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PVPerformance MODELING COLLABORATIVE

# 2017 IEEE PVSC Tutorial
# PV System Modeling

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# PV Performance Modeling Collaborative

- http://pvpmc.sandia.gov
- Provides an information hub on PV performance modeling
  - Model agnostic, focus on algorithms, methods, data, etc.
  - Model descriptions (online textbook)
  - Matlab™ code library : PV_LIB Toolbox at github.com/sandialabs/MATLAB_PV_LIB (or from pvpmc.sandia.gov/Applications & Tools)
  - Python code: pvlib-python
    - `pip install pvlib` or `conda install -c pvlib pvlib`
    - Code at github.com/pvlib/pvlib-python
  - Document library, blog, events, …
- 8th PV Performance Modeling Workshop (Albuquerque, NM)
- We welcome contributions to the PVPMC website and code

# PV Performance Modeling Steps

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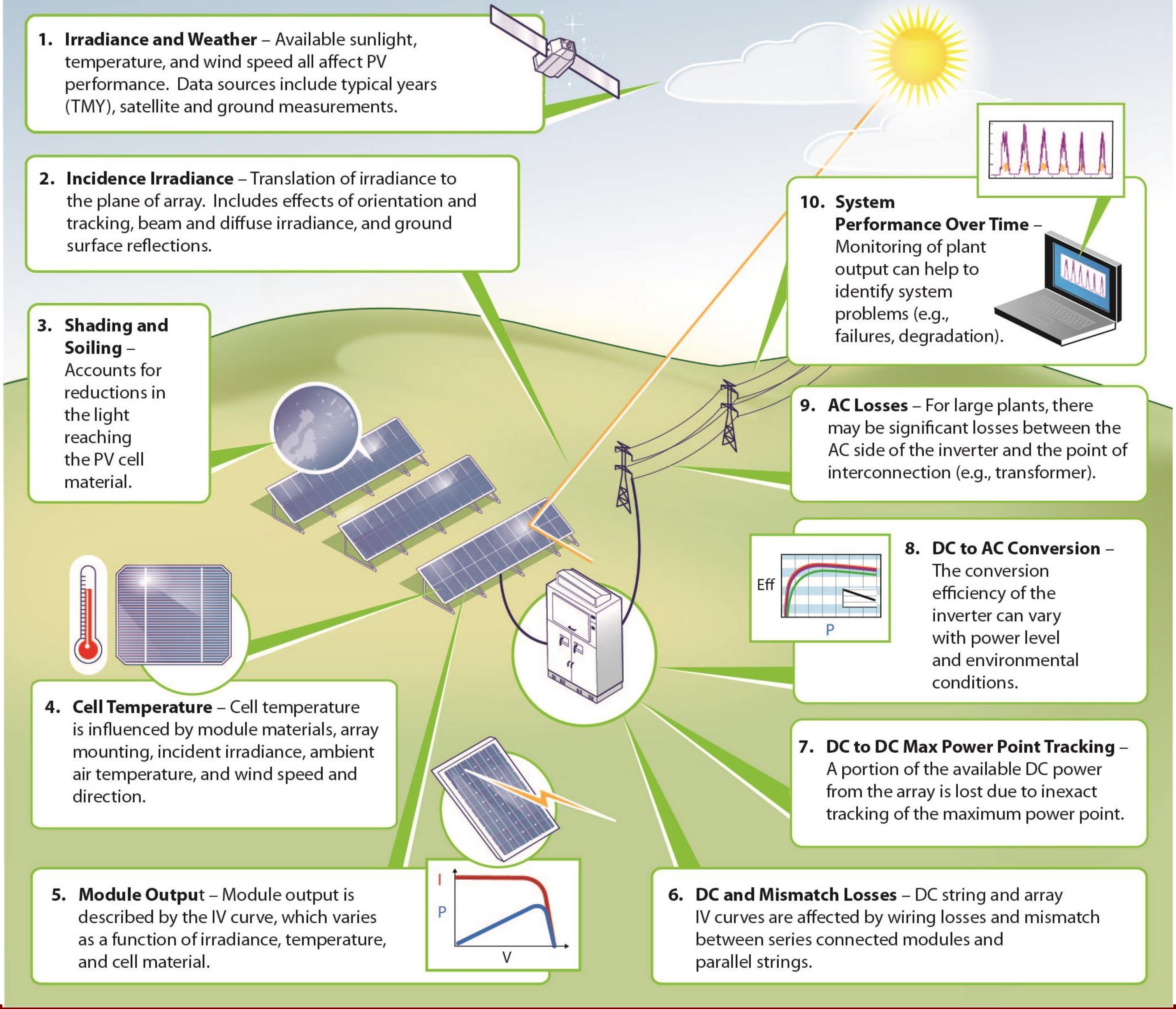

# Modeling Steps (PVPMC)

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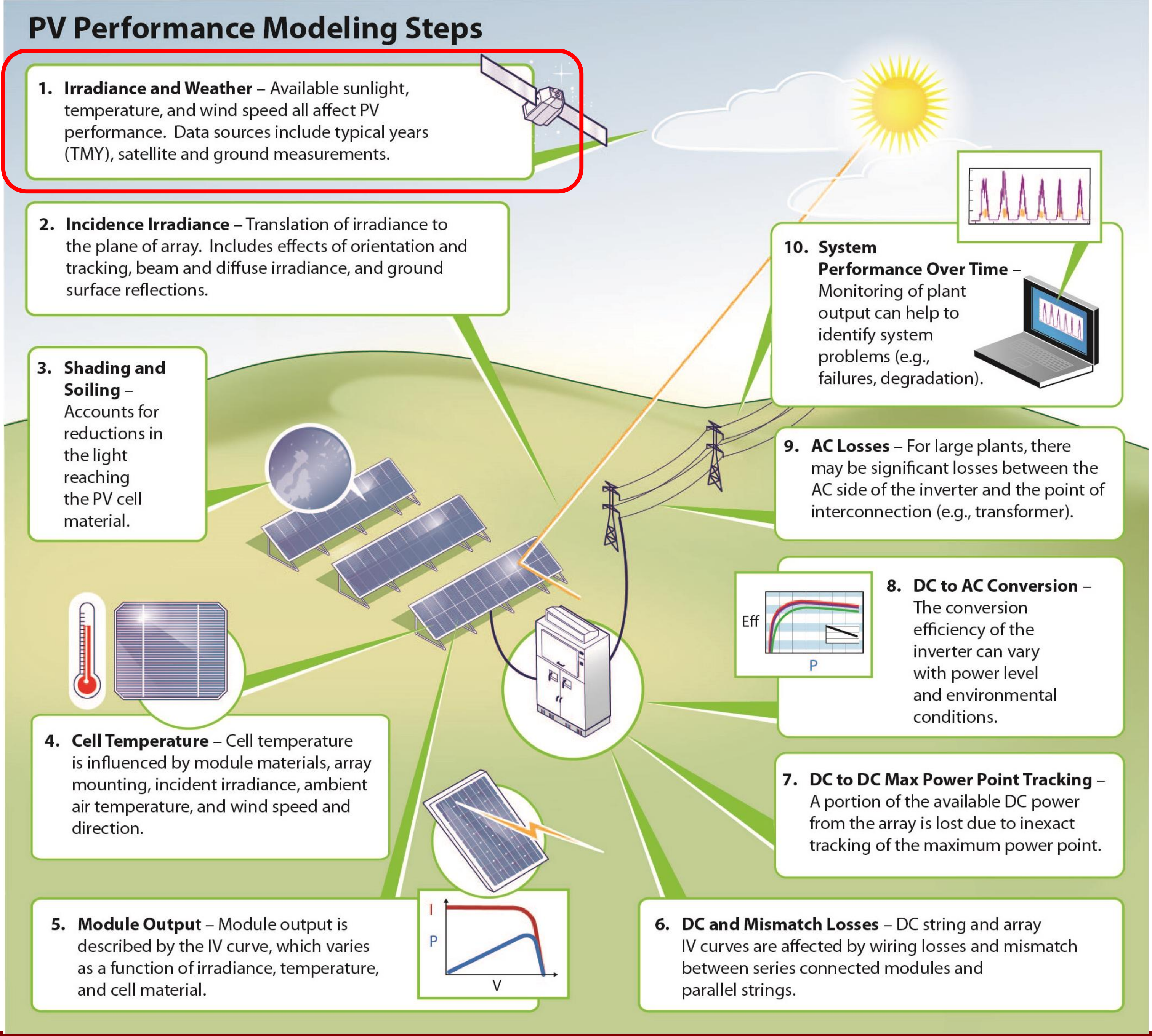
- Irradiance and Weather
  - Definitions and Overview
  - Sun Position
    - Solar Position Algorithm (SPA)
    - Simple models
    - Sandia's code
  - Irradiance and Insolation
    - Extraterrestrial radiation
    - Air Mass
    - Direct Normal Irradiance
      - DISC Model
      - DIRINT Model
    - 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

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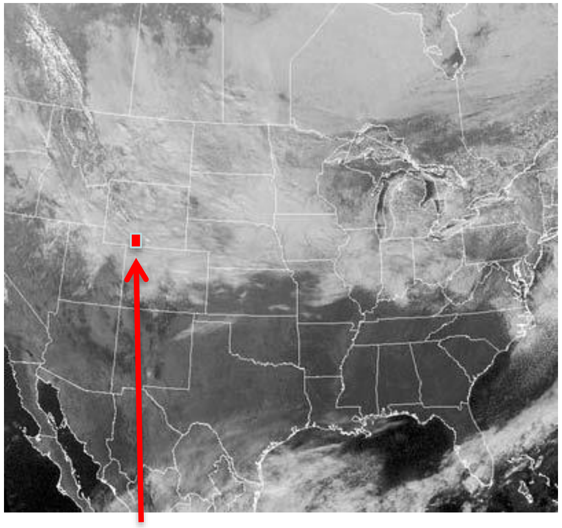
# 1. Irradiance and Weather Data

- Weather is a primary input for a PV performance model
  - E.g., 8760 hourly values of **<u>irradiance</u>**, temperature, precipitation, wind speed, etc.
  - Wide variety of sources, but generally, three options to choose from:
    - Ground measurements
    - Satellite/modeled data
    - A typical meteorological year (TMY)
- Largest source of uncertainty in PV performance modeling

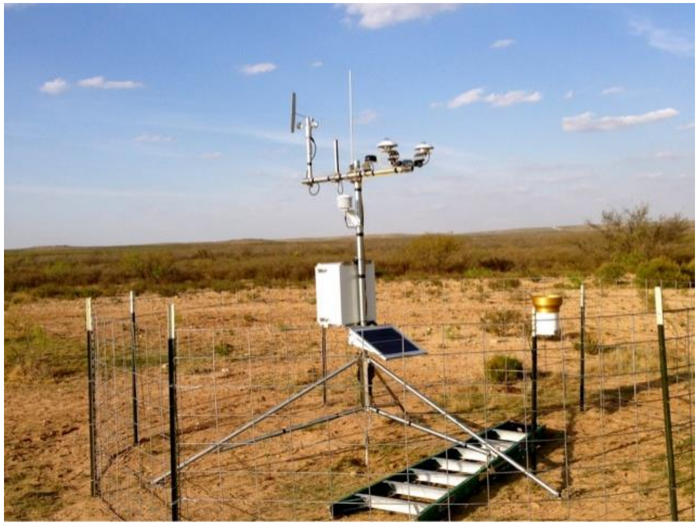
~1 cm$^2$, time averages

~2 km$^2$, snapshot 30 min



# Irradiance and Weather Data

- https://nsrdb.nrel.gov
- NSRDB v1 ’61-90, v2 ’91-10,
  - Hourly values
  - v2 : 237 locations,
  - v3 : 1,454 locations
  - Most values are modeled, not measured
  - TMY2/3: “Average” months are concatenated.
- NSRDB v3 1998 – 2015
  - 30 min., 2km grid
  - New NREL Physical Solar Model applied to GOES imagery + weather data + weather models
  - Includes other meteorological data (air temp, RH, etc.) (model results)
- Purchase irradiance/weather data
  - Most derived from satellite imagery
- Ground measurements
  - ~1 minute, point values



PV_LIB functions
- pvl_readtmy2
- pvl_readtmy3

# Irradiance Components

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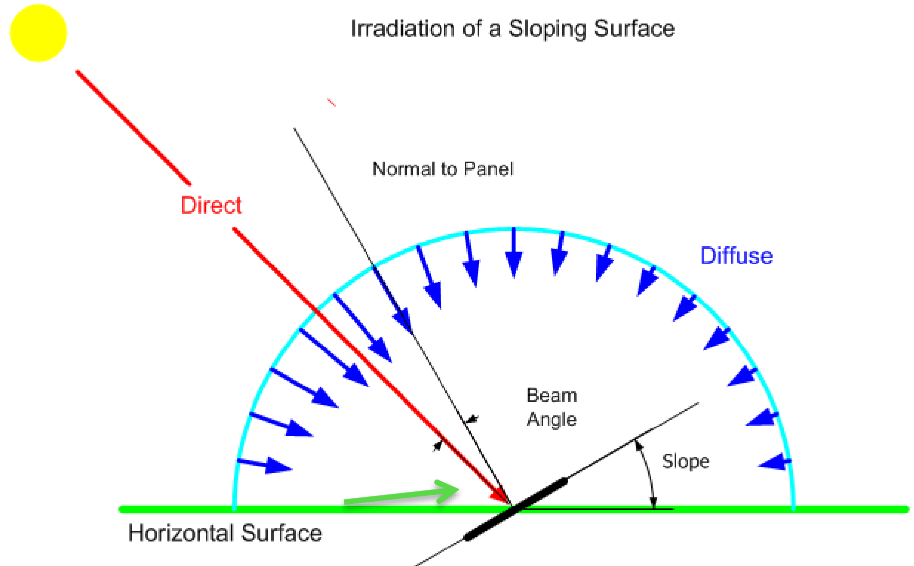
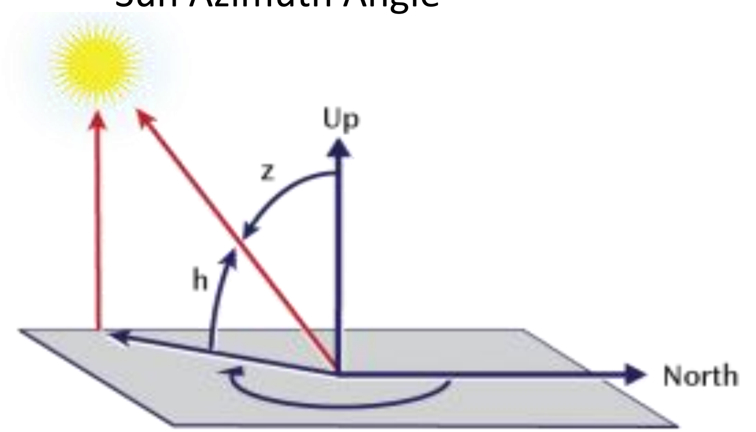
- Direct Normal Irradiance (DNI)
  - Light hitting a plane normal to the sun's rays that comes directly from the sun.
- Diffuse Horizontal Irradiance (DHI)
  - Light on a horizontal plane that does NOT come directly from the sun
- Global Horizontal Irradiance (GHI)
  - All light hitting a horizontal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




# Solar Position

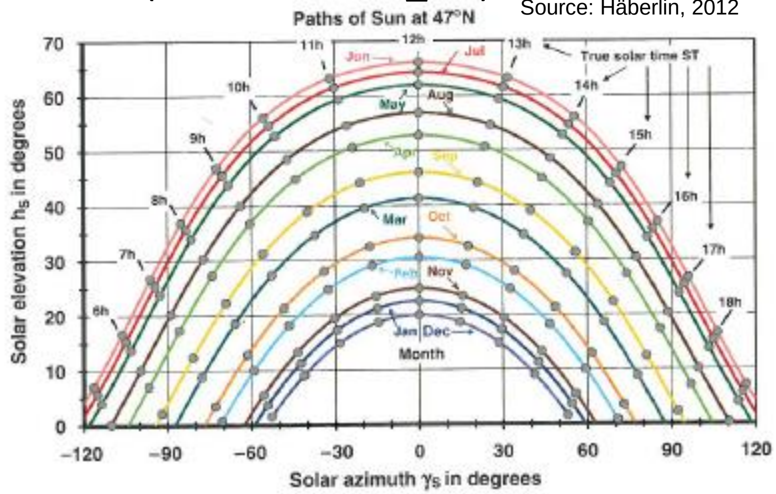
- Solar position relative to an observer on Earth is a critical input to PV performance models.
- Imbedded in PV simulation programs
- Described with:
  - Sun Elevation Angle
    - Zenith = 90 – Sun Elevation Angle
  - Sun Azimuth Angle




## Example Algorithms

- Various online calculators, e.g.
  - http://www.esrl.noaa.gov/gmd/grad/solcalc/azel.html
- NREL Solar Position Algorithm (SPA) (also available in PV_LIB)
  - "Gold Standard"
  - Sandia "ephemeris" algorithm (available in PV_LIB)

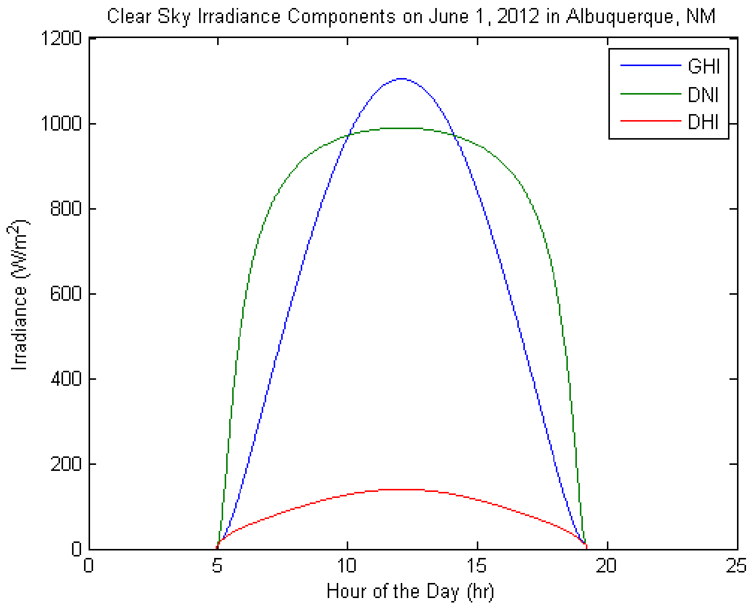
Source: Häberlin, 2012




PV_LIB functions
- pvl_spa
- pvl_ephemeris

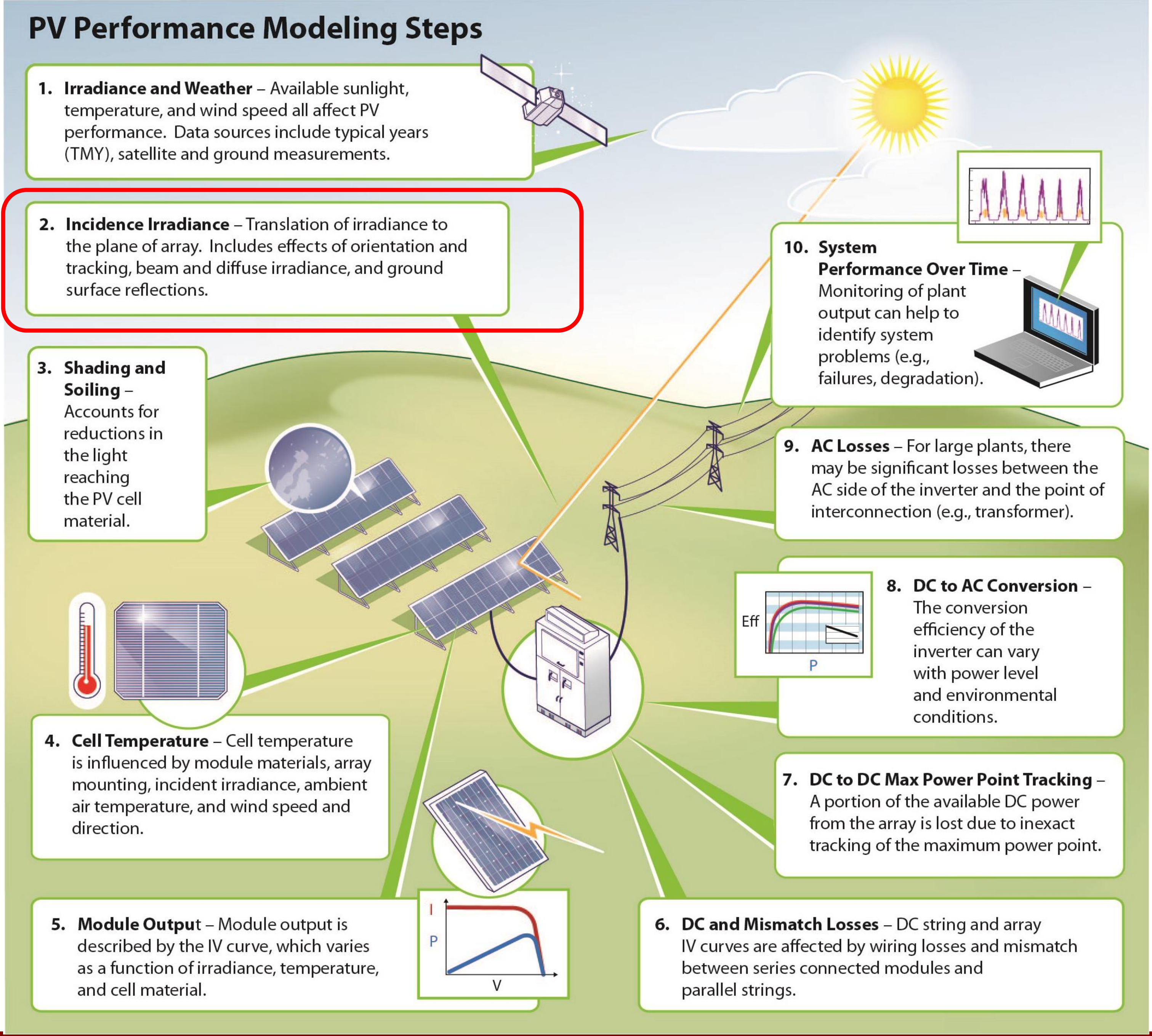
# More Irradiance Concepts

- Extraterrestrial radiation
  - Not constant because orbit is elliptical
  - 1,322 to 1,415 W/m$^2$)
- Irradiance arriving at the ground surface is substantially less than extraterrestrial irradiance
  - Absorption, scattering, reflectance
  - Cloud shadowing
- Clear Sky vs. All Sky conditions
  - Clear-sky: no clouds 'anywhere'
  - All-sky: clouds present, not necessarily in the direct irradiance path
- *Many* models for clear-sky global horizontal irradiance




PV_LIB functions
- pvl_extraradiation

- pvl_clearsky_haurwitz
- pvl_clearsky_ineichen
- pvl_erbs, pvl_louche, pvl_orgill_hollands, pvl_reindl_1, pvl_reindl_2

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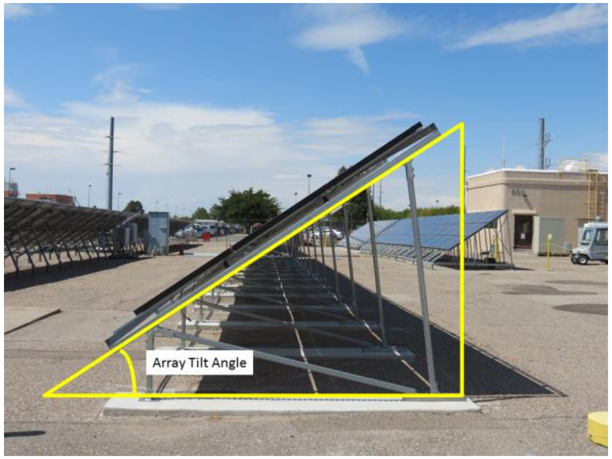
# 2. Incident Irradiance

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 often proprietary
- 2-axis tracking can keep array normal to the sun (AOI=0)

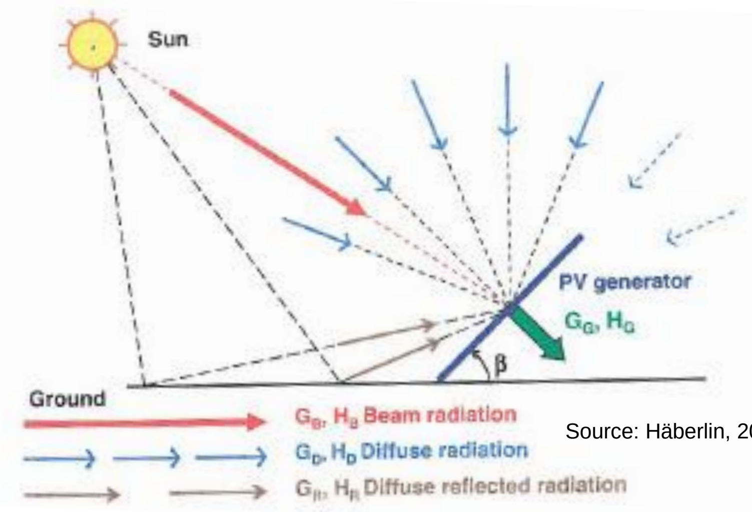
Vertical Axis

Horizontal Axis

PV_LIB functions
- pvl_singleaxis
- pvl_getaoi

# 2. Incident Irradiance

- Incident, or plane-of-array (POA), irradiance is the light that hits the plane of the array
- Sum of three components
  - Beam component
  - Ground reflected
  - Sky diffuse component
- Beam irradiance = DNI × cos(AOI)
- Ground reflected irradiance
  - Array tilt angle β
  - Ground surface albedo
    - Concrete/light gravel ≈ 0.2
    - Snow ≈ 0.5 – 0.82




Source: Häberlin, 2012

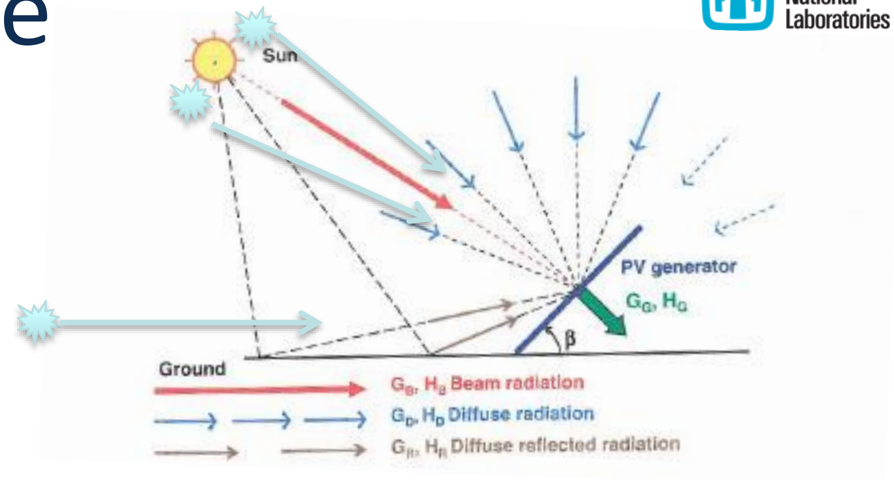
$$G_R = GHI \times albedo \times \frac{1 - \cos\beta}{2}$$

PV_LIB functions
- pvl_getaoi
- pvl_grounddiffuse

# 2. Incident Irradiance

## Sky Diffuse Models

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

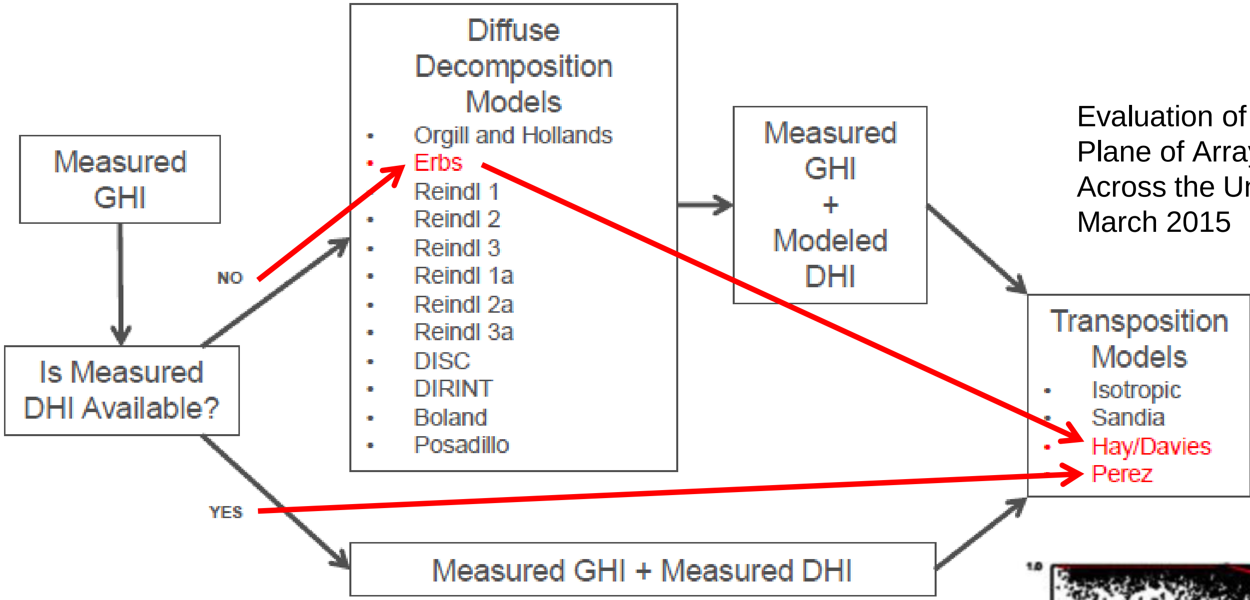



Source: Häberlin, 2012

- Perez model (1991)
  - Isotropic + circumsolar + horizon brightening using empirical functions based on clearness. (PVsyst)

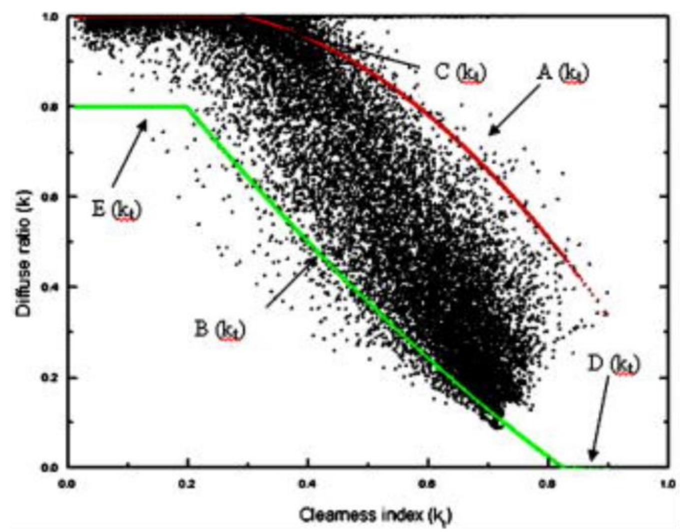
PV_LIB functions
- pvl_isotropicsky
- pvl_haydavies1980
- pvl_reindl1990
- pvl_perez
- + others

# 2. Incident Irradiance Modeling

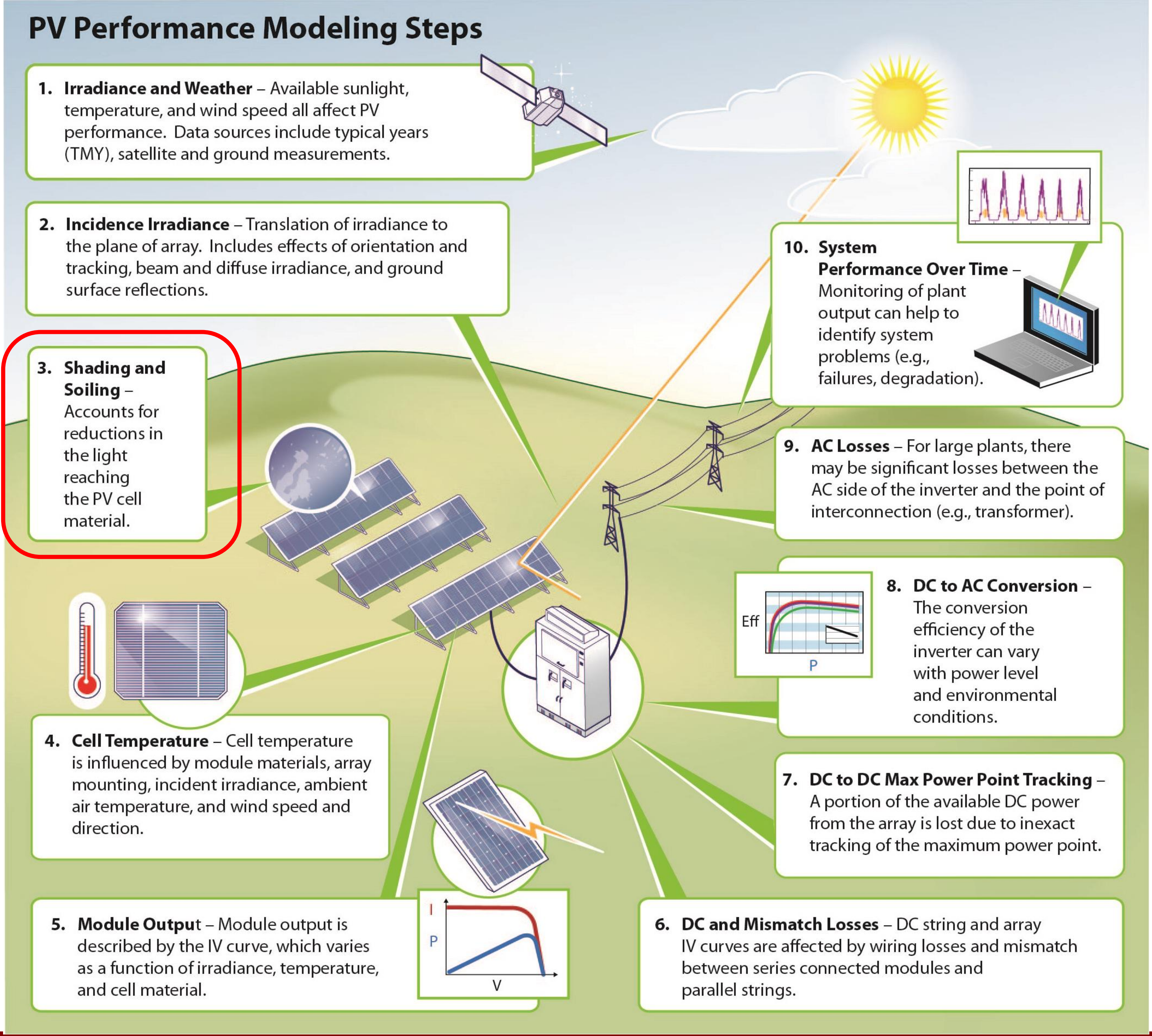



Evaluation of Global Horizontal Irradiance to Plane of Array Irradiance Models at Locations Across the United States, Lave et al, JPV 5(2), March 2015

- 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

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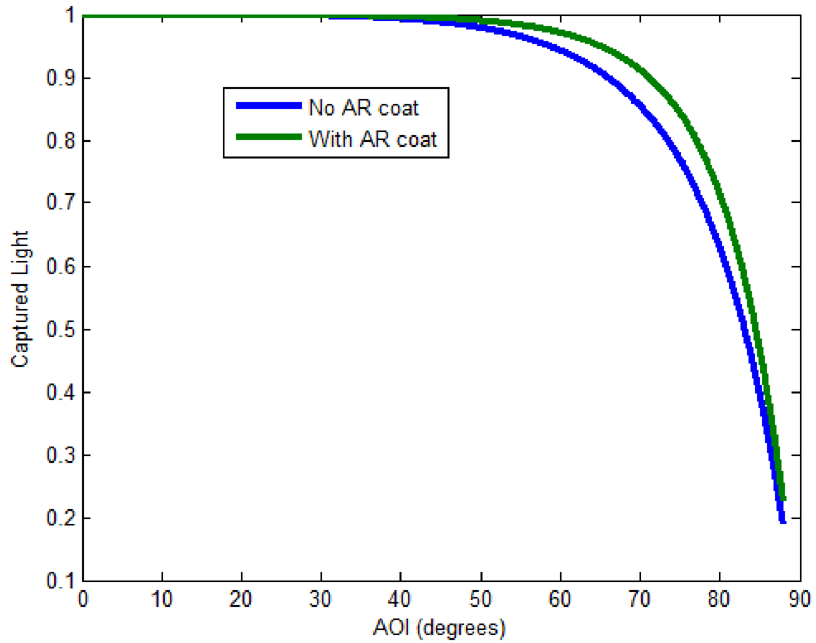
# 3. Reflections

- Reflections are influenced by:
  - Angle of incidence
  - Coatings (e.g., anti-reflective)
  - Soiling
- Reflection models predict a reduction factor for direct (beam) irradiance as a function of AOI
- Reflections models :
  - Physical (optical) model based on Snell's and Bougher's laws
  - Empirical models
    - ASHRAE
    - Martin and Ruiz
    - 5th order polynomial (Sandia)
- Lookup tables are also being implemented in modeling tools.




$$IAM_B = 1 - b_0 \left( \frac{1}{\cos\left(\theta_{AOI}\right)} - 1 \right)$$

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

# 3. Soiling and snow

- Not all POA irradiance reaches the cells
- Soiling or snow can prevent light from getting to the cells

## Soiling Loss Models

- PVLib: Constant factor applied to POA irradiance
- Pvsyst and SAM: monthly energy loss factor (user input)

More detailed soiling models are challenging

- Soiling loss is highly dependent on composition of adhered material
- Adhesion, retention is dependent on local weather

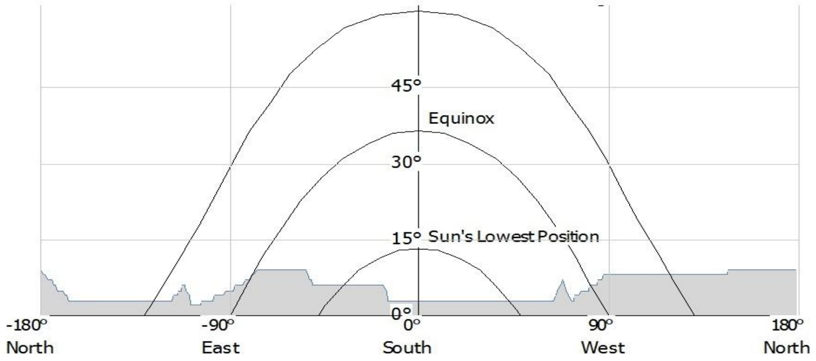
## Snow Loss Models

- PVLib, PVsyst: None
- SAM: Marion et al. (2013) model
  - Calculates fraction of array covered by snow from tilt, daily snow depths, POA irradiance and temperature
  - Snow slides off tilted modules over time
  - Strings without snow produce energy; others don't

# Shading effects

## Near shading

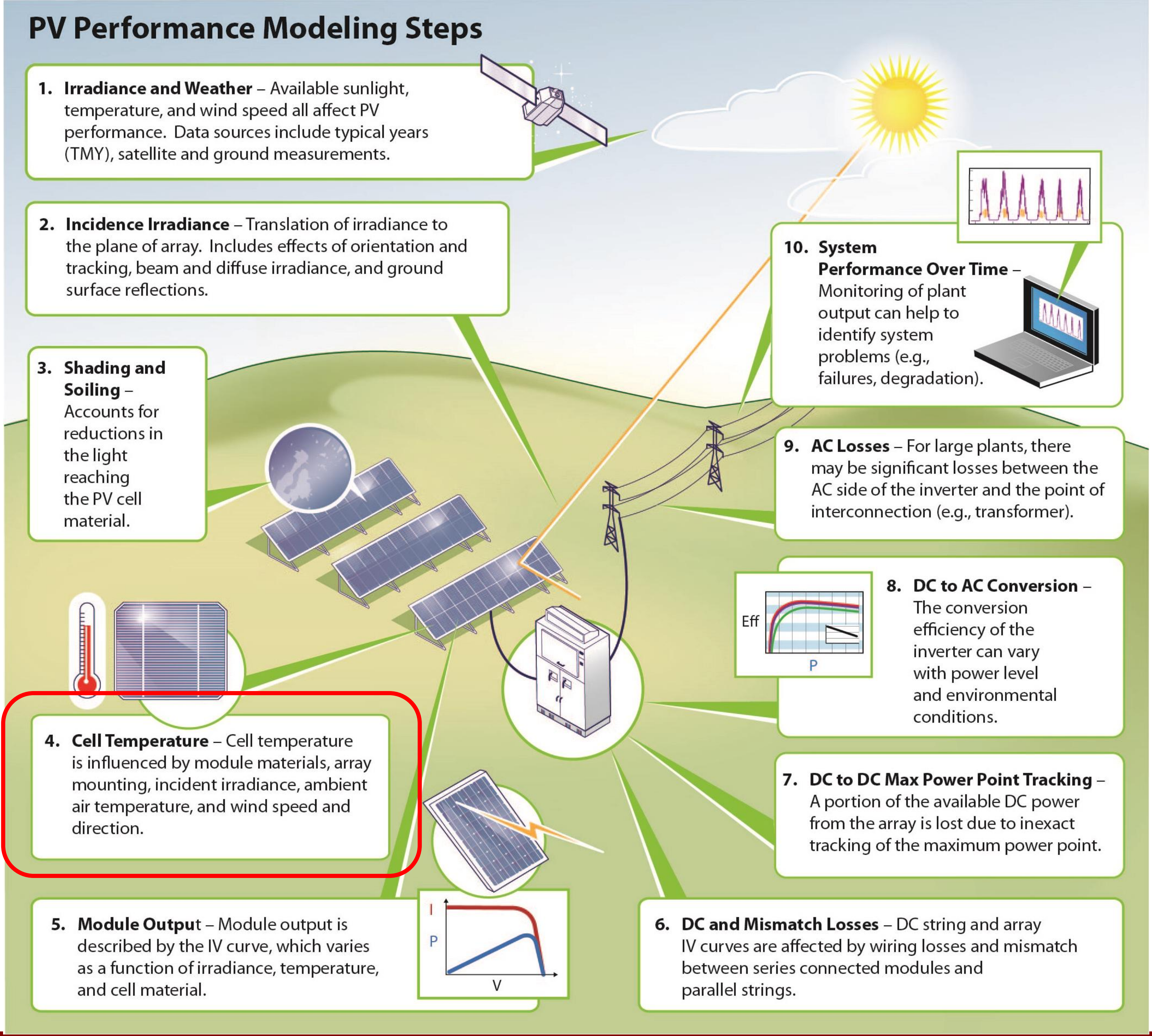
- Near shade has sharp edges, affects parts of the array
  - Buildings, trees, appliances, wires, chimney, etc.
  - Row-row shading within array
- Effects are complex due to mismatch among modules and strings
- Software packages are integrating design tools to help model shading (e.g. Helioscope and PVSyst). Near-field object data is required.




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

## Far shading

- Considered to affect whole array
- Blocks direct irradiance, reduces diffuse irradiance
- Can be represented by defining horizon(azimuth)

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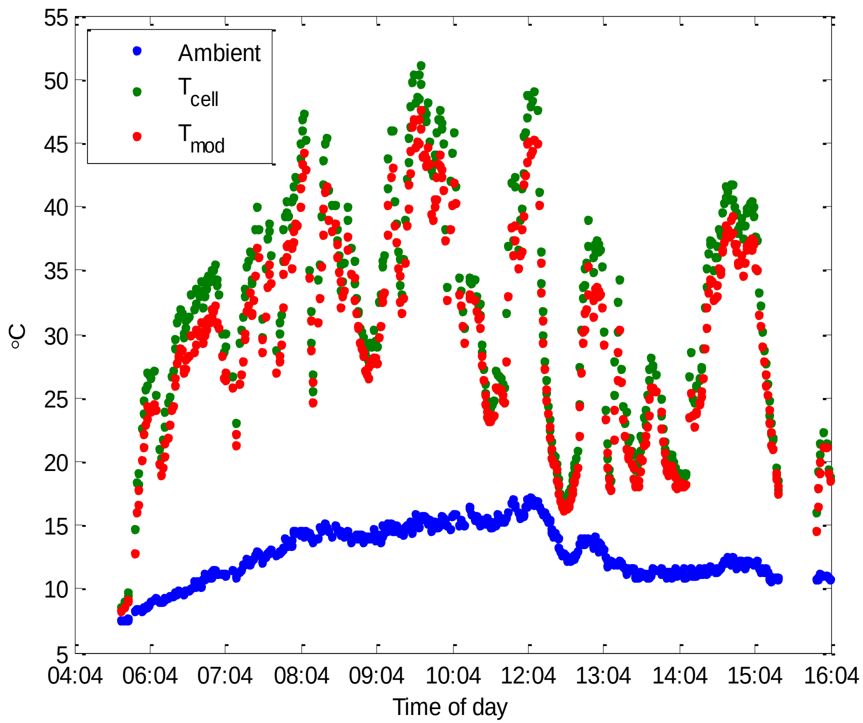
# 4. Cell Temperature

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



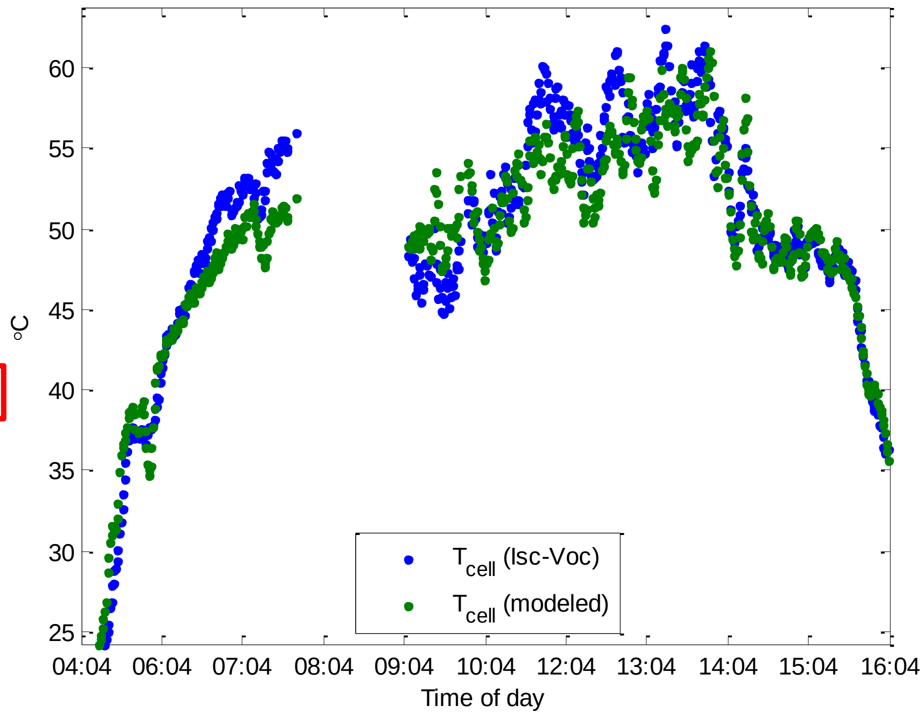
# 4. Cell Temperature Models

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

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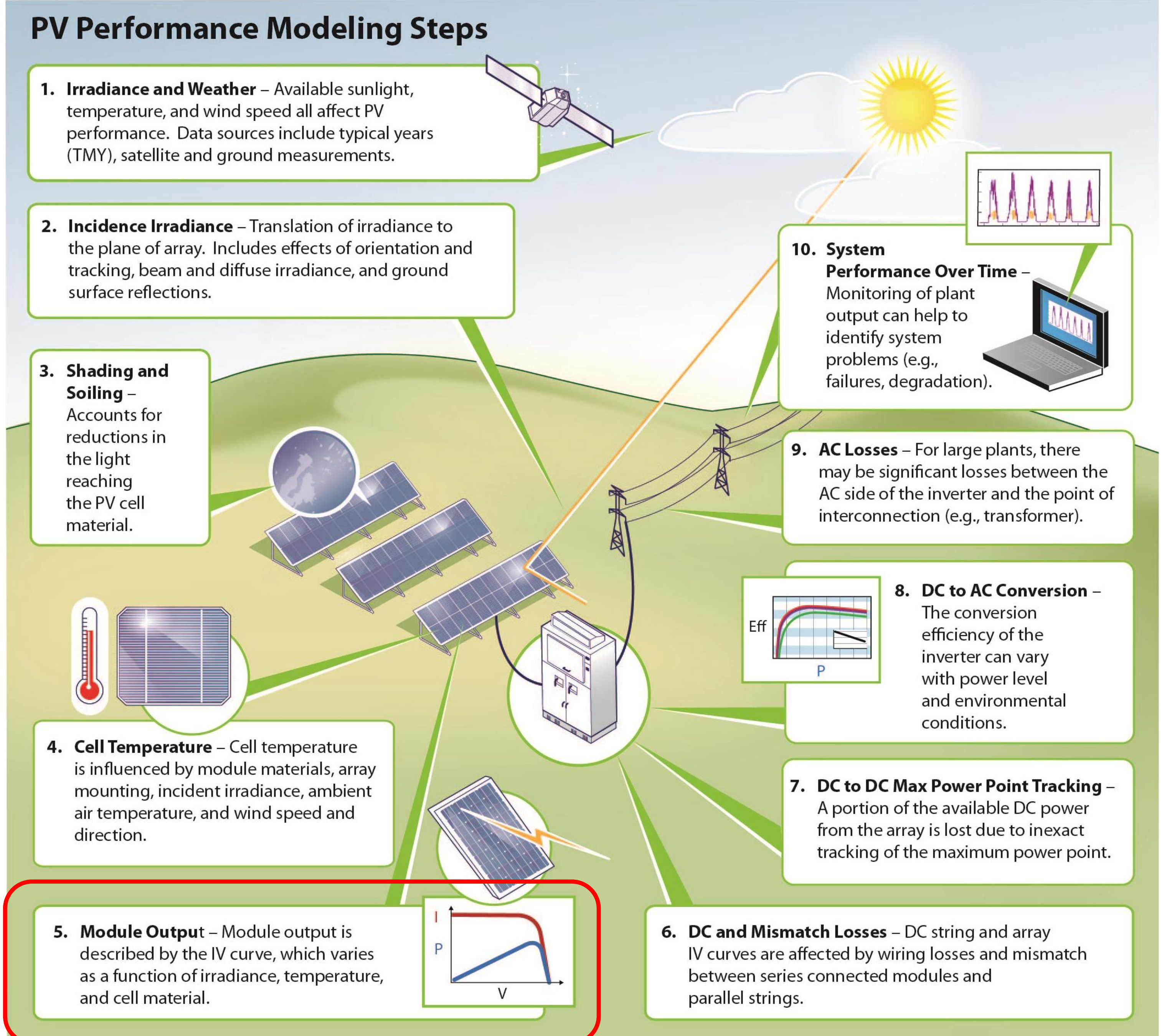
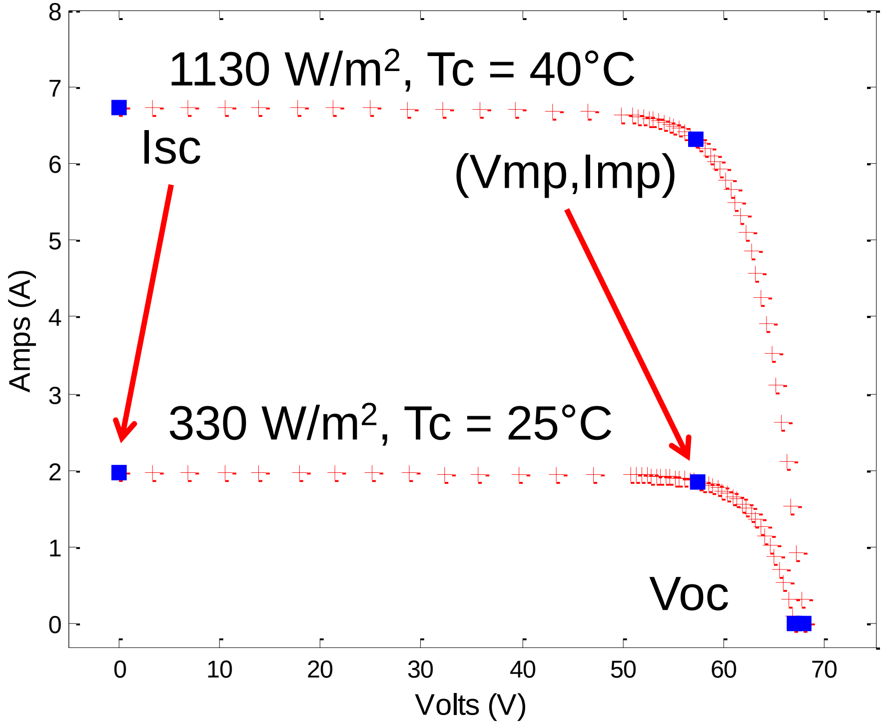


# 5. Module Output

- 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

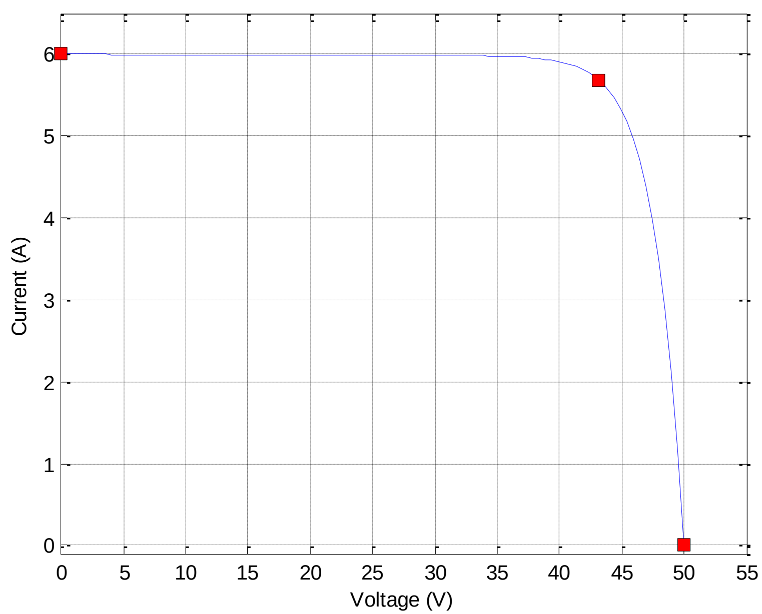



$$P_{dc} = \frac{I_{tr}}{1000} P_{dc0}(1 + \gamma(T_{cell} - T_{ref}))$$

# 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 $T_C$




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

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

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

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

$R_s, n$ constant

De Soto et al, 2006

# 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

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

Effective irradiance : light flux that becomes electrical current

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

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

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

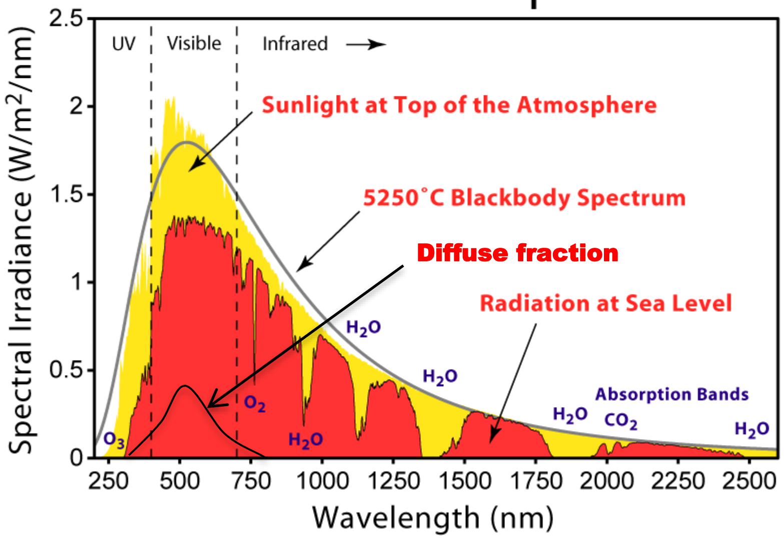
$$I_{MP} = I_{MP0}\left(C_0 E_e + C_1 E_e^2\right)\left(1 + \alpha_{MP}(T_C - T_0)\right)$$

PV_LIB functions
- pvl_sapm

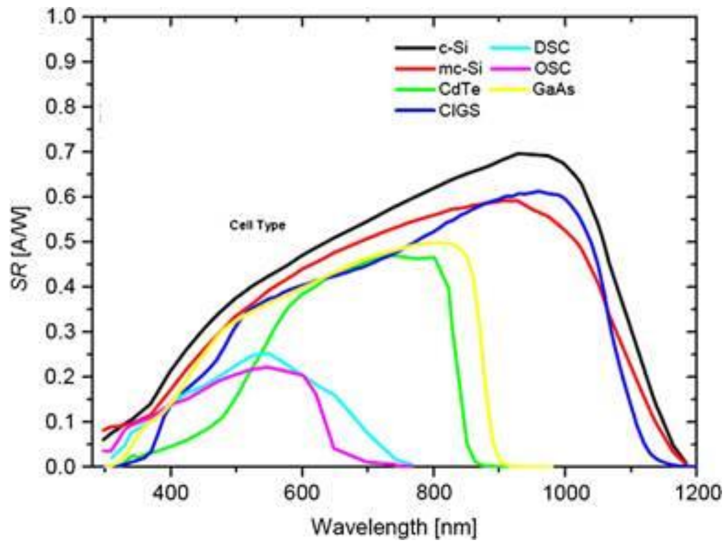
# Solar Spectrum

- 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

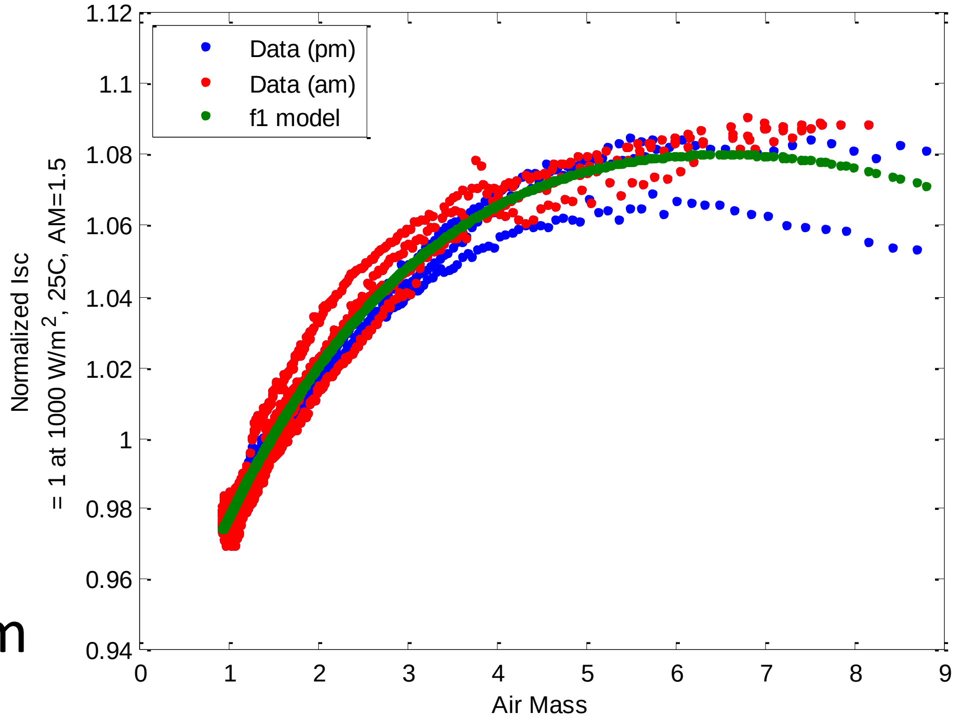
PV_LIB functions
- pvl_pres2alt
- pvl_alt2pres
- pvl_relativeairmass
- pvl_absoluteairmass

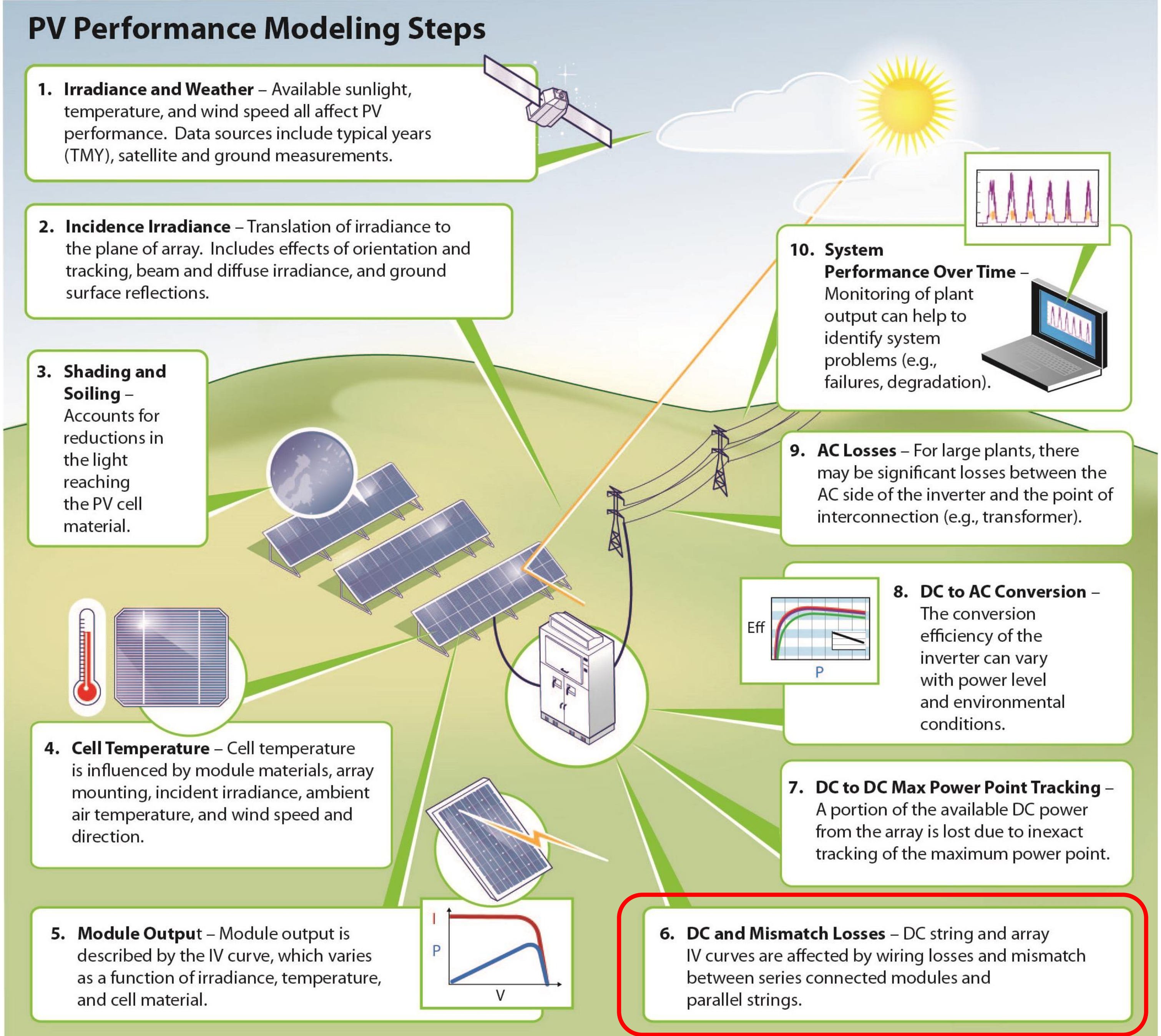
# Effective irradiance

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 common, convolution of spectrum and spectral response
- E.g., Sandia model

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



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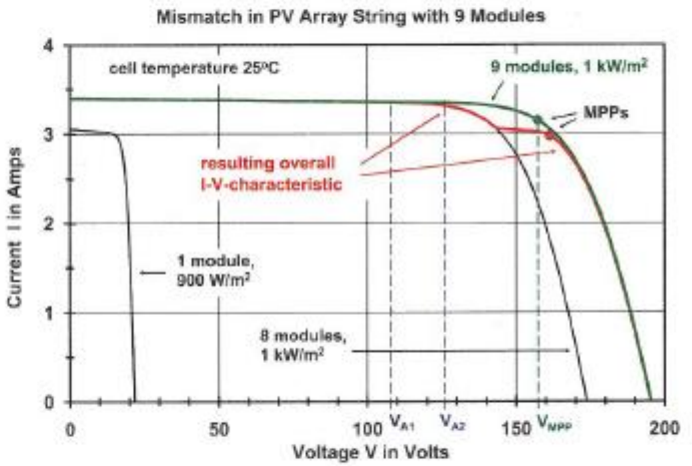
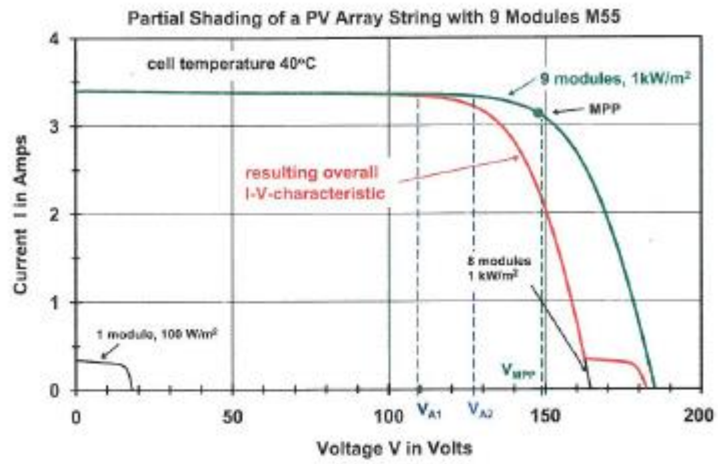
# 6. DC and Mismatch Losses

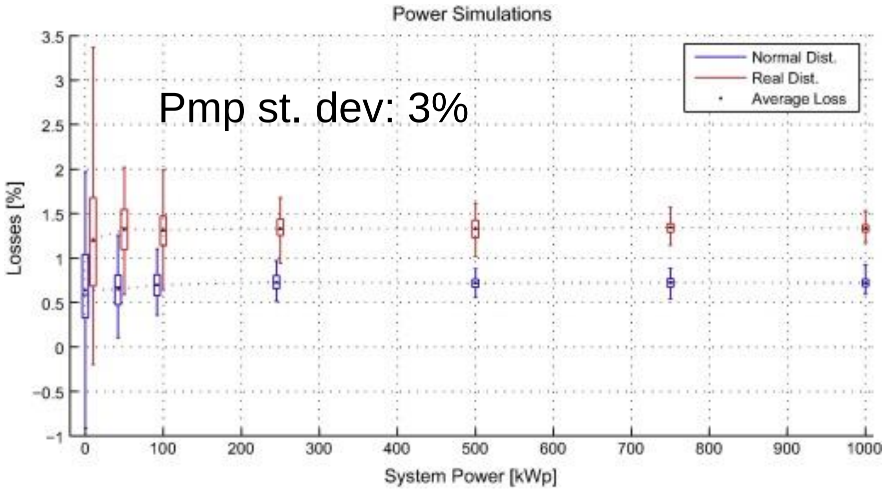
- DC wiring loss increases with the square of the current and the wire resistance ($I^2R$).
- Increasing the wire gauge increases the system cost and designers try to calculate an optimal balance between cost and long-term performance.
- Mismatch losses occur when current differs among cells and modules in series. Some mismatch is intrinsic due to variation in the hardware. Other mismatch is caused by shading.



# Mismatch from Module Variation

- Typically represented by a 'derate' factor applied to DC power, often 1-2%
- Modules are binned based on power or current.
  - Variation increases over time due to degradation or failure.
- Rough rule of thumb:
  - Mismatch loss ~module st. dev. / 3
  - Vargas (2016); Lorente (2014); Spertino (2009)
  - MacAlpine (2013) supports lower rates
  - Does NOT account for module failures
- Power-current curves are relatively flat at the peak.

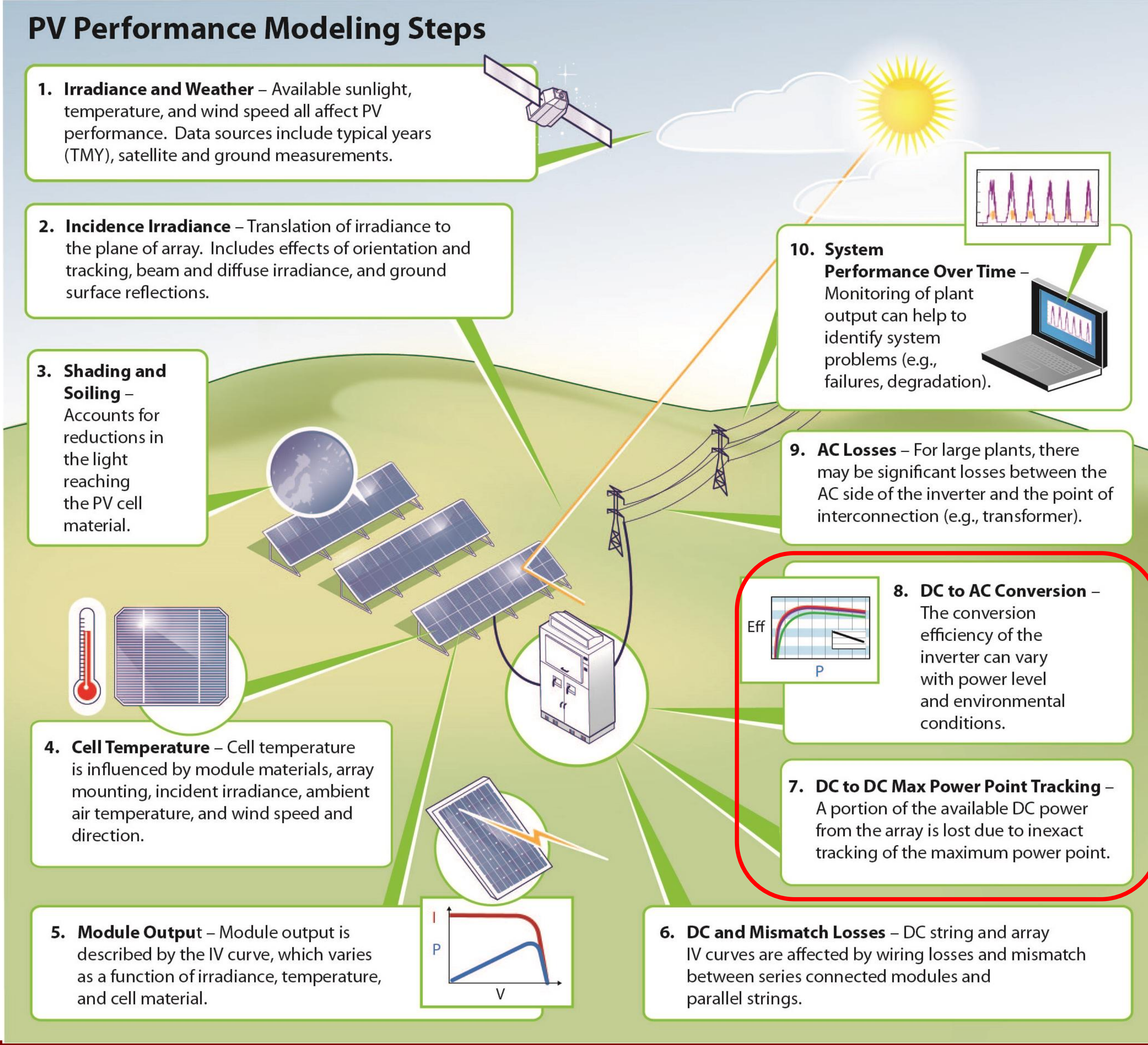



Source: Solar Energy, 2015;116:303-313. doi:10.1016/j.solener.2015.03.041

**Table 6.3. Measured and modeled mismatch power loss for single run arrays**

| Array | Native Array Config. | Measured Mismatch Loss | | Modeled Mismatch Loss | |
|---|---|---|---|---|---|
| | | High Irradiance | Low Irradiance | High Irradiance | Low Irradiance |
| Mono 1A | 3 strings of 8 | 0.3% | 1.3% | 0.4% | 1.5% |
| Mono 2A | 1 string of 9 | 0.2% | 0.3% | 0.1% | 0.3% |
| Mono 1B | 1 string of 21 | 0.1% | 0.1% | 0.2% | 0.0% |
| Mono 2B | 1 string of 21 | 1.1% | 0.7% | 1.2% | 0.6% |
| Mono 3B | 1 string of 27 | 0.0% | 0.1% | 0.0% | 0.1% |
| Mono 5B | 1 string of 9 | 0.0% | 0.4% | 0.0% | 0.5% |
| Mono 6B | 2 strings of 9 | 0.4% | 0.4% | 0.4% | 0.4% |
| Poly 2A | 3 strings of 5 | 0.1% | 0.9% | 0.1% | 1.1% |
| Poly 1B | 1 string of 21 | 0.3% | 0.5% | 0.4% | 0.6% |
| Poly 2B | 1 string of 21 | 0.0% | 0.2% | 0.0% | 0.2% |
| Poly 3B | 2 strings of 9 | 1.3% | 0.3% | 1.3% | 0.4% |
| Poly 4B | 1 string of 10 | 0.0% | 0.2% | 0.0% | 0.2% |

Source: S. MacAlpine, Dissertation, Univ. of Colorado 2013, UMI Number: 3621376

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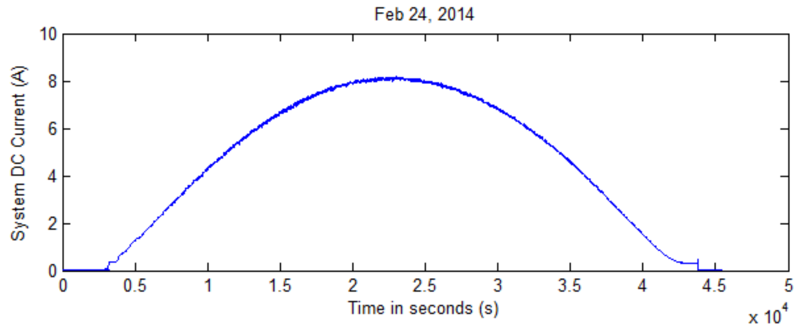
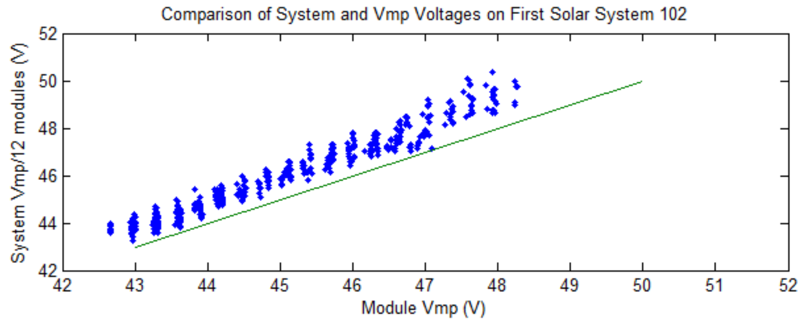
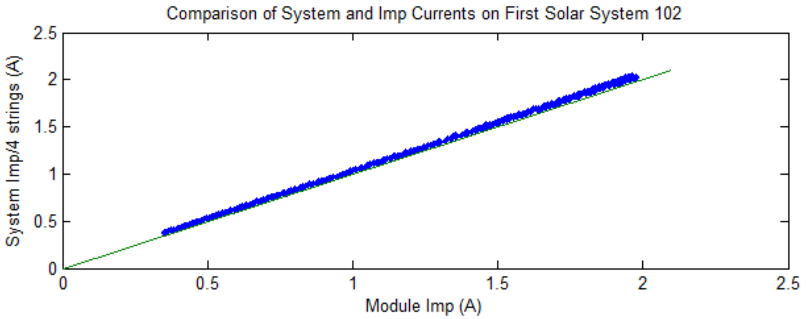
# 7. DC to DC MPPT

- 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 is 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 that
  - Vary with $I^2$ (e.g., resistance)
  - Vary with I (e.g., switching, voltage drops)
  - 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
- Inverter efficiency generally decreases at non-unity power factors
  - Bleeding edge of modeling at present

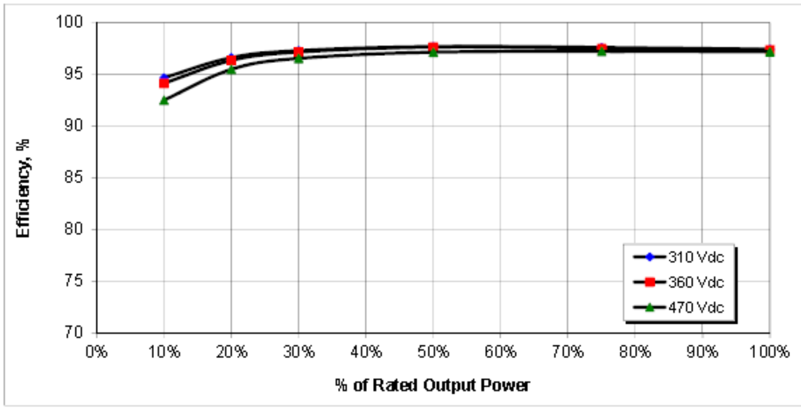
# 8. DC to AC Conversion

- 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

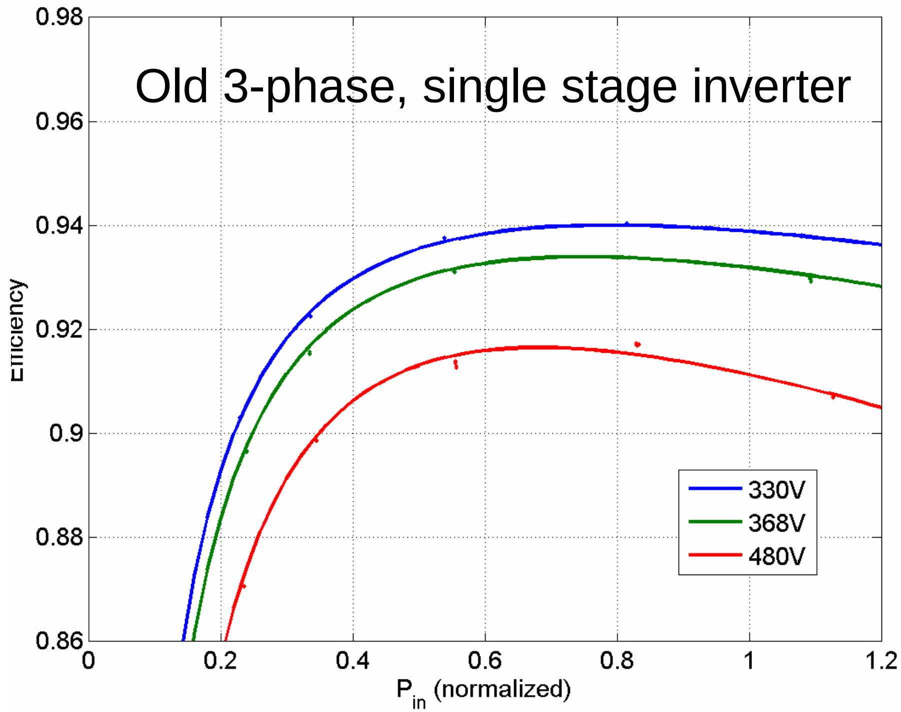
| Input Voltage (Vdc) | | Power Level (%; kW) 10% 0.37 | 20% 0.74 | 30% 1.11 | 50% 1.85 | 75% 2.77 | 100% 3.69 | Wtd |
|---|---|---|---|---|---|---|---|---|
| Vmin | 310 | 94.7 | 96.6 | 97.3 | 97.7 | 97.6 | 97.4 | 97.4 |
| Vnom | 360 | 94.1 | 96.4 | 97.2 | 97.6 | 97.5 | 97.4 | 97.3 |
| Vmax | 470 | 92.5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

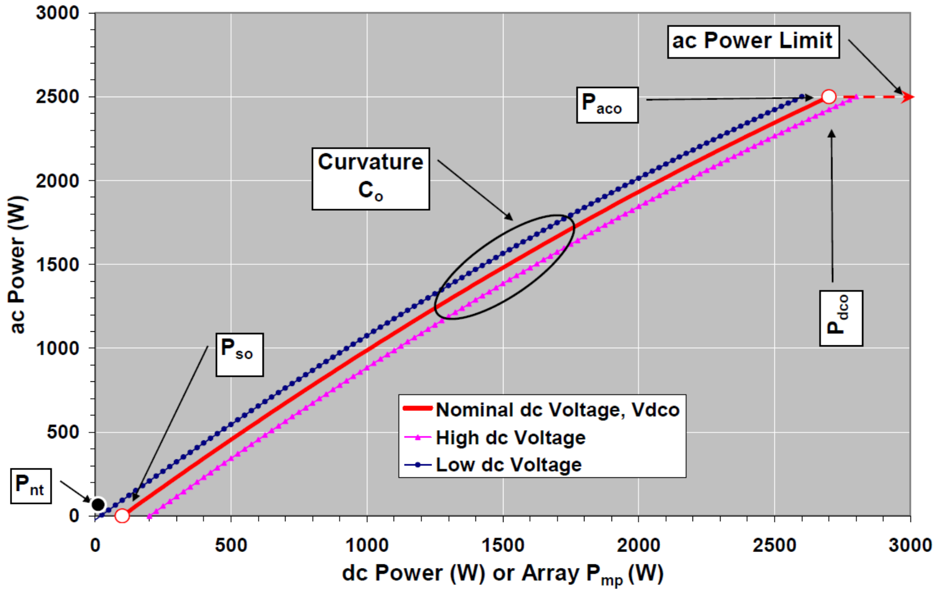



http://www.gosolarcalifornia.ca.gov/equipment/inverters.php

# 8. DC to AC Conversion

- Sandia Inverter Performance Model

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



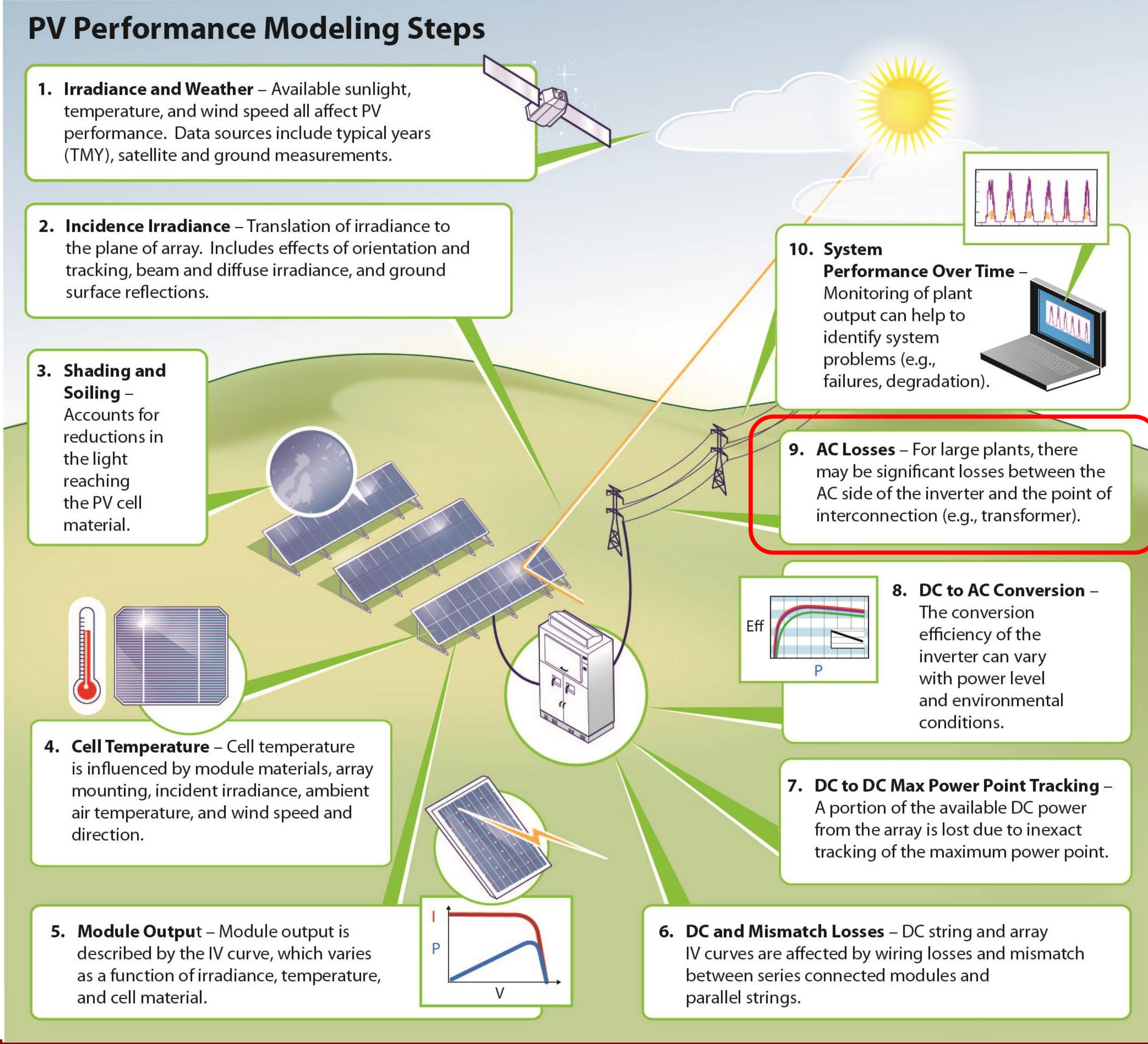

$$P'_{dco} = P_{dco}\left\{1 + C_1\left(V_{dc} - V_{dco}\right)\right\}$$

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

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

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

PV_LIB functions
- pvl_snlinverter
- pvl_snlinverterdb
- pvl_adrinverter

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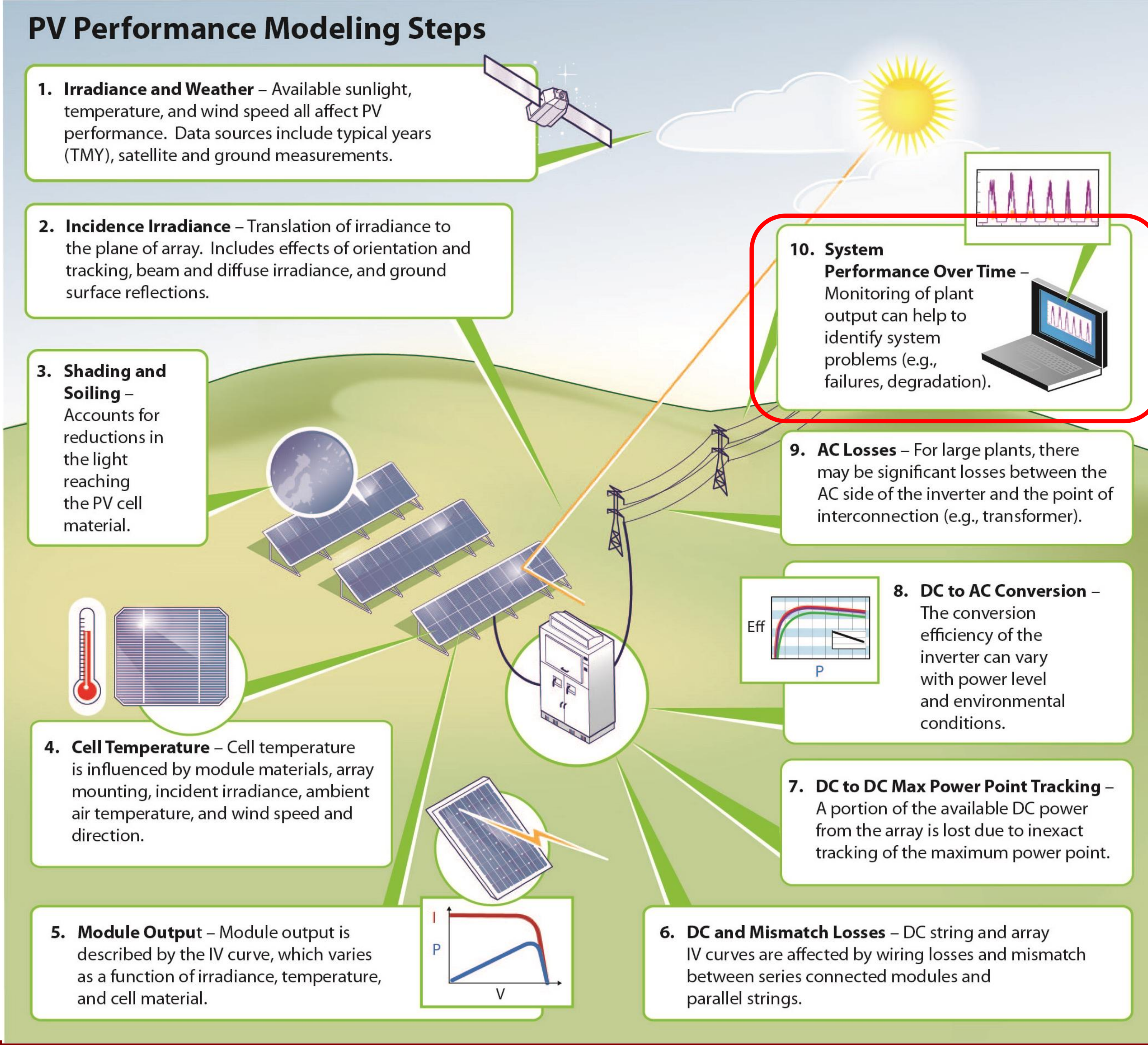
# 9. AC Losses

- 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 factor.

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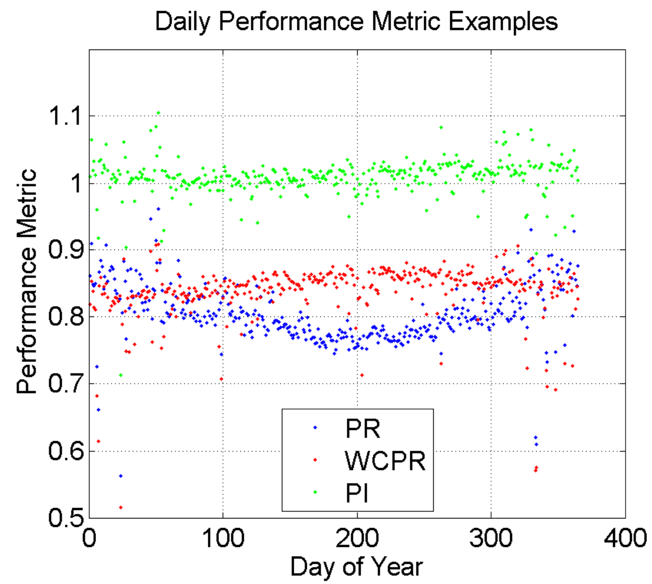
# 10. Performance over Time

- Energy production over time is affected by
  - Module degradation – efficiency generally decreases
  - Module, inverter and other component failure
  - Loss of availability due to grid disturbances, and O&M events.
- Module degradation is usually expressed as a %/yr reduction in DC power (e.g., 0.5%/yr)
  - Most models use a constant for all modules
  - Pvsyst, Helioscope accept a distribution of degradation rates
- Failure and repair models are not common
  - SAM is implementing a Monte Carlo failure and repair model

# 10. Monitoring Performance

- **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 can help identify problems with model or system.



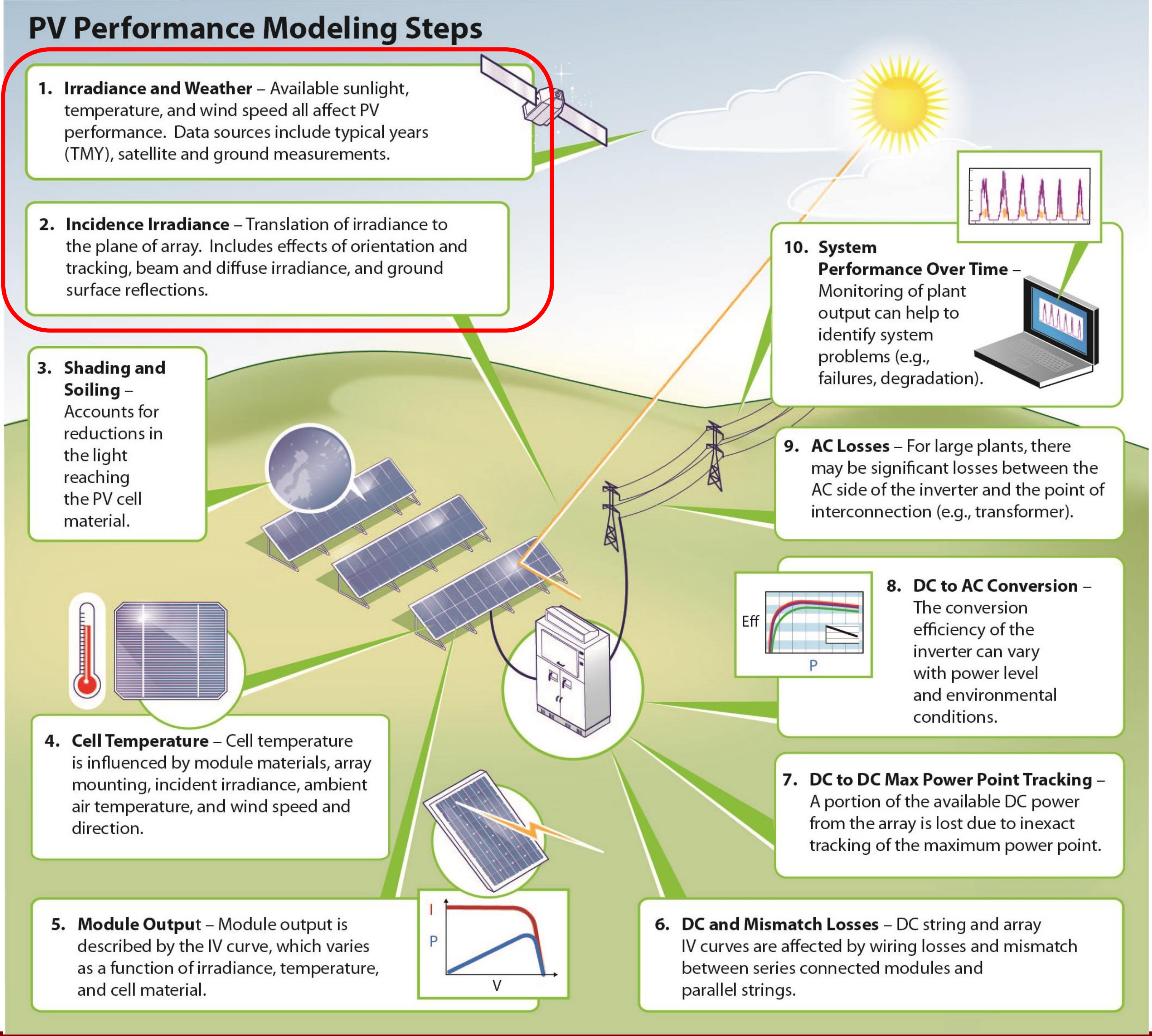
Source: Stein and Green, 2015

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

# Cautions with monitoring data

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

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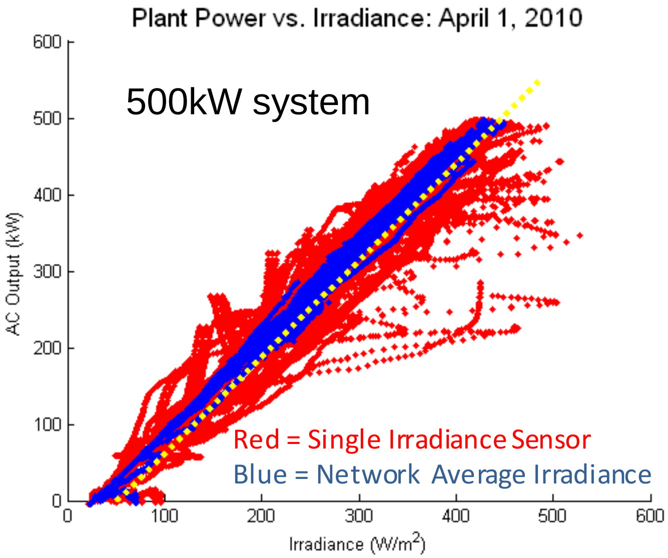
# Spatial Aggregate Irradiance

- To simulate power for a large plant, nearly all models assume uniform irradiance
- Plant power correlates well with spatial average irradiance.
- But we typically have
  - Temporally resolved irradiance (ground measurements) at a few points
  - Spatially averaged data (satellite) at a few times



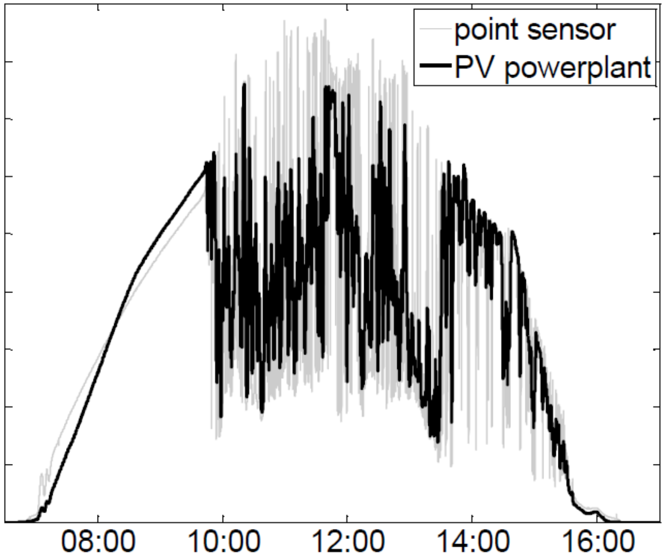

Source: Kuszmaul et al. 2010

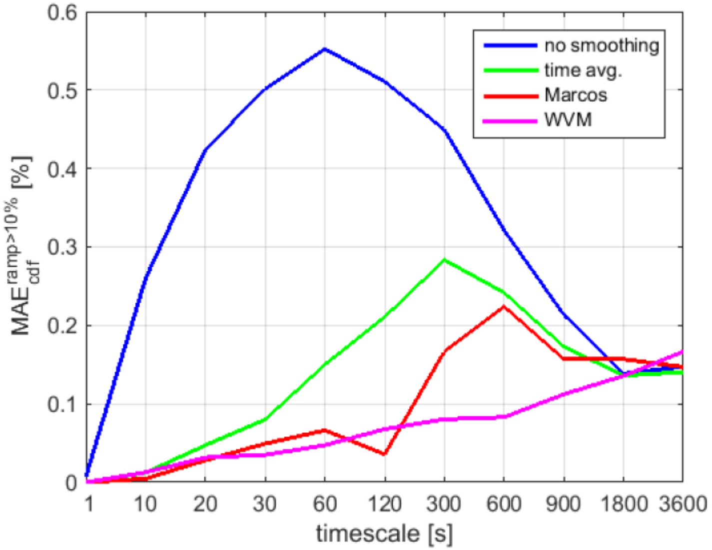
~1 cm$^2$

# Modeling spatio-temporal irradiance

- Interpolate satellite irradiance in time
  - Cloud advection algorithms
- Smooth point measurements over space
  - Power variability < point sensor variability
  - Methods for smoothing
    - Time-averaging
    - Low-pass filtering
    - Wavelet-based smoothing

Analysis of predicted vs. observed ramps in power for a 19MW PV plant



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https://github.com/sandialabs/MATLAB_PV_LIB

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SAM: https://sam.nrel.gov

PVsyst: http://www.pvsyst.com

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