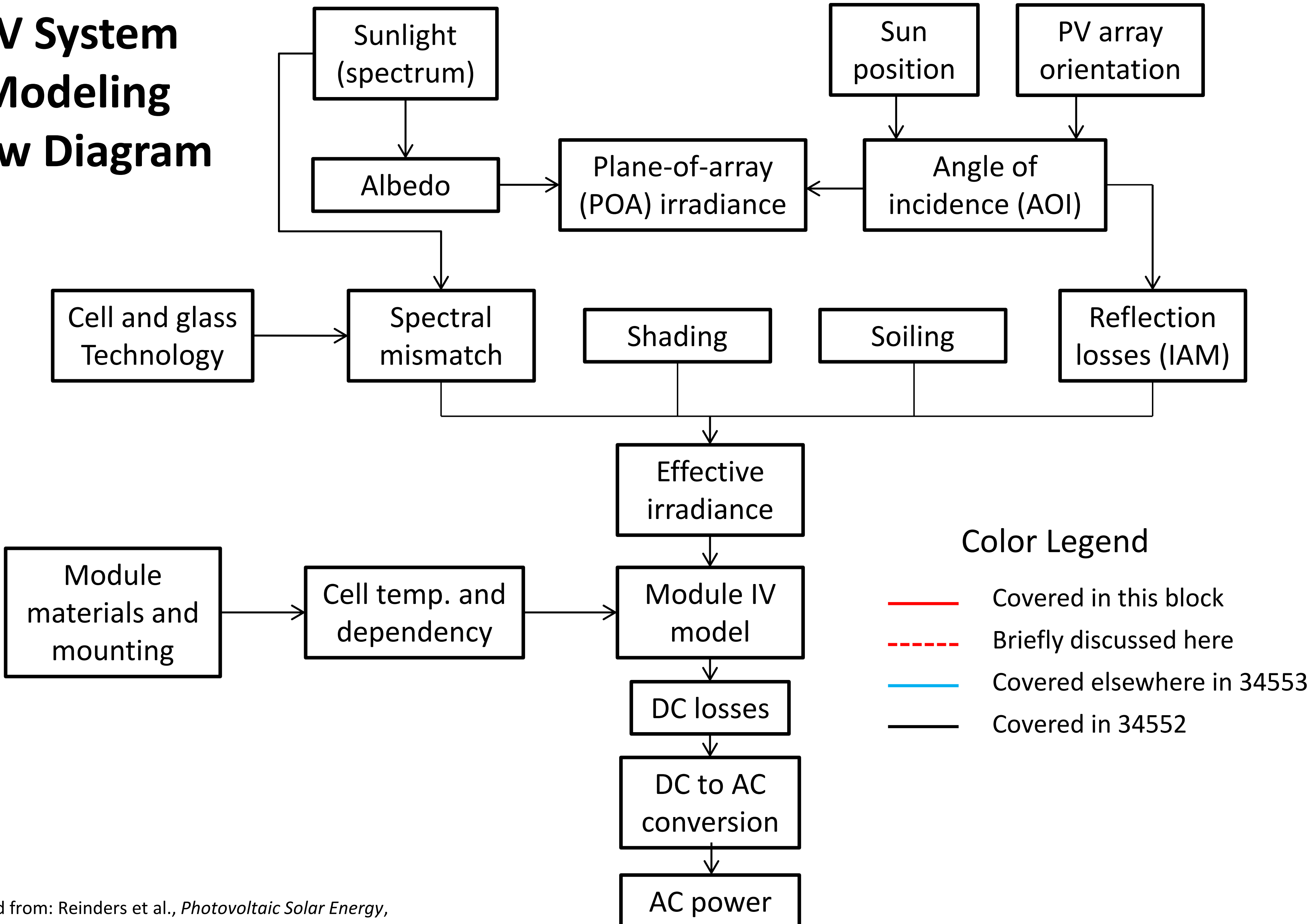
Spectral, Angular and Thermal Dependency on PV Performance

34553: Applied Photovoltaics

Outline

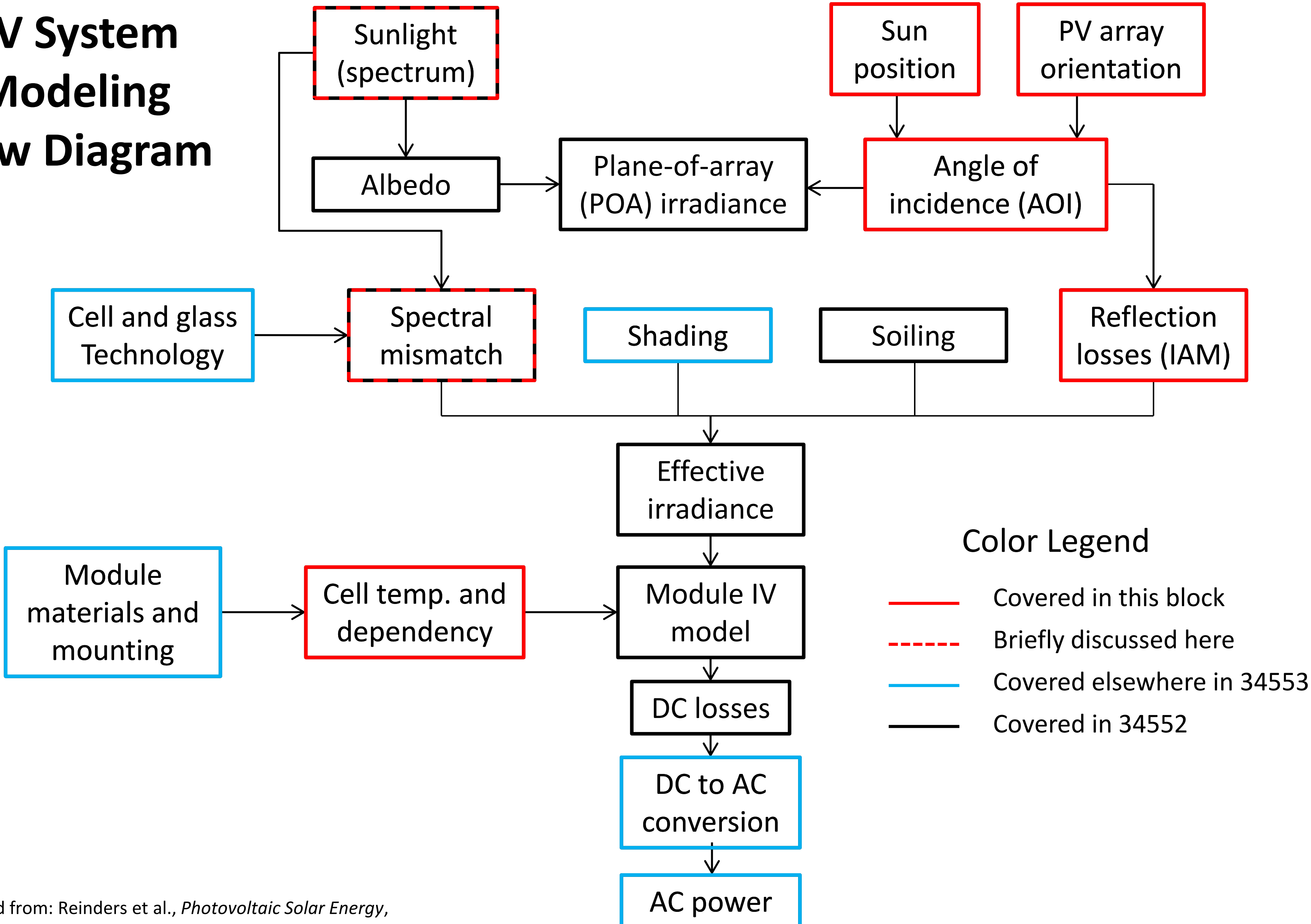
- Environmental variables affecting PV output (DC side) and how to characterize the effect of each.
  1. Solar spectrum
  2. Sun angle of incidence (AOI)
  3. Temperature

PV System Modeling Flow Diagram



Adapted from: Reinders et al., *Photovoltaic Solar Energy*,
Chapter 11.5: Energy Prediction and Modeling

PV System Modeling Flow Diagram



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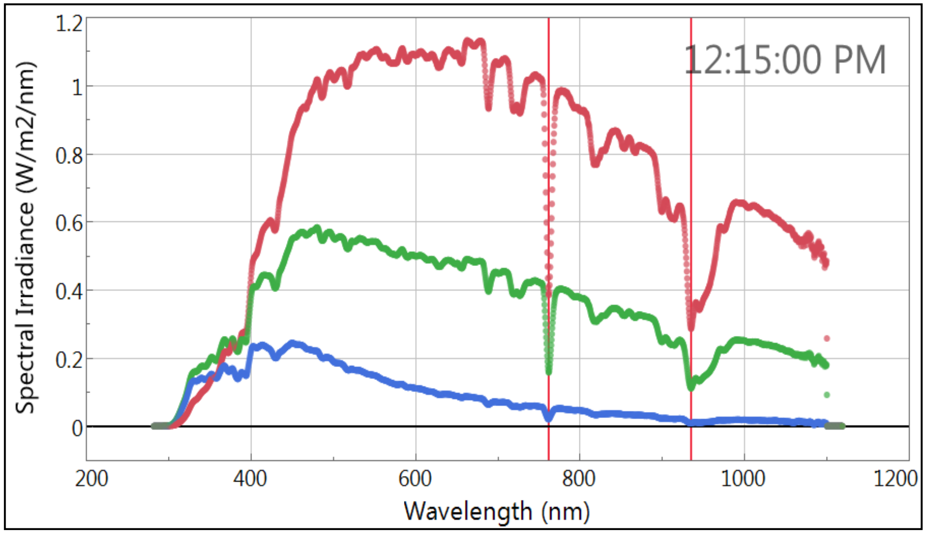
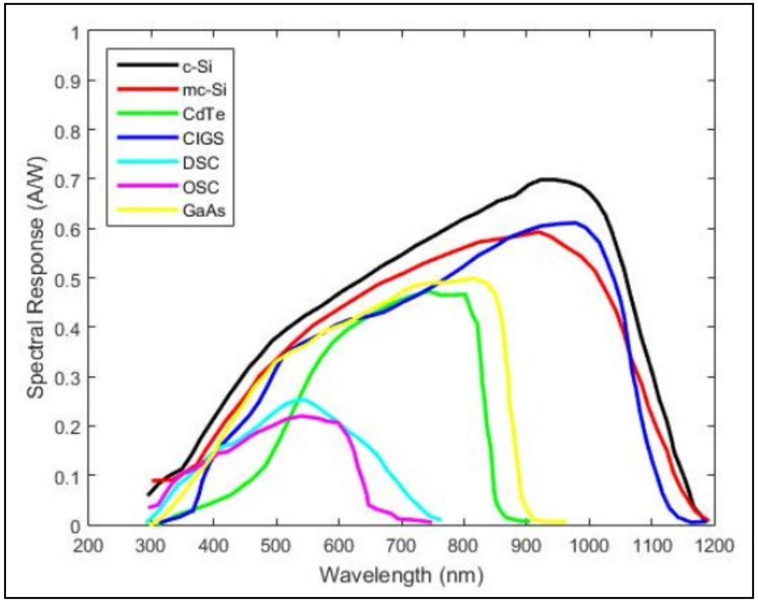
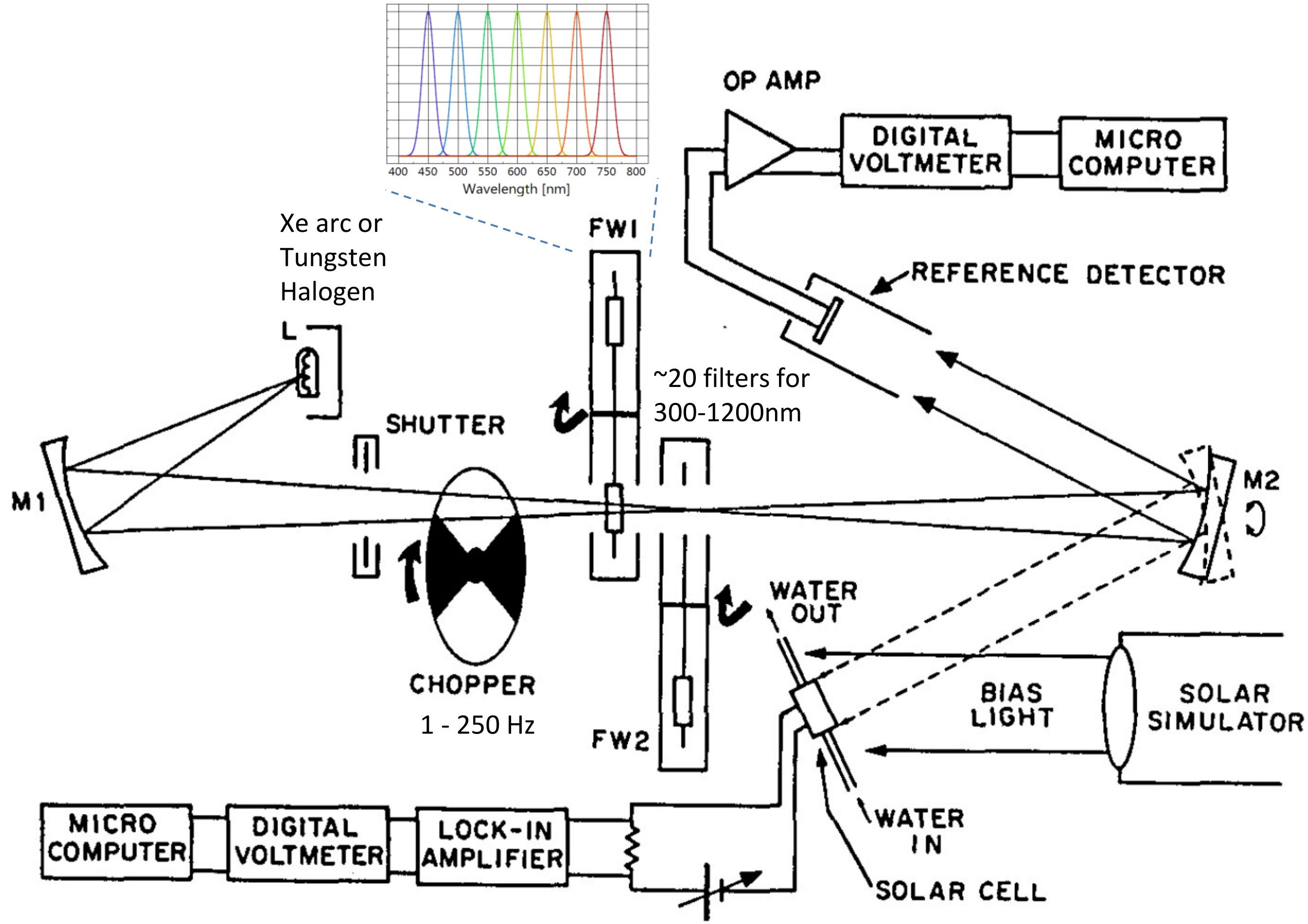
Spectral Impact on PV Performance

- The sun's spectrum changes throughout the day and throughout the year.
- Different PV technologies will respond more/less efficiently at different wavelengths.
  - Based on their spectral response (A/W) or quantum efficiency (%)





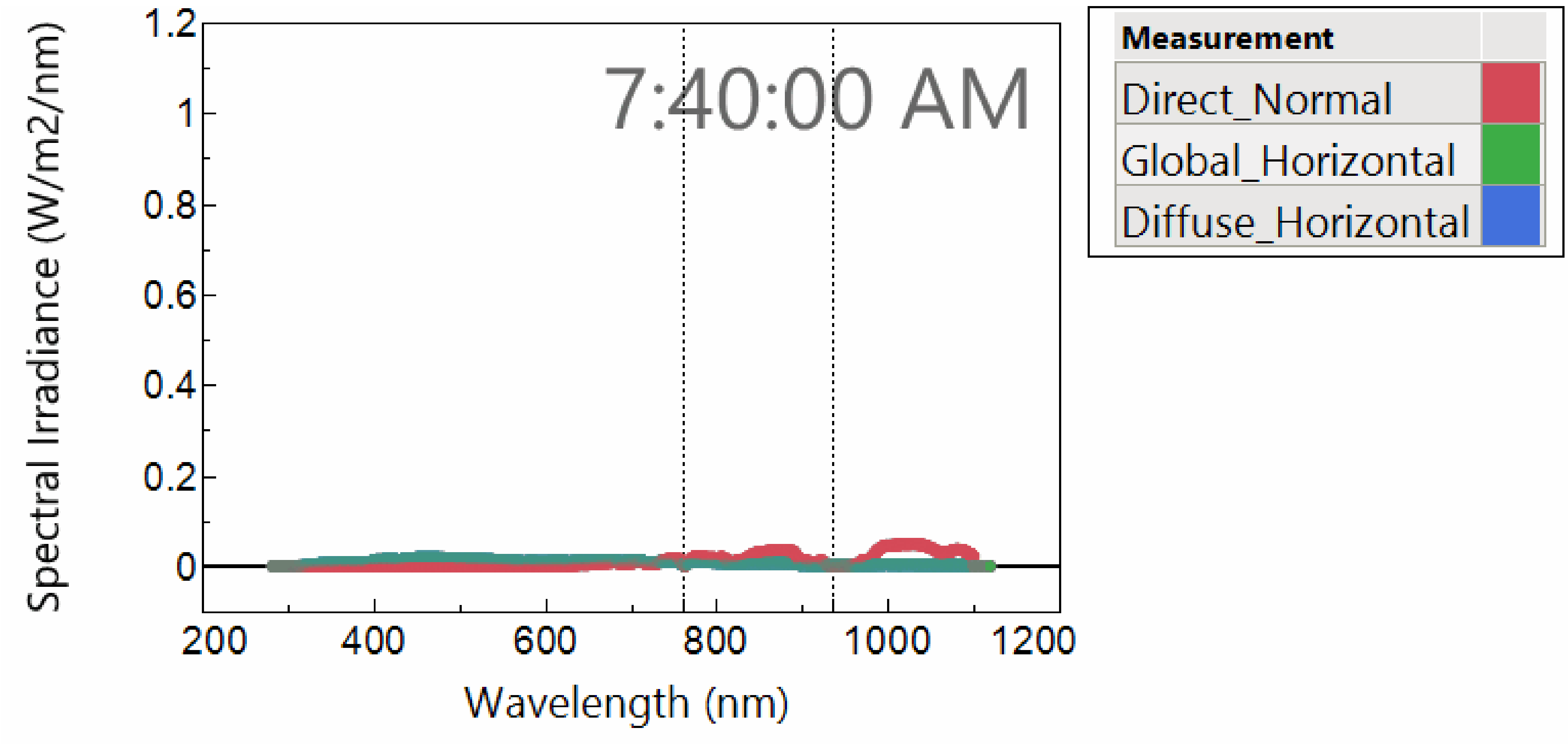
Notes on How to Measure Spectral Response



- We're not measuring spectral response in this class but here's a common approach:
- Create mono-chromatic beams using filter wheels (FW).
- Mechanical chopper and lock-in amp to improve SNR.
- Bias light to prevent low-light performance artifacts.
- Measure Isc of the test cell and reference

L. Philippe Boivin, Wolfgang Budde, C. X. Dodd, and S. R. Das, "Spectral response measurement apparatus for large area solar cells," Appl. Opt. 25, 2715-2719 (1986)
https://www.osapublishing.org/ao/abstract.cfm?uri=ao-25-16-2715

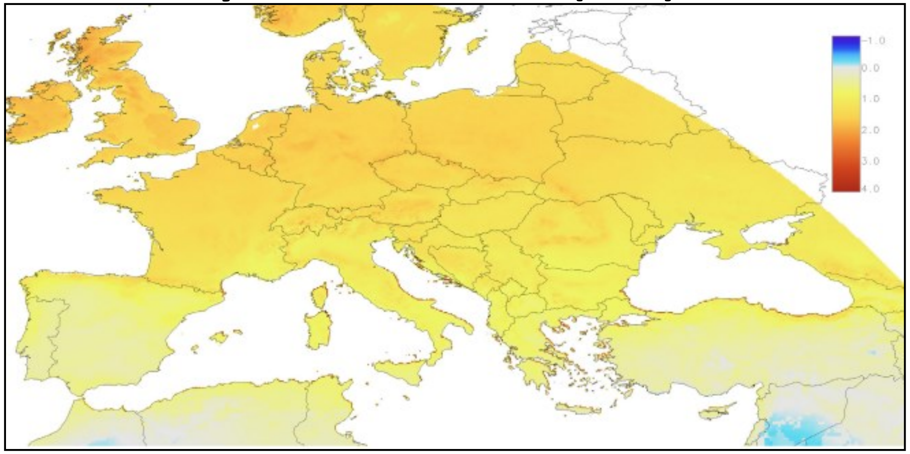
Daily Solar Spectral Irradiance Profiles

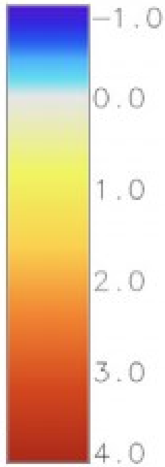


Measured 15 Feb, 2017 at Risø

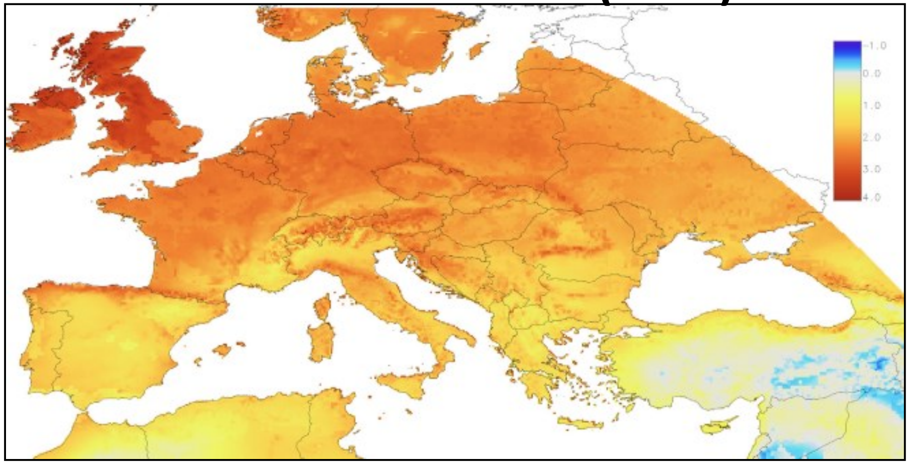
Annual spectral impact (loss/gain) due to spectrum: c-Si vs. CdTe

Crystalline Silicon (c-Si)





Cadmium Telluride (CdTe)



T. Huld et. al, (2016) “Photovoltaic energy rating data sets for Europe”, Solar Energy Vol. 133. pp. 349-362

Outline

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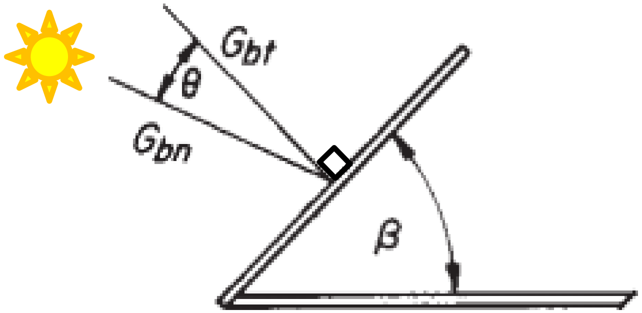
Review of the Angle of Incidence (AOI) Formula

$$\cos\theta = \cos\beta\cos\theta_Z + \sin\beta\sin\theta_Z\cos(\gamma_S - \gamma).$$

Where:
Θ = AOI
β = PV tilt angle
Θ_Z = solar zenith angle
γ_s = solar azimuth angle
γ = PV azimuth angle
Gbt = normal to the PV panel

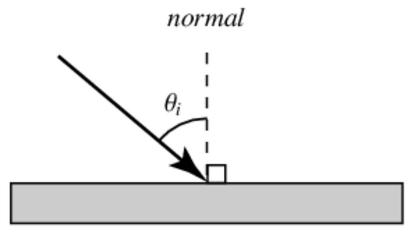


Fixed tilt rack

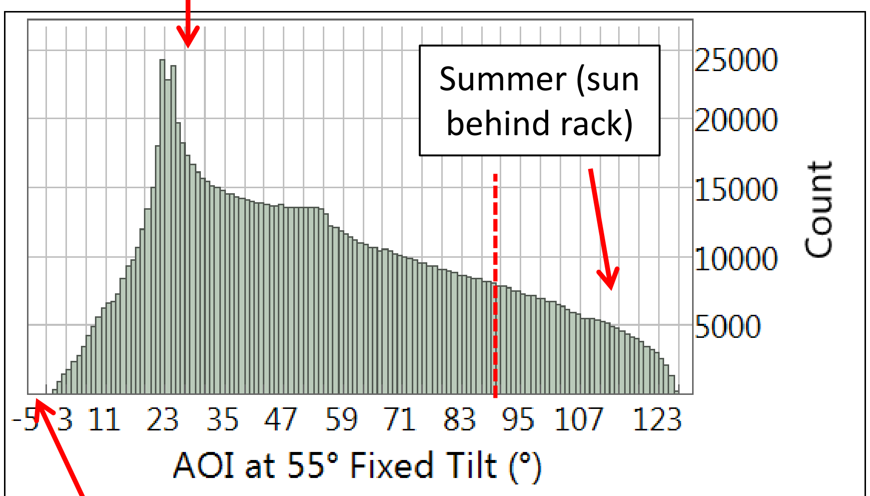
- The equation above describes the sun's angular deviation from the normal to a surface (i.e. PV panel/array).
  - AOI = 0° when sun is normal to the panel

Distribution of Angle of Incidence (AOI)

- The STC measurement is done at normal incidence.
  - Modules in the field are exposed to a wide range of AOIs.
- Distributions below are AOIs observed over 1 yr on 2 fixed tilt systems in Roskilde.

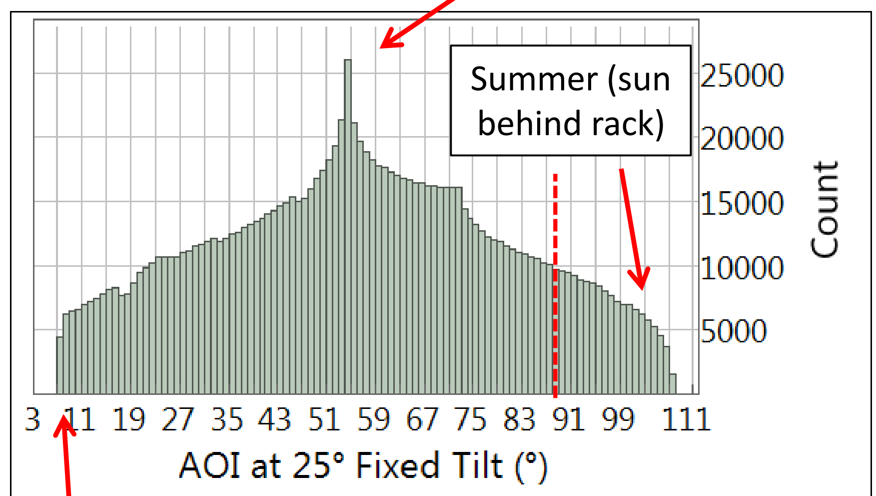


Most frequent AOI = 23°
Mean AOI = 55°



Equinoxes at solar noon ($\theta_Z \approx 55°$, AOI ≈ 0°)

Most frequent AOI = 55°
Mean AOI = 56°



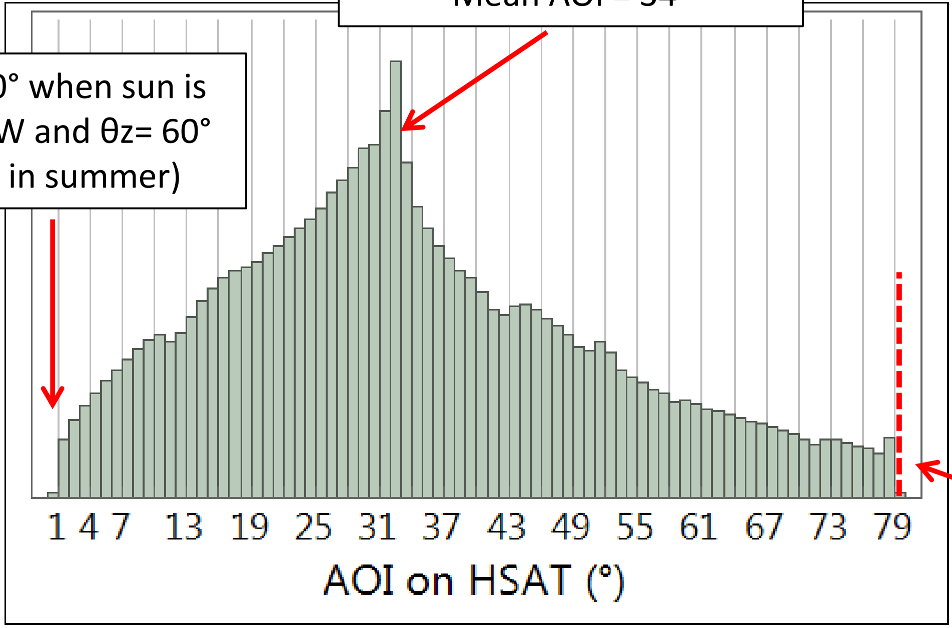
Summer solstice at solar noon ($\theta_Z = 34°$, AOI = 9°)

Distribution of Angle of Incidence (AOI)

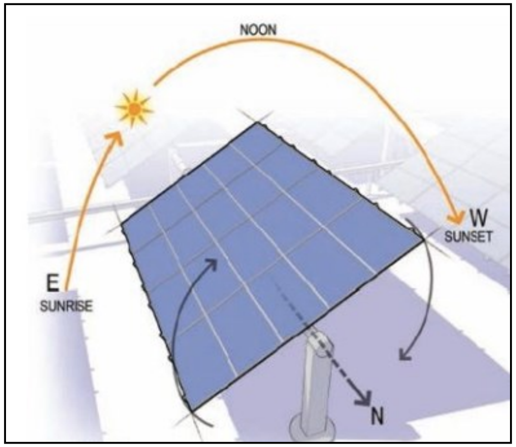
- Modules in the field are exposed to a wide range of AOIs.
  - Unless two axis tracking is used.
  - Single axis tracking reduces the AOI, but not completely.
- Distribution below shows AOIs observed over 1 yr on a horizontal single axis tracker (HSAT) in Roskilde. This tracker is limited to ±60° tilts in the E/W direction.

Most frequent AOI = 31°
Mean AOI = 34°

AOI ≈ 0° when sun is due E/W and θz= 60° (only in summer)

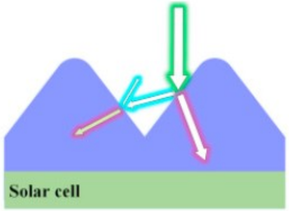


AOI < 80°
(unlike fixed tilt)



List of Effects Caused by Change in AOI

1. Geometrical cosine loss
2. Changing reflectance at the intersection of two media
3. Changing **external** light trapping of pyramidal structures
   – A single photon can intersect multiple times with a front surface
4. Changing **internal** light trapping
   – Includes all inactive and active layers
5. Changing parasitic absorption
   – Absorption in glass, EVA and cell increases with AOI
6. Changing generation profile inside the cell
   – Isc and Jsc are reduced, especially at AOI > 45°



Light trapping of pyramidal structures

N. Reiners, U. Blieske, and S. Siebentritt (2018) "Investigation on the Angle and Spectral Dependency of the IQE and EQE of C-Si cells and modules," *Journal of Photovoltaics*

List of Effects Caused by Change in AOI

1. Geometrical cosine loss
2. Changing reflectance at the intersection of two media

Primary Effects

3. Changing **external** light trapping of pyramidal structures
   - A single photon can intersect multiple times w/ a front/glass surface
4. Changing **internal** light trapping
   - Includes all inactive and active layers
5. Changing parasitic absorption
   - Absorption in glass, EVA and cell increases with AOI

Secondary Effects

6. Changing generation profile inside the cell
   - Isc and Jsc are reduced, especially when AOI > 45°

Result

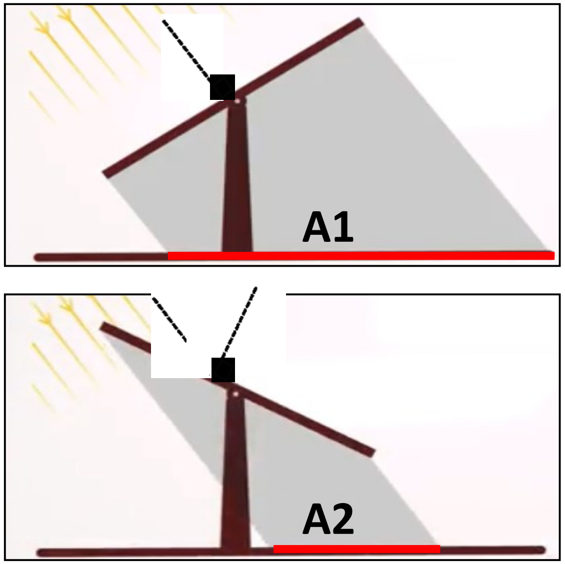
N. Reiners, U. Blieske, and S. Siebentritt (2018) "Investigation on the Angle and Spectral Dependency of the IQE and EQE of C-Si cells and modules," *Journal of Photovoltaics*

The Cosine Law

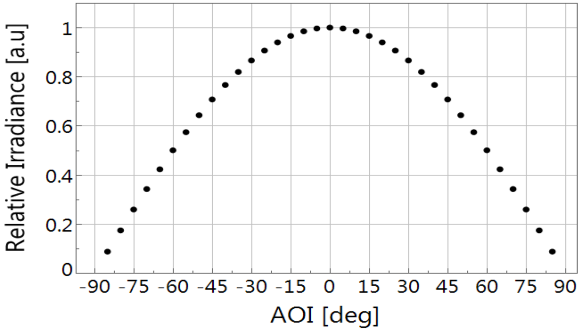
- When a PV device is not positioned normal to the sun, a loss of effective irradiance occurs due to **geometry** and **reflection**.
- Geometrical effect (Lambert Cosine Law)
  - Reduction of irradiance is proportional to cosine(AOI).

Normal Incidence
AOI (θ) = 0°

Non-normal Incidence
AOI (θ) > 0°



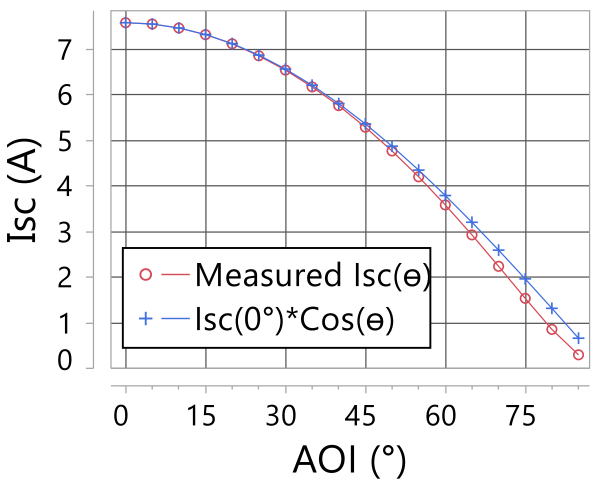
$$A2 = A1 * \cos(\theta)$$



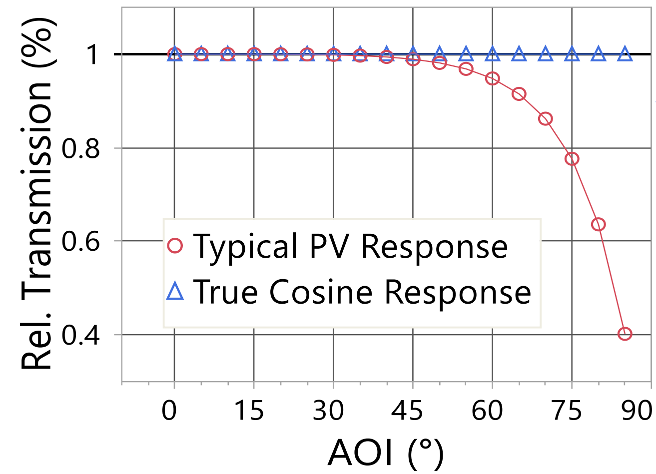
The Incidence Angle Modifier (IAM)

- The IAM normalizes the cosine effect to isolate reflection losses.
- IAM is obtained by measuring short circuit current (I_{SC}) over a range of AOIs (θ).
    - Normalized to the I_{SC} measured at normal incidence (AOI = 0).
    - Indoor and outdoor test procedures are stipulated in IEC 61853-2:2016

$$\mathrm{IAM}(\theta) = \frac{I_{SC}(\theta)}{\cos(\theta) * I_{SC}(0^\circ)} = \frac{\textit{Beam irrad. received by PV Device}}{\textit{Total beam irrad. available to PV Device}}$$



$$\frac{I_{SC}(\theta)}{I_{SC}(0^\circ) * \cos(\theta)}$$

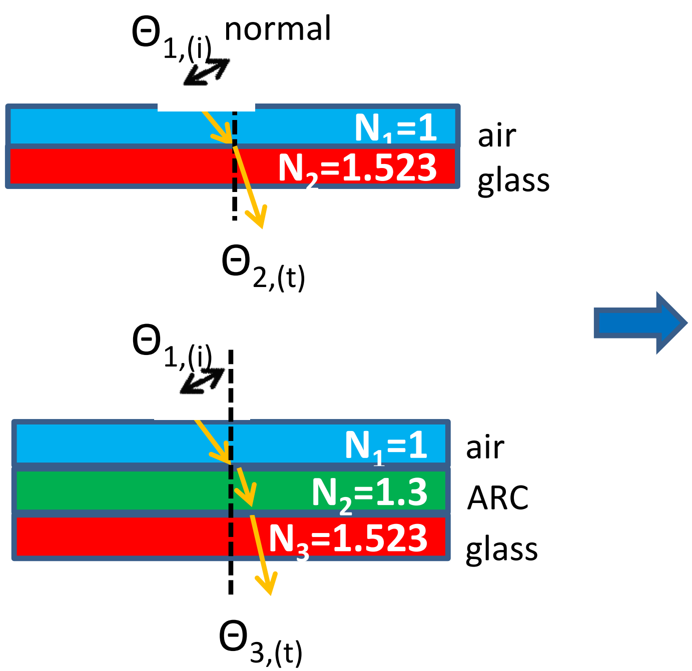


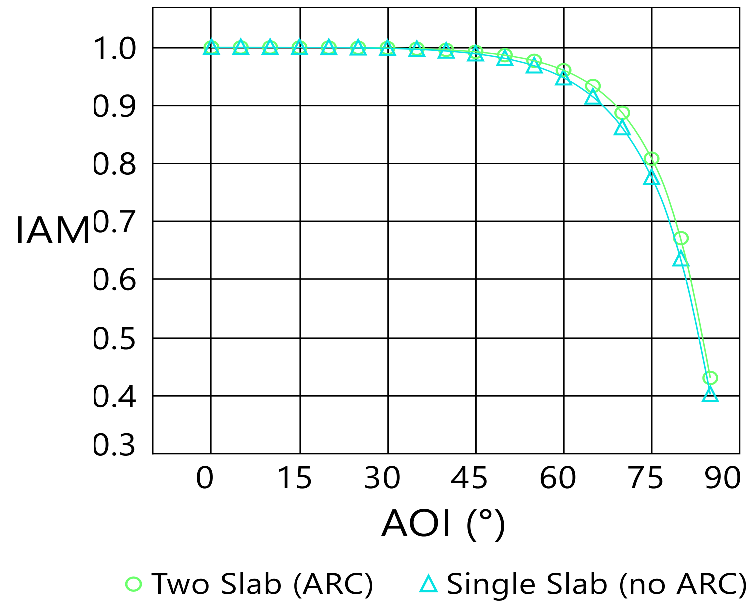
How to Use Theory to Calculate the Incidence Angle Modifier (IAM)

- Reasonable 1st approximation is possible using Snell's law and the Fresnel equations [1].
- For the single slab model (no ARC) w soda-lime glass ***n2* ≈ 1.523.**
- For the two slab model (ARC) ***n2* ≈ 1.3** and ***n3* ≈ 1.523.**
- Unpolarized light (50% p-polarized, 50% s-polarized).

Single slab model
(soda-lime glass w/ no ARC)

Two slab model
(soda-lime glass w/ ARC)



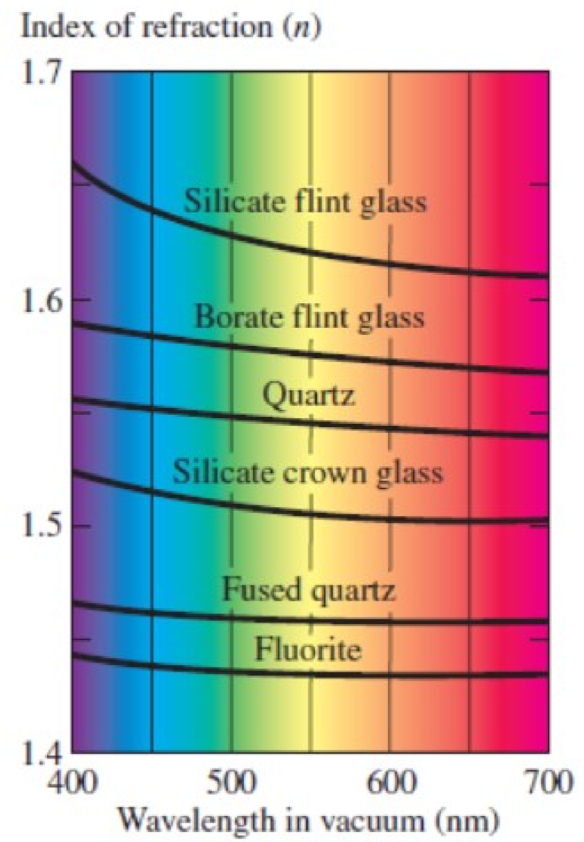


[1] A. Dobos, PV Watts V5 Manual, 2014.

Quantum efficiency (QE) Changes as a Function of AOI

- We're going to use a broadband light source to measure IAM, so we won't observe this effect, but it's good to note that:
  - In transparent materials the refractive index (*n*) decreases with increasing WL.
  - light tends to travel through these materials slower at short WLs (blues) and faster at longer WLs (reds).

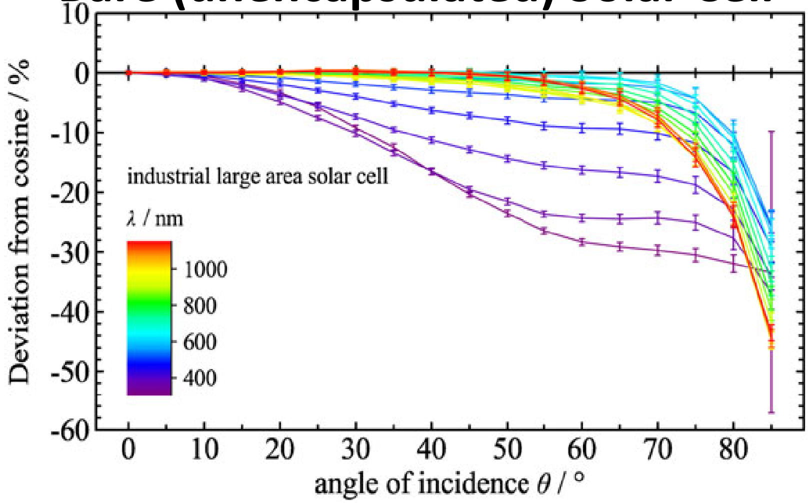
- https://refractiveindex.info/
  - Is a great database for optical properties of many PV materials



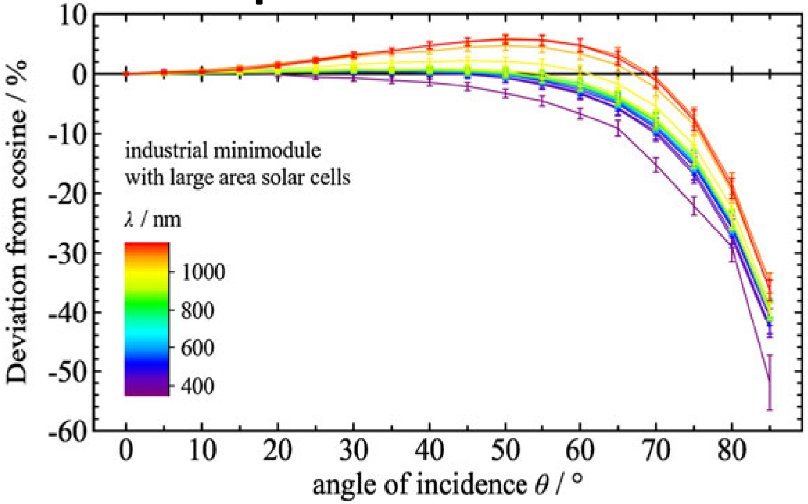
Variation of refractive index with wavelength for a different transparent materials-Source: Young and Freedman 2004

Example Data: External Quantum Efficiency (eQE) as a Function of AOI

Bare (unencapsulated) Solar Cell



Encapsulated Solar Cell



Wavelength dependence of the IAM curve for a bare Si cell (left) and encapsulated Si cell (right)

F. Plag et. al (2017), *Angular-dependent spectral responsivity—Traceable measurements on optical losses in PV devices*, PiP, DOI: 10.1002

The Incidence Angle Modifier (IAM)

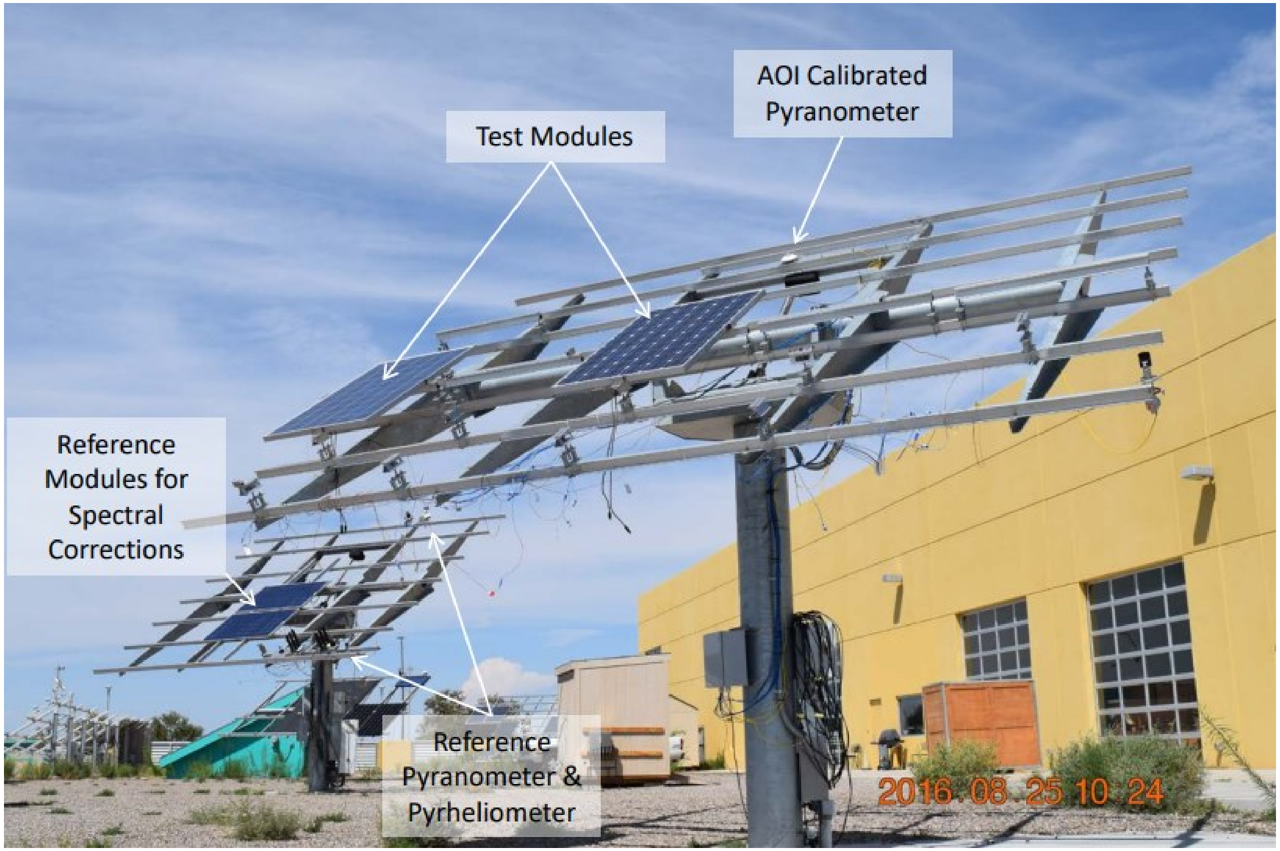
- Anti-reflective coatings (ARC), texturing, or etching can be applied to the glass to increase the amount of light transmitted to the cells.

  - Performance gains of ARCs (smooth) can be approximated using Snell's law and Fresnel equations.
  - Modeling performance gains of texturing (structures) is more complex and requires ray tracing.

  - The transmission/reflection can also be measured in the lab.

^This is what we'll do in this class 34553^

Notes on how to measure IAM Outdoors



- A 2-Axis tracker w/ test modules moves "off sun" to preset AOIs.
- Sun and tracker position are recorded to calculate AOI.
- Isc of test modules is measured at each AOI.
- A 2nd tracker continues tracking the sun with:
  - pyrheliometer for DNI measurement
  - Reference module to account for spectral changes.

D. Zirzow (2018) "Improvements in CFV's Outdoor IAM Measurements" proceedings from the 10th PV Performance Modeling Workshop

Notes on How to Measure IAM Outdoors

$$Diff_{POA}(\theta) = G_{POA}(\theta) - \mathrm{DNI}(\theta) * \cos\theta$$

$$\boldsymbol{IAM(\theta)} = \frac{I_{SC}(\theta) * G_{POA,0} - I_{SC}(0°) * Diff_{POA}(\theta)}{I_{SC}(0°) * \mathrm{DNI}(\theta) * \cos\theta}$$

$$= \frac{Beam\ irrad.received\ by\ PV\ Device}{Total\ beam\ irrad.available\ to\ PV\ Device}$$

Challenges with outdoor IAM measurement

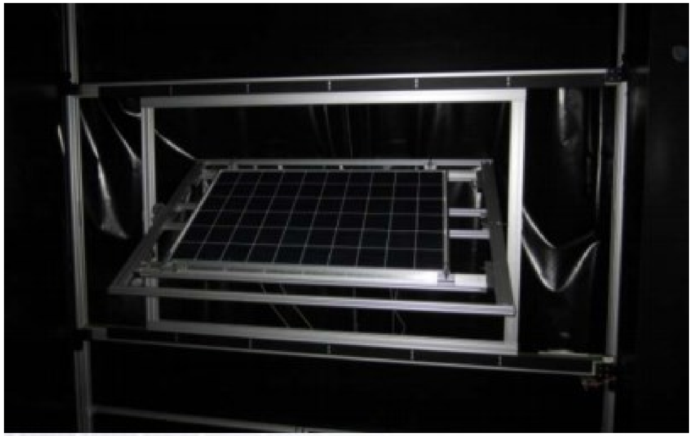
- Specialized trackers and equipment are needed
- Accurately obtaining the diffuse irradiance in POA
- Pyranometer characteristics
  - Non-negligible response time
  - Cosine response -> calibrated at each AOI
- Temperature uniformity of test module
  - Test modules should be in Voc between Isc measurements
- Changing solar spectrum during the test

Q: can you think of advantages/disadvantages to performing the IAM test outdoors?

Notes on How to Measure IAM Indoors

- Same concept as outdoors: measure (I_{SC}) over a range of AOIs (θ).
  - Normalized to the I_{SC} measured at normal incidence (AOI = 0).

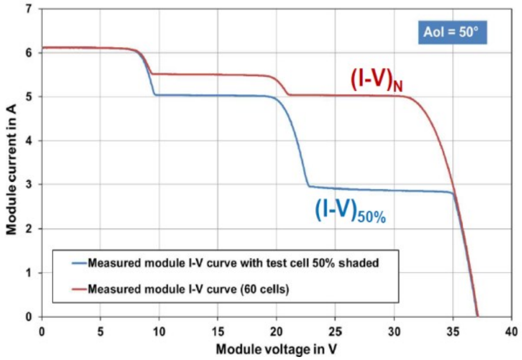
$$\mathrm{IAM}(\theta) = \frac{I_{SC}(\theta)}{\cos(\theta) * I_{SC}(0^\circ)}$$



Indoor IAM measurement at Fraunhofer ISE. The test module is mounted in a pulsed light (Xe arc lamp) solar simulator

Challenges with indoor IAM measurement

- Spatial non-uniformity in the test plane changes significantly when the test module is rotated (beam divergence).
- Therefore, testing must be made using single cell coupons, specially made modules, a destructive method, or specialized methods.



I-V curves with bypass diodes activated due to non-uniform POA irradiance at AOI = 50°

M. Schweiger (2014) "Solar simulator measurement procedures for determination of the angular characteristics of PV modules" 29th EUPVSEC, Amsterdam

Notes on How to Measure IAM Indoors

Approach 1: Manufacture a mini-module

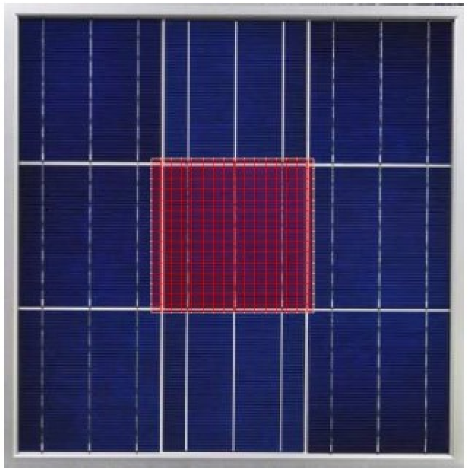
- Identical optical construction as PV module
- Test cell = center cell

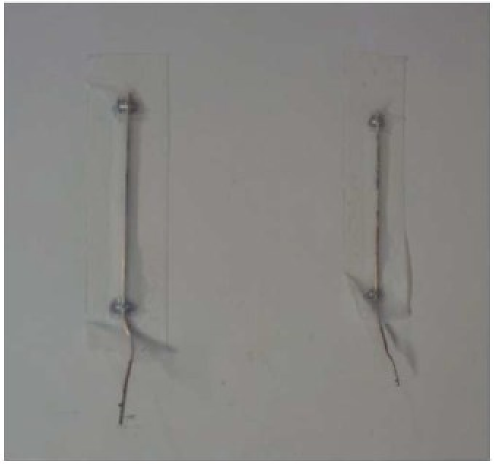
Approach 2: Destructive method

- Standard PV module
- Test cell is contacted through the backsheet

Approach 3: non-destructive method

- Standard PV module
- Isc of test cell is identified from I-V measurements under partial shade





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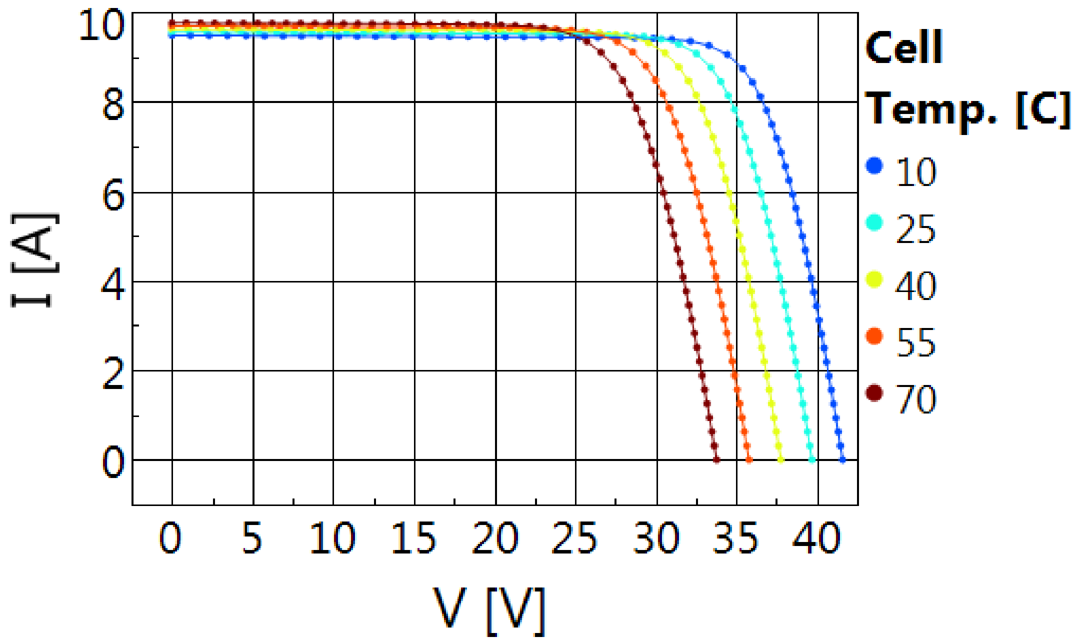
The Effect of Temperature on the I-V Curve

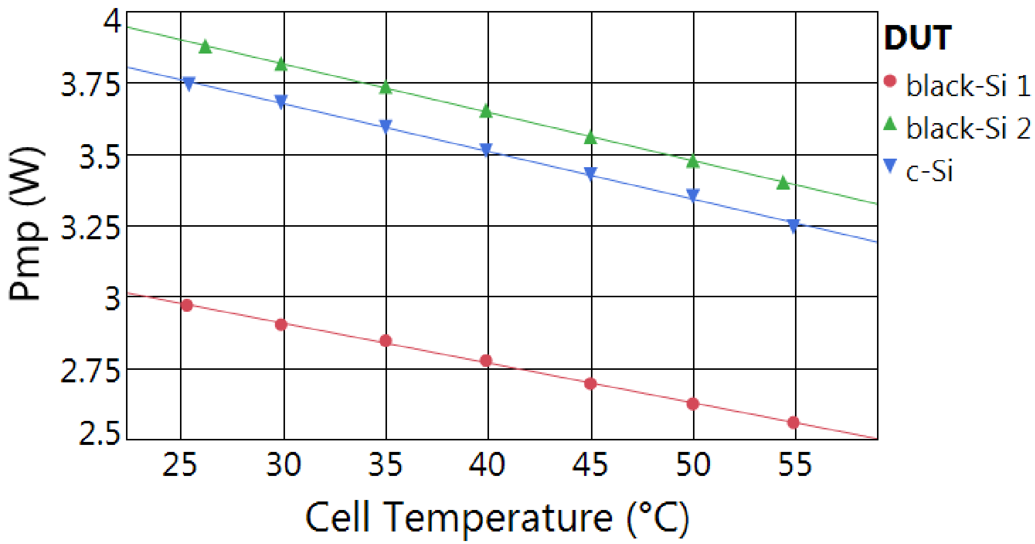


$$I_0 = qA\left(\frac{D_n}{L_n}\frac{\boxed{n_i^2}}{N_A} + \frac{D_p}{L_p}\frac{\boxed{n_i^2}}{N_D}\right)$$

- Voc, Vmp and Pmp *decrease* with increasing temperature.
  - High intrinsic carrier concentration (n_i)-> higher saturation current (I_o)-> lower Voc.

- Isc *increases* with increasing temperature
  - Due to decreased bandgap energy at higher temperature

Typical Regressions and Temperature Coefficients for c-Si PV Modules in 2019



Graph Source: personal measurements of 3 different c-Si cells

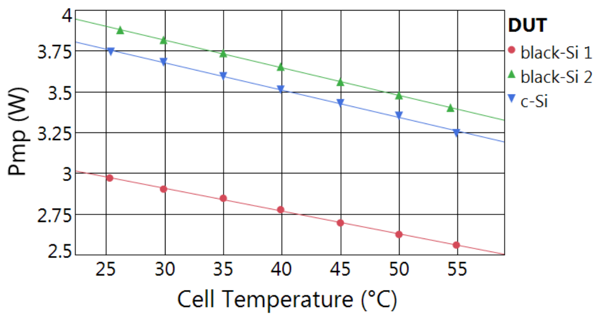
I-V Point	Temp. Coeff. [%/°C]	Symbol
Isc	0.04	α
Imp	-0.02	-
Pmp	-0.42	γ
Vmp	-0.40	-
Voc	-0.30	β

Table Source: personal survey of module data sheets

How to Measure a Temperature Coefficient

- Temperature coefficients describe the relative change in I-V characteristics as a function of cell temperature.

- Coefficients are commonly determined by linear regression of measured module output (Isc, Voc, Pmp) at a fixed irradiance and varying temperatures.
  - Can be reported in percentage (%/°C) or absolute (e.g. V/°C).



$$y = mx + b$$

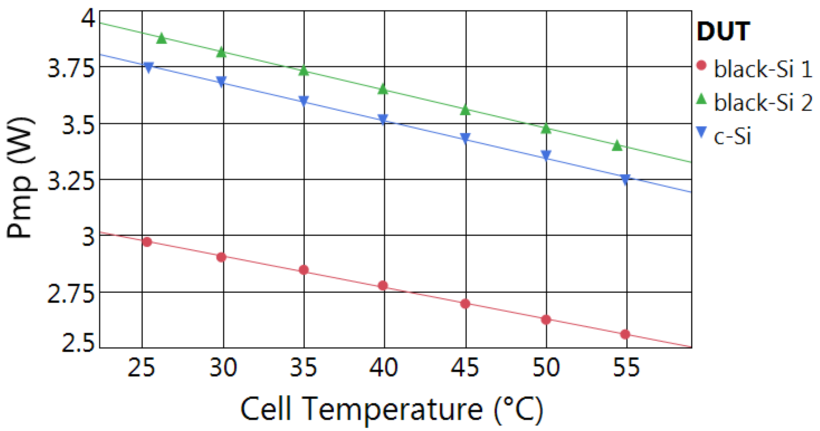
$$m = \gamma = {}^{W}/_{°\mathrm{C}}$$

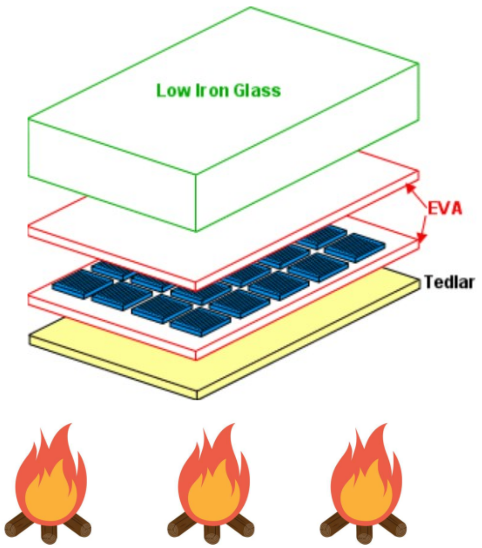
$$\beta = {}^{V}/_{°\mathrm{C}}$$

$$\alpha = {}^{A}/_{°\mathrm{C}}$$

- Coefficients expressed as %/°C can be determined by dividing the value of α, β, and γ by the values of current, voltage and peak power at 25 °C, respectively.

How to Measure a Temperature Coefficient

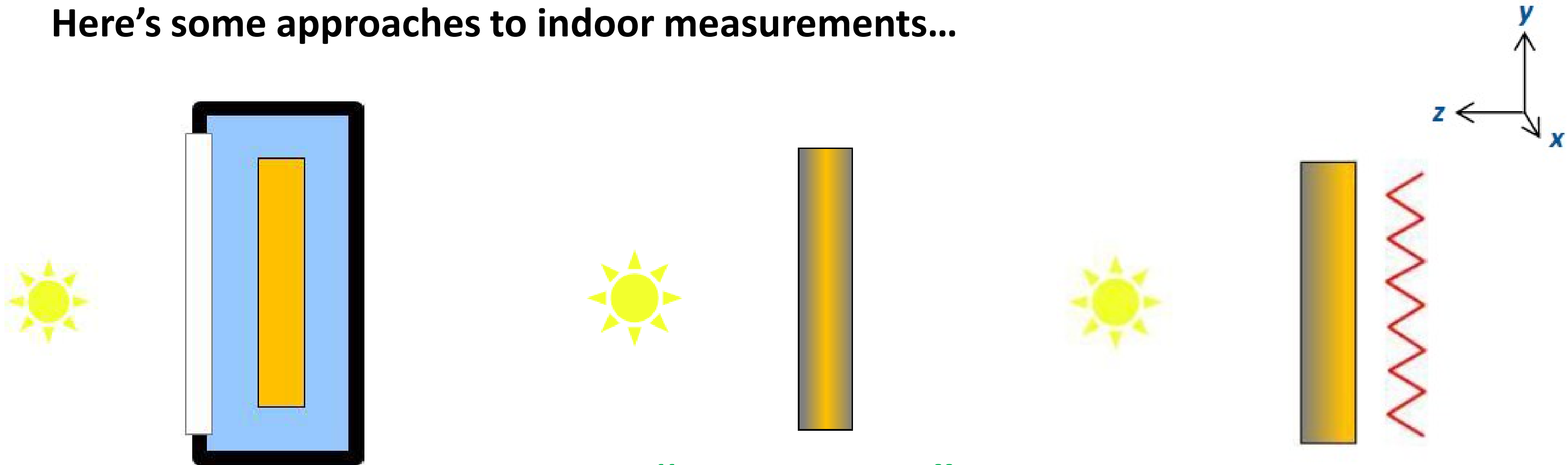




Q: Can you think of experimental methods to measure the temperature coefficients of a PV module?

How to Measure a Temperature Coefficient

Here's some approaches to indoor measurements…



"Oven" Method

- Module heated on all sides by laminar flow of hot air.
- Uniform module temperature is possible.
- Isothermal environment.

"Hot Potato" Method

- Module heated in a chamber -> placed in ambient.
- Susceptible to non uniform module temperature.
- Non-steady state.

"Toaster" Method

- Constant heat source applied to backside
- Uniform x-y profile possible
- Non-uniform thermal profile in z direction

M. Joshi (2014) "Toward Reliable Module Temperature Measurements: Considerations for Indoor Performance Testing" proceedings from the 3rd PV Performance Modeling Workshop

I-V Curve Correction Equations: Irradiance

- Recall that the I-V curve changes w.r.t irradiance
- You will not observe the same irradiance for all I-V measurements during a temperature coefficient test!
- Therefore, you should correct the measured current to a common condition of 1000 W/m^2

$$I_{corr} = I_{meas} * \frac{1000\ W/m^2}{G_{meas}}$$

Where:

I_{corr} = The current corrected to 1000W/m^2 (A)

I_{meas} = The measured PV current (A)

G_{meas} = The measured solar radiation in plane of array (W/m^2)

I-V Curve Correction Equations: Temperature

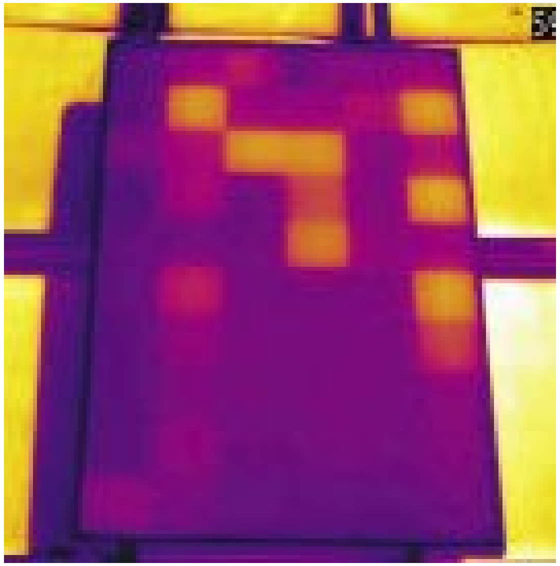
- The temperature of the reference cell (irradiance monitor) will not stay stable during the test
- This device has a temperature coefficient, which should be accounted for.

$$I_{SC,corr} = I_{SC,meas} * \{1 + \alpha * (25°C - T_{meas})\}$$

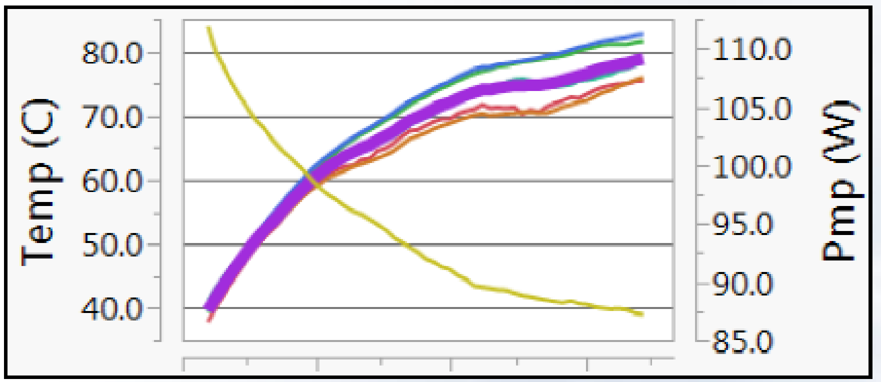
Where:
$I_{SC,corr}$ = The Isc corrected to 25C (A)
$I_{SC,meas}$ = The measured Isc of the reference device (A)
T_{meas} = The measured reference cell temperature (°C)
α = The Isc temperature coefficient for the reference device

Measurement of Tcell. Easy, right?

- $T_{backsheet}$ is typically measured, but there is an inherent difference between T_{cell} and $T_{backsheet}$
- When module temperature is non-uniform, you will get a different temperature coefficient depending on which T_{cell} you use.
- It is best to **average** the T_{cell} measurements
  - More temperature measurements can improve accuracy, but not always practical

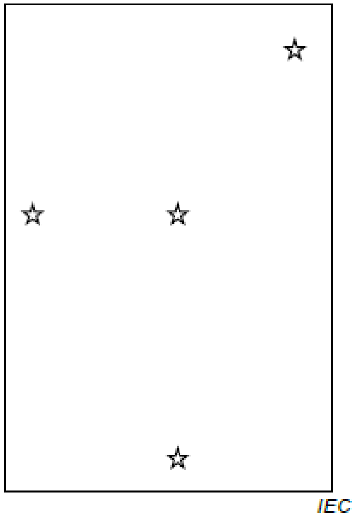


IR image of PV module with temperature mismatch between cells



Sensor	ßVmp (%/C)
BS average	-0.48
TC1	-0.52
TC2	-0.42
TC3	-0.42
TC4	-0.55
TC5	-0.49

Where to Place the Temperature Sensors?

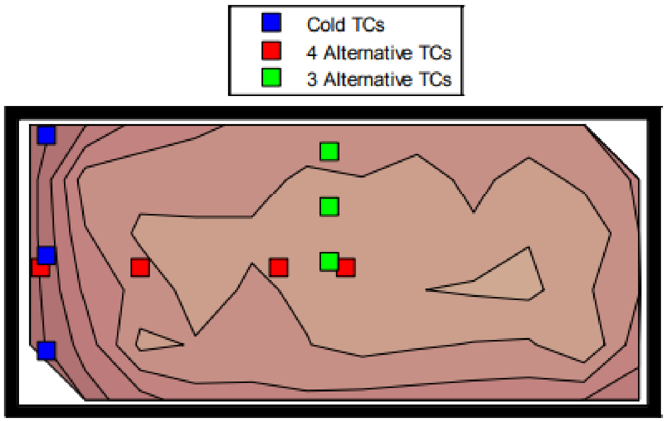


IEC 60891 recommended positions to place temperature sensors behind PV module.

Where to place TC/RTDs?

Which pattern gives an accurate avg. module temp.?

Sandia Labs tried to answer these questions by measuring temperature coefficients on a 72 cell module with 36 TCs on it!



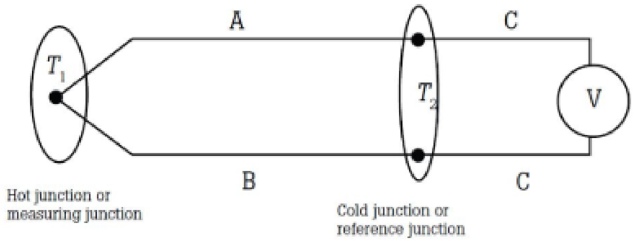
Sandia proposed to place temperature sensors in the 3 locations as shown above in **green**.

The **blue** tend to under predict and the **red** over predict module temp.

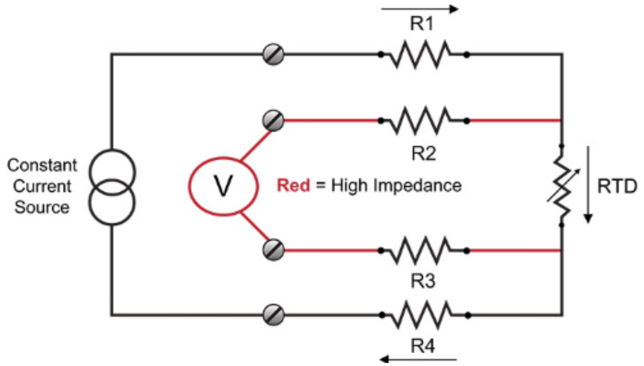
C. Hansen, M. Farr, and L. Pratt "Correcting Bias in Measured Module Temperature Coefficients" proceedings of the 40th IEEE PVSC conference (2014)

Which Type of Temperature Sensor to Use?

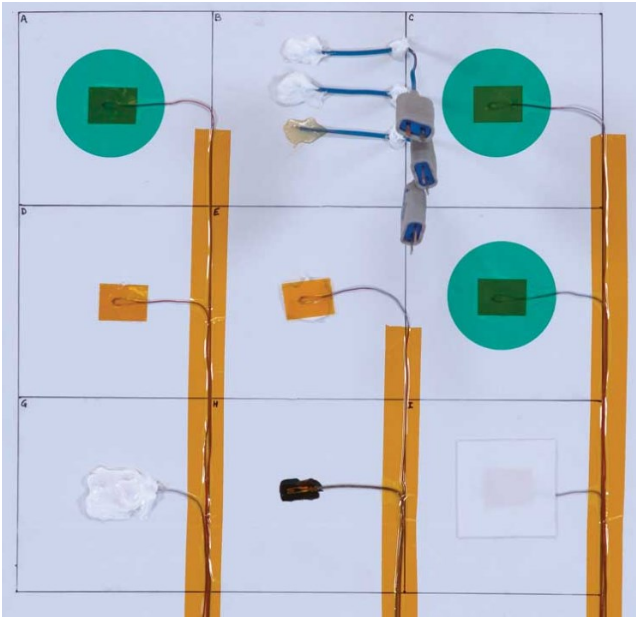
- Selection of temperature sensor and application of sensor to surface are important!
  - TC vs. RTD vs. thermistor
  - Bare-weld vs. Pad-type.
  - Kapton tape vs. Thermal paste vs. probe



Thermocouple (TC) schematic



Resistive temperature device (RTD) schematic



Back of module temperature study (NREL)

GOOD THERMAL CONTACT is necessary regardless of which sensor type is used

Further Reading: Back-of-Module Temperature Measurement Methods by R. Smith, S. Kurtz and B. Sekulic

Relationships between $T_{backsheet}$ and T_{cell}

- $T_{backsheet}$ is typically measured, but there is an inherent difference between T_{cell} and $T_{backsheet}$
  - ΔT Dependent on material construction.
  - The correction is larger at higher irradiance.
  - Relationships only valid for outdoor testing.

$$T_{cell} = T_{BS} + \frac{G_{POA}}{1000} * \Delta T$$

Module Type	Mount	ΔT (°C)
Glass/cell/glass	Open rack	3
Glass/cell/glass	Closed roof mount	1
Glass/cell/polymer backsheet	Open rack	3
Glass/cell/polymer backsheet	Insulated back	0
Polymer/thin-film/steel	Open rack	3

https://energy.sandia.gov/wp-content/gallery/uploads/043535.pdf

Summary

- Environmental variables affecting PV output (DC side) and how to characterize the effect of each.
  1. Solar spectrum
  2. Sun angle of incidence (AOI)
  3. Temperature