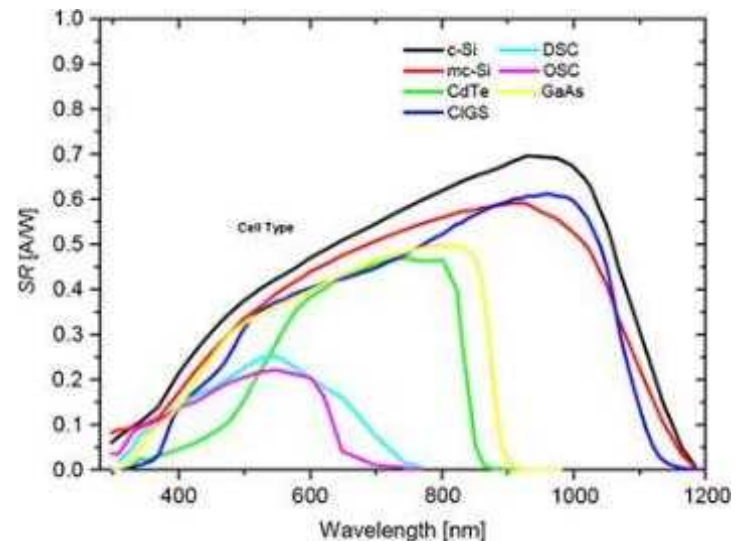
Solar Spectrum

- Sunlight has a spectrum is influenced by the sun and thickness and composition of the atmosphere.
- PV cell technologies respond to the spectral range differently
- PV is rated a standard spectrum (AM1.5 – computer model)



- CdTe and GaAs cells do not respond to wavelengths above ~ 950 nm.
- c-Si and CIGS do respond.
- Because both are rated at same spectrum, performance differences do occur (H_2O).
- Spectral mismatch accounts for differences.

PV Cell Absorption Spectrum



Air Mass

- Air mass is a relative measure the optical length or thickness of the atmosphere. It is used as a proxy for spectral changes in sunlight at the ground.
- At sea level, with the sun is directly overhead (zenith angle = 0) the air mass is equal to 1. As the zenith angle becomes larger, the path of direct sunlight through the atmosphere grows longer and air mass increases. In contrast, as land elevation increases, the thickness of the atmosphere lessens and the air mass is reduced.
- The simplest estimate of relative air mass (ignoring land elevation effects) assumes a spherical earth and atmosphere. The relative air mass is simply a trigonometric function of the zenith angle:
$$AM = \frac{1}{\cos(Z)}$$
- Absolute air mass (AMa) includes effects of elevation.
- PV modules are rated at AM1.5

PV_LIB functions

- pvl_pres2alt
- pvl_alt2pres
- pvl_relativeairmass
- pvl_absoluteairmass

Weather Data

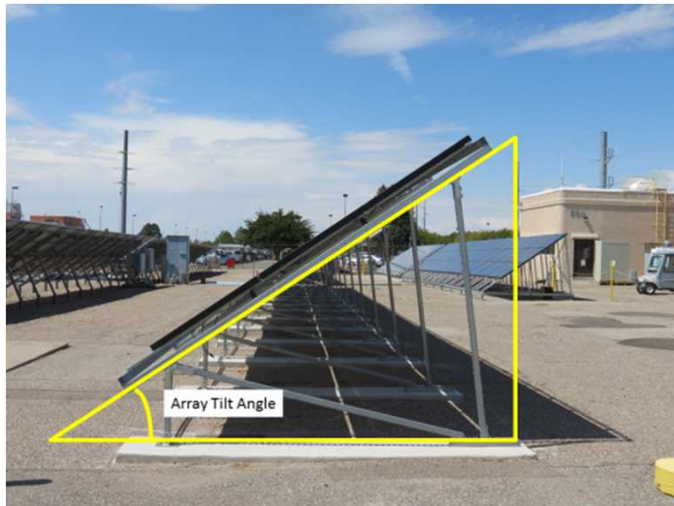
- In addition to irradiance, temperature, wind speed, RH, precipitation (rain and snow) all are usually required to model PV system performance.
- Annual datasets are needed
- Multiple years of data
 - Interannual variability
- State of the Art is to use “typical” meteorological year” (TMY)
 - Many years of hourly data are collected (or modeled)
 - “Average” months are selected from collection to develop a TMY.
 - TMY2 (237 locations) 1961-1990
 - TMY3 (1,454 locations) 1991-2005
 - 1991-2010 Update available
- TMY month selection weights based on 25% GHI, 25% DNI, and 50% on non irradiance factors
 - PV would be better served by 100% on GHI (TGY: Typical GHI Year???)
- Satellite data is becoming more accepted.
 - Measurements available almost everywhere
 - Validation studies are leading to higher accuracies (e.g., snow)

PV_LIB functions

- `pvl_readtmy2`
- `pvl_readtmy3`
- `pvl_maketimestruct`
- `pvl_makelocationstruct`

2. Incident Irradiance

Array Tilt Angle



Array Azimuth Angle

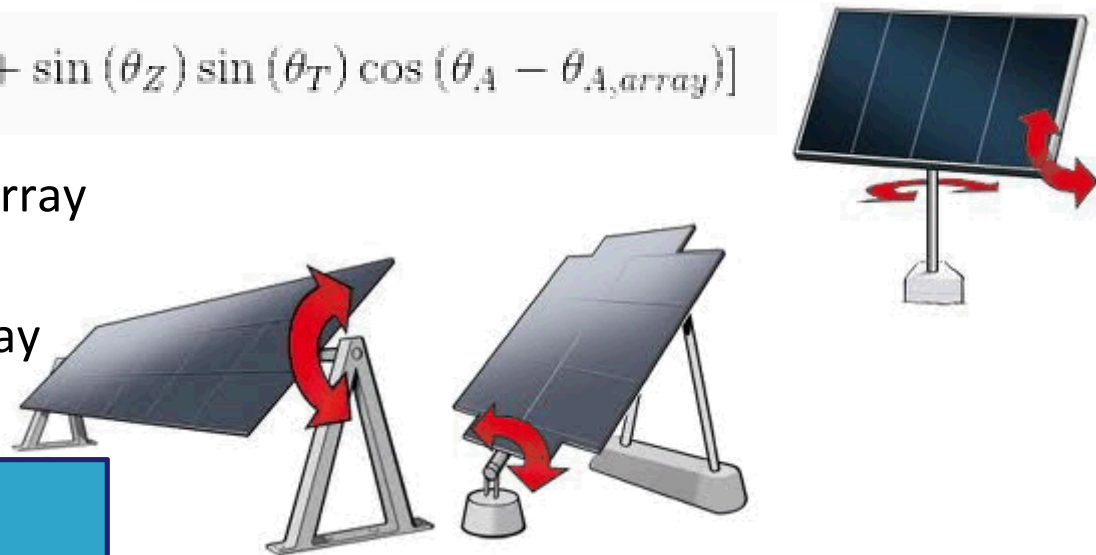


$$AOI = \cos^{-1} [\cos (\theta_Z) \cos (\theta_T) + \sin (\theta_Z) \sin (\theta_T) \cos (\theta_A - \theta_{A,array})]$$

- Single axis tracking moves array to partially follow sun
- 2-axis tracking can keep array normal to the sun (AOI=0)

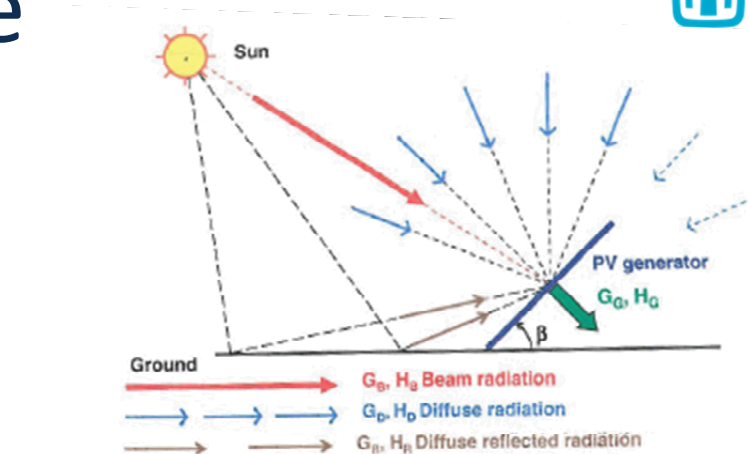
PV_LIB functions

- pvl_singleaxis



2. Incident Irradiance

- Incident irradiance is the light that hits the plane of the array (a.k.a Plane-of-array irradiance).
 - Beam component
 - Sky diffuse component
 - Ground reflected
- Beam irradiance = $\text{DNI} * \cos(\text{AOI})$
- Sky diffuse models account for:
 - Isotropic component
 - Circumsolar – forward scattering around sun disk
 - Horizon brightening
- Ground reflected irradiance
 - Array tilt angle
 - Ground surface albedo
 - Grass = 0.15-0.25
 - Snow = 0.5 -0.82



Source: Häberlin, 2012

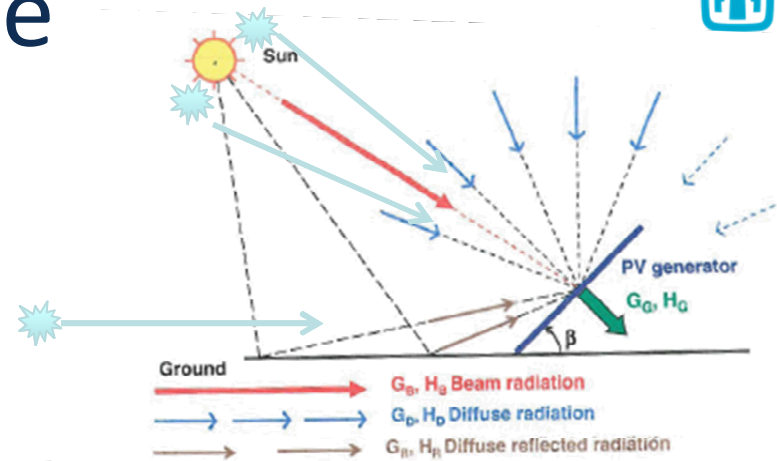
PV_LIB functions

- `pvl_getaoi`
- `pvl_grounddiffuse`
- `pvl_isotropicsky`
- `pvl_haydavies1980`
- `pvl_klucher1979`
- `pvl_perez`
- `pvl_kingdiffuse`
- `pvl_reindl1990`

2. Incident Irradiance

Sky Diffuse Models

- Isotropic model
 - Assumes uniform diffuse light and is geometric
- Hay and Davies model
 - Isotropic model + circumsolar enhancement (PVsyst)
- Reindl model
 - Isotropic + circumsolar + horizon brightening
- Perez model (1991)
 - Isotropic + circumsolar + horizon brightening, where circumsolar and horizon components are empirical functions based on clearness. Site calibration may be needed. (PVsyst)

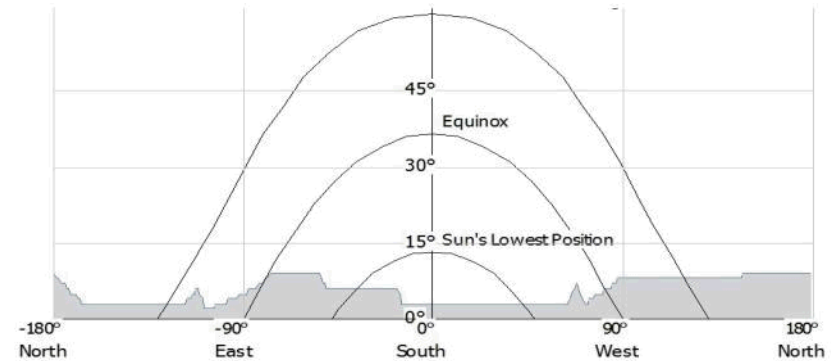


Source: Häberlin, 2012

- King diffuse model
 - Isotropic + lumped empirical term based on fitting data collected at Sandia. At Sandia, this model has proved to be most accurate. Could easily be fit to other data
- Many more....

3. Shading, Soiling, and Reflections

- Not all POA irradiance is available
- Dirt and grime prevent light from getting to the cells (soiling)
- Snow can cover all or part of array (soiling)
- Objects and terrain shade array
- Near shade has sharp edges
 - Buildings, trees, appliances, wires, chimney, etc.
 - Row-row shading within array
- Far shade is more diffuse
 - Mountains, horizon

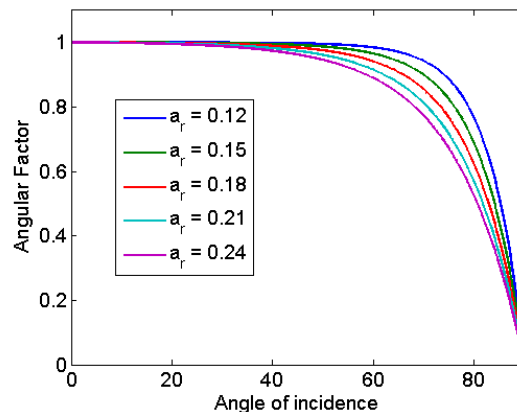
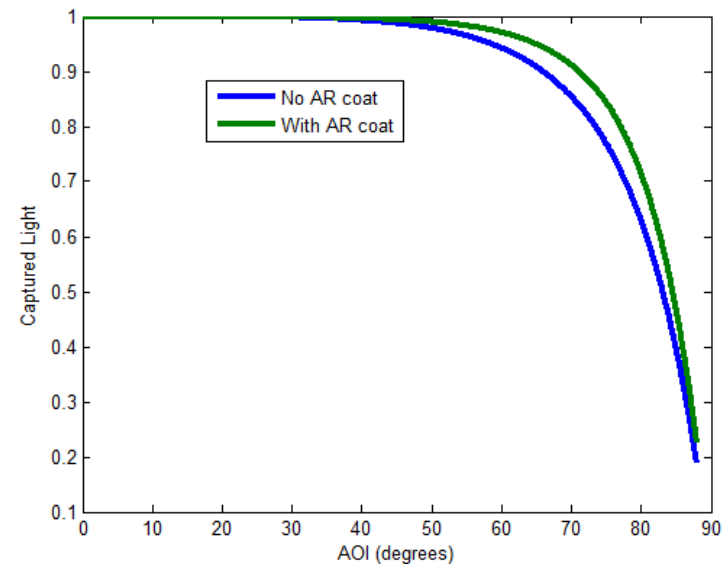


A 2D sunpath diagram in PV*SOL, with horizon data imported.

- Shading effects are assigned to certain time periods and irradiance is reduced.
- Partial shading is much more complex. Modeling approaches are still evolving.

3. Shading, Soiling, and Reflections

- Reflections are influenced by:
 - Angle of incidence
 - Coatings (e.g., anti-reflective)
 - Soiling
- Reflections models include:
 - Physical (optical) model based on Snell's and Bouguer's laws
 - Empirical models
 - Sandia has used a 5th order polynomial form (F2)
 - ASHRAE
 - Martin and Ruiz (includes effects of soiling)

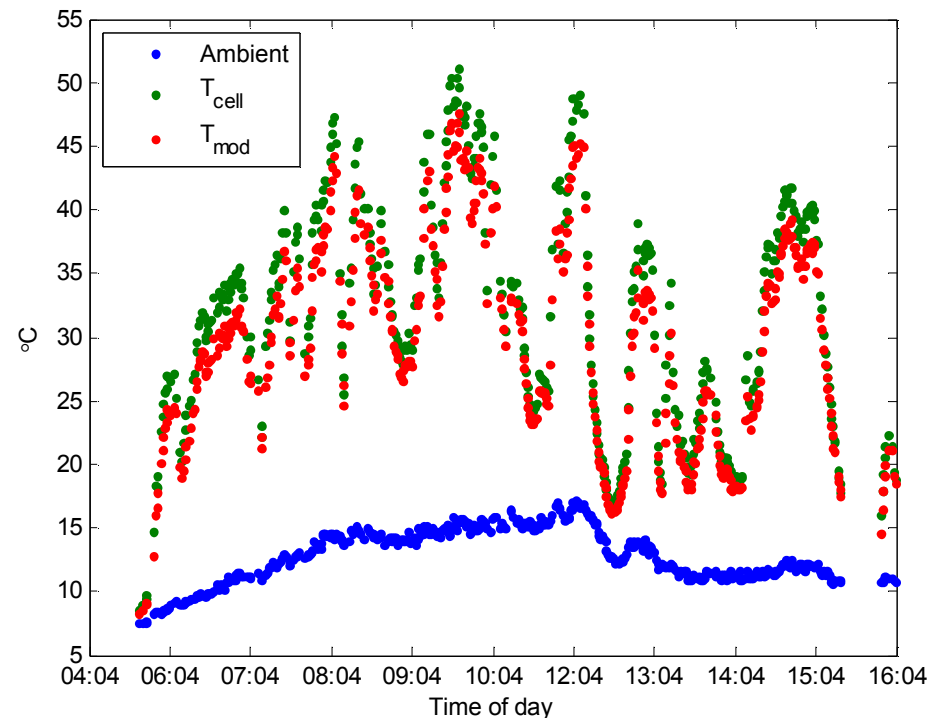


PV_LIB functions (reflection losses)

- pvl_physicaliam
- pvl_ashraeiam

4. Cell Temperature

- Power decreases with increasing cell temperature
 - -0.3 to -0.5 %/C (depends on cell tech., module materials)
- Cell temperature difficult to measure directly in situ
 - Can be inferred from V_{oc} and I_{sc} (e.g., IEC 60904-5)
 - Thermocouples attached to module backsheet + delta
- Cell temperature > ambient (~ 30 C difference)
- Cell temperature > back-of-module temperature ($\sim 2 - 4$ C)
- Models predict cell temperature from POA irradiance, ambient temperature and wind conditions

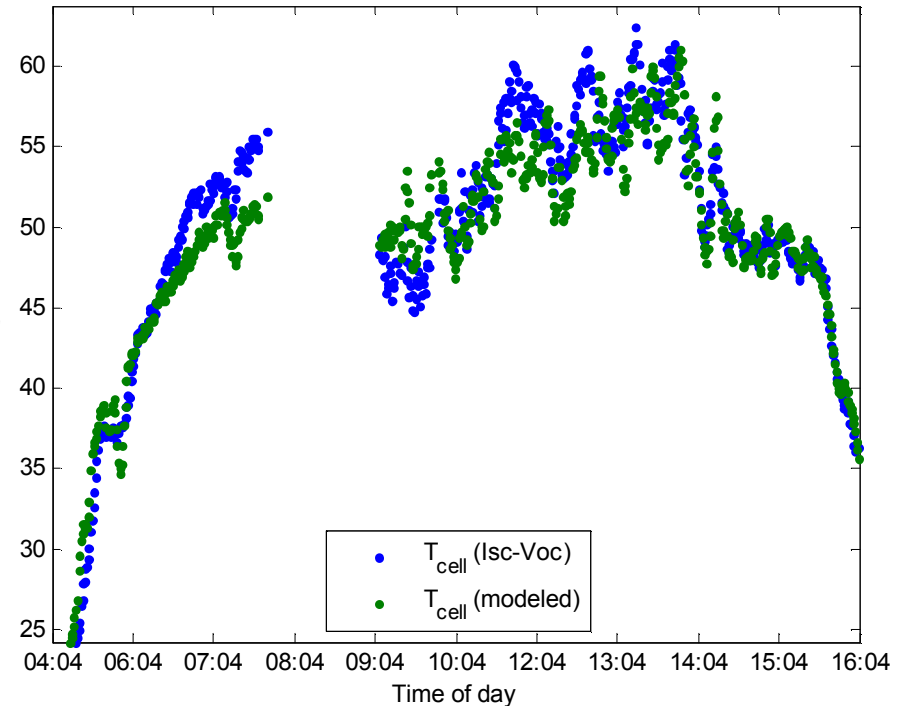


4. Cell Temperature Models

- Most are steady-state

$$T_C = T_M + \frac{E}{E_0} \Delta T$$
$$= T_{amb} + \frac{E}{E_0} \exp(a + bWS) + \frac{E}{E_0} \Delta T$$

- Typical assumptions:
 - Represents average cell temperature across module
 - Represents average across an array

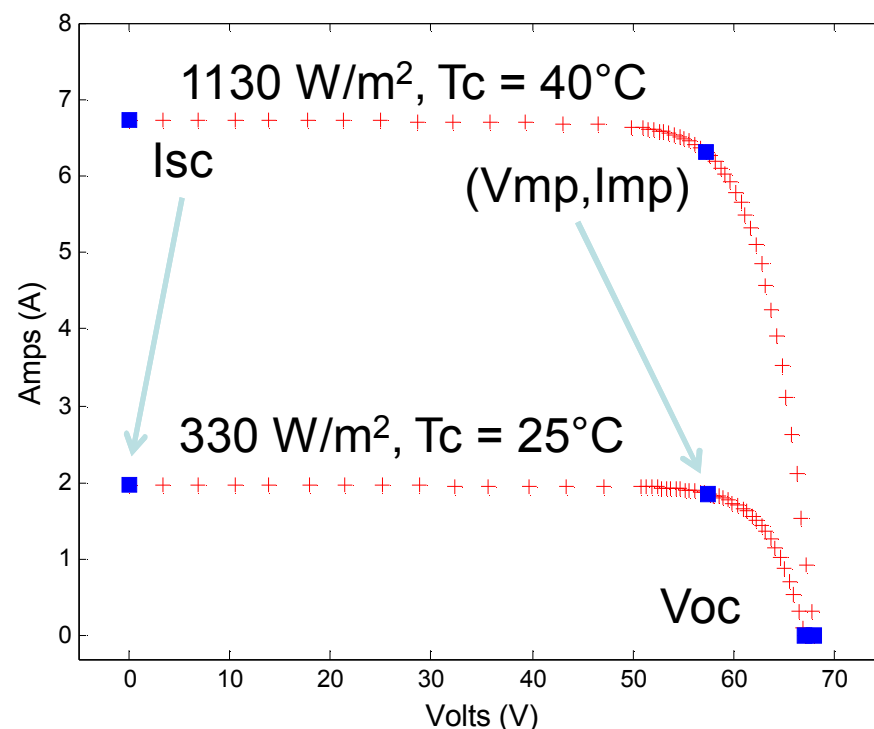


PV_LIB functions

- pvl_sapmcelltemp

5. Module Output

- Don't confuse a model with the software that implements it
- Predict DC voltage and current over the range of POA irradiance and cell temperature
 - IV curve models (aka 'diode' models)
 - E.g., '5 parameter model'
 - Point models
 - E.g., Sandia model
 - Simple efficiency
 - E.g., PVWatts



$$P_{dc} = \frac{I_{tr}}{1000} P_{dc0} (1 + \gamma(T_{cell} - T_{ref}))$$

The Sandia Array Performance Model

- Describes module output at SC, OC and MP points
- As a function of beam and diffuse irradiance (E_b and E_{diff}), cell temperature (T_C), air mass (AM_a) and angle of incidence (AOI)
- 14 empirical coefficients, 2 empirical functions (f_1 and f_2)
- With exception of f_2 , coefficients determined for individual modules

$$E_e = f_1(AM_a) \left(E_b f_2(AOI) + E_{diff} f_d \right) \leftarrow \text{Effective irradiance : light flux that becomes electrical current}$$

$$I_{SC} = I_{SC0} E_e \left(1 + \alpha_{SC} (T_C - T_0) \right)$$

$$V_{OC} = V_{OC0} + N_s n \delta (T_C) \ln(E_e) + \beta_{OC} (T_C - T_0)$$

$$V_{MP} = V_{MP0} + C_2 N_s n \delta (T_C) \ln(E_e) + C_3 N_s \left(n \delta (T_C) \ln(E_e) \right)^2 + \beta_{MP} (T_C - T_0)$$

$$I_{MP} = I_{MP0} \left(C_0 E_e + C_1 E_e^2 \right) \left(1 + \alpha_{MP} (T_C - T_0) \right)$$

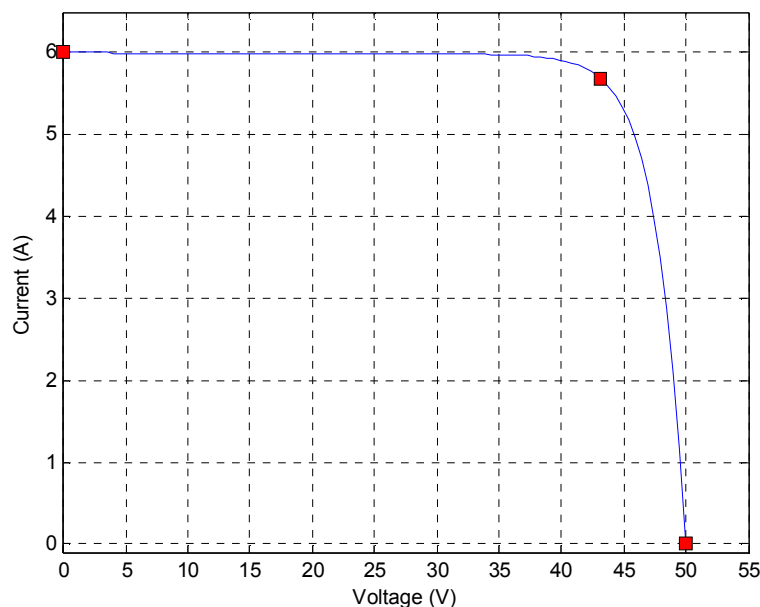
PV_LIB functions
• pvl_sapm

Single Diode Models

- CEC, PVsyst, PV*SOL, others
 - IV curve described by single diode equation
 - “5 parameters” – for each IV curve
 - Additional equations describe how parameters change with effective irradiance E , temperature T_c

PV_LIB functions

- pvl_singlediode
- pvl_calparams_desoto
- wapr_vec
- pvl_fminbnd_vec



$$I = I_L - I_0 \left[\exp \left(\frac{V + IR_s}{nV_T} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}}$$

$$I_L(E, T_c) = \frac{E}{E_0} [I_{L0} + \alpha_{Isc} (T_c - T_0)]$$

$$I_0 = I_{00} \left(\frac{T_c}{T_0} \right)^3 \exp \left(\frac{1}{k} \left(\frac{E_{g0}}{T_0} - \frac{E_g(T_c)}{T_c} \right) \right)$$

$$R_{sh} = R_{sh0} \frac{E_0}{E} \quad R_s, n \text{ constant}$$

De Soto et al, 2006

Effective irradiance

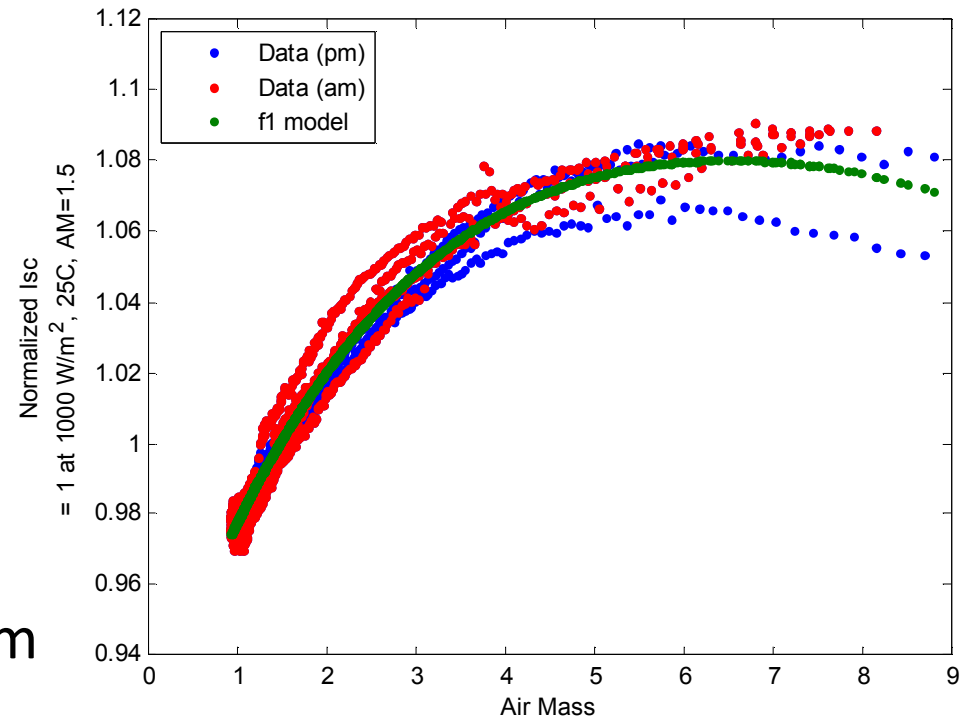
PV_LIB functions

- pvl_relativeairmass
- pvl_absoluteairmass
- pvl_sapm

- Accounts for changing spectral content of light and response of cells
- Implemented in different ways
 - Most common, mismatch factor/function
 - Less commonly, convolution of spectrum and spectral response

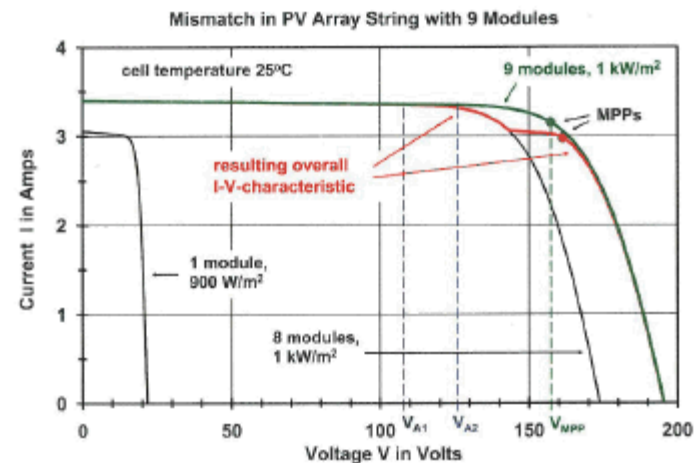
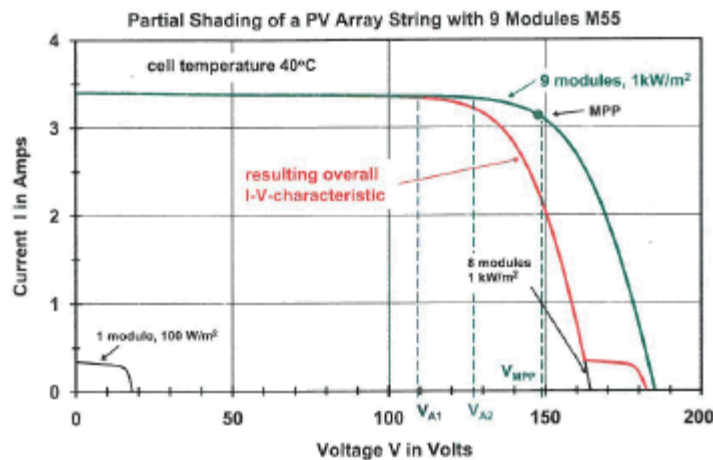
- E.g., Sandia model

$$E_e = f_1(AM_a) \left(E_b f_2(AOI) + E_{diff} f_d \right)$$



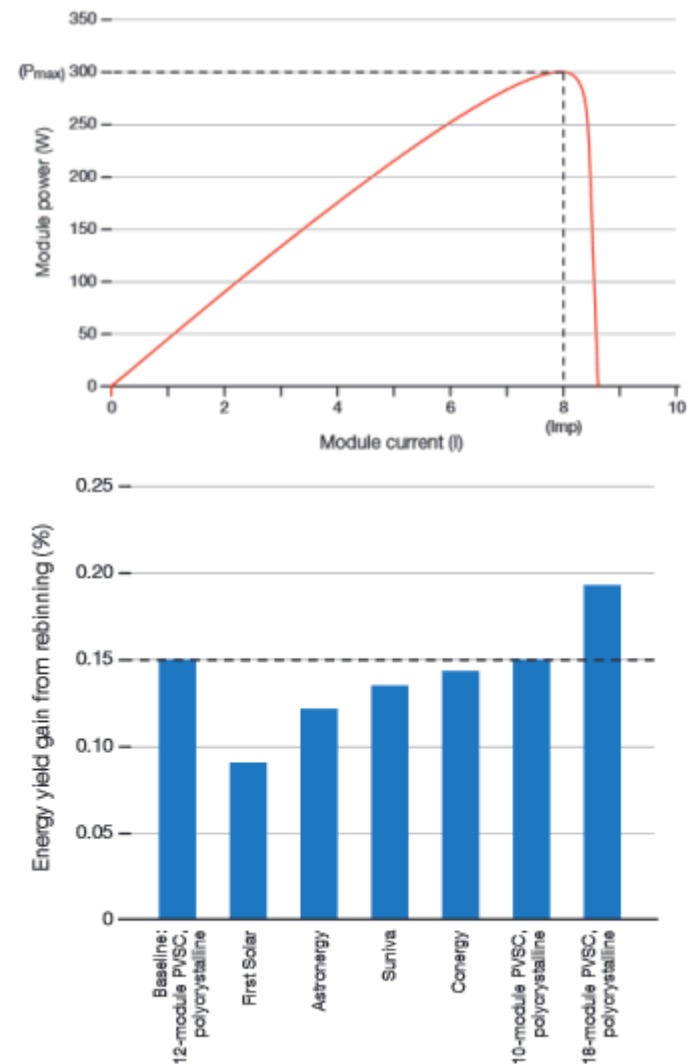
6. DC and Mismatch Losses

- DC wiring loss increases with the square of the current and the wire resistance (I^2R). Increasing the wire gauge increases the system cost and designers try to calculate an optimal balance between cost and long-term performance.
- Mismatch losses can occur as the result of mismatched modules and strings, but is typically more important when it is caused by partial shading on the array.



Mismatch from Module Binning?

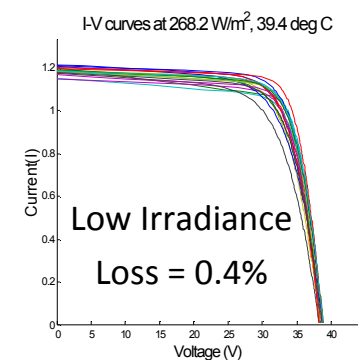
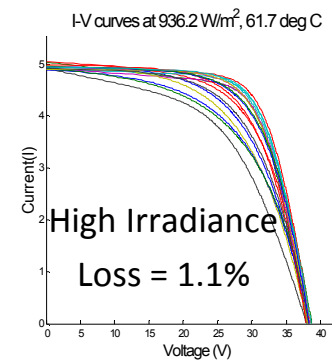
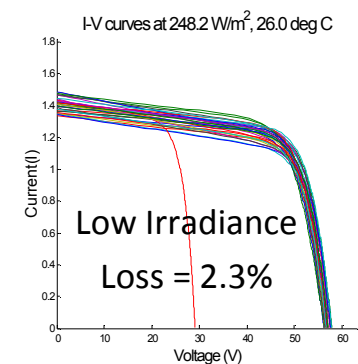
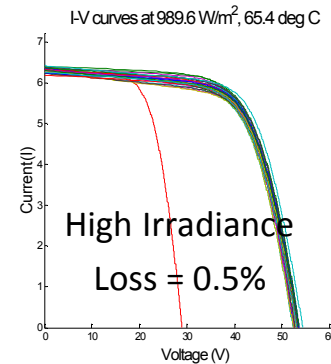
- Many people ask about the effect of module binning tolerance on energy production.
- Most modules are $\pm 5\%$ based on power or current.
- Is it worth insisting on tighter bins? Or testing on site?
- Folsom Labs recently published a study showing that the advantages are very minor.
- Power-current curves are relatively flat at the peak.
- This result also applies to uneven soiling or degradation.



Source: Grana and Gibbs, 2014

Mismatch Losses and Degradation

- Standard mismatch derate is 1-2%. This appears to be reasonable or even overly conservative for modern arrays.
- Losses appear to change with irradiance. Higher at low irradiance.
- Mismatch losses depend more on an individual array's panels and configuration than on age or technology



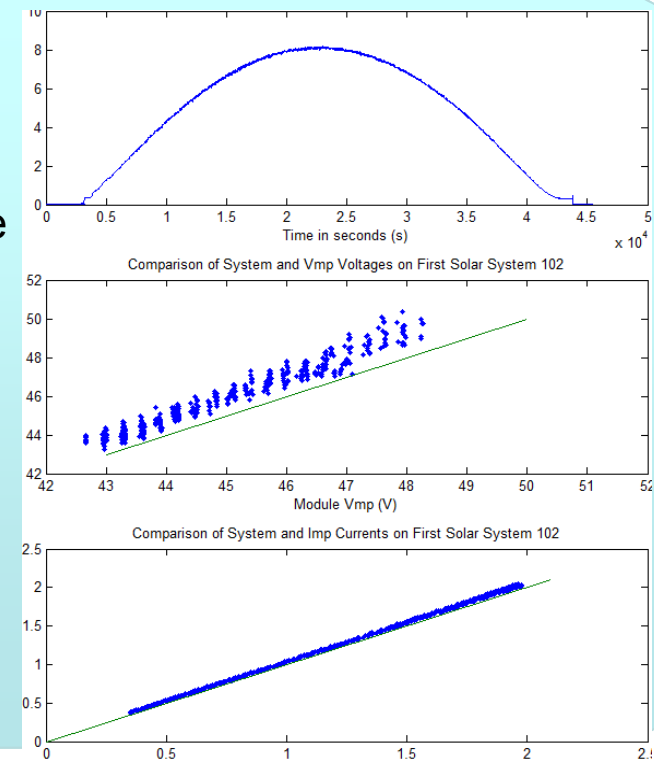
Source: S. MacAlpine, 2013

7. DC to DC MPPT

- This step answers the question: “How well can the inverter follow the MPP?”
- EN-50530 describes a test protocol to measure MPPT efficiency but it difficult to measure.
- Nearly all modern inverters can hold MPPT at >99% efficiency!

Example Field Evaluation:

- We measured module IV curves while simultaneously measuring current and voltage at the inverter of a PV system.
- Inverter dithered +/- about 2V (clear day)
- Offset by approximately 1V is likely measurement error
- Dither increases when irradiance varies



8. DC to AC Conversion

- Inverters experience power conversion losses
 - Losses that vary with I^2 (e.g., resistance)
 - Losses that vary with I (e.g., switching, voltage drops)
 - Losses that are constant (e.g., parasitic loads)
- Inverter losses vary with voltage
 - How it varies depends on topology (single/multi stage), input vs. output voltage, and other design factors → modeled empirically



8. DC to AC Conversion

- Input Data: Efficiency measured in a lab at 3 voltages and 6 power levels.

CEC List of Eligible Inverters

Vmin: 330 Vdc Vnom: 368 Vdc Vmax: 480 Vdc

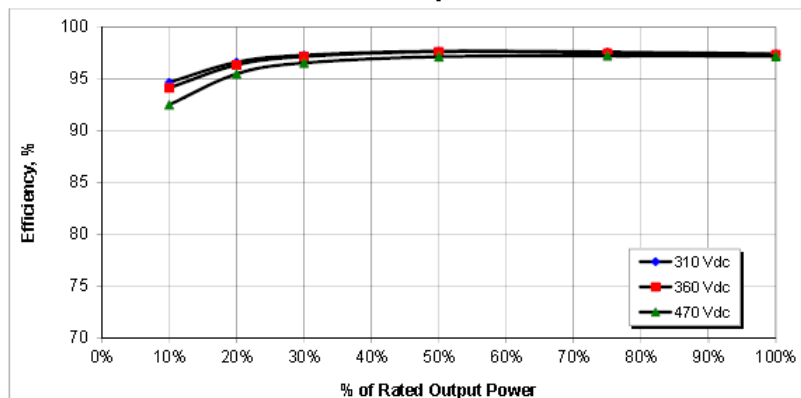
Input Voltage (Vdc)	Power Level (%; kW)						Wtd
	10%	20%	30%	50%	75%	100%	
Vmin 330	84.7	90.3	92.3	93.8	94.0	93.8	93.2
Vnom 368	83.9	89.7	91.6	93.1	93.4	93.0	92.5
Vmax 480	81.3	87.1	89.9	91.3	91.7	90.7	90.7

Newer 3-phase, multistage inverter

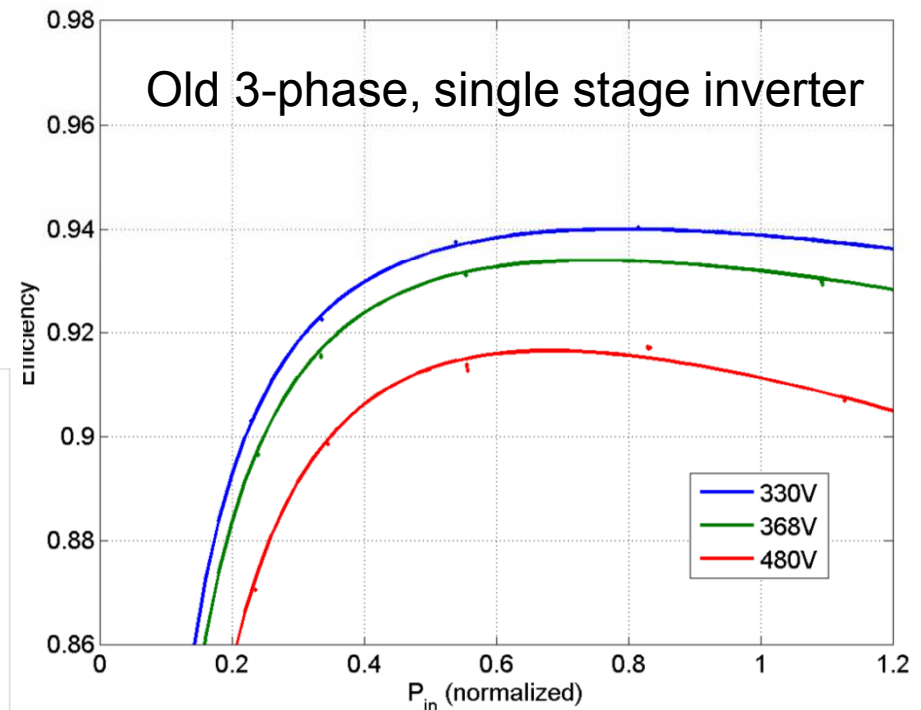
Vmin: 310 Vdc Vnom: 360 Vdc Vmax: 470 Vdc

Input Voltage (Vdc)	Power Level (%; kW)						Wtd
	10%	20%	30%	50%	75%	100%	
Vmin 310	94.7	96.6	97.3	97.7	97.6	97.4	97.4
Vnom 360	94.1	96.4	97.2	97.6	97.5	97.4	97.3
Vmax 470	92.5	95.5	96.6	97.2	97.2	97.2	96.9

CEC Efficiency = 97.0%



Old 3-phase, single stage inverter

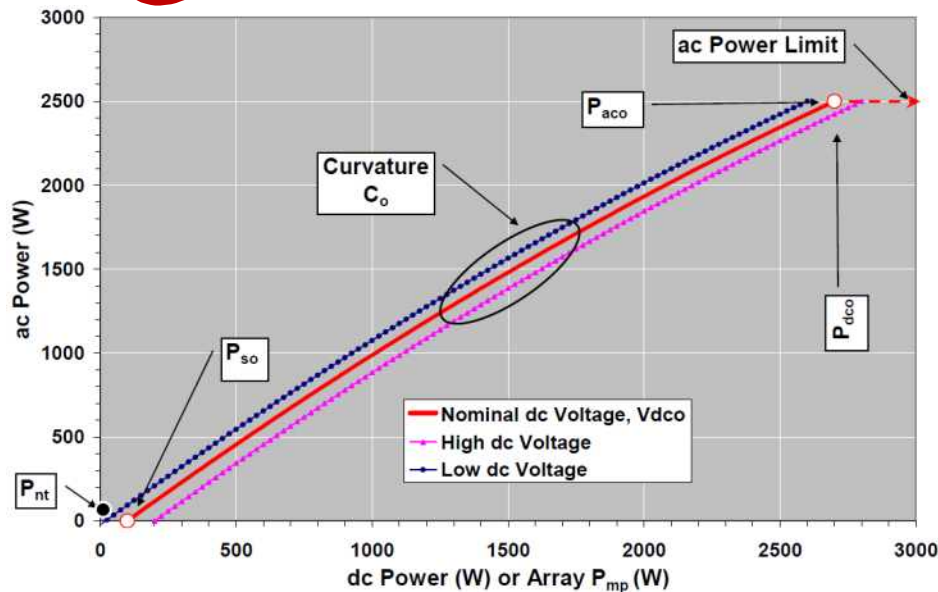


<http://www.gosolarcalifornia.ca.gov/equipment/inverters.php>

8. DC to AC Conversion

■ Sandia Inverter Performance Model

$$P_{ac} = \left\{ \left(\frac{P_{aco}}{P'_{dco} - P'_{so}} - C'_o \right) (P'_{dco} - P'_{so}) \right\} (P_{dc} - P'_{so}) + C'_o (P_{dc} - P'_{so})^2$$



$$P'_{dco} = P_{dco} \{1 + C_1(V_{dc} - V_{dco})\}$$

$$P'_{so} = P_{so} \{1 + C_2(V_{dc} - V_{dco})\}$$

$$C'_o = C_o \{1 + C_3(V_{dc} - V_{dco})\}$$

- PVsyst does a quadratic interpolation between the 3 CEC efficiency curves.

9. AC Losses

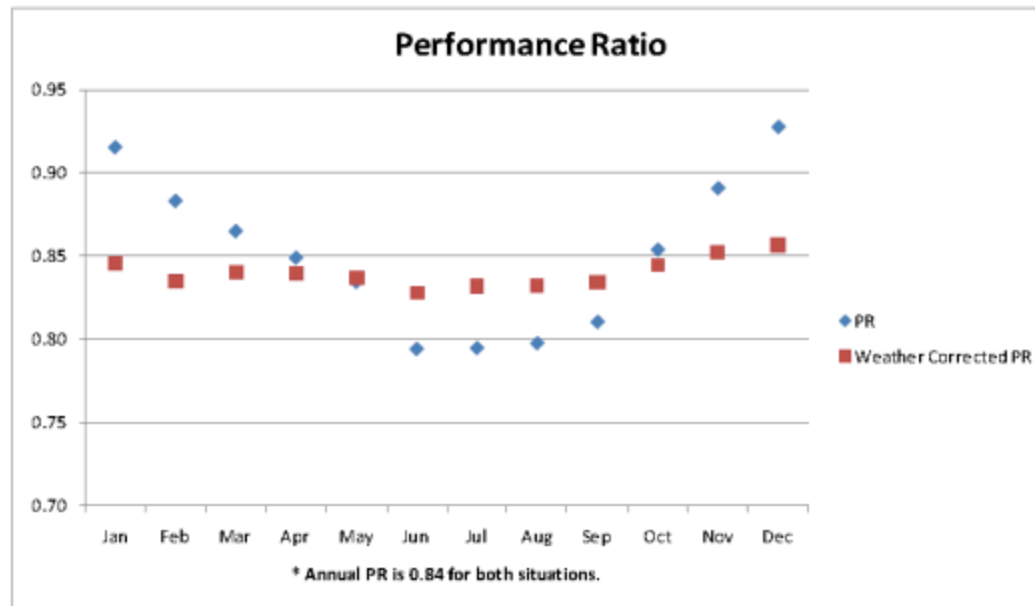
- AC losses include transformer and AC cabling conductive losses. These losses are very project specific and depend where the revenue meter is located.
- Some larger projects have to move AC power considerable distances and these losses can be significant.
- Most models assume a fixed percent loss derate.

10. Performance over Time

- Long term performance must account for equipment degradation and loss of availability due to grid disturbances and O&M events.
- Degradation is usually expressed as a %/yr reduction (e.g., 0.5%/yr)
- **Performance Ratio (PR)** is AC energy / (DC rating*sun hours)
 - IEC 61724
 - 500 W/m² for 1 hour = 0.5 sun hours
 - PR values are typically ~0.8-0.9
- **“Performance Index” (PI)** is AC energy (measured) / AC energy (predicted) using a performance model.
 - PI values should be close to 1. Analysis of deviations from 1 (residual analysis) can help identify problems with model or system.

10. Performance over Time

- **Weather-Corrected Performance Ratio** is AC energy / (DC rating*sun hours*temperature correction term)
 - Temperature correction = $\left(1 - \frac{\delta}{100} (T_{cell,avg} - T_{cell})\right)$
 - Δ is temperature coefficient for power (%/ degC)
 - $T_{cell,avg}$ is the annual average computed cell temperature
 - T_{cell} is the cell temperature



Source: NREL/TP-5200-57991

10. Performance over Time

Other reasons PV system performance can deviate from expectations.

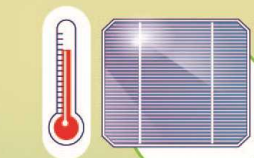
- PV systems are required to disconnect from the grid if voltage or frequency deviates from limits (IEEE 1547)
 - Inverters stay off for 5 minutes
 - Neighbor causes voltage fluctuations (utility issue)
- Equipment failures
 - PV systems have many separate components
 - Small proportion of failures may be “invisible” but can contribute to modeling errors when comparing to measured data
- “Availability” is a term used in the energy industry to describe such issues but there is no recognized definition for solar.
 - Is the system available at night?

PV Performance Modeling Steps

1. Irradiance and Weather – Available sunlight, temperature, and wind speed all affect PV performance. Data sources include typical years (TMY), satellite and ground measurements.

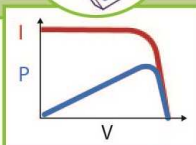
2. Incidence Irradiance – Translation of irradiance to the plane of array. Includes effects of orientation and tracking, beam and diffuse irradiance, and ground surface reflections.

3. Shading and Soiling – Accounts for reductions in the light reaching the PV cell material.

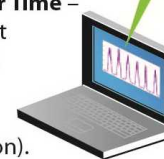
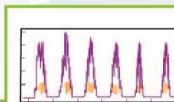


4. Cell Temperature – Cell temperature is influenced by module materials, array mounting, incident irradiance, ambient air temperature, and wind speed and direction.

5. Module Output – Module output is described by the IV curve, which varies as a function of irradiance, temperature, and cell material.

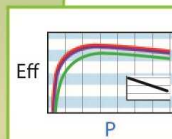


10. System Performance Over Time – Monitoring of plant output can help to identify system problems (e.g., failures, degradation).



9. AC Losses – For large plants, there may be significant losses between the AC side of the inverter and the point of interconnection (e.g., transformer).

8. DC to AC Conversion – The conversion efficiency of the inverter can vary with power level and environmental conditions.



7. DC to DC Max Power Point Tracking – A portion of the available DC power from the array is lost due to inexact tracking of the maximum power point.

6. DC and Mismatch Losses – DC string and array IV curves are affected by wiring losses and mismatch between series connected modules and parallel strings.

Thank You!

jsstein@sandia.gov

<http://solar.sandia.gov>

<http://PV.sandia.gov>

<http://pvpmc.org> → <http://pvpmc.sandia.gov>

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