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PVPerformance MODELING COLLABORATIVE

2015 IEEE PVSC Tutorial on PV System Performance

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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PV Performance Modeling Collaborative

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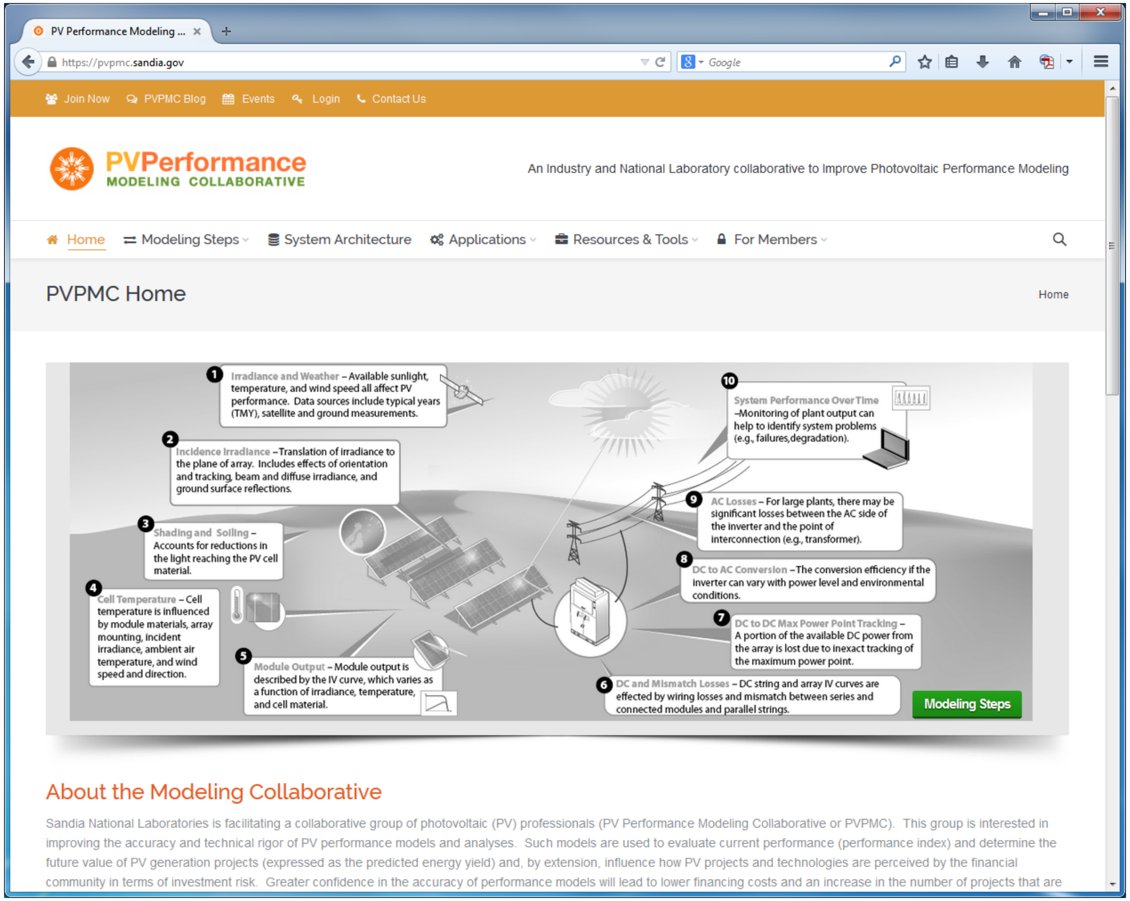
- Find it at http://pvpmc.sandia.gov
- Started after 1st PV Performance Modeling Workshop (Albuquerque, NM, Sept. 2010)
- PV performance modeling lacked organization.
  - Accurate information about algorithms, validation data, best practices difficult to find and access.
- PVPMC.org started to provide 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)
- 4th PV Performance Modeling Workshop (Cologne, Germany, Oct. 22-23 2015)
  - Registration open at www.tuv.com/solarenergy

Website: http://pvpmc.sandia.gov

Sandia National Laboratories

- 2058 Members (and growing)
- 10,000 to 15,000 visits per month
- 205 web pages published



When you join you will set up a *username* and *password*

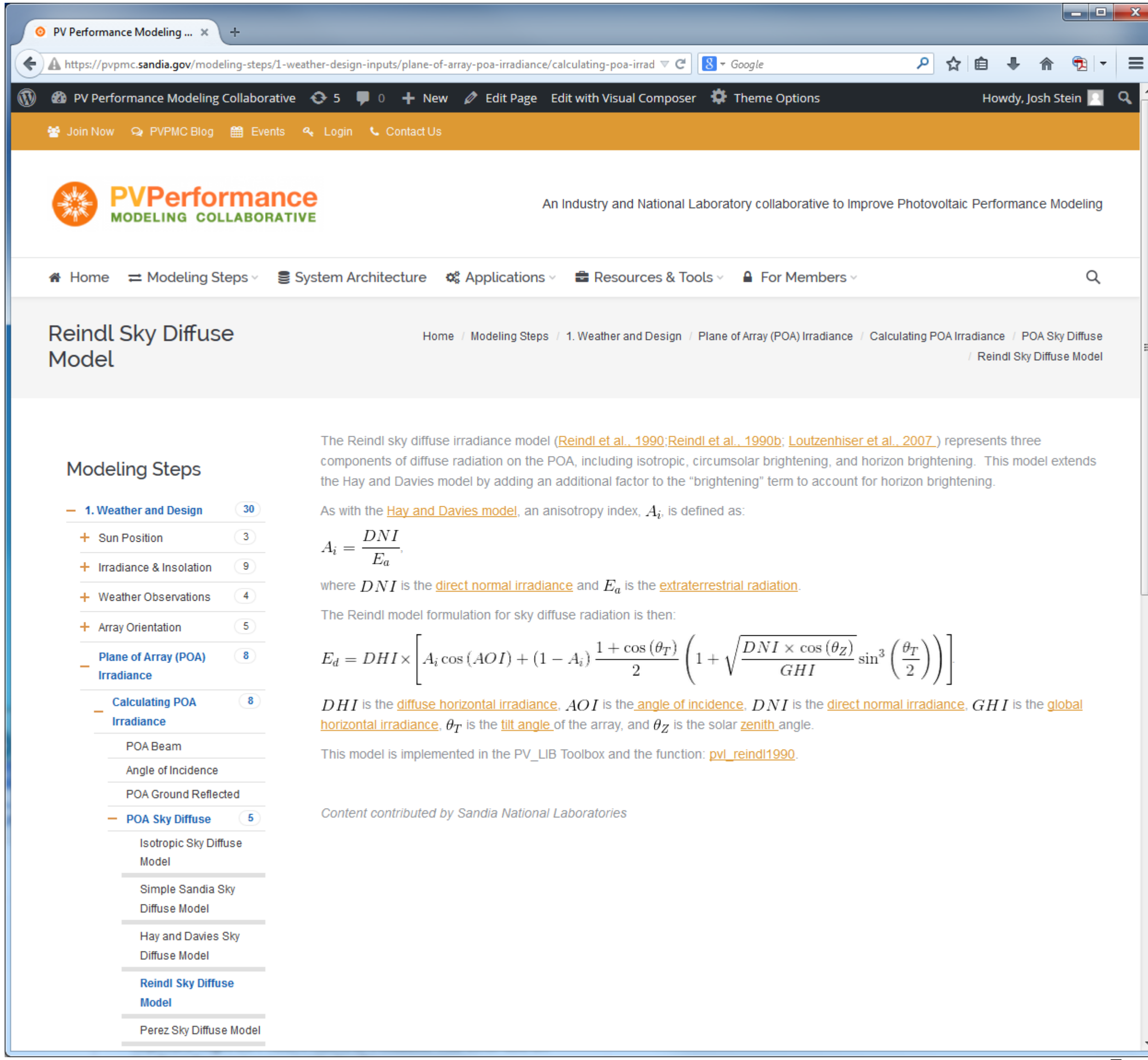
Standard Modeling Steps (PVPMC)

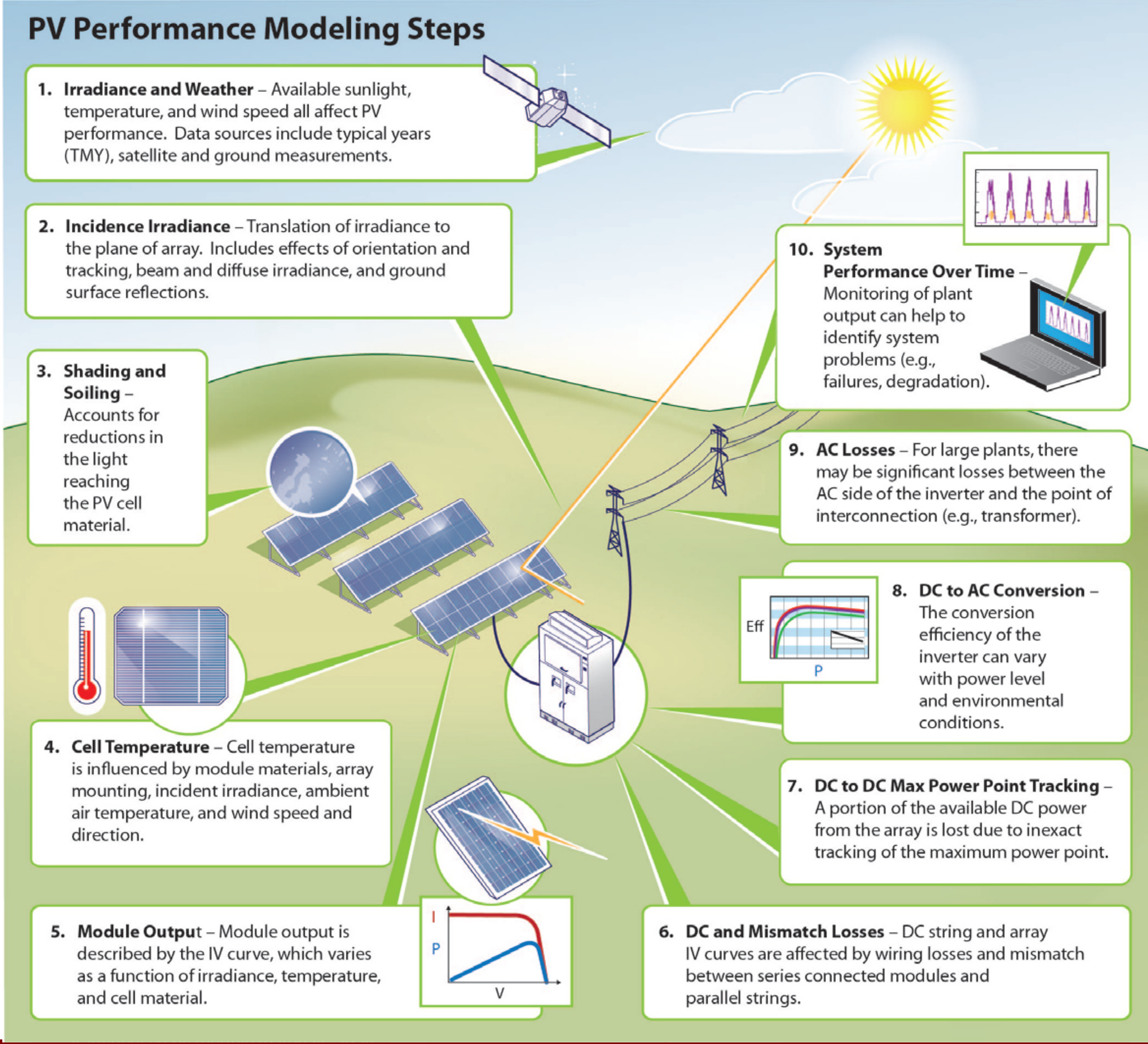
- Irradiance and Weather
  - Definitions and Overview
  - Sun Position
    - Solar Position Algorithm (SPA)
    - Simple models
    - Sandia's code
  - Irradiance and Insolation
    - Extraterrestrial radiation
    - Air Mass
    - Direct Normal Irradiance
      - DISC Model
      - DIRINT Model
    - Global Horizontal Irradiance
    - Diffuse Horizontal Irradiance
    - Spectral Content
      - AM 1.5 Standard Spectrum
    - Satellite derived data
  - Weather Observations
    - Air Temperature
    - Wind Speed and Direction
    - Precipitation
    - Air Pressure
  - Irradiance Data Sources for Performance Modeling
    - National Solar Radiation Database
    - Typical Meteorological Years
    - Site-Specific Data
    - Measure Correlate Predict
    - Irradiance Modeling
  - Uncertainty and Variability
    - Characterization of Irradiance Variability
      - Interannual variability
      - Short-term variability
      - Spatial variability
    - Clear Sky Irradiance models
- Incident Irradiance
  - Definitions and Overview
  - Array Orientation
    - Fixed tilt
    - Single Axis Tracking
      - 1-Axis Horizontal Roll
      - 1-Axis Tilted Roll
      - 1-Axis Equatorial
    - Two-Axis Tracking
      - 2-Axis Azimuth-Elevation
      - 2-Axis Polar
      - 2-Axis Tilt-Roll
    - Array Orientation Errors
      - Effect of Array Tilt Errors
      - Effect of Array Azimuth Errors
  - Plane of Array (POA) Irradiance
    - Measuring POA Irradiance
    - Calculating POA Irradiance
      - POA Beam
      - Angle of Incidence
      - POA Ground Reflected
        - Albedo
      - POA Sky Diffuse
        - Isotropic Sky Diffuse Model
        - Simple Sandia Sky Diffuse Model
        - Hay Sky Diffuse Model
        - Reindl Sky Diffuse Model
        - Perez Sky Diffuse Model
    - Concentrators
    - POA Irradiance Uncertainty and Validation
- Shading, Soiling, and Reflection Losses
  - Definitions and Overview
  - Shading
    - Far Shading
    - Near Shading
  - Soiling and Snow
    - Soil Monitoring Studies
    - Snow Effects
  - Incident Angle Reflection Losses
    - Physical Model of IAM
    - ASHRAE Model
    - Martin and Ruiz IAM Model
      - Soiling effects on Incident Angle Losses
    - Sandia Model
- Cell Temperature
  - Definitions and Overview
  - Module Temperature
    - Thermocouple
    - Voc method
    - Sandia Module Temperature Model
    - Faiman Module Temperature Model
  - Cell temperature
    - Sandia Cell Temperature Model
    - PVsyst Cell Temperature Model
    - Transient Cell Temperature Models
- Module IV Curve
  - Definitions and Overview
  - Effective Irradiance
    - Spectral Mismatch
  - Single Diode Equivalent Circuit Models
    - De Soto "Five-Parameter" Module Model
    - PVsyst Module Model
  - Point-value models
    - Sandia PV Array Performance Model
    - Loss Factor Model
    - PVWatts
      - Improvements to PVWatts
- DC and Mismatch Losses
  - Definitions and Overview
  - Module IV Curves
  - String IV Curves
    - String Mismatch Losses
  - Array IV Curves
    - Array Mismatch Losses
  - DC Wiring Losses
  - Uncertainty and Validation Studies
- Maximum Power Point Tracking
  - Definitions and Overview
  - Array Utilization
  - MPPT Voltage
  - MPPT Efficiency
  - MPPT Algorithms
  - Uncertainty and Validation
- DC to AC Conversion
  - Definitions and Overview
  - Inverter Efficiency
    - CEC Inverter Test Protocol
    - Operating Temperature
    - Sandia Inverter Model
    - Driesse Inverter Model
  - Inverter Saturation
  - Loss of Grid
  - Advanced Inverter Features
    - Power Factor Control
  - Uncertainty and Validation
- AC Losses
  - Definitions and Overview
  - AC Wiring Losses
  - Transformer Losses
- PV System Output
  - Definitions and Overview
  - PV System Monitoring
    - Monitoring Equipment
    - 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





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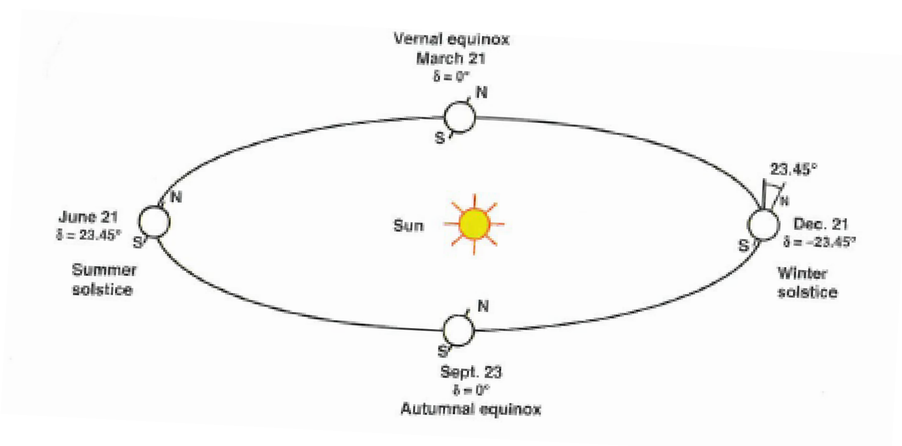
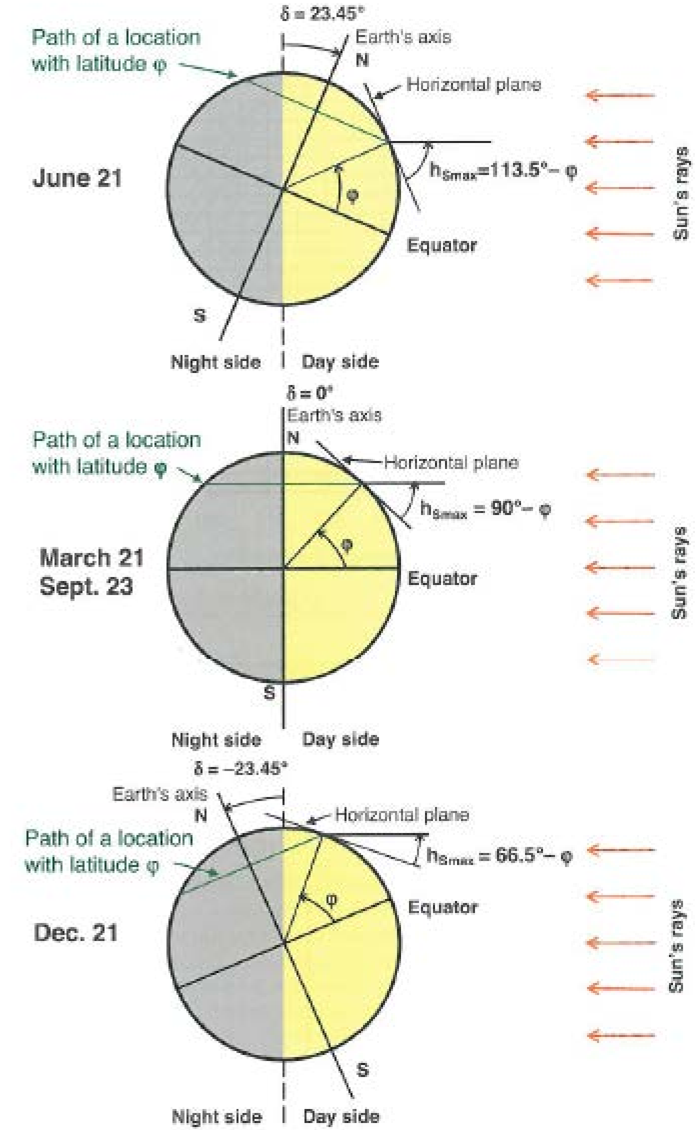
Earth-Sun System

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%) (1,415-1,322 W/m^2)



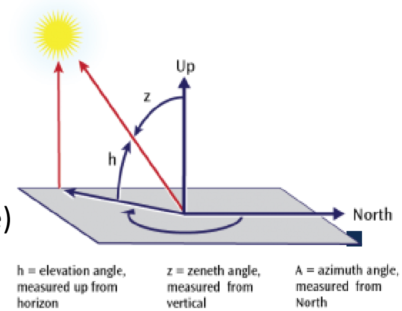
Source: Häberlin, 2012

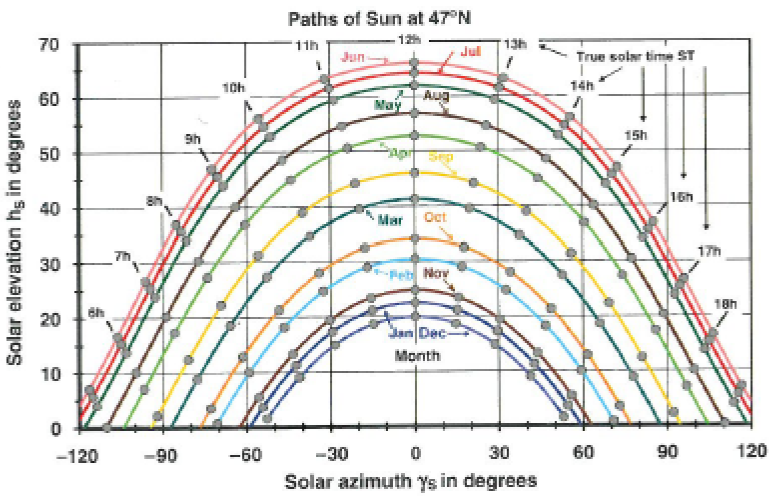


Source: Häberlin, 2012

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





Source: Häberlin, 2012

Example Algorithms

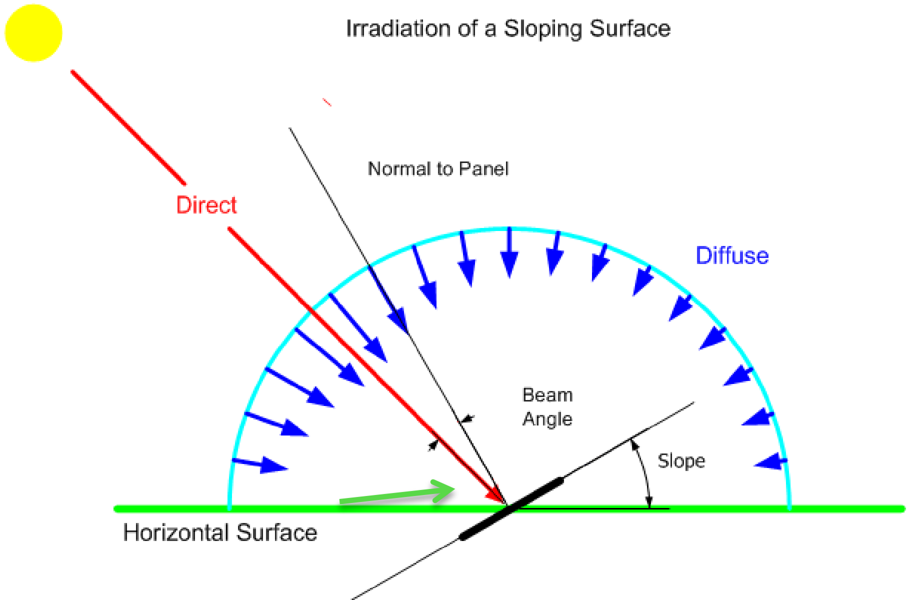
- Various online calculators
  - http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html
  - http://solardat.uoregon.edu/SolarPositionCalculator.html
  - http://www.pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator
  - http://www.suncalc.net
  - http://www.sunearthtools.com/dp/tools/pos_sun.php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

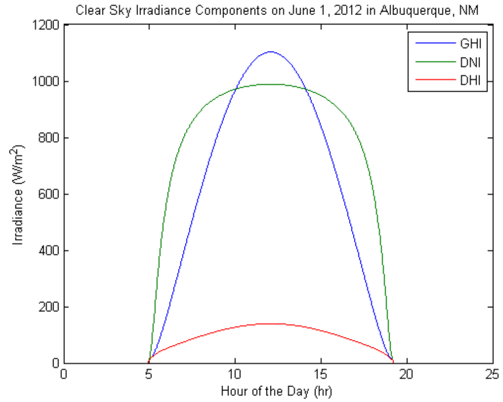
Reference Quantities

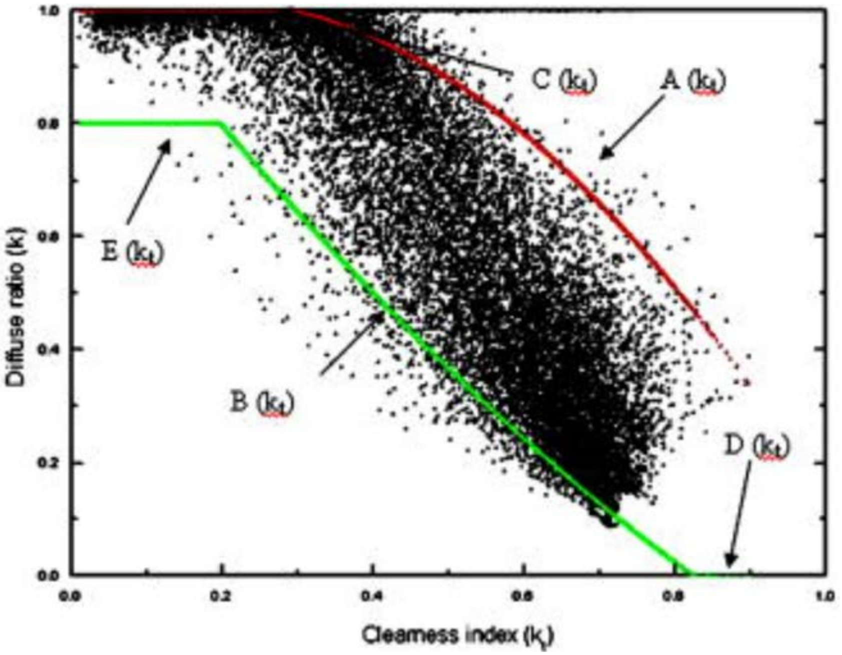
- Direct Normal Irradiance (DNI)
  - Light hitting a plane normal to the sun's rays that comes directly from the sun.
- Global Horizontal Irradiance (GHI)
  - All light hitting a horizontal plane
  - Horizontal beam irradiance = DNI*cos(Zenith Angle)
- Diffuse Horizontal Irradiance (DHI)
  - Light hitting 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

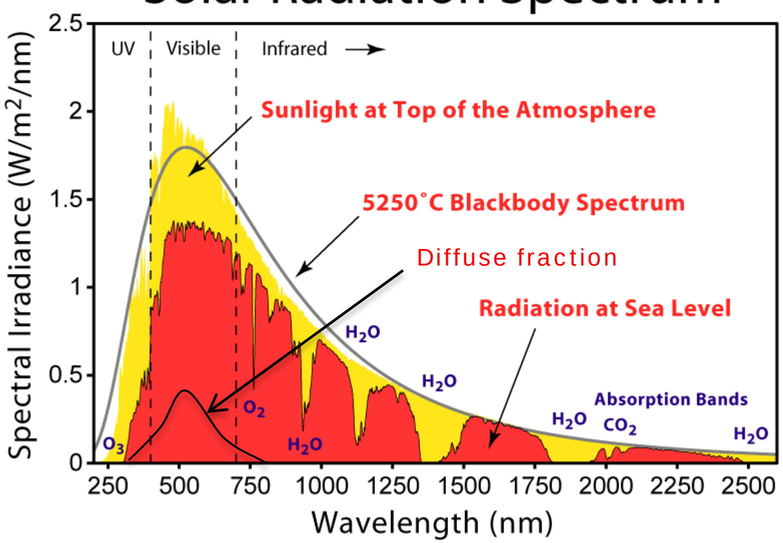
Example PV_LIB functions

- pvl_disc
- pvl_dirint
- pvl_extraradiation
- pvl_clearsky_haurwitz
- pvl_clearsky_ineichen
- pvl_erbs, pvl_louche, pvl_orgill_hollands, pvl_reindl_1, pvl_reindl_2

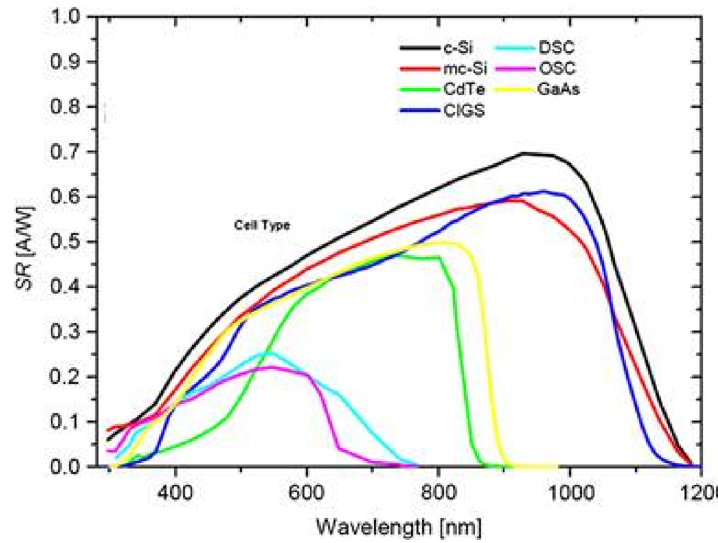
Solar Spectrum

- 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.

Solar Radiation Spectrum



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

1. Irradiance and Weather Data

- 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

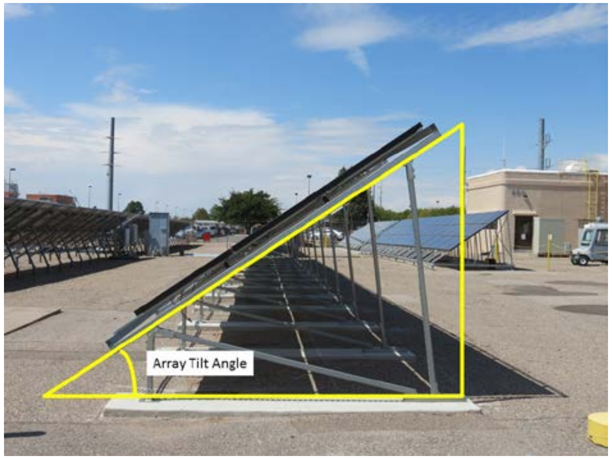
Irradiance and Weather Data

- NSRDB '61-90, '91-10, TMY2/3
  http://rredc.nrel.gov/solar/old_data/nsrdb/
  - Many years of hourly values (most are 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
- NSRDB 2005 – 2012 (beta)
  https://mapsbeta.nrel.gov/nsrdb-data-viewer/
  - 30 min., 2km grid
  - New NREL GSIP algorithm for irradiance from GOES
  - Includes other meteorological data (air temp, RH, etc.) (model results)
- Purchased satellite irradiance data
  - CleanPowerResearch, Meteonorm, GeoModel, AWSTruepower, …
  - Validation studies are leading to higher accuracies (e.g., snow)
- Sources for other weather data
  - NOAA National Climatic Data Center (recent years)
- Ground measurements

PV_LIB functions
- pvl_readtmy2
- pvl_readtmy3

2. Incident Irradiance

Array Tilt Angle

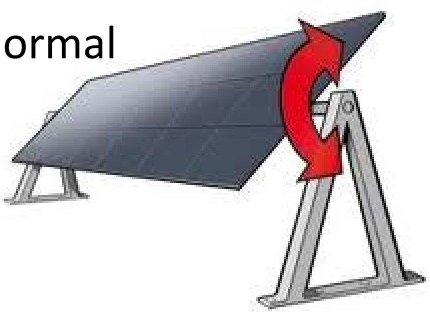


Array Azimuth Angle

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

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

Vertical Axis



Horizontal Axis

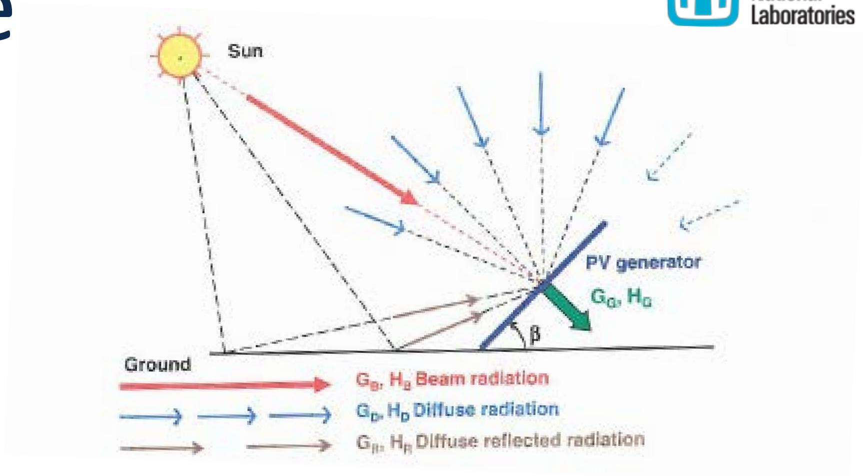
Tilted Axis

PV_LIB functions

- pvl_singleaxis
- pvl_getaoi

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 = DNI * cos(AOI)
- Ground reflected irradiance
  - Array tilt angle
  - Ground surface albedo
    - Grass = 0.15-0.25
    - Snow = 0.5 -0.82



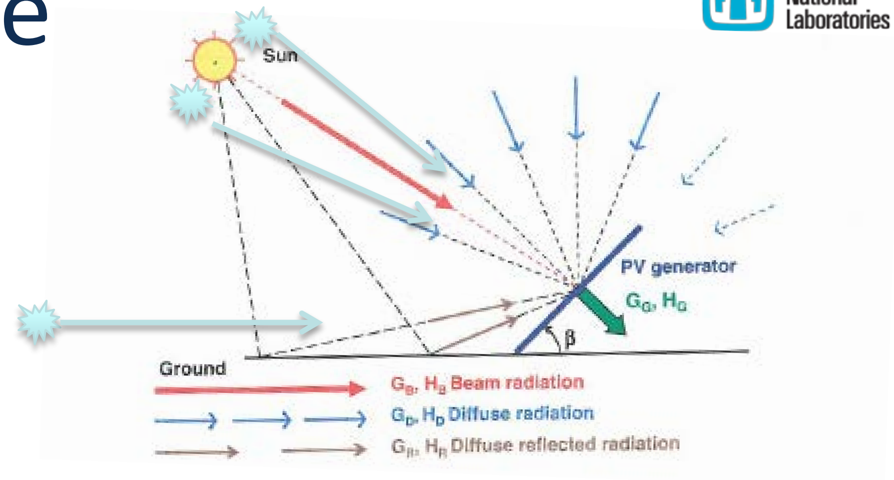
Source: Häberlin, 2012

PV_LIB functions

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

2. Incident Irradiance

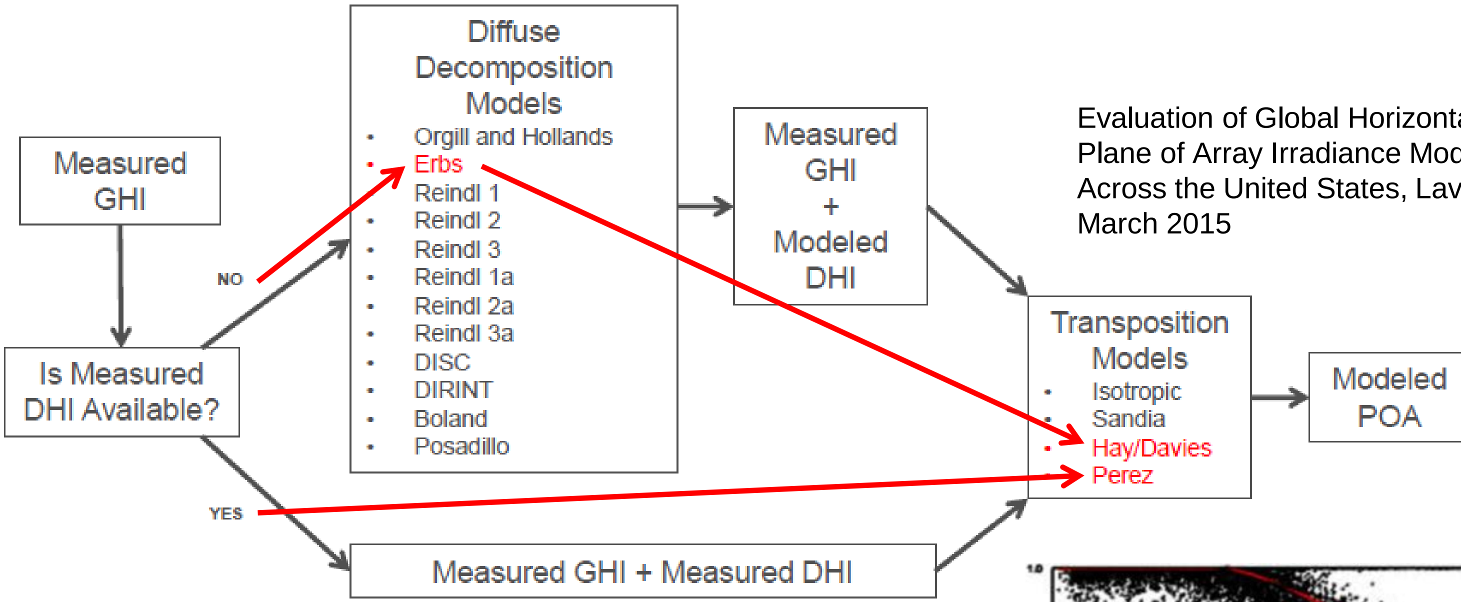
Sky Diffuse Models



Source: Häberlin, 2012

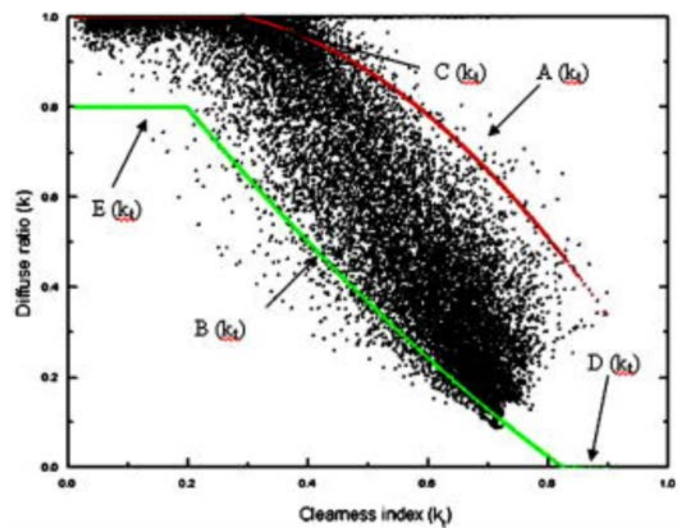
- Diffuse on a tilted plane
- Account for:
  - Circumsolar – forward scattering around sun disk
  - Horizon brightening
  - Rest of sky
- Isotropic model
  - Assumes uniform diffuse light and is geometric
- Hay and Davies model
  - Isotropic model + circumsolar enhancement (PVsyst)
- Reindl model
  - 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)

2. Incident Irradiance Modeling



Evaluation of Global Horizontal Irradiance to Plane of Array Irradiance Models at Locations Across the United States, Lave et al, JPV 5(2), March 2015

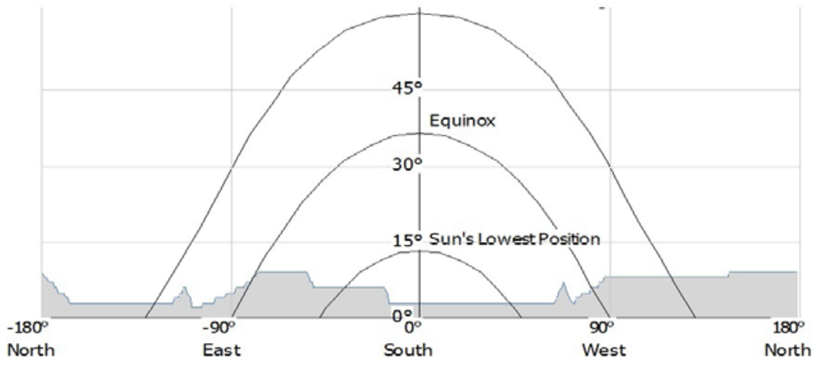
- Diffuse Decomposition
  - Fraction of GHI that is diffuse (direct)
  - Dozens of models in literature
  - Which is best? Not a simple answer
  - General recommendations from mean bias in annual insolation
  - Site-specific empirical model can be best



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

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)



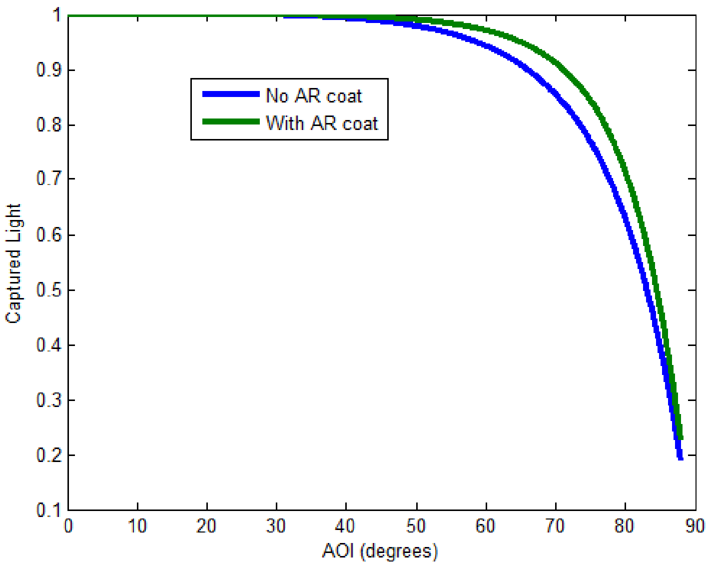
A 2D sunpath diagram in PV*SOL, with horizon data imported.

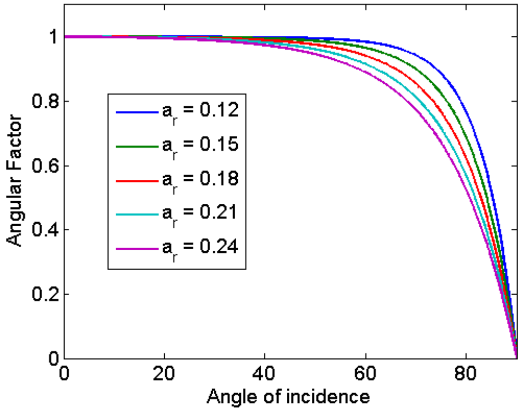
- Objects and terrain shade array
- Near shade has sharp edges
  - Buildings, trees, appliances, wires, chimney, etc.
  - Row-row shading within array
- Far shade is more diffuse
  - Mountains, horizon

- Shading effects are assigned to certain time periods and irradiance is reduced.
- Partial shading is much more complex. Modeling approaches are still evolving.
- Tools are using design tools to help address shading (e.g. Helioscope and PVSyst). Near field data is required.

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 Bougher's laws
  - Empirical models
    - Sandia has used a 5th order polynomial form (f_2)
    - ASHRAE
    - Martin and Ruiz (includes effects of soiling)





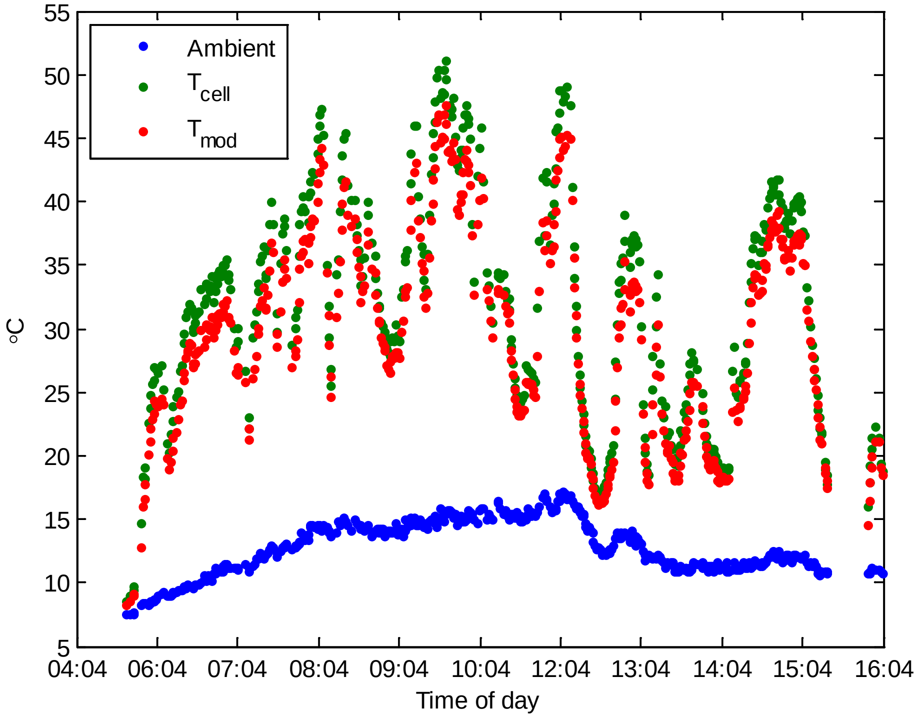
- Simple lookup tables are also being implemented in modeling tools. These may prove to be the best solution.

PV_LIB functions (reflection losses)
- pvl_physicaliam
- pvl_ashraeiam
- pvl_martinruiziam

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 Voc and Isc (e.g., IEC 60904-5)
  - Thermocouples attached to module backsheet + delta
- Cell temperature > ambient (~30C difference)
- Cell temperature > back-of-module temperature (~2 – 4 C)

- Models predict cell temperature from POA irradiance, ambient temperature and wind conditions



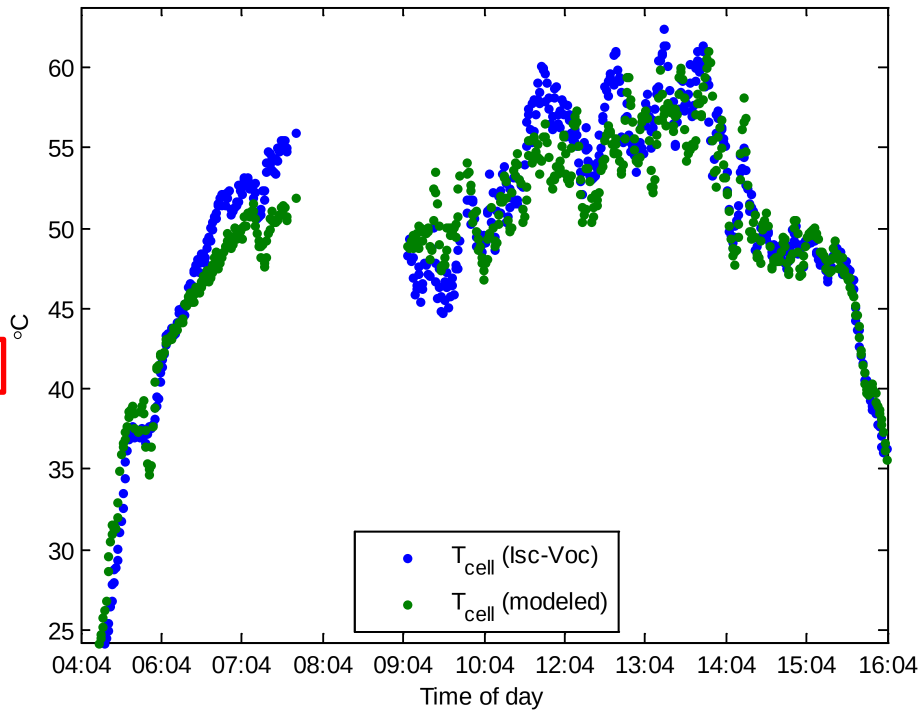
4. Cell Temperature Models

- Most are steady-state

$$T_C = T_M + \frac{E}{E_0}\Delta T$$

$$= T_{amb} + \frac{E}{E_0}\exp\left(\boxed{a} + \boxed{b}WS\right) + \frac{E}{E_0}\boxed{\Delta T}$$

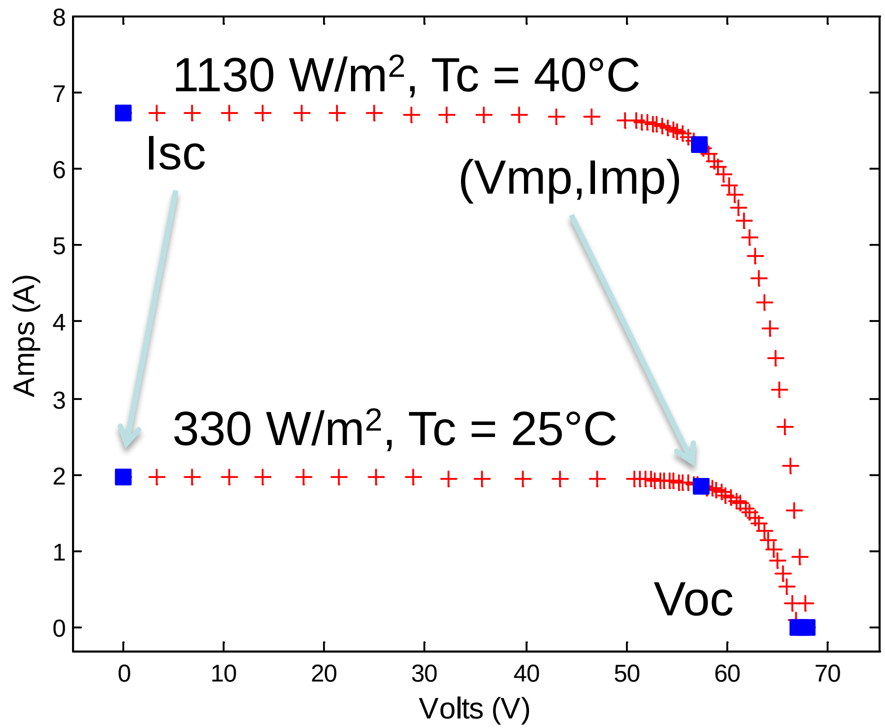
- Typical assumptions:
  - Represents average cell temperature across module
  - Represents average across an array



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

Sandia National Laboratories

- 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

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

← Effective irradiance : light flux that becomes electrical current

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

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

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

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

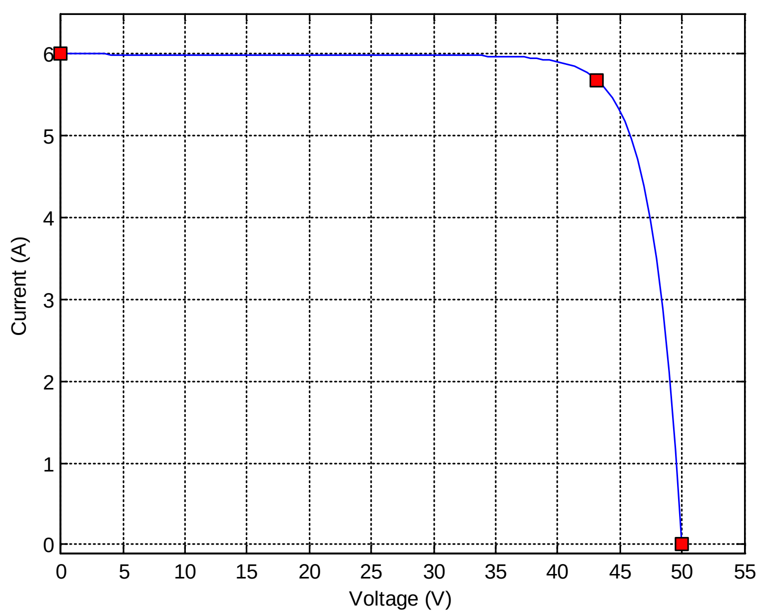
PV_LIB functions

- pvl_sapm

Single Diode Models

PV_LIB functions
- pvl_singlediode
- pvl_calcparams_desoto

- 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



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

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

$$I_O = I_{O0}\left(\frac{T_C}{T_0}\right)^3 \exp\left(\frac{1}{k}\left(\frac{E_{g0}}{T_0} - \frac{E_g(T_C)}{T_C}\right)\right)$$

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

De Soto et al, 2006

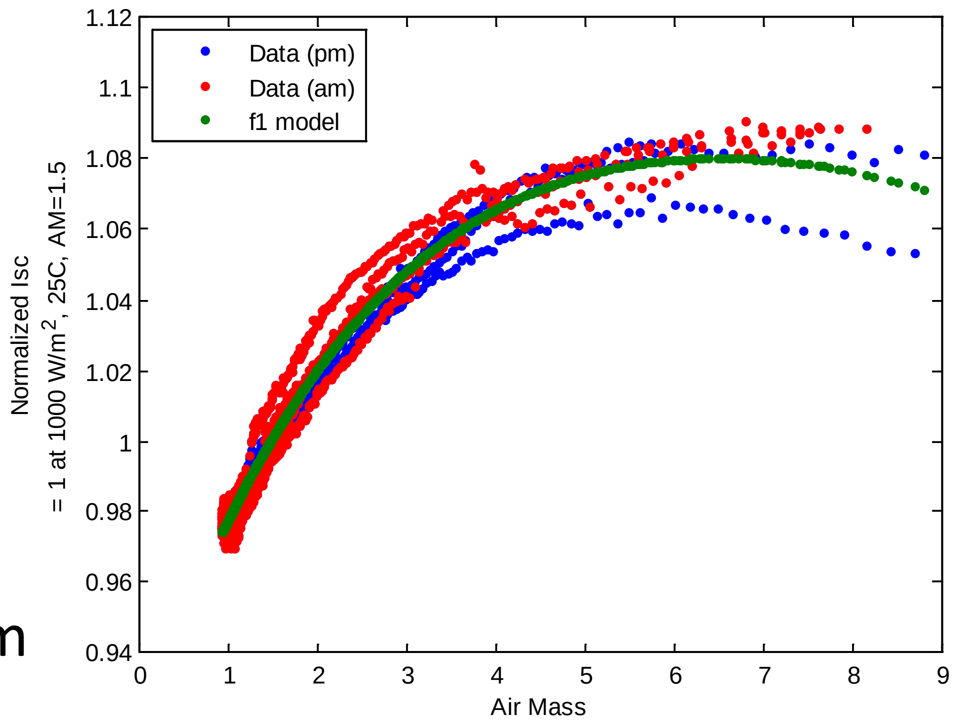
Effective irradiance

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

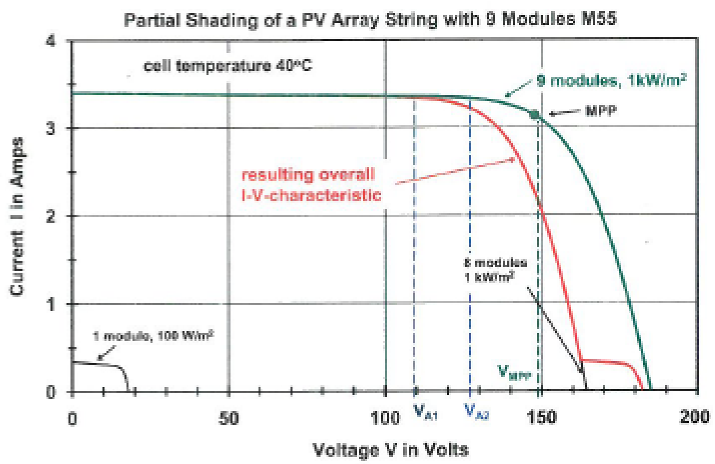
- E.g., Sandia model

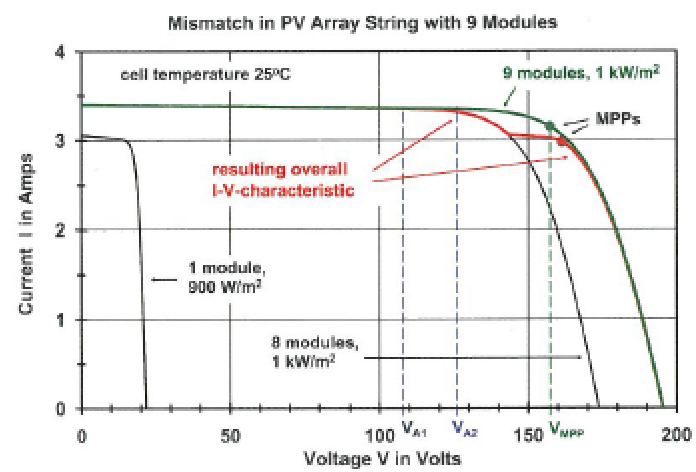
$$E_e = f_1(AM_a)\left(E_b f_2(AOI) + E_{diff} f_d\right)$$



6. DC and Mismatch Losses

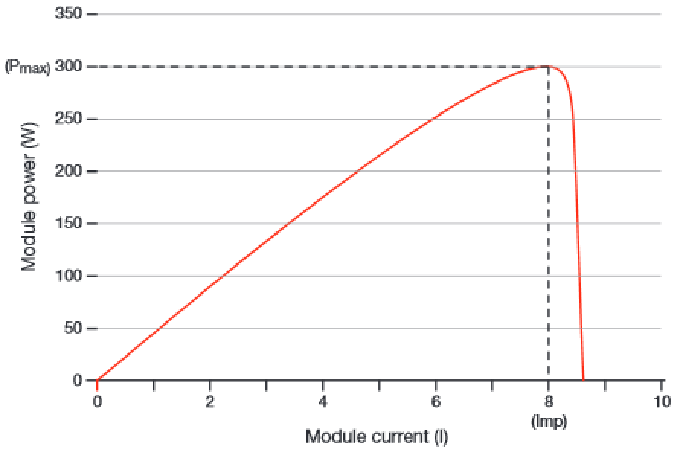
- DC wiring loss increases with the square of the current and the wire resistance (I^2R). Increasing the wire gauge increases the system cost and designers try to calculate an optimal balance between cost and long-term performance.
- Mismatch losses can occur as the result of mismatched modules and strings,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

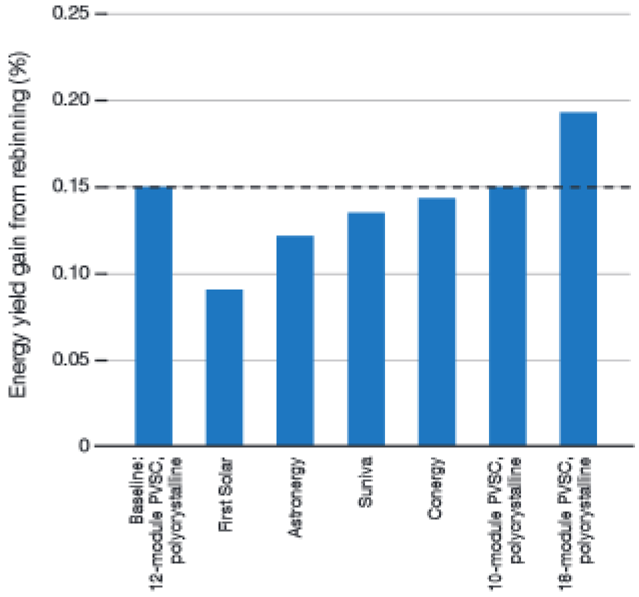




Mismatch from Module Binning?

- Many people ask about the effect of module binning tolerance on energy production.
- Most modules are +/- 5% based on power or current.
- Is it worth insisting on tighter bins? Or testing on site?
- Folsom Labs 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.

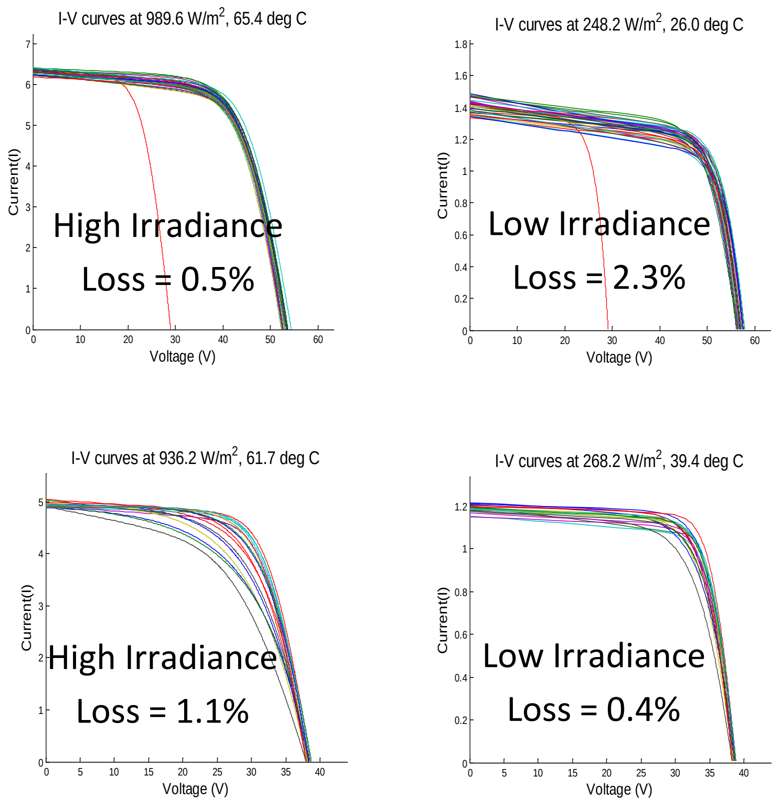




Source: Grana and Gibbs, 2014

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



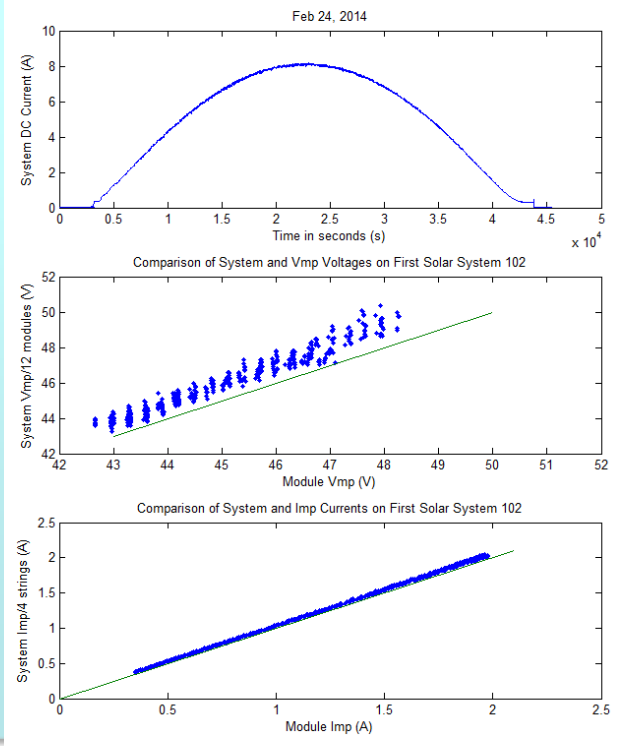
Source: S. MacAlpine, 2013

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

Sandia National Laboratories

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

CEC List of Eligible Inverters

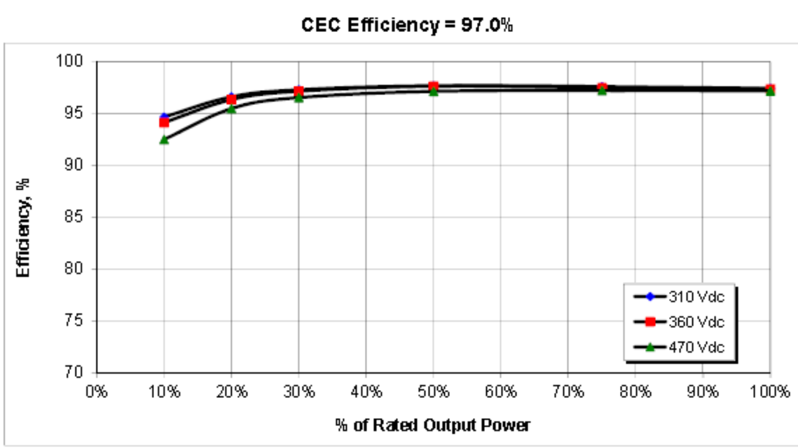
Vmin: 330 Vdc   Vnom: 368 Vdc   Vmax: 480 Vdc

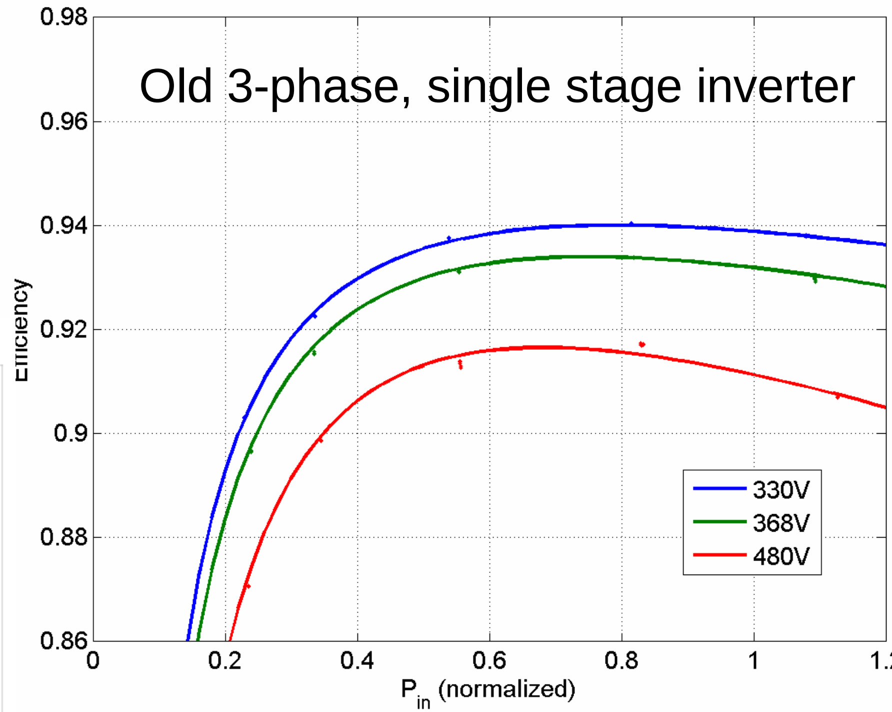
Input Voltage (Vdc)		10% 2.05	20% 4.10	30% 6.15	50% 10.25	75% 15.37	100% 20.49	Wtd
		Power Level (%; kW)						
Vmin	330	84.7	90.3	92.3	93.8	94.0	93.8	93.2
Vnom	368	83.9	89.7	91.6	93.1	93.4	93.0	92.5
Vmax	480	81.3	87.1	89.9	91.3	91.7	90.7	90.7

Newer 3-phase, multistage inverter

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

Input Voltage (Vdc)		10% 0.37	20% 0.74	30% 1.11	50% 1.85	75% 2.77	100% 3.69	Wtd
		Power Level (%; kW)						
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





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

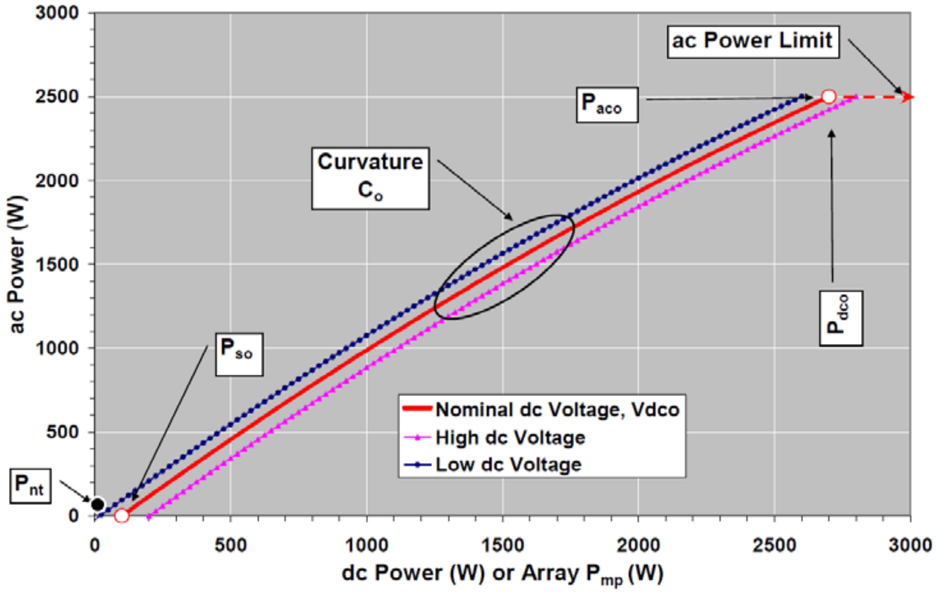
8. DC to AC Conversion

PV_LIB functions

- pvl_snlinverter
- pvl_snlinverterdb
- pvl_adrinverter

- Sandia Inverter Performance Model

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



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

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

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

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

9. AC Losses

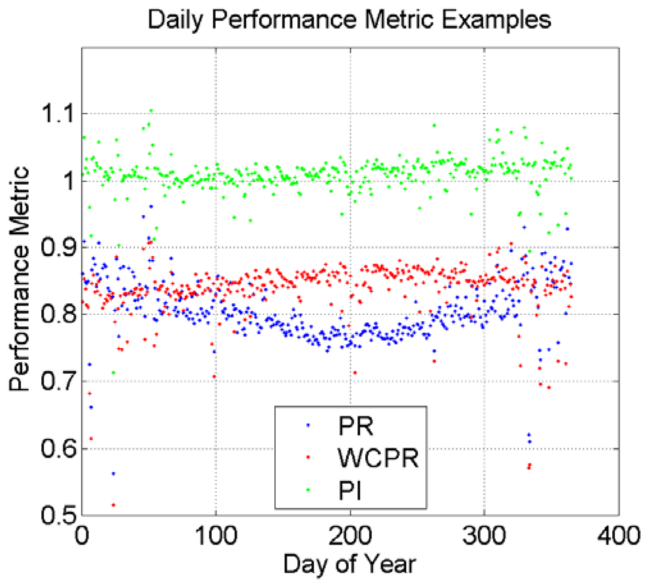
- AC losses include transformer and AC cabling conductive losses. These losses are very project specific and depend where the revenue meter is located.
- Some larger projects have to move AC power considerable distances and these losses can be significant.
- Most models assume a fixed percent loss derate.

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/m^2 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** (WCPR) is AC energy / (DC rating*sun hours*temperature correction term)
  - Temperature correction = $\left(1 - \frac{\delta}{100}\left(T_{cell,avg} - T_{cell}\right)\right)$
    - Δ is temperature coefficient for power (%/ degC)
    - $T_{cell,avg}$ is the annual average computed cell temperature
    - T_{cell} is the cell temperature

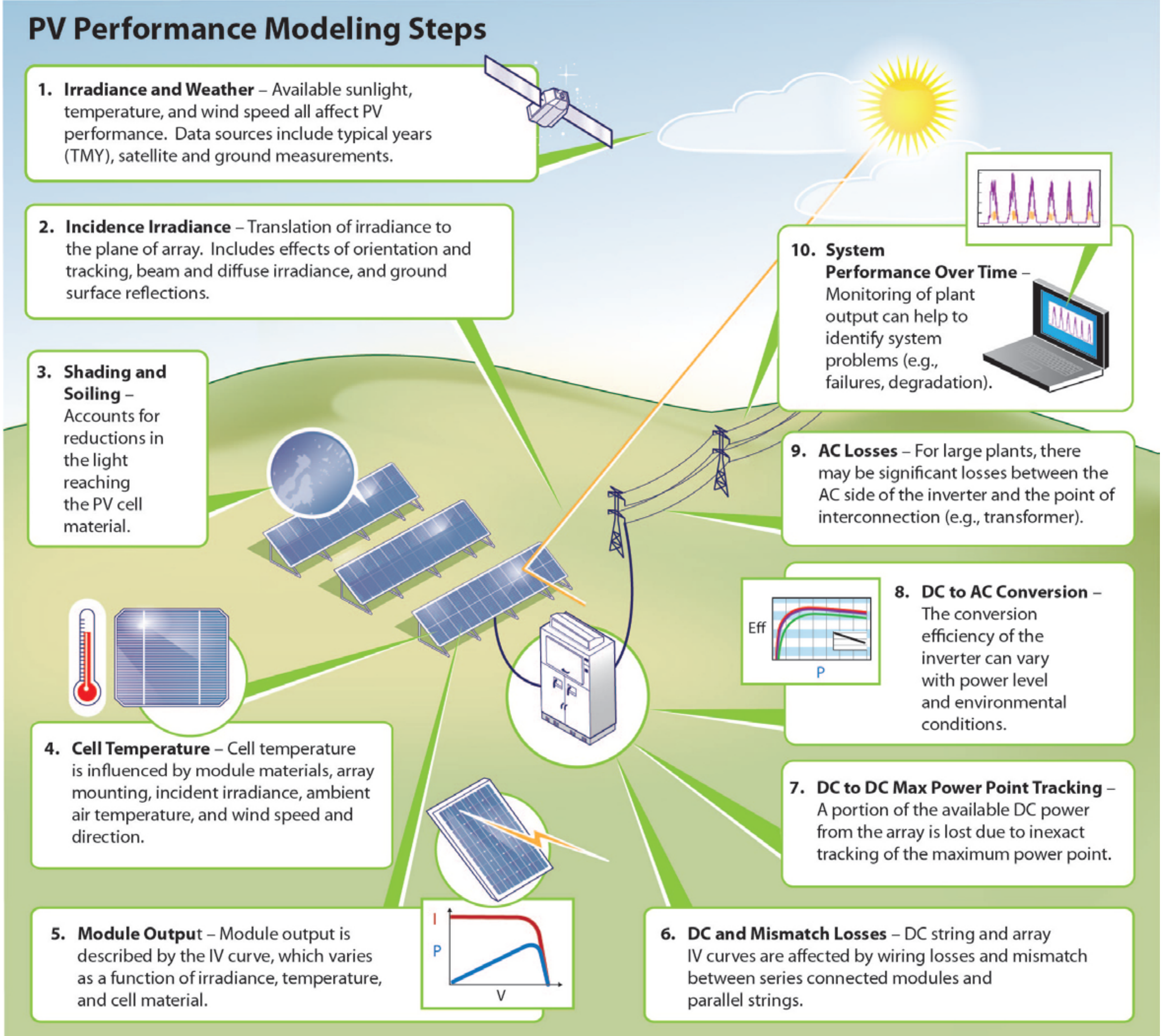


Source: Stein and Green, 2015

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)
- Operation of inverters at non-unity power factor results in decreases in inverter efficiency
- 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?



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