SAND2014-4672P

Exceptional service in the national interest

Sandia National Laboratories

PVPerformance MODELING COLLABORATIVE

2014 IEEE PVSC Tutorial on PV System Performance Modeling

Joshua S. Stein, Ph.D. [1]
Clifford W. Hansen, Ph.D. [1]
Daniel Riley[1]
Rob Andrews[2]
[1] Sandia National Laboratories, Albuquerque, NM – *pv.sandia.gov*
[2] Calama Consulting, Toronto, ON – *calamaconsulting.ca*

June 8, 2014 Denver, CO

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

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

PV Performance Modeling Collaborative

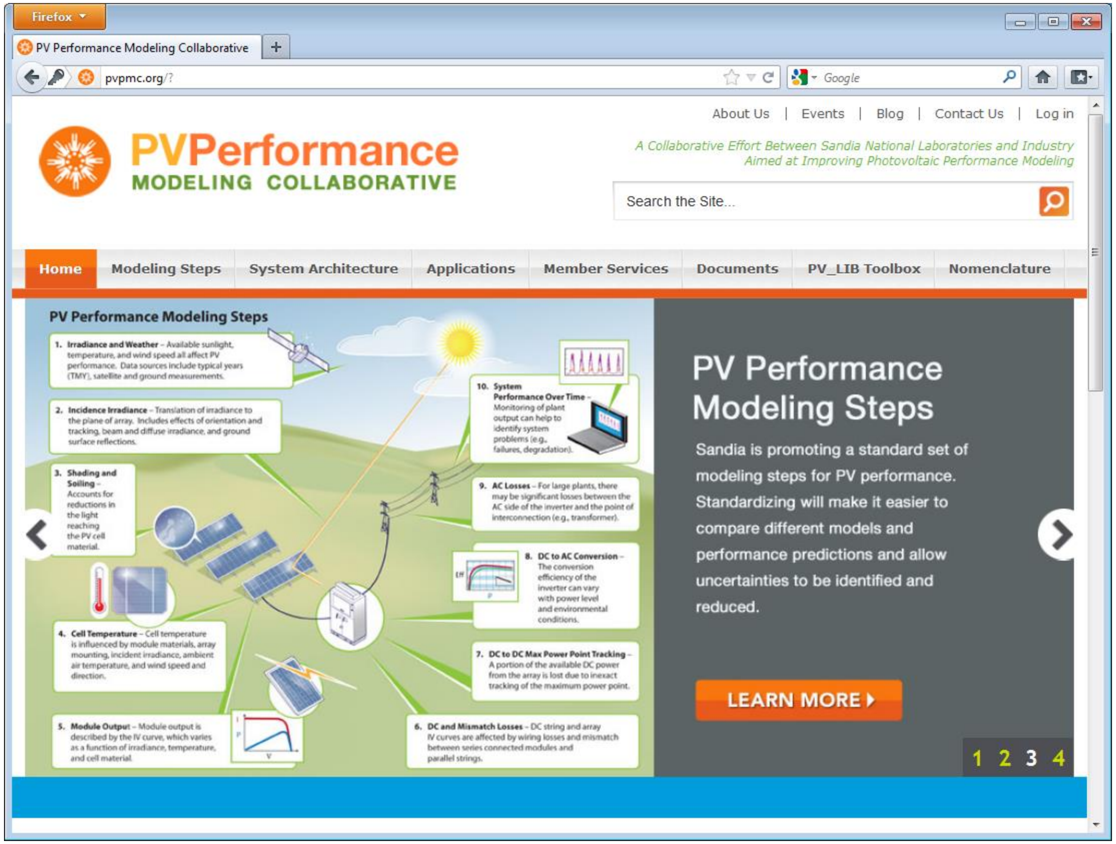
Sandia National Laboratories

- http://pvpmc.org will be changing to http://pvpmc.sandia.gov
  - Old address will be redirected
- 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.org
New site: http://pvpmc.sandia.gov

Sandia National Laboratories

- 1330 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)

Sandia National Laboratories

- 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

About Us | Events | PVPMC Blog | Contact Us | Log in

PVPerformance MODELING COLLABORATIVE

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., 1990;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:

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

.

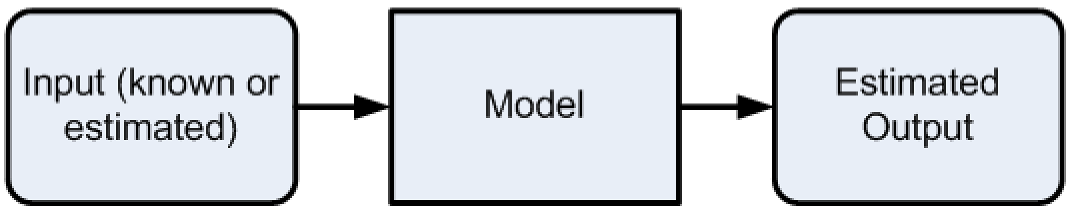
DHI is the diffuse horizontal irradiance, AOI is the angle of incidence, DNI is the direct normal irradiance, GHI is the global horizontal irradiance, T_a is the tilt angle of the array, and Z is the solar zenith angle.

This model is implemented in the PV_LIB Toolbox and the function: pvl_reindl1990.

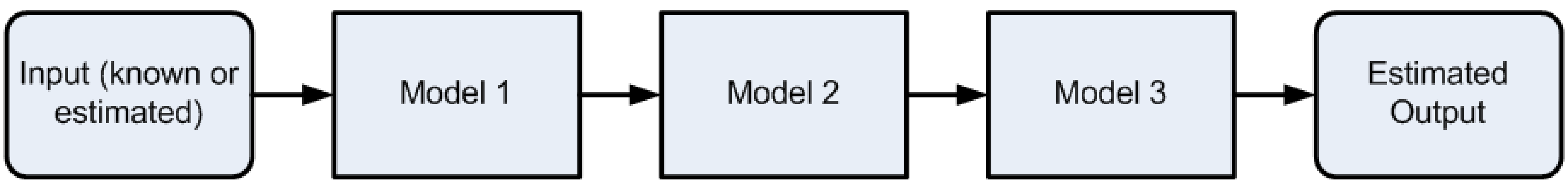
Content contributed by Sandia National Laboratories

What is a model?

- A model is a mathematical process which attempts to simulate a given system by predicting output information from known or estimated input information
  - I can employ a single model:



  - Or I can employ a number of models sequentially:



The Purpose of PV Modeling

- We can classify two primary needs which are addressed by accurate model predictions.
  - Modeling for systems which do not exist
    - Design tradeoffs
    - Potential value
  - Modeling for systems which are already built
    - Determining if the system is performing and “healthy”
- The method of modeling for each of these needs *may* vary due to the differences in the typical input information required for each need.
  - Existing PV systems may have a plane-of-array (POA) irradiance sensor, removing the need to perform some modeling steps.
  - Potential systems may have no on-site irradiance.

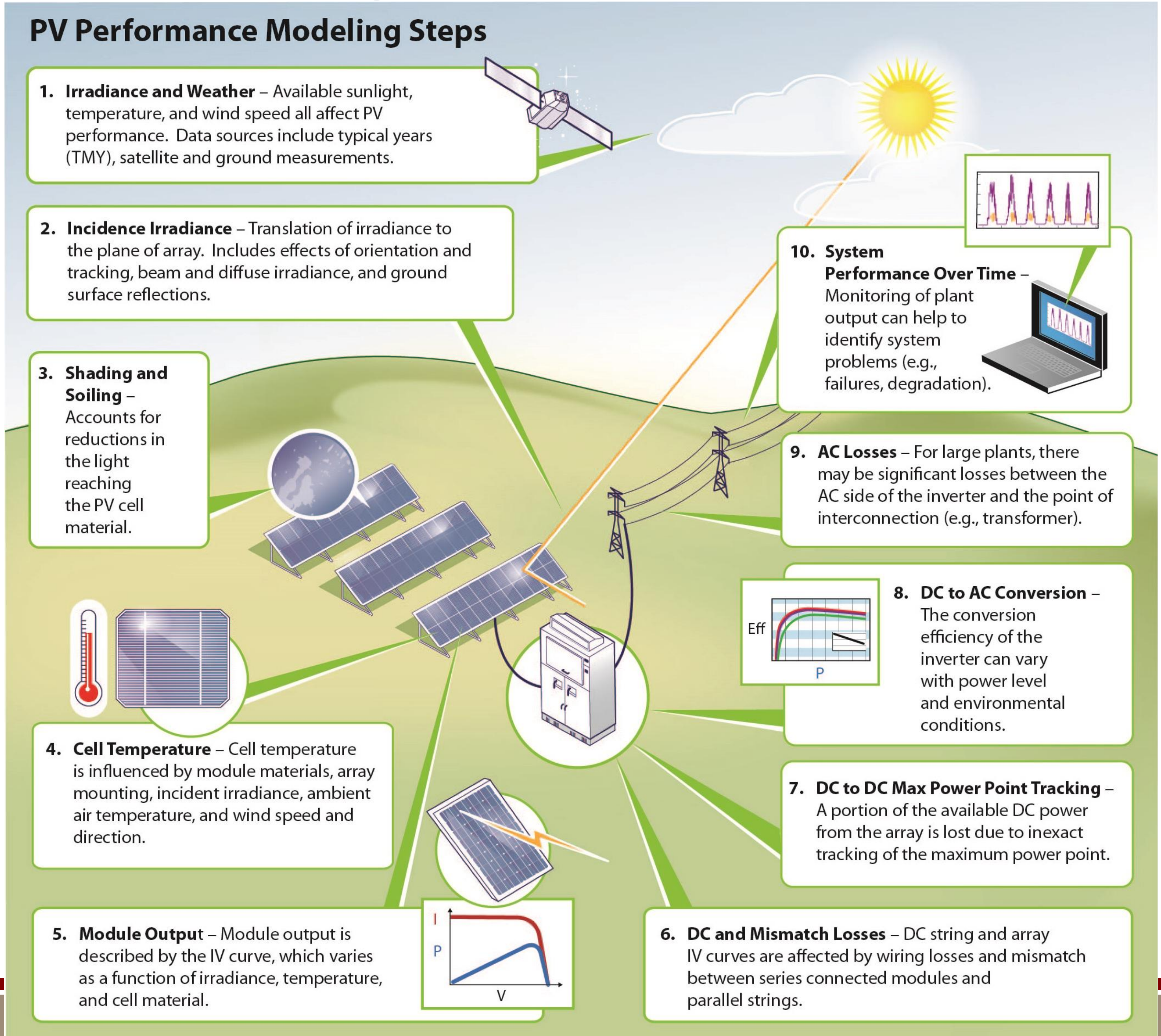
Why Model Unbuilt Systems?

- Investigate how differences in the potential design could affect system performance
  - Should I use modules from First Solar or SunPower?
  - How much energy might be lost due to inverter power limiting (clipping) if I use a 5kW inverter instead of a 6 kW inverter?
  - Will reducing the PV module tilt by 10° greatly affect energy output?
- Correctly valuing a potential PV system
  - Value may be determined by a variety of factors such as energy generation or the time at which the energy is generated.
  - Annual energy may be warranted by an installer, that installer needs to predict a lower bound of energy generation.
  - In some U.S. jurisdictions the owner of a potential system is “paid” according to the energy prediction of a model .

Why Model Existing Systems?

- Determine if a system is performing adequately
  - Input actual conditions to a PV system model and compare the model output to the measured system output.
  - We will focus on predictive models, but other types of models (e.g., neural networks) may be available for characterizing existing PV systems.

PV Modeling from 20,000 Feet



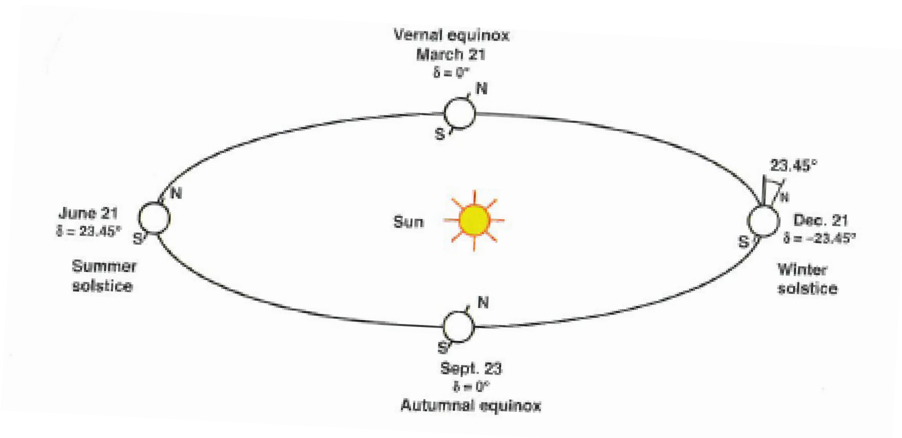
1. Irradiance and Weather

- 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

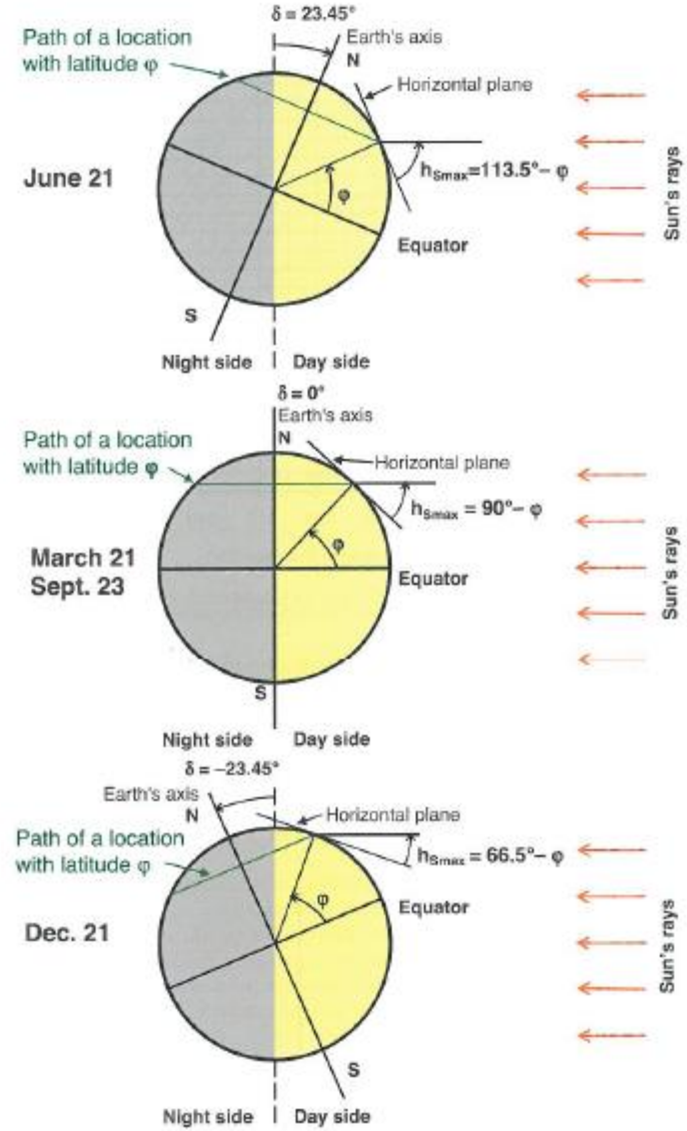
Earth-Sun System

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



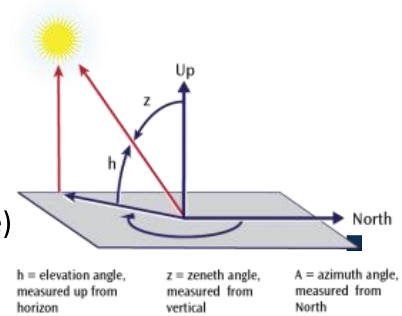
Source: Häberlin, 2012

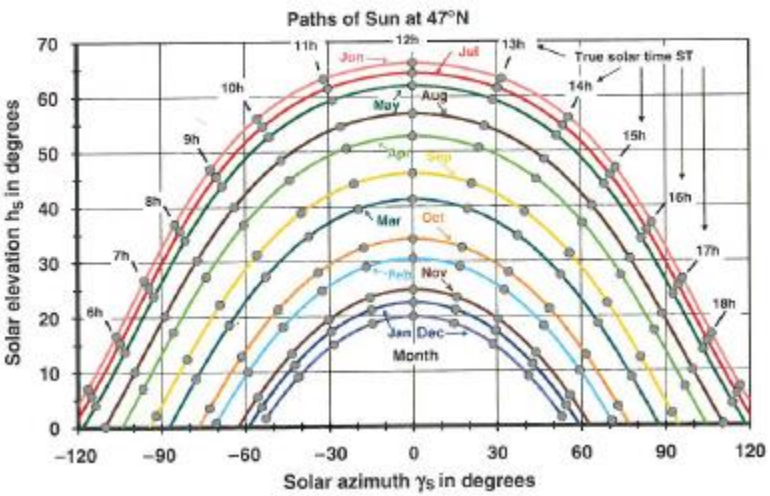


Source: Häberlin, 2012

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

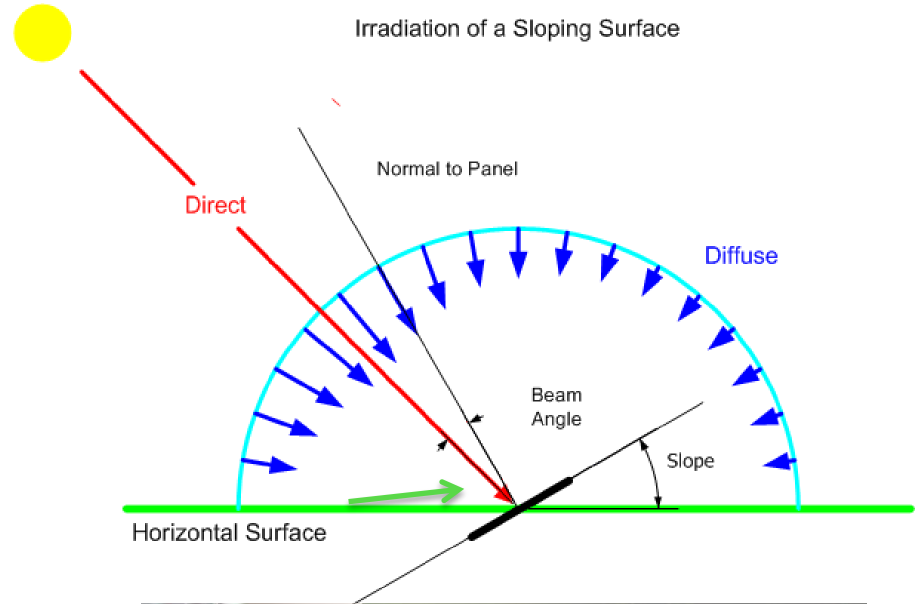
- Various online calculators
  - http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html
  - http://solardat.uoregon.edu/SolarPositionCalculator.html
  - http://www.pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator
  - http://www.suncalc.net
  - http://www.sunearthtools.com/dp/tools/pos_sun.php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

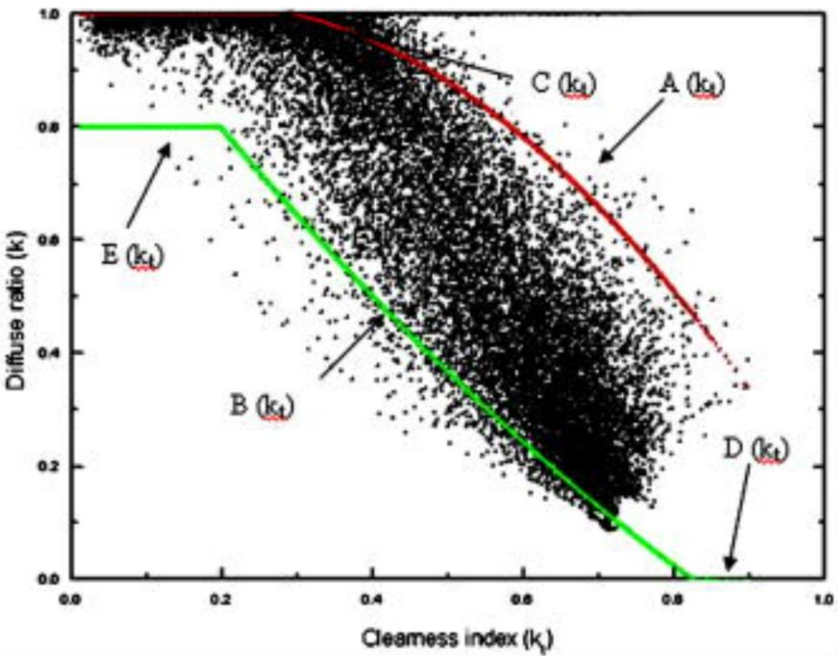
Reference Quantities

- 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)

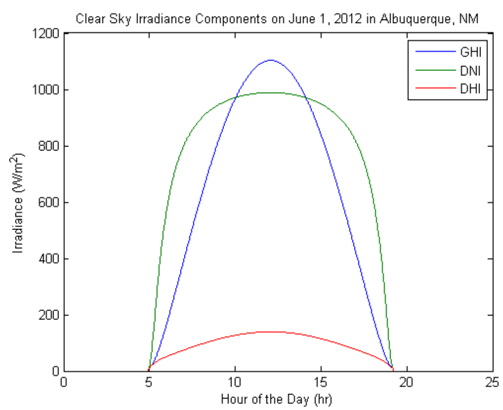


More Irradiance Concepts

- 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



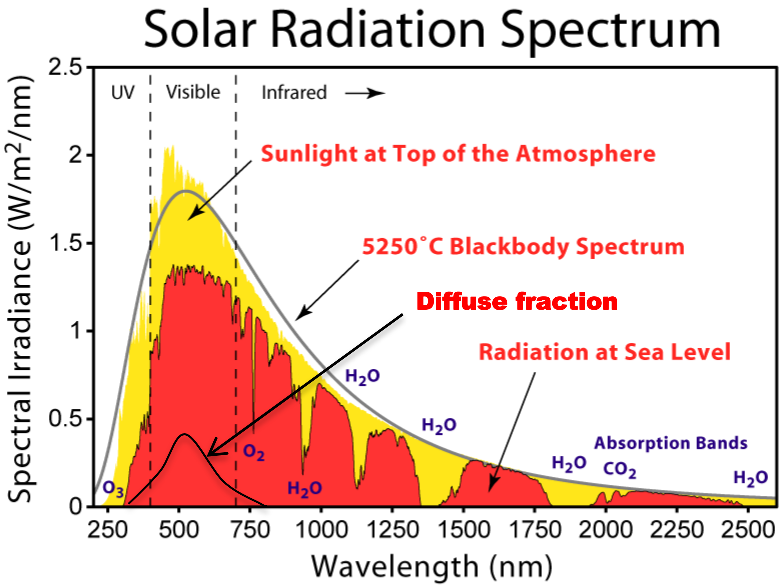
Source: J. Sol. Energy Eng.. 2005;128(1):104-117. doi:10.1115/1.2148972



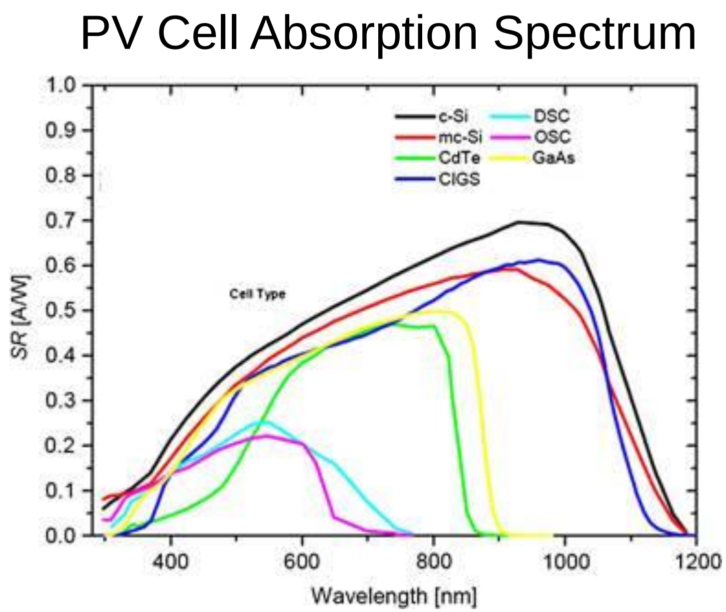
PV_LIB functions
- pvl_disc
- pvl_dirint
- pvl_extraradiation
- pvl_clearsky_haurwitz
- pvl_ineichen

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.



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

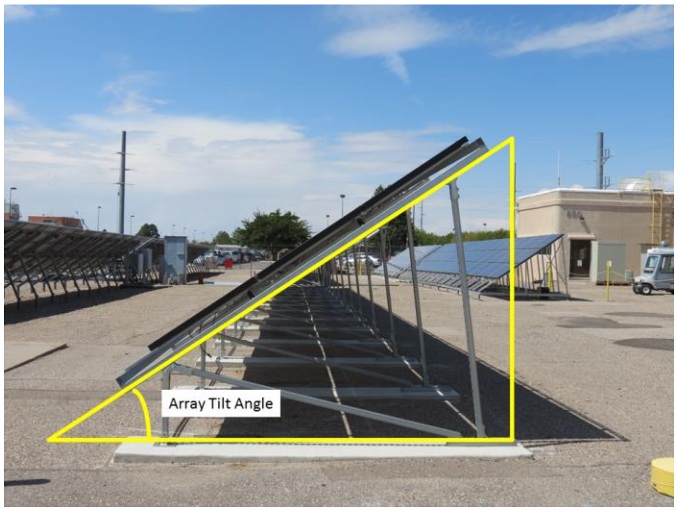
Weather Data

- 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

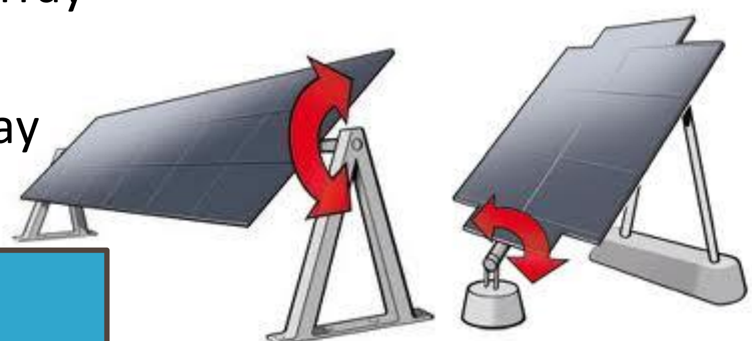
Array Tilt Angle



Array Azimuth Angle

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

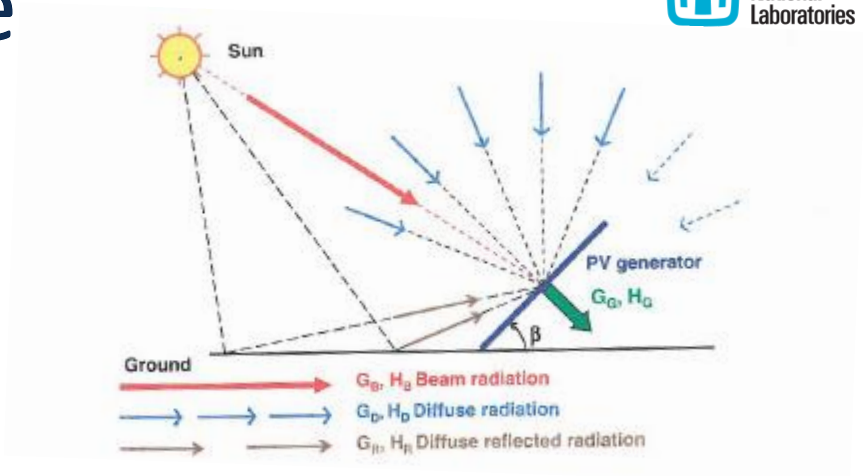
- Single axis tracking moves array to partially follow sun
- 2-axis tracking can keep array normal to the sun (AOI=0)



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 = DNI * cos(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



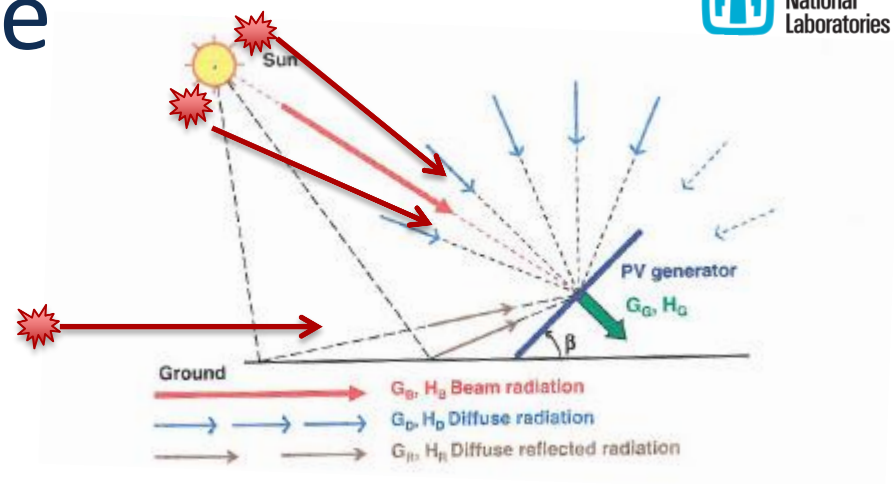
Source: Häberlin, 2012

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)



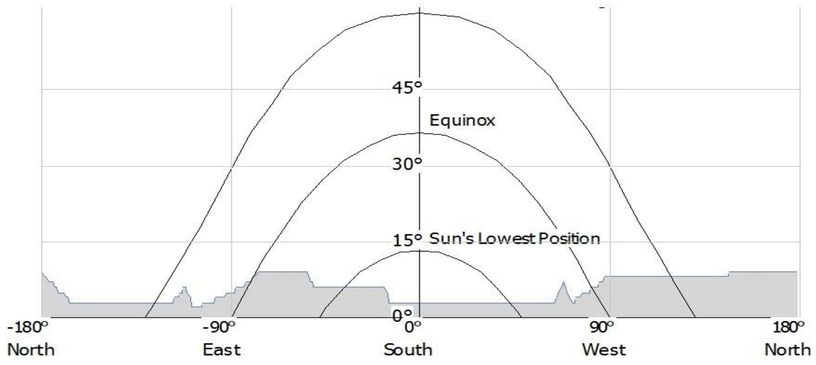
Source: Häberlin, 2012

- 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



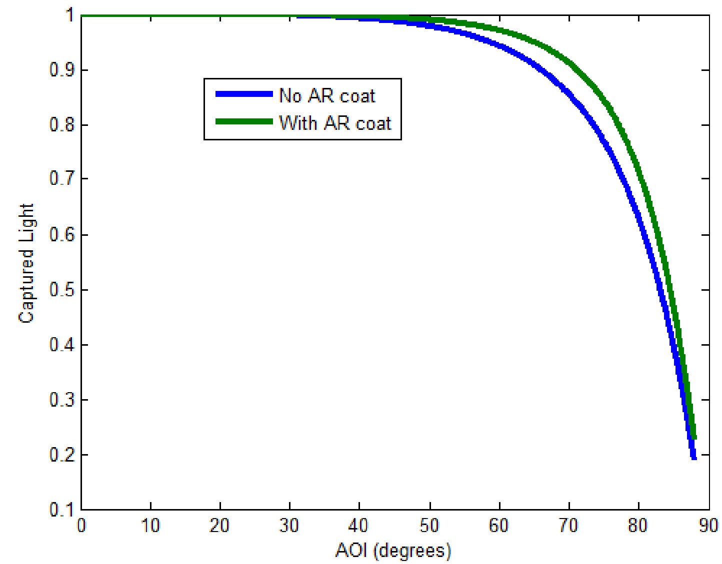
A 2D sunpath diagram in PV*SOL, with horizon data imported.

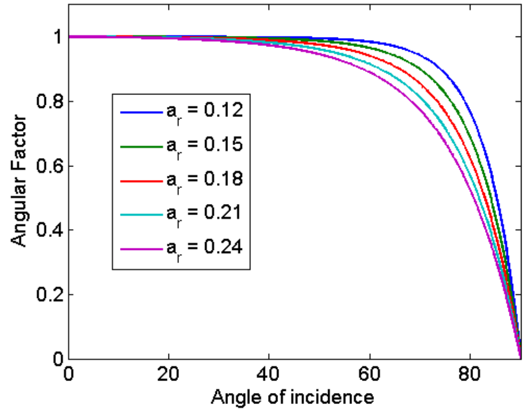
- Shading effects are assigned to certain time periods and irradiance is reduced.
- Partial shading is much more complex. Modeling approaches are still evolving.

3. Shading, Soiling, and Reflections

Sandia National Laboratories

- 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 orderpolynomial form (F2)
    - ASHRAE
    - Martin and Ruiz (includes effects of soiling)



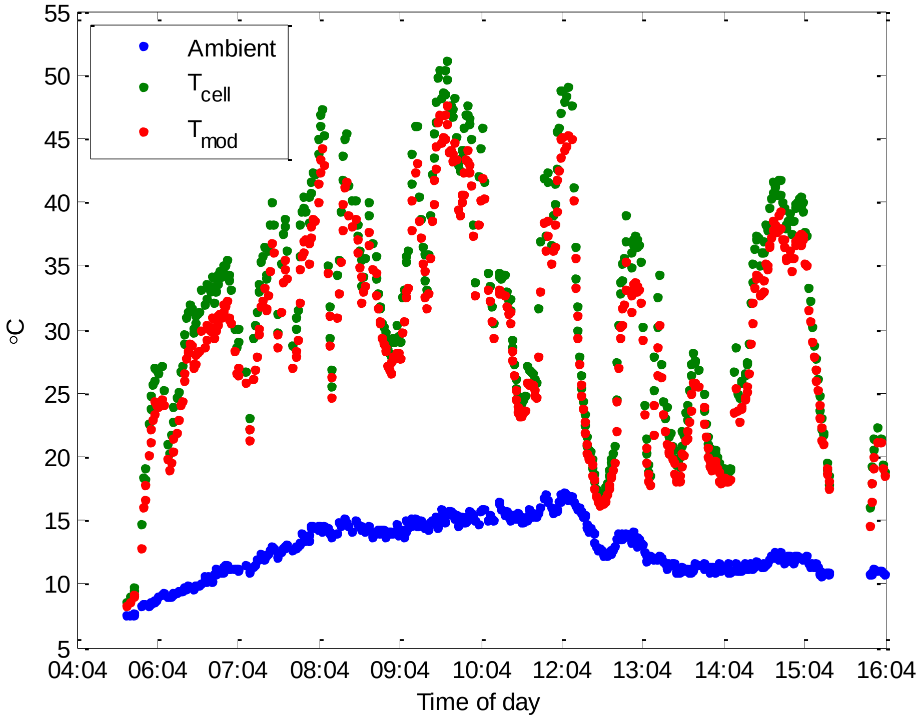


PV_LIB functions (reflection losses)
- pvl_physicaliam
- pvl_ashraeiam

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 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

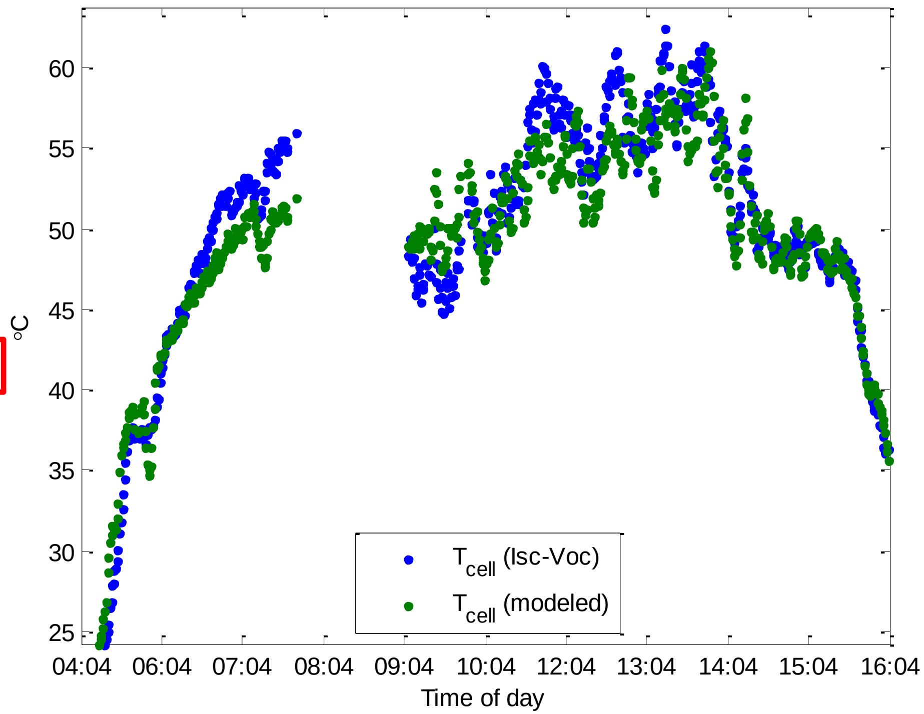
Sandia National Laboratories

- Most are steady-state

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

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

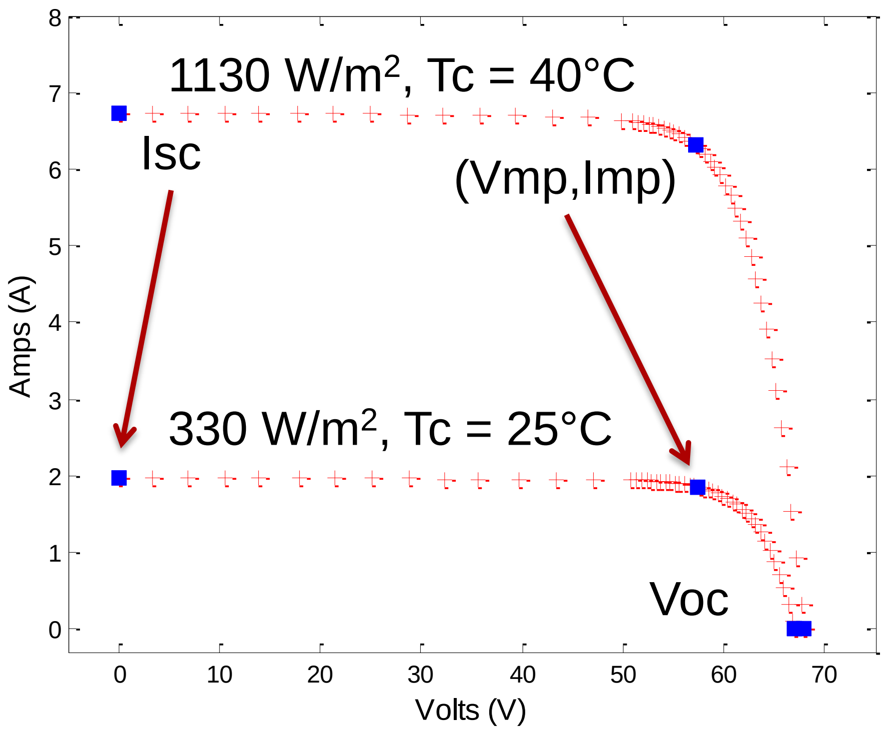
- Typical assumptions:
  - Represents <u>average</u> cell temperature across module
  - Represents <u>average</u> across an array



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

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

Effective irradiance : light flux that becomes electrical current

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

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

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

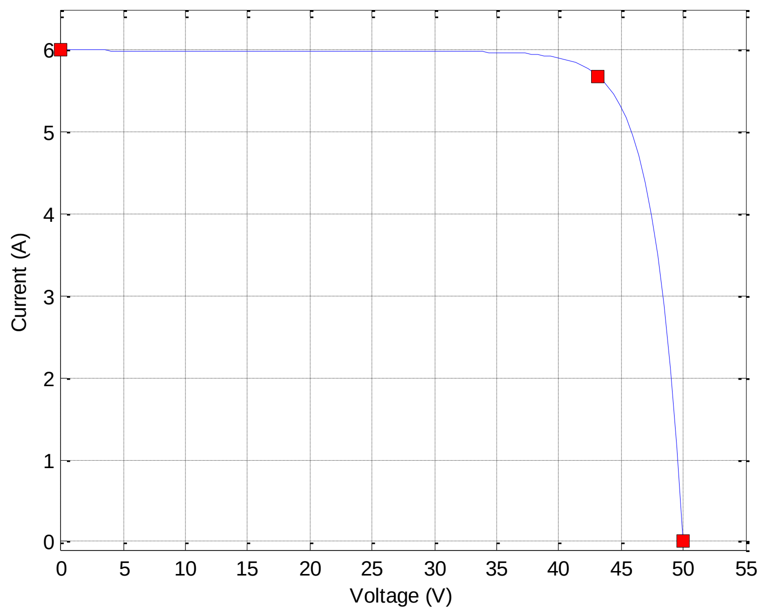
$$I_{MP} = I_{MP0}\left(C_0 E_e + C_1 E_e^2\right)\left(1 + \alpha_{MP}\left(T_C - T_0\right)\right)$$

PV_LIB functions
- pvl_sapm

Single Diode Models

- 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_calcparams_desoto
- wapr_vec
- pvl_fminbnd_vec



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

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

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

$$R_{sh} = R_{sh0}\frac{E_0}{E}$$

R_s, n constant

De Soto et al, 2006

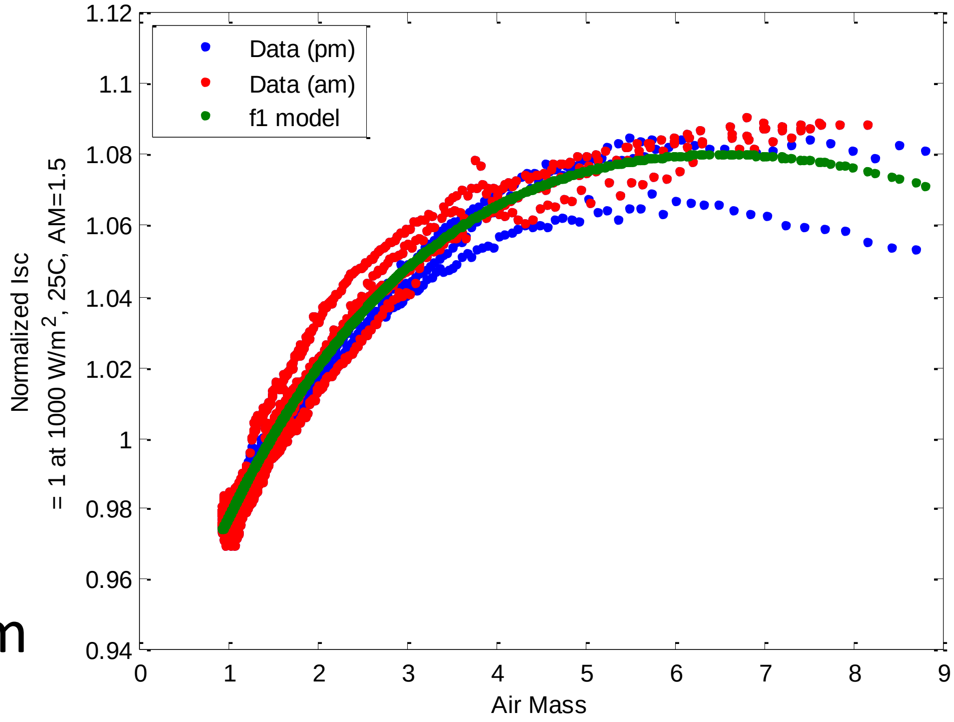
Effective irradiance

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

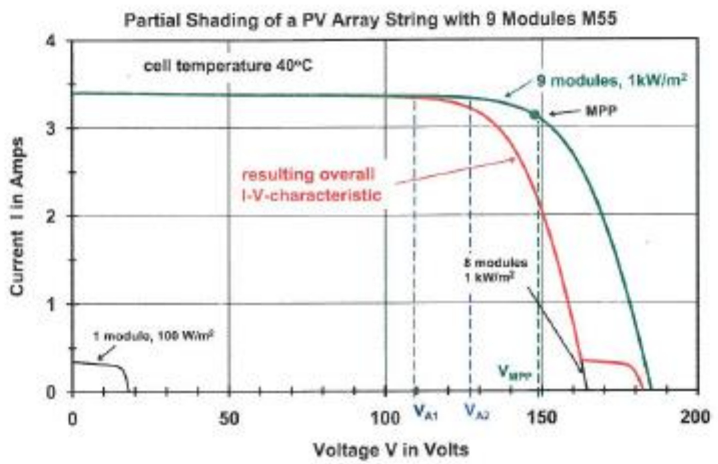
- E.g., Sandia model

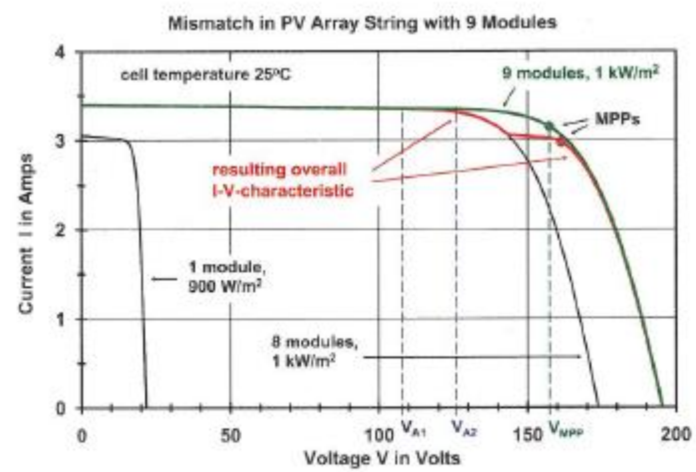
$$E_e = f_1(AM_a)\left(E_b f_2(AOI) + E_{diff} f_d\right)$$



6. DC and Mismatch Losses

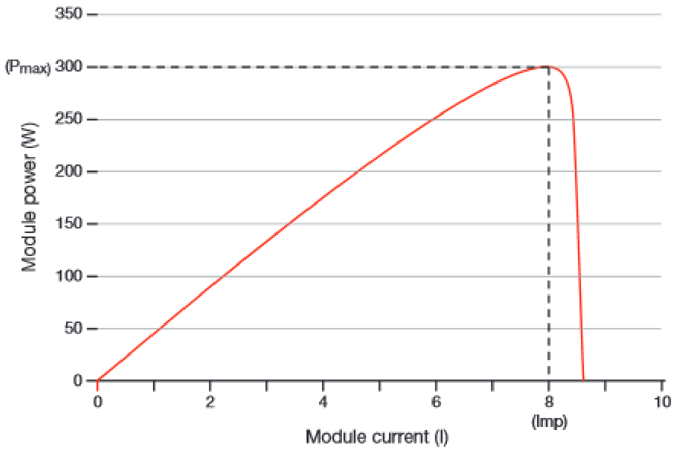
- DC wiring loss increases with the square of the current and the wire resistance (I^2R). Increasing the wire gauge increases the system cost and designers try to calculate an optimal balance between cost and long-term performance.
- Mismatch losses can occur as the result of mismatched modules and strings,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

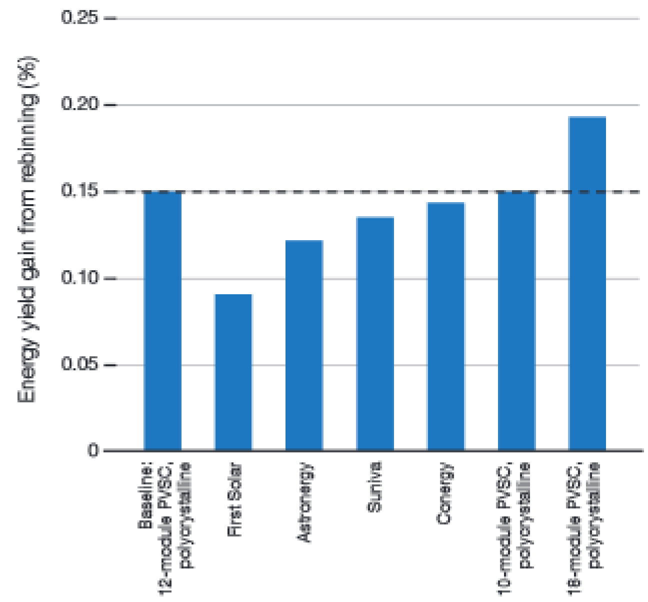




Mismatch from Module Binning?

- 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 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.



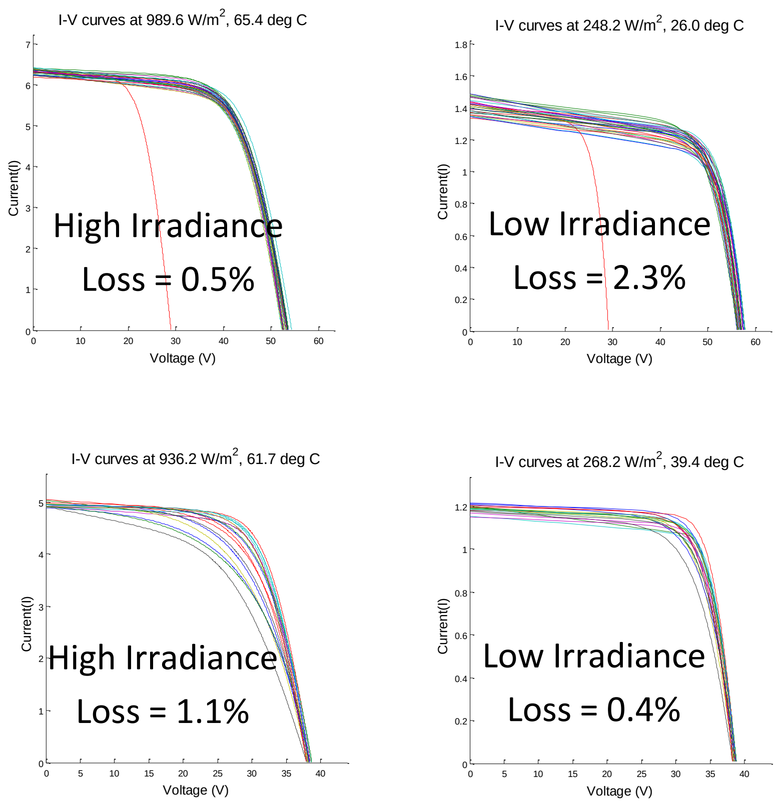


Source: Grana and Gibbs, 2014

Mismatch Losses and Degradation

Sandia National Laboratories

- 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



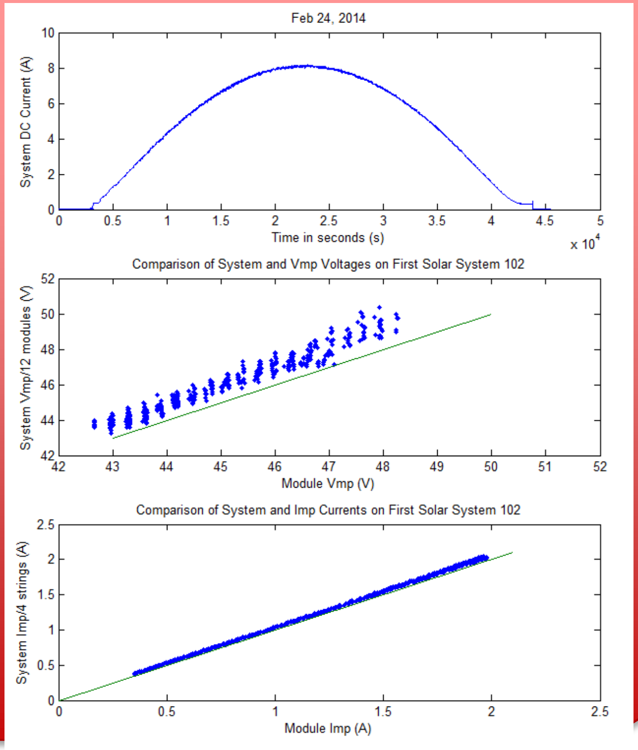
Source: S. MacAlpine, 2013

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

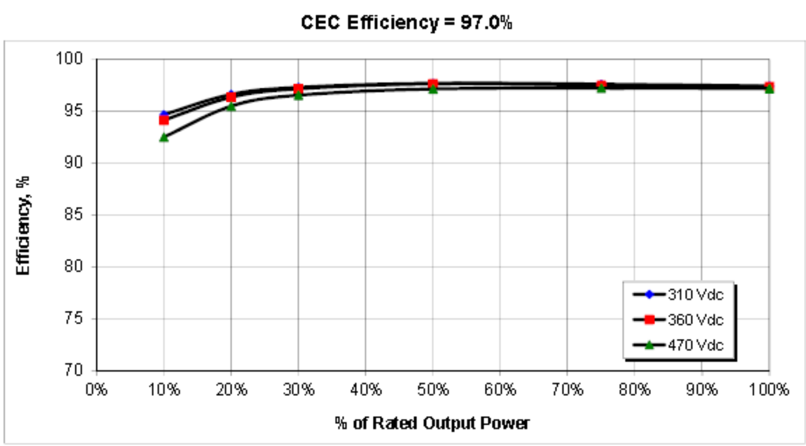
8. DC to AC Conversion

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

Newer 3-phase, multistage inverter

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

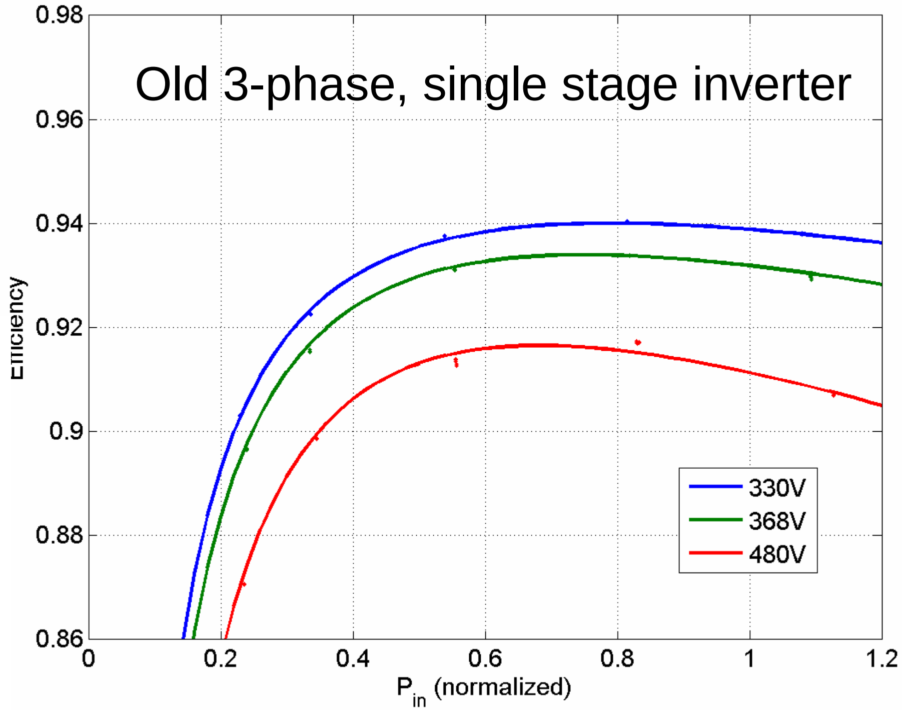
Input Voltage (Vdc)		Power Level (%; kW) 10% 0.37	20% 0.74	30% 1.11	50% 1.85	75% 2.77	100% 3.69	Wtd
Vmin	310	94.7	96.6	97.3	97.7	97.6	97.4	97.4
Vnom	360	94.1	96.4	97.2	97.6	97.5	97.4	97.3
Vmax	470	92.5	95.5	96.6	97.2	97.2	97.2	96.9



CEC List of Eligible Inverters

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

Input Voltage (Vdc)		Power Level (%; kW) 10% 2.05	20% 4.10	30% 6.15	50% 10.25	75% 15.37	100% 20.49	Wtd
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

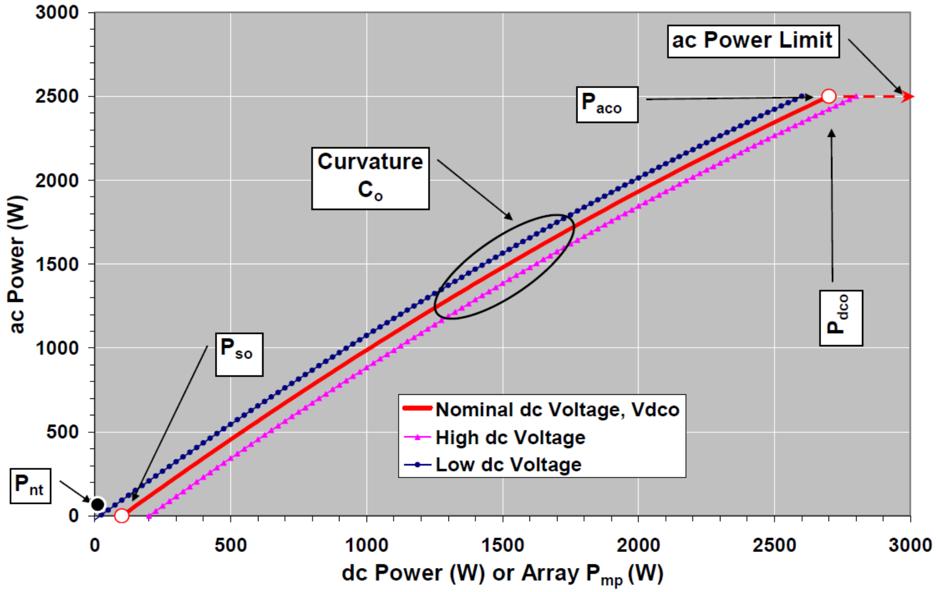


http://www.gosolarcalifornia.ca.gov/equipment/inverters.php

8. DC to AC Conversion

- Sandia Inverter Performance Model

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



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

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

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

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

9. AC Losses

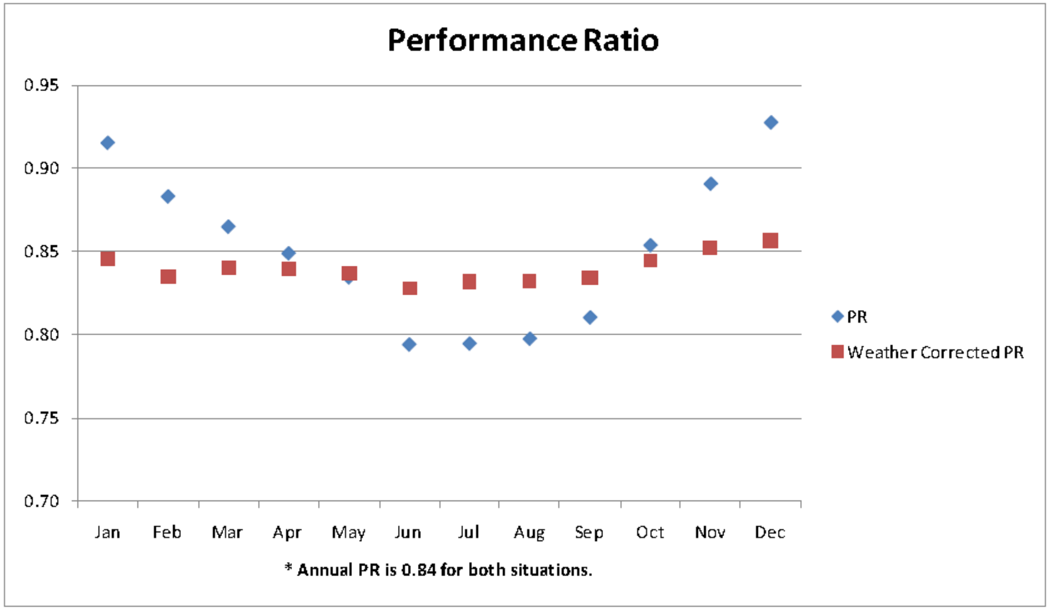
- AC losses include transformer and AC cabling conductive losses. These losses are very project specific and depend where the revenue meter is located.
- Some larger projects have to move AC power considerable distances and these losses can be significant.
- Most models assume a fixed percent loss derate.

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/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** 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

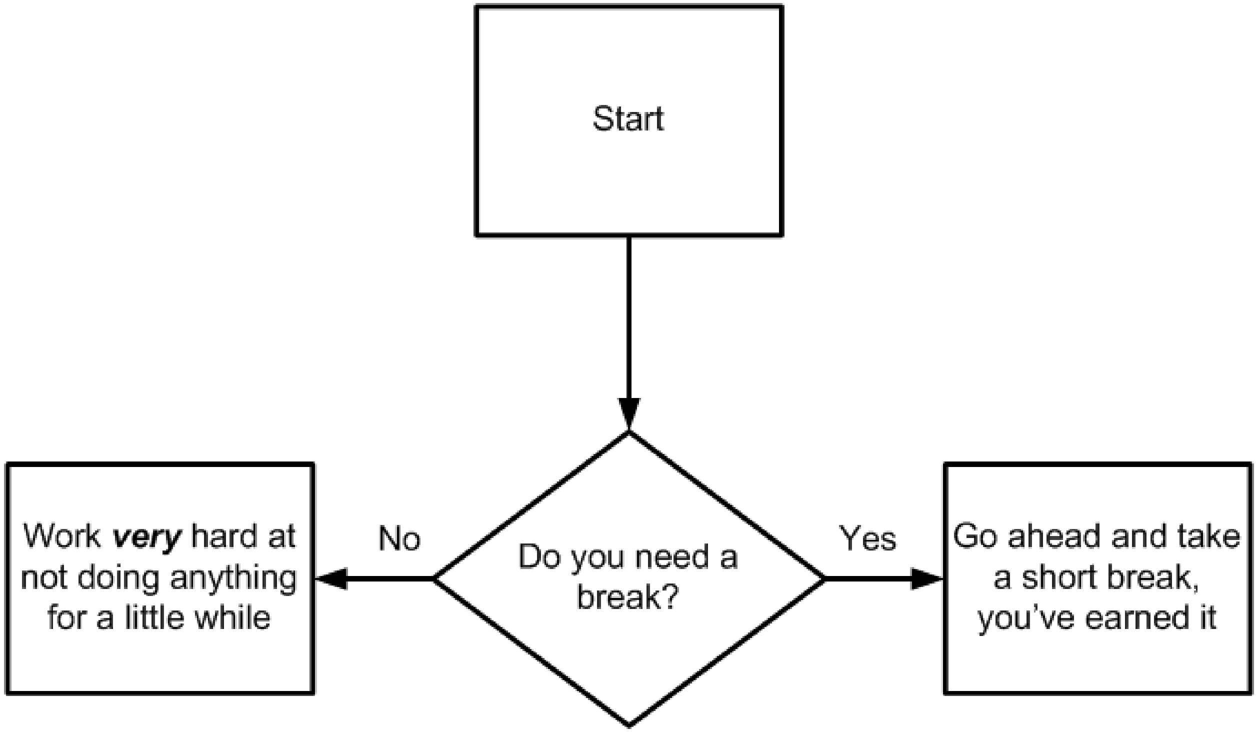


Source: NREL/TP-5200-57991

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?


Start
Do you need a break?
No
Yes
Work *very* hard at not doing anything for a little while
Go ahead and take a short break, you've earned it

Demo Goals

- Take measured DNI, GNI, DHI for a site in Albuquerque, NM, and estimate the Plane of Array (POA) irradiance on the array.
  - Presented in MATLAB
- Use the estimated POA irradiance and estimate the PV system output.
  - Presented in Python
- Perform comparisons against measured data if time permits.

Steps in the MATLAB and Python Tutorial

1. Import the system and weather data (provided)
2. Create the time structure (location structure is provided)
3. Determine the sun position
4. Estimate the Plane of Array (POA) irradiance on our array
    1. Get solar angle of incidence (AOI)
    2. Determine POA irradiance due to the sun beam
    3. Determine POA irradiance due to the ground reflected irradiance
    4. Determine POA irradiance due to diffuse irradiance from the sky using Reindl's 1990 model
    5. Sum all POA components to determine the total POA irradiance
5. Estimate the average cell temperature
6. Estimate the DC output of a single module using Sandia (SAPM) model
    1. Determine effective irradiance (E_e) on the PV cells including any losses due to incident angle (reflections) and spectrum changes (airmass is a proxy for spectrum)
7. Estimate the DC output of an array of modules
8. Estimate the AC output of the system using Sandia inverter model

PV_LIB for MATLAB Demonstration

Sandia National Laboratories

- All (except one) PV_LIB MATLAB functions use the “pvl_” prefix. Any functions without the “pvl_” prefix are from MATLAB.
- PV_LIB functions requiring time or location use a specified time or location structure
  - See pvl_maketimestruct and pvl_makelocationstruct

Let's MATLAB!

PVLIB_Python

- All PVLIB functions translated to the Python programming language
- What is python?
  - A programming kernel, which can run interpreted commands
  - Open source (Free!) language, with a strong scientific toolset and very large user base
- Installing python:
  - Easiest method is to Install Anaconda: https://store.continuum.io/cshop/anaconda/
    - Includes python and most required modules (Numpy, Scipy, Pandas, Datetime)
- Installing pvlib_python:
  - Anaconda doesn't include the pvlib functions, but they can be easily installed:
  - Osx/linux
    - At the shell, enter: `pip install pvlib`
  - Windows
    - In the Anaconda command line, enter :`pip install pvlib`

Running python

- How to run python?
  - Directly from command line: $ `python program.py`
  - Through the python interpreter

```
Robs-MacBook-Air:~ robandrews$ python
Python 2.7.5 (default, Aug 13 2013, 09:55:55)
[GCC 4.2.1 Compatible Apple LLVM 4.2 (clang-425.0.28)] on darwin
Type "help", "copyright", "credits" or "license" for more information.
>>> x=1
>>> print x
1
```

  - Through the Ipython interpreter: (Better for most applications)

UNIX

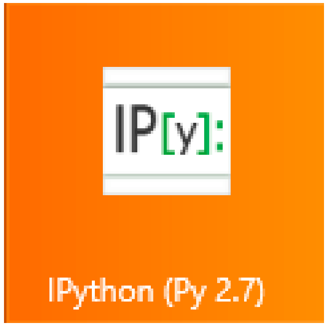
```
Robs-MacBook-Air:~ robandrews$ ipython --pylab
Python 2.7.5 (default, Aug 13 2013, 09:55:55)
Type "copyright", "credits" or "license" for more information.

IPython 1.0.0 -- An enhanced Interactive Python.
?         -> Introduction and overview of IPython's features.
%quickref -> Quick reference.
help      -> Python's own help system.
object?   -> Details about 'object', use 'object??' for extra details.
Using matplotlib backend: MacOSX

In [1]: x=1

In [2]: x
Out[2]: 1
```

Windows

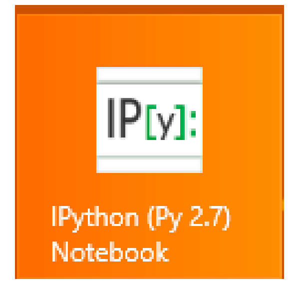


How to run python(cont)

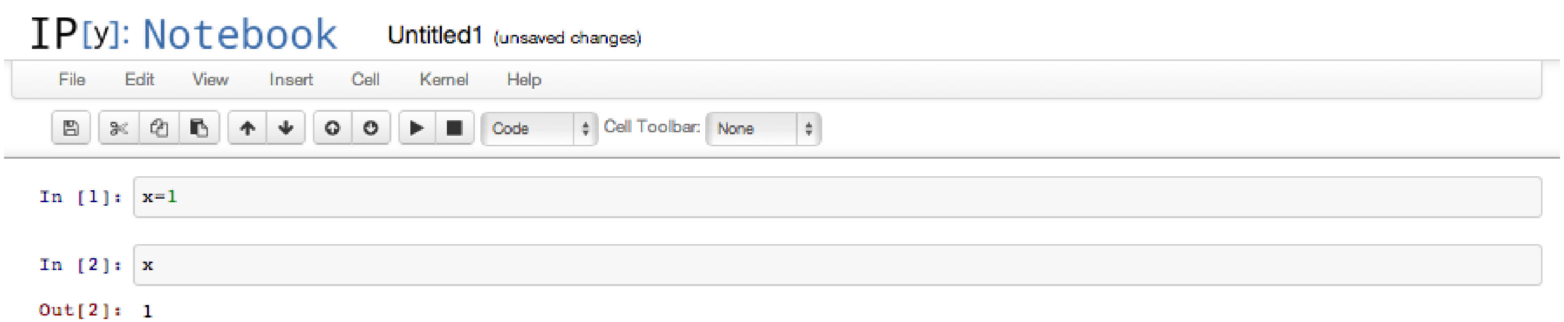
- Through an Ipython notebook (preferred for prototyping)

UNIX

Windows



- Which loads a notebook in a browser window:



For Power Users

- You can create your own python scripts in any text editor
  - Sublime text is recommended (http://www.sublimetext.com/)
- Save the file as a .py file, in the same directory as your Ipython console, or Ipython notebook
  - Alternatively, place it in a directory that is on your python path
- Import the script into your session and run it
  - Eg. test.py :

```
print 'i am outside the function'

def function(inputstring):
    print 'This is the input'+inputstring
```

  - Running it in Ipython:

```
In [1]: import test
i am outside the function

In [2]: test.function('hello')
This is the inputhello
```

- If you make a change to the underlying test.py file, you will need to reload it using:

```
In [2]: reload(test)
i am outside the function
Out[2]: <module 'test' from 'test.pyc'>
```

For Developers

- Installing pvlib through `pip` won't give you the ability to edit the underlying files easily
- All source code is stored in a git repository at:

  https://github.com/Sandia-Labs/PVLIB_Python
- In order to edit the source, you can 'fork' the repository and 'clone' it onto your computer (see git online help for how to do this)
- In order to import the package, enter the following commands at the top of your python code:

```
import sys
sys.path.append('path/to/pvlib/')
import pvlib
```

- NOTE: If you modify a pvlib function you will need to restart the kernel and re-import the module for the changes to take effect
  - Alternatively, you can explicitly import the function, and reload it in the namespace:

```
Import pvl_perez
Reload(pvl_perez)
Output=pvl_perez.pvl_perez(inputs)
```

Let’s Python

Resources

- *http://pvpmc.org → http://pvpmc.sandia.gov*
  - PV Performance Modeling Collaborative
  - PV models explained by topic
  - Get PV_LIB for MATLAB at no cost
- *https://github.com/Sandia-Labs*
  - PV_LIB for Python and MATLAB at no cost
- *https://sam.nrel.gov*
  - System Advisor Model
- *http://www.pvsyst.com*
  - PVsyst
- *http://pvwatts.nrel.gov*
  - PVWatts v1, PVWatts v2, IMBY (In My BackYard)
- *http://www.valentin-software.com*
  - PV*SOL®

Thank You!

jsstein@sandia.gov

cwhanse@sandia.gov

driley@sandia.gov

Rob.Andrews@calamaconsulting.ca

http://solar.sandia.gov

http://PV.sandia.gov

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

The PV Performance Modeling Collaborative is currently supported by the DOE EERE SunShot Program as part of a LPDP award to Sandia National Laboratories.