



Improving Photovoltaic System Modeling with High-Accuracy Measurement of the Incidence Angle Modifier

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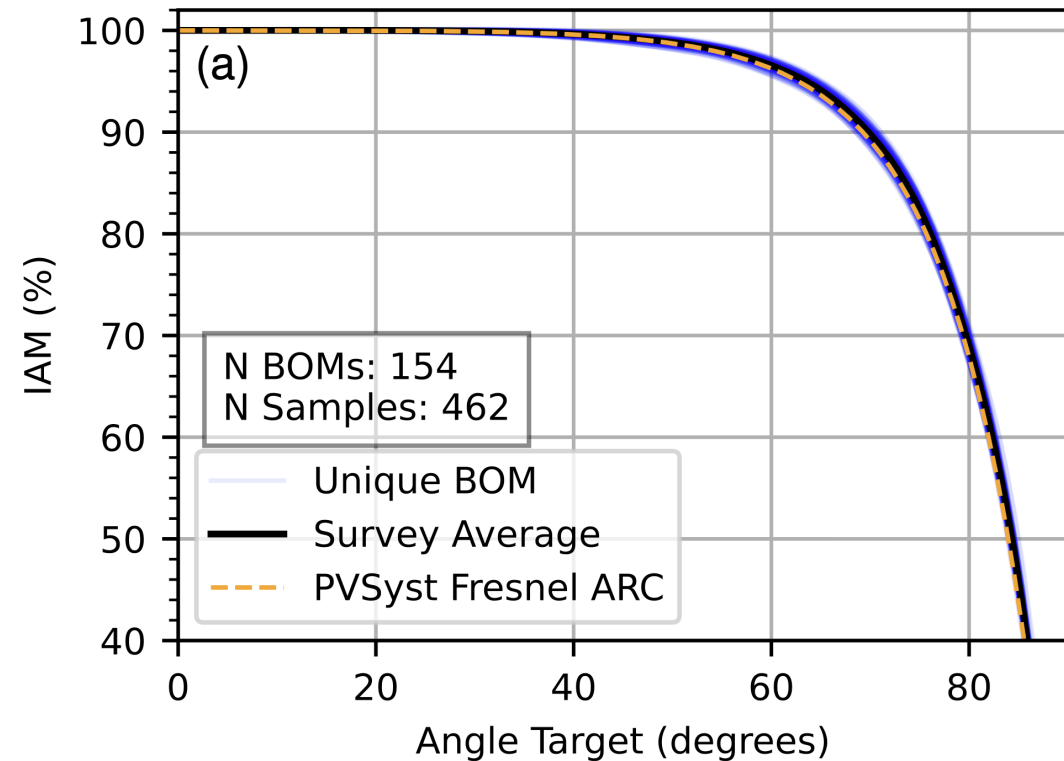
Services at a glance:

- Extended reliability and performance testing for PV modules
- Batch testing of PV modules
- Outdoor testing of PV modules, inverters and energy storage
- Data services for PV buyers and investors

See more details at kiwa.com/pvel

Outline

- Introduction
- Kiwa PVEL's solution
 - Uncertainty budget
 - Advantages
- Results
 - IAM of >400 modules
- Energy Yield
- Optical Model
- Issues

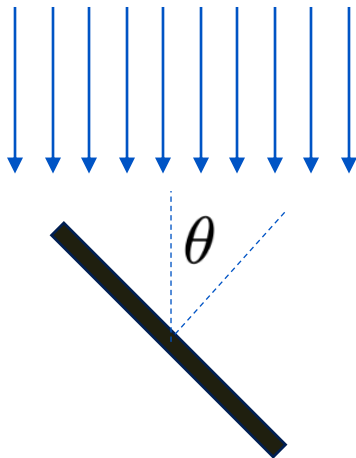


What is IAM?

IAM is deviation of module response from that of a perfect absorber.

Perfect Absorber

$$\text{Absorption} = E \cos(\theta)$$

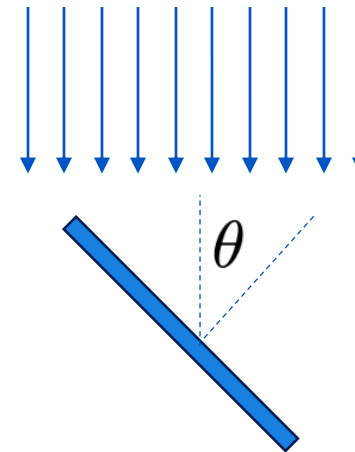


PV Device

$$\text{Absorption} = E \cos(\theta) \text{IAM}(\theta)$$

$$\text{IAM}_{E(\lambda)}(\theta, \phi) \equiv \frac{I_{\text{sc}}(\theta, \phi)}{I_{\text{sc}}(0, 0) \cos(\theta)} \frac{1}{\eta(I_L)}$$

Spectrum
specific!

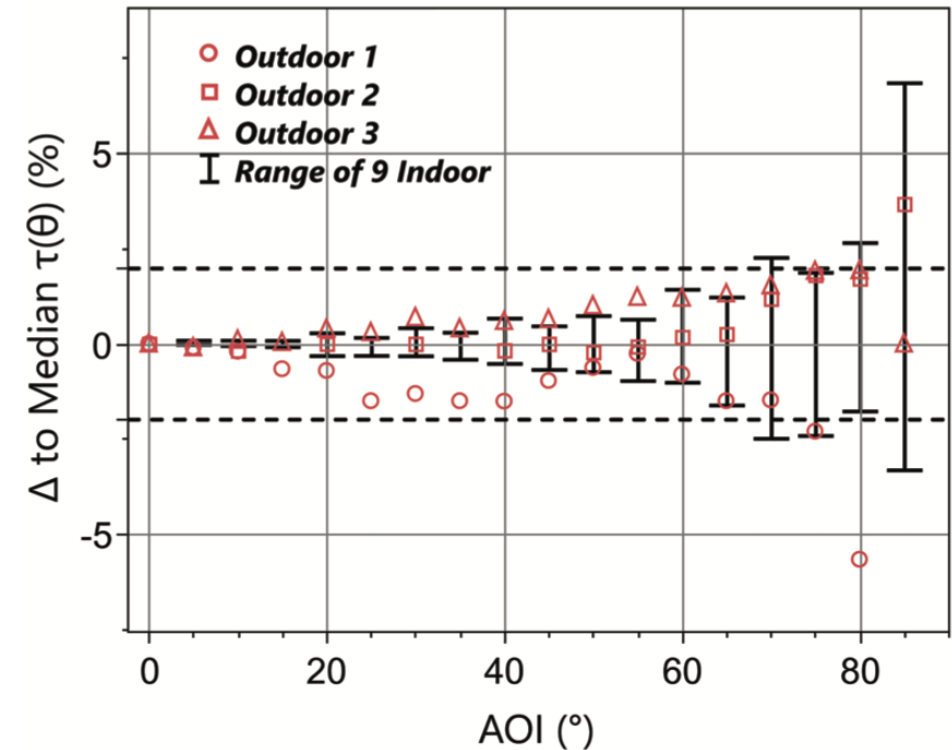


(non-linearity
correction
based on
photocurrent)

Prior Work: IAM measurements are notoriously difficult

- Range at 60 degrees is 3%!
- **IAM variability** measured at different laboratories is responsible for **1.0%-1.5% error in energy yield**.
- Variability has real-world financial consequences

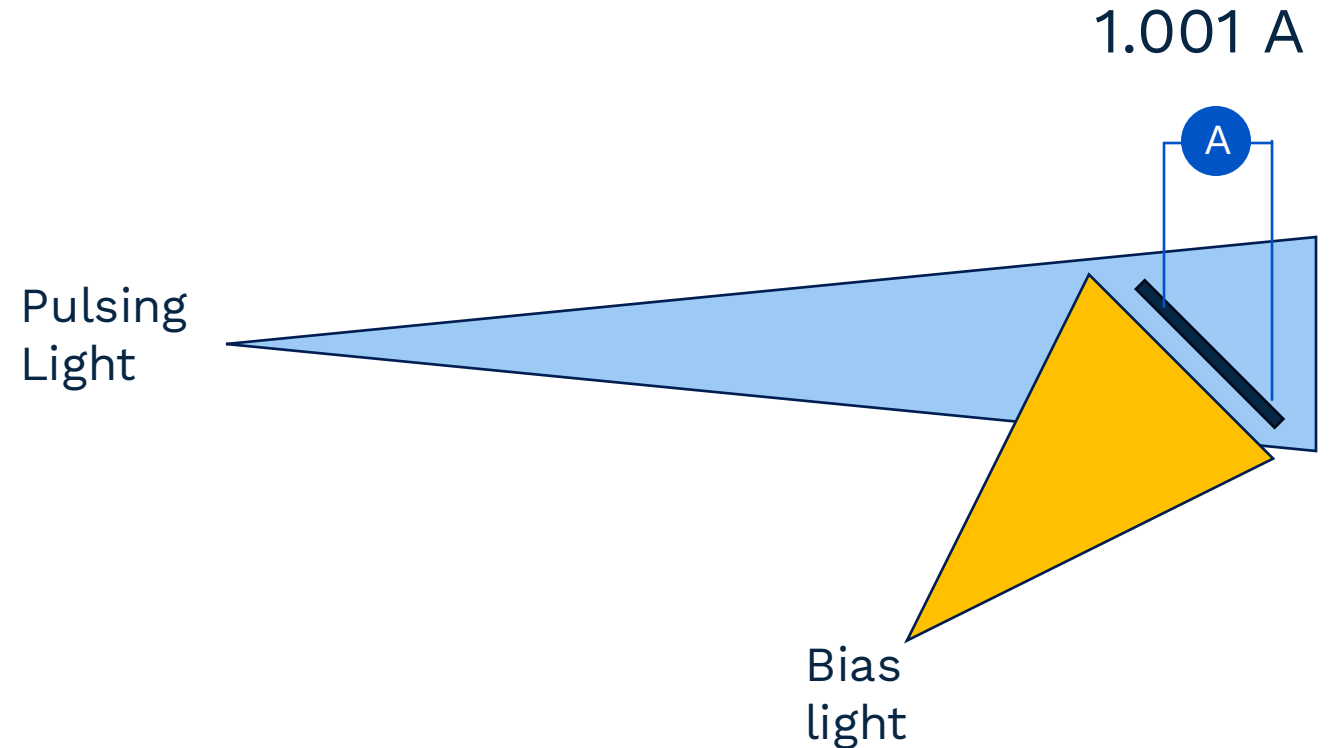
Goal: improve the accuracy of the IAM test



Riedel et. al. Progress in PV (2020) doi.org/10.1002/pip.3365

Differential Responsivity

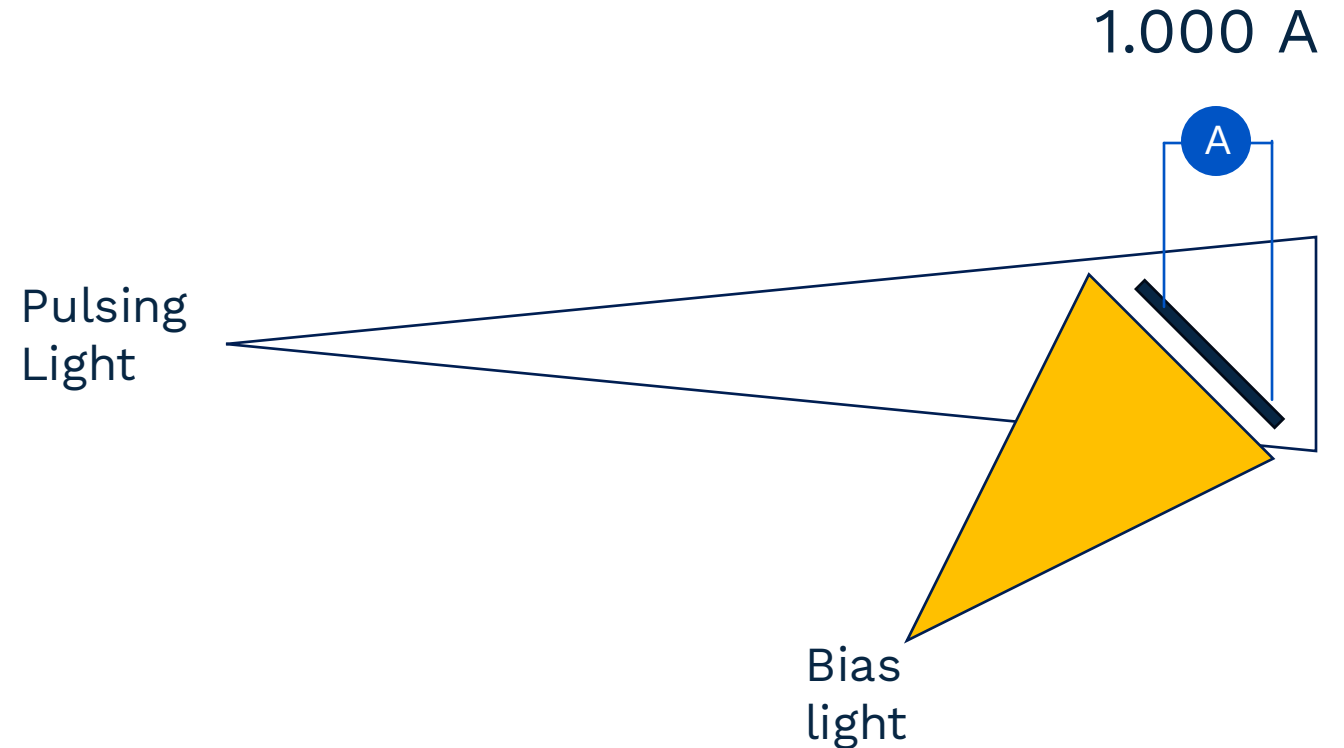
- Responsivity = Current out / Optical Power In
- **Differential Responsivity**: change in I_{sc} per change in irradiance.
- Established technique, but not commonly used for IAM.



$$\tilde{s}(\theta) \propto \frac{I_{SC}(\theta, \text{Pulse On}) - I_{SC}(\theta, \text{Pulse Off})}{E_{Ref}(\text{Pulse On}) - E_{Ref}(\text{Pulse Off})}$$

Differential Responsivity

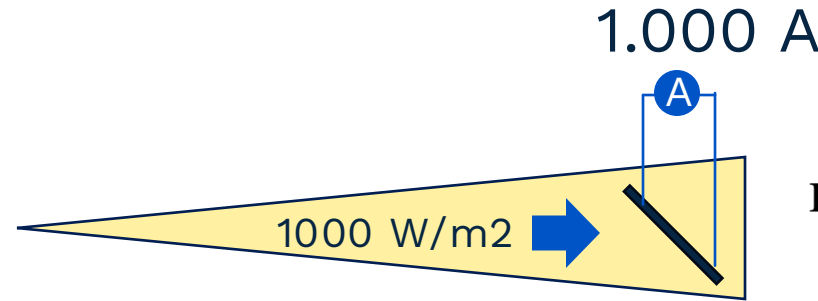
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Advantage of differential responsivity

Standard IAM using a 1 sun beam measurements: at higher angles, the photocurrent is lower, so find that the IAM includes a non-linearity term.

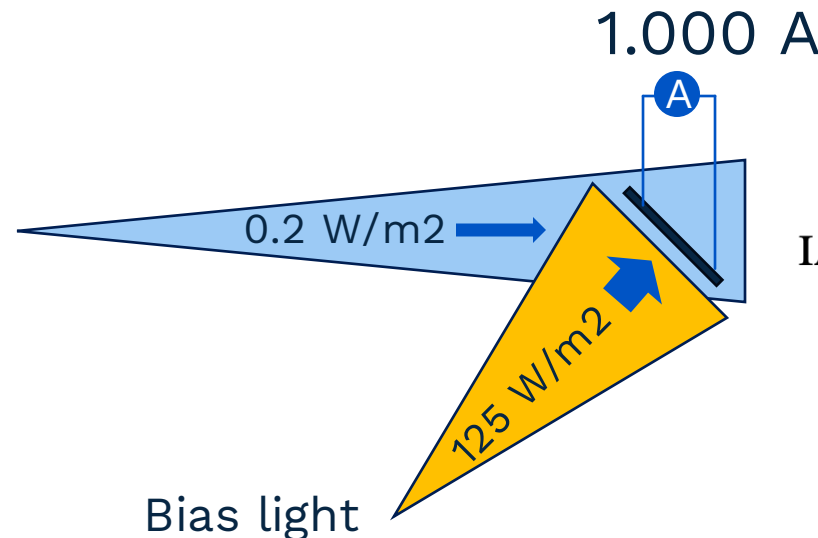


$$\text{IAM}_{E(\lambda)}(\theta, \phi) \equiv \frac{I_{\text{sc}}(\theta, \phi)}{I_{\text{sc}}(\theta = 0, \phi) \cos(\theta)} \frac{1}{\eta(I_L)}$$

On standard modules,

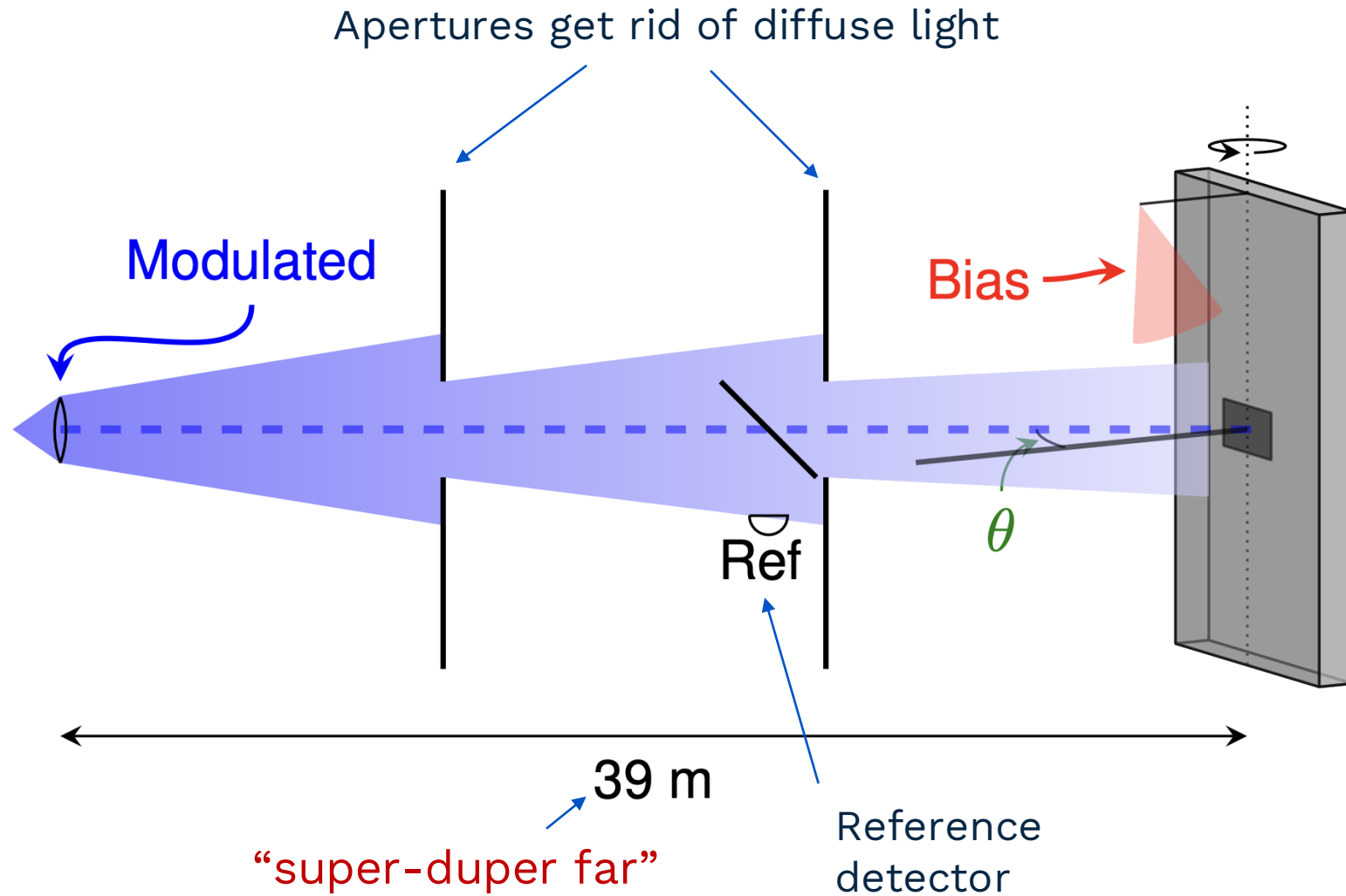
Differential Responsivity

When measuring IAM with differential responsivity, the non-linearity term cancels



$$\text{IAM}_{E_{\text{direct}}(\lambda)}(\theta, \phi) = \frac{\Delta I_{\text{sc}}(\theta, \phi)}{\Delta I_{\text{sc}}(\theta = 0, \phi) \cos \theta}$$

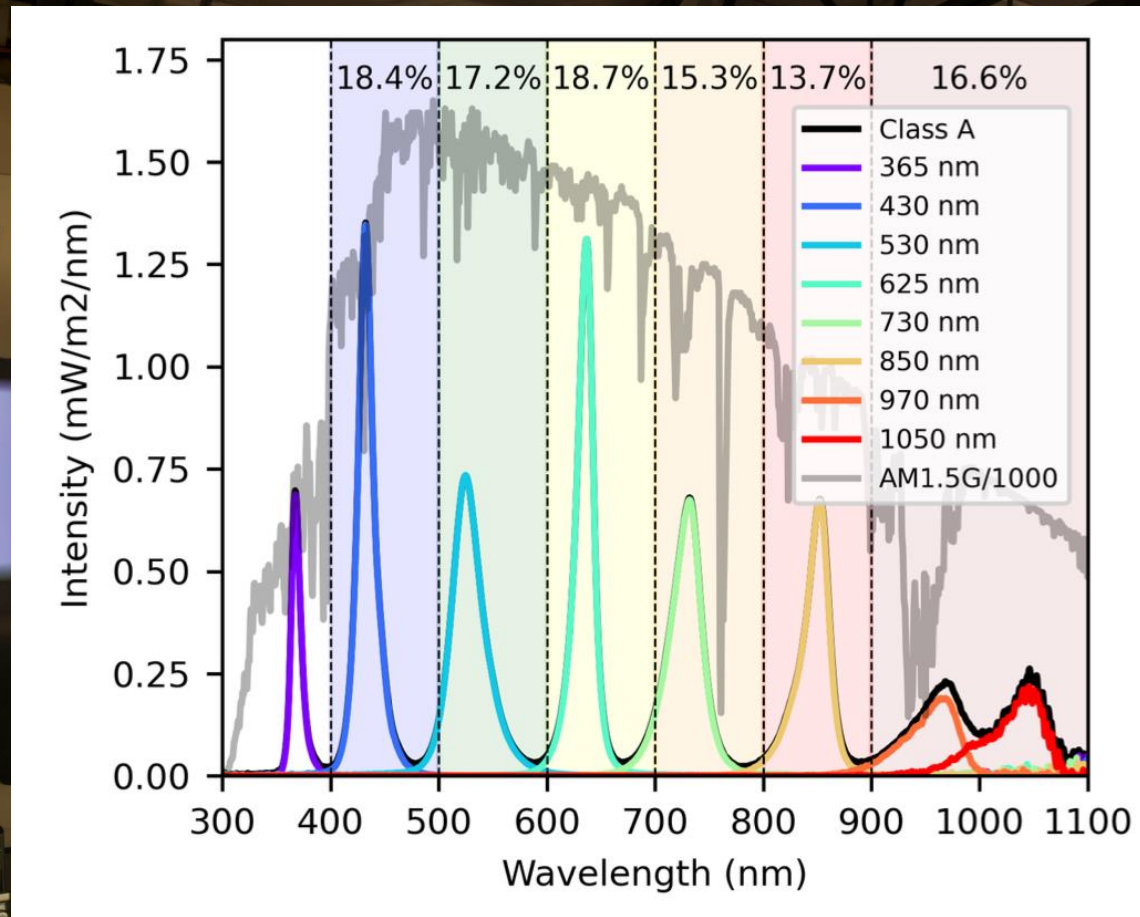
Experimental Setup





Experimental Setup.

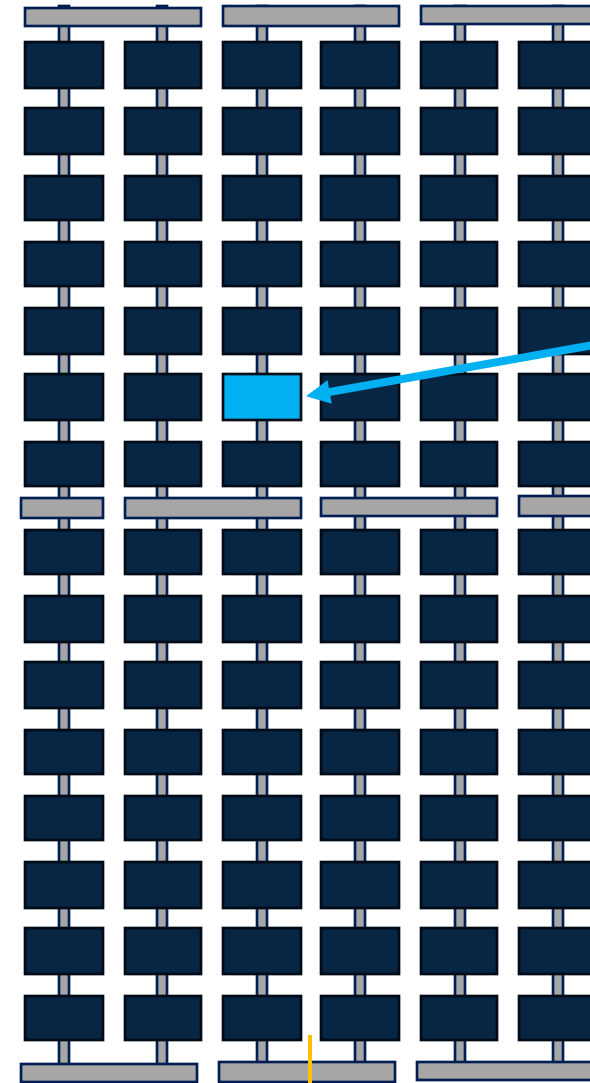
Class A LED Simulator



Experimental Setup.

PVEL's IAM protocol

- All modules measured indoors on the same tester: glass//glass and glass//backsheet
- Using IAM of a single cell to represent the module.



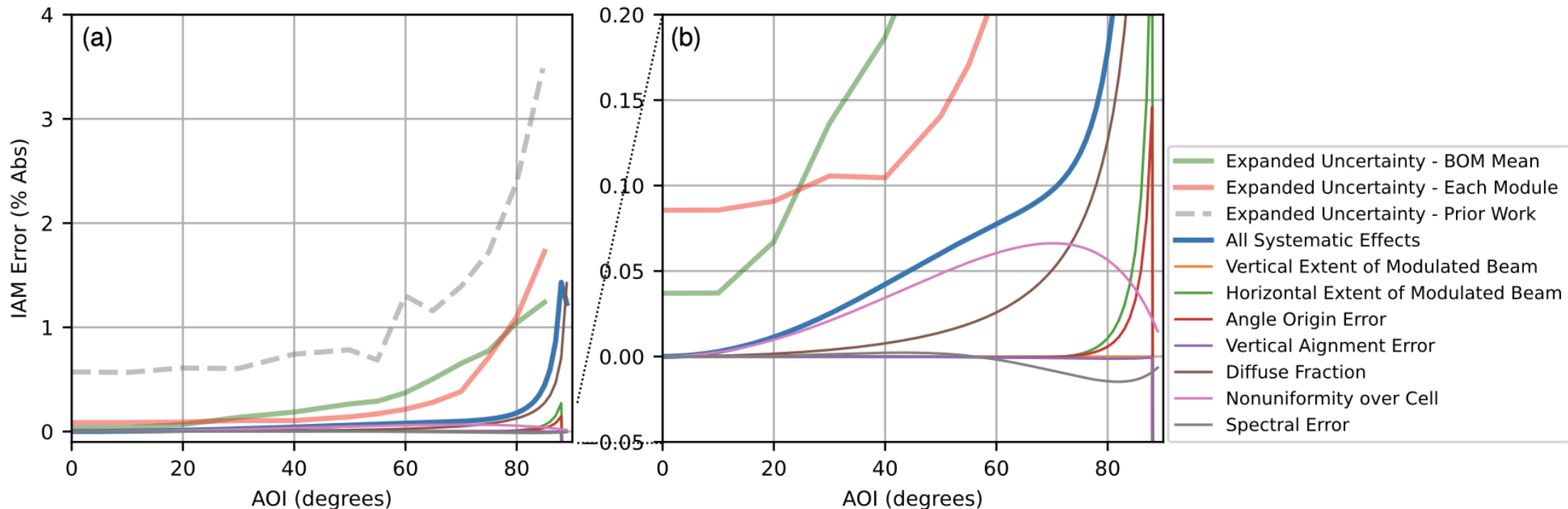
- Cell of interest contacted through backside
- Temperature monitored

PVEL's IAM test is the most accurate yet reported

Reduced IAM uncertainty from previous work by factor of 5

- **Large effort to reduce uncertainties.**

- Diffuse light <0.2%
- High-precision angle measurement: 0.01 deg
- Electromagnetic noise.
- Spectral tuning before each scan.
- Each data point is average of over 2000 pulses.
- Three repetitions of IAM scan per module.
- Three different modules averaged per BOM
- Error-compensation Analysis:
 - Positive and negative angle averaging.
 - Correction for small temperature changes.





Results

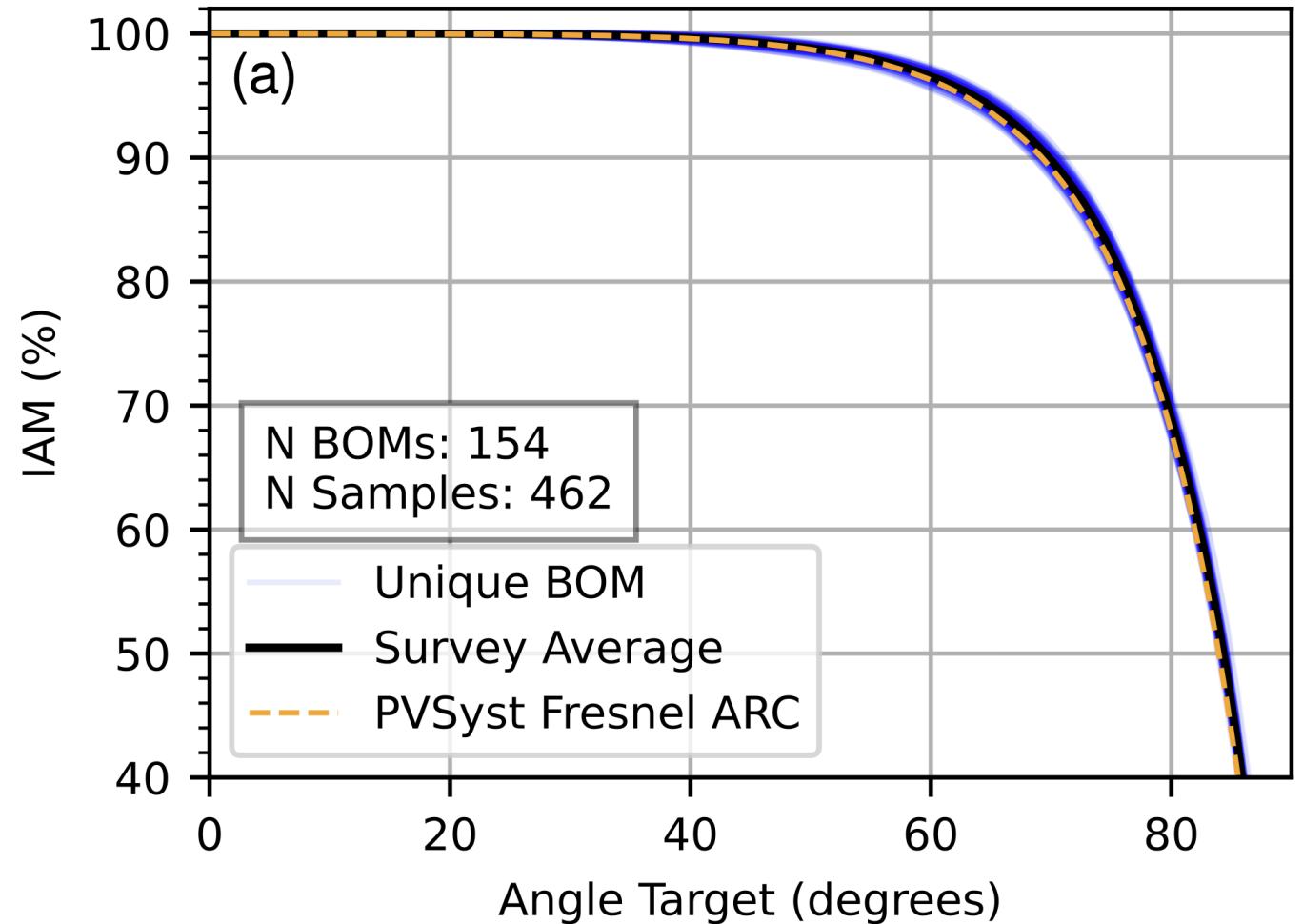
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IAM Survey

- **154 unique BOMs** tested. 3 modules per BOM
- These are modules submitted to PVEL for IAM testing, and are a somewhat random sample of the current generation of commercial modules.
- **Wow, they look very similar.**



Fleet Average

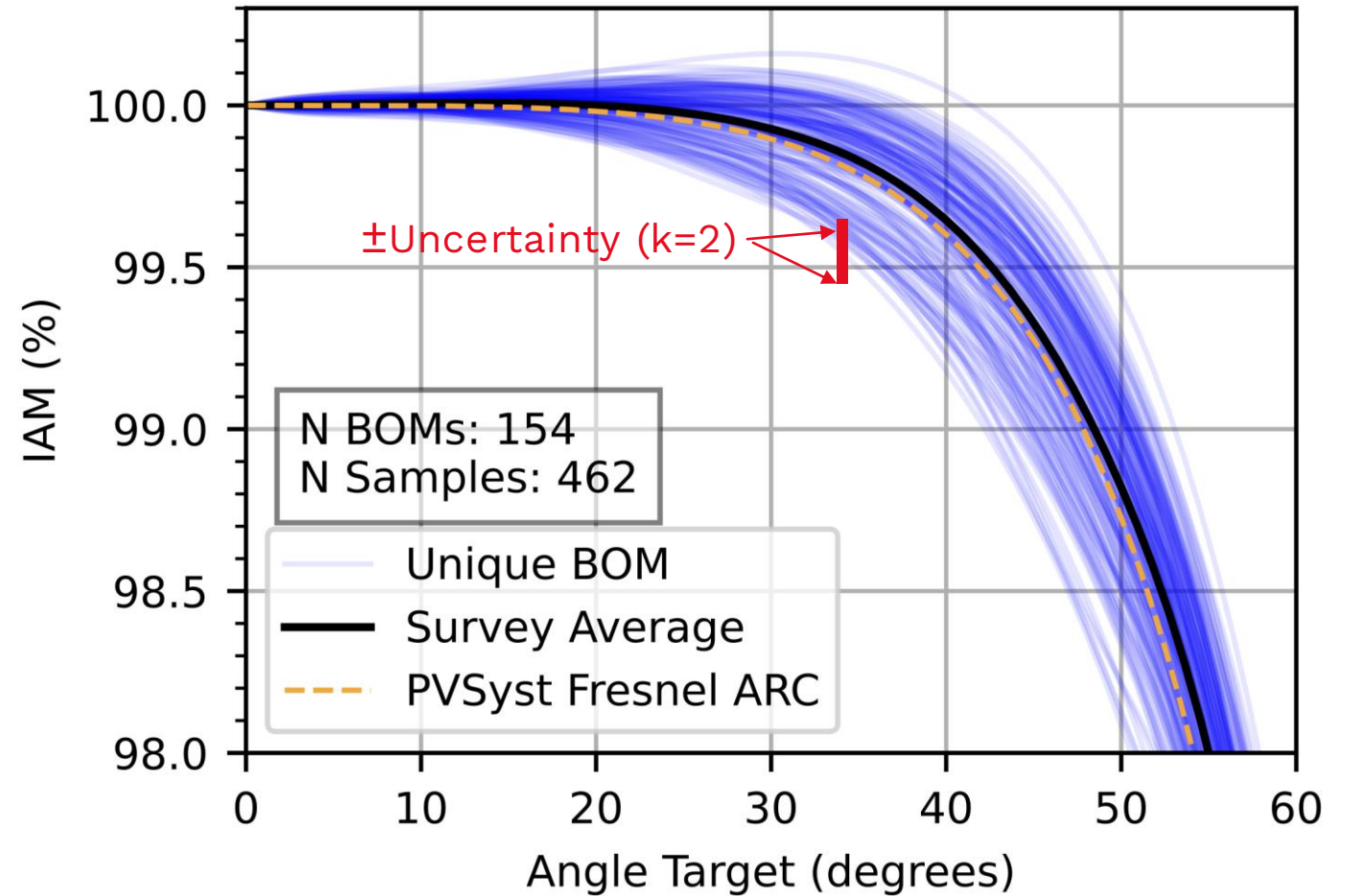
- For energy modelers: in the absence of validated IAM data, use the fleet average presented here!
- **Be wary of IAM measurements that fall above or below the highest and lowest here.**
- Note: strange module designs (colored glass, roof shingles) can and do fall outside of these bounds.

TABLE I
FLEET AVERAGE IAM MEASUREMENTS

AOI (°)	IAM Fleet Average (%)	IAM Fleet 2 σ (%)	IAM PVSyst Fresnel ARC (%)	IAM Lowest (%)	IAM Highest (%)
0	100.000	0.000	100.000	100.000	100.000
10	100.011	0.080	99.999	99.806	100.271
20	100.008	0.158	99.982	99.508	100.216
30	99.944	0.281	99.897	99.280	100.297
40	99.669	0.426	99.601	98.847	100.141
50	98.852	0.594	98.727	97.893	99.459
55	97.993	0.633	97.804	97.024	98.657
60	96.547	0.783	96.252	95.499	97.367
65	94.085	0.914	93.631	92.939	95.163
70	89.718	1.212	89.157	88.271	91.293
75	82.249	1.519	81.427	80.354	84.142
80	68.807	1.772	67.877	66.295	71.219
85	45.902	2.090	43.747	43.080	50.287
90	0.000	0.000	0.000	0.000	0.000

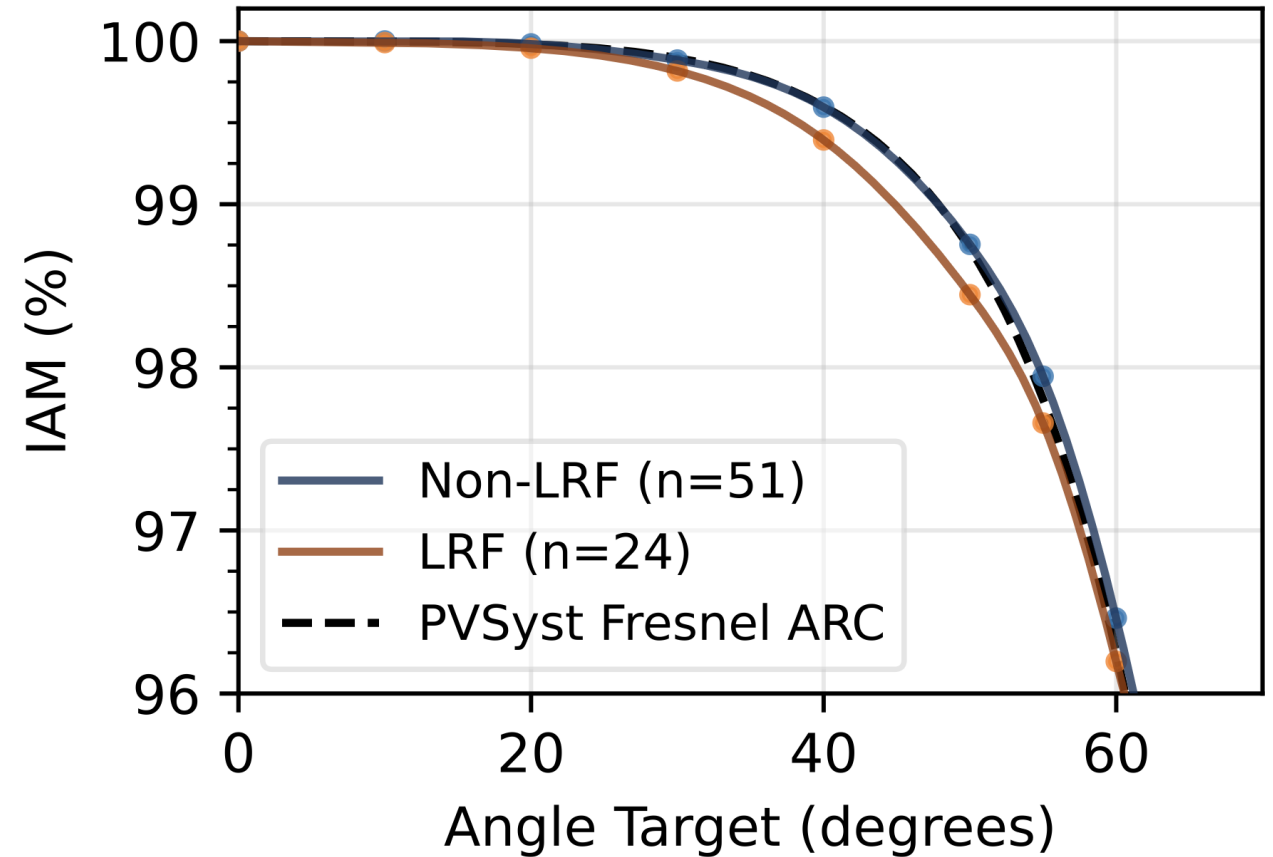
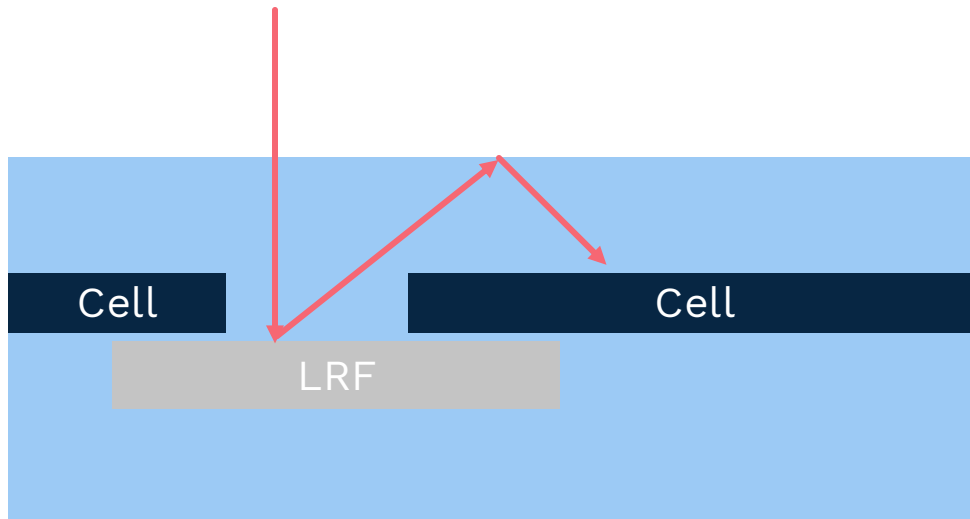
Variations Exist

- Zooming in: there are significant differences between BOMs.
- Expanded uncertainty (k=2) of BOM mean at 30 degrees: 0.1% abs (95% of repetitions should fall within this range).



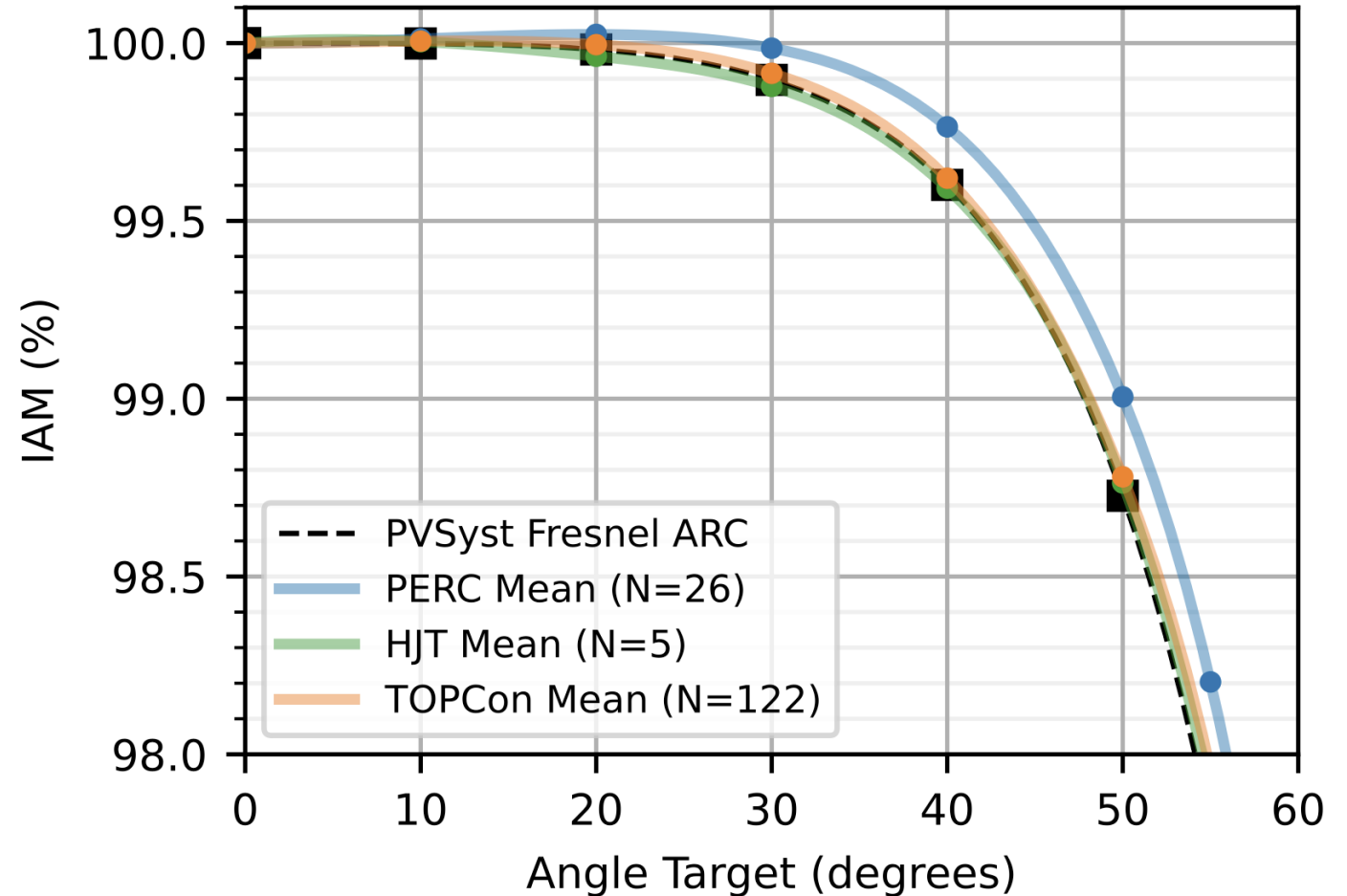
What drives IAM variation Part 1: Light Redirecting Films

- Light redirecting films direct light that would escape from the front side of the module over to the cells.
- This is usually tuned to increase performance at normal incidence, and seems to lower IAM.

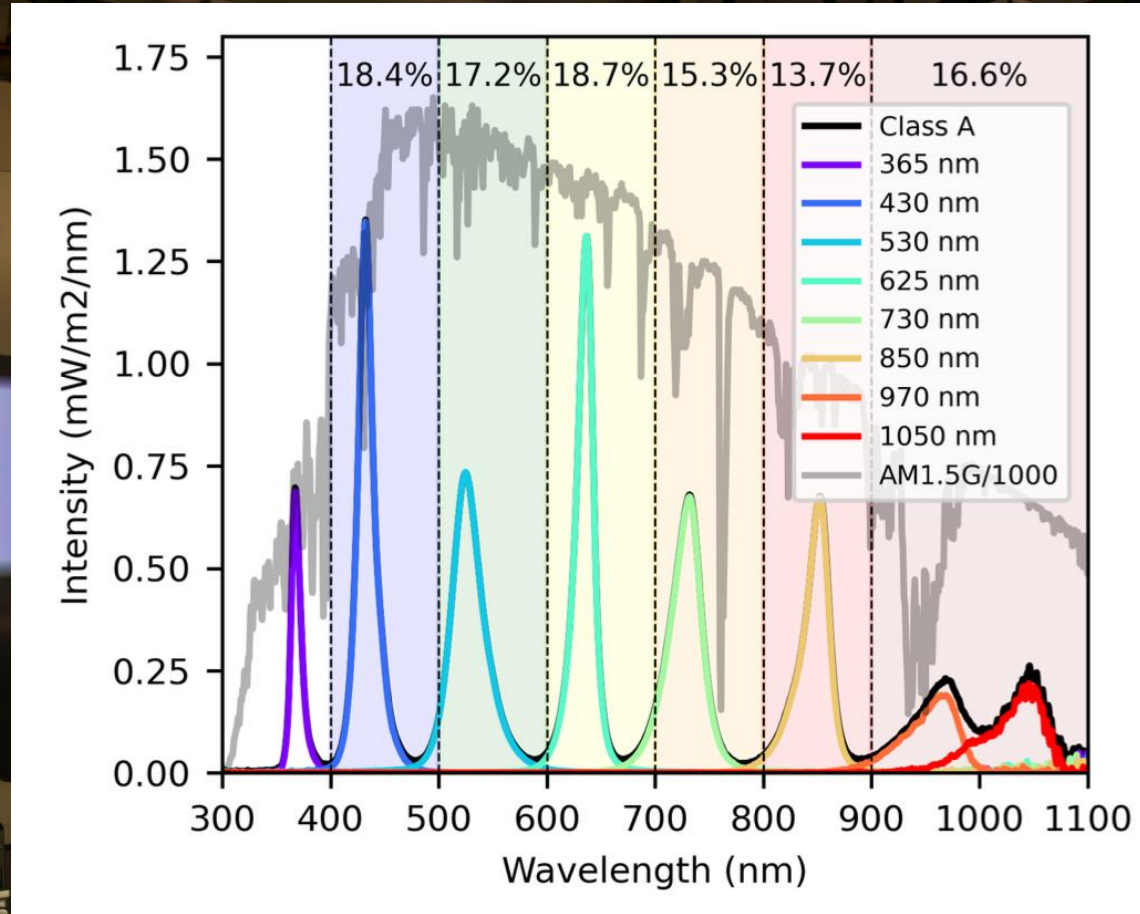


What drives IAM variation Part 2: Cell Technology

- HJT under-performs TOPCon and PERC.
 - Due to blue absorption of amorphous silicon layer in HJT cells.
- TOPCon and PERC expected to behave the same (front cell stacks are the same).
- PERC looks better than TOPCon because more TOPCon use light redirecting films.



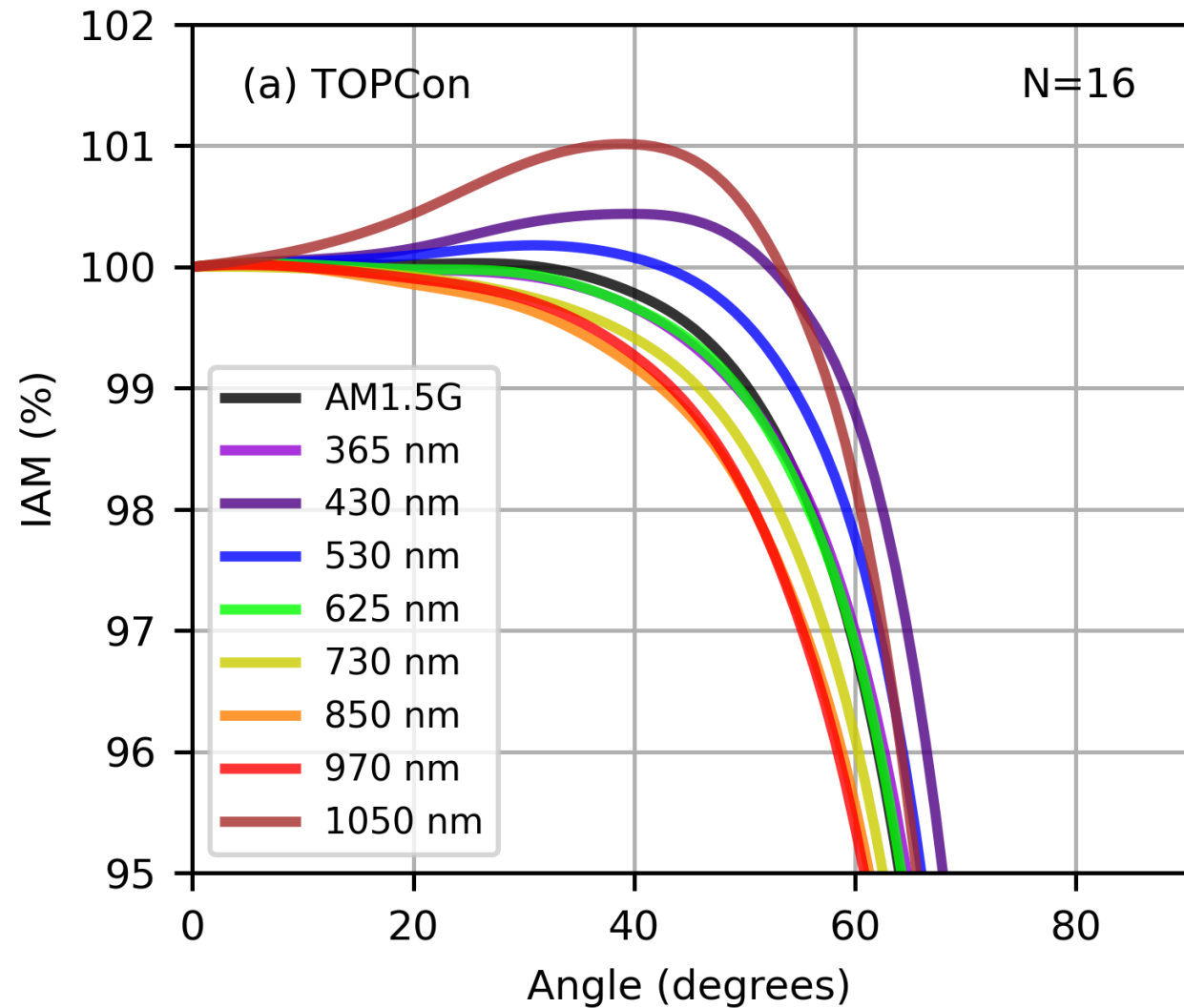
Class A LED Simulator



Spectral IAM

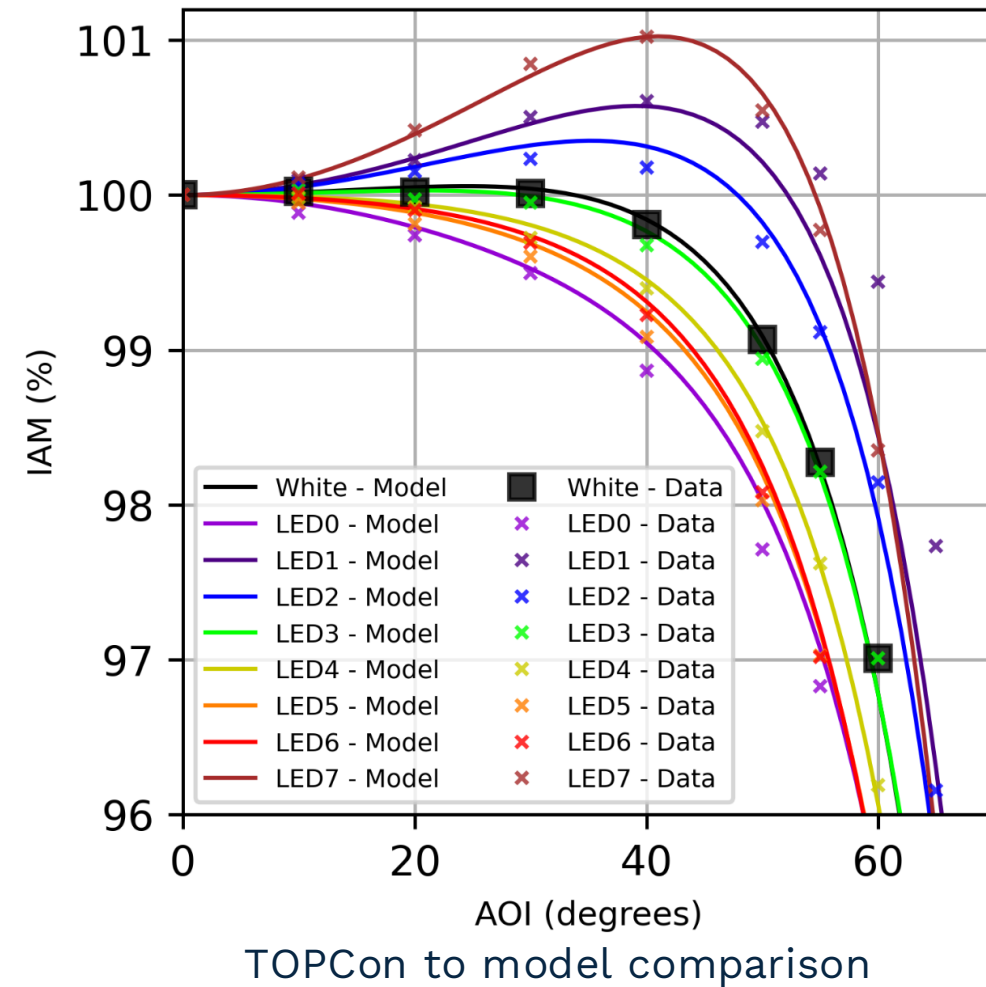
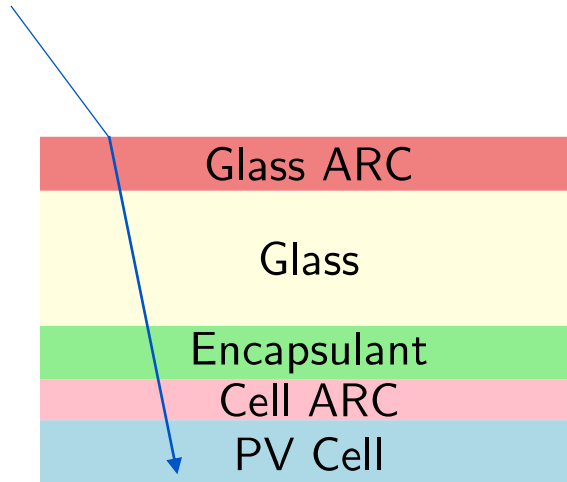
Spectral IAM

- We can measure IAM using each of the LED color individually.
- There is “nowhere” to put this data right now. Energy models do not accept a spectral IAM.
- Note: PVSyst’s default “Fresnel ARC” model has NO wavelength dependence.



Optical Model

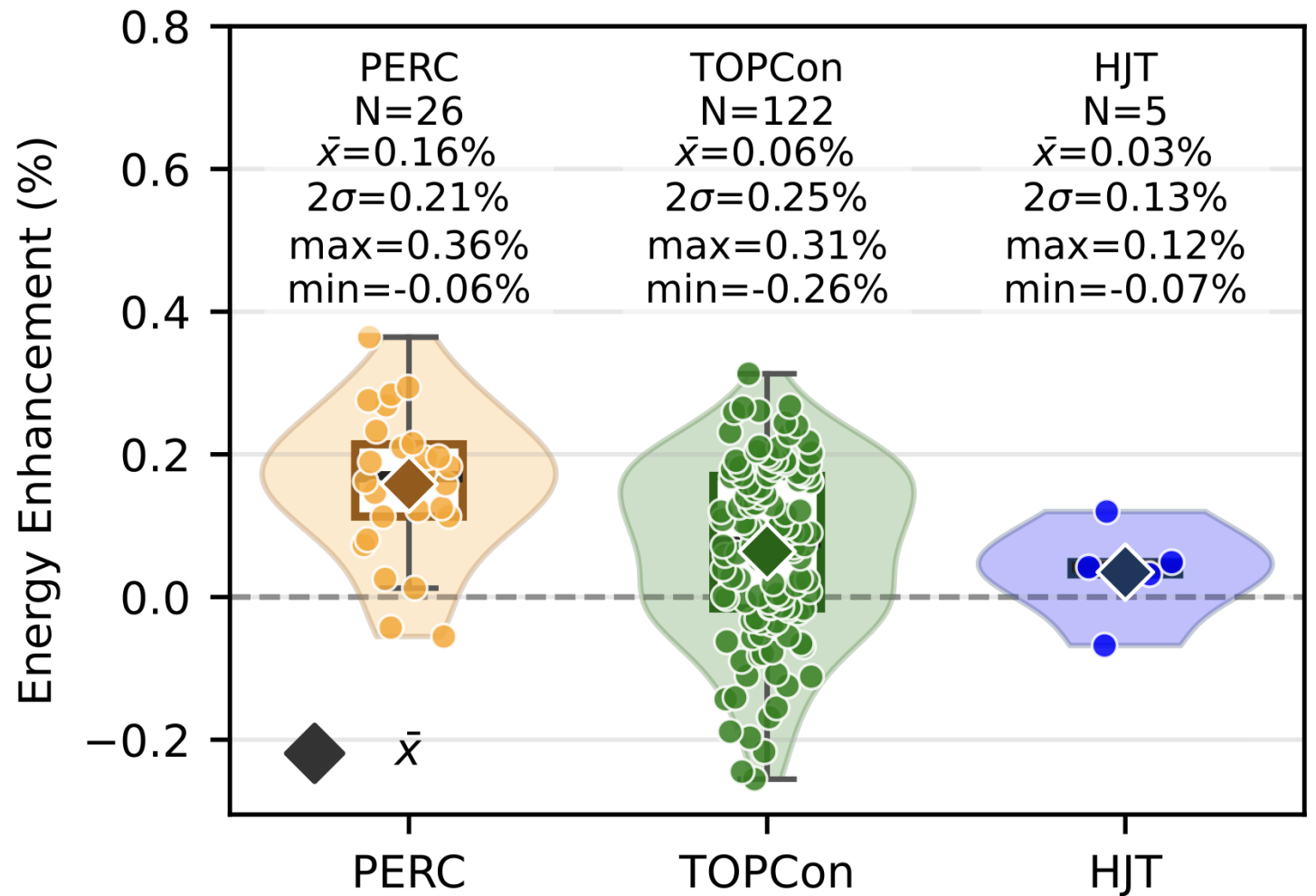
- What's causing this spectral IAM?
- IAM is mostly due to glass ARC.
- Created vectorized 1D optical model
- A 1D all-optical model fits very well.



T. Karin, D. Miller and A. Jain, "Nondestructive Characterization of Antireflective Coatings on PV Modules," in IEEE Journal of Photovoltaics, vol. 11, no. 3, pp. 760-769, May 2021, doi: 10.1109/JPHOTOV.2021.3053482.

Energy Yield

- Using PVSyst, we can model energy production for different IAM curves for a single axis tracking system in Las Vegas, NV.
- We compare the energy yield of a measured IAM curve with the PVSyst Fresnel ARC.
- This allows us to translate IAM differences into an understanding of energy yield impact.



Shhh... IAM Secrets

We made IAM measurements much more accurate, but there are other issues with current modeling methods (related to IAM) that cause bigger errors.

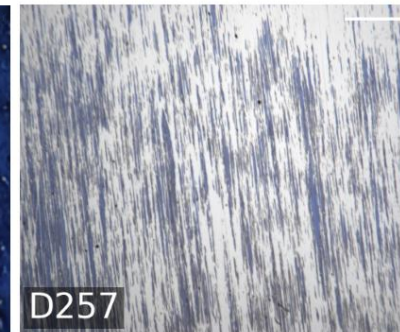
Secret 1: Most of IAM is due to the coating – but coatings don't necessarily last

- Good IAM performance is mostly due to the glass coating.
- **But**, coating lifetime can be 7 years (or less) when vigorously cleaned.
- Energy simulations could model IAM changing with time.

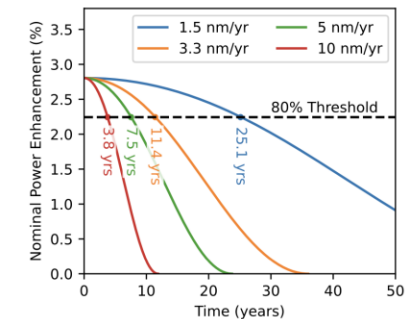
(a) Very high performance coating



(g) Abrasive coating loss, major (coupon)



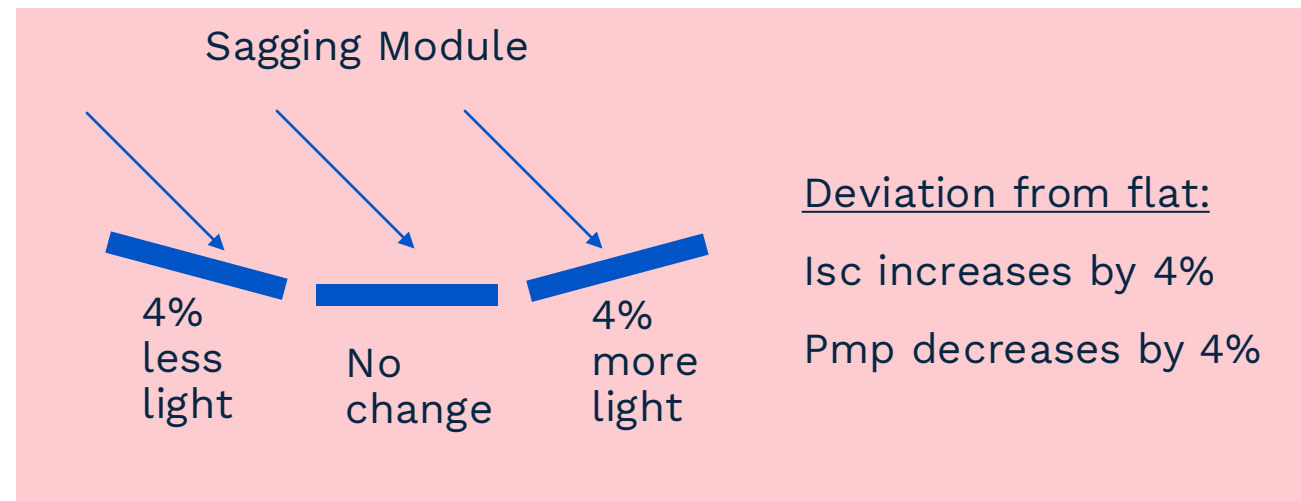
(h) Total abrasive ARC loss except in pockets of glass texture



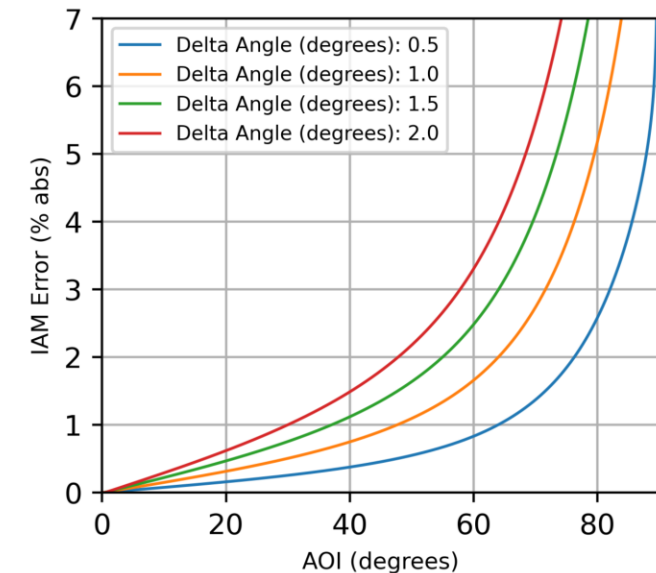
Photovoltaic module antireflection coating degradation survey using color microscopy and spectral reflectance. Todd Karin, Mason Reed, Jim Rand, Robert Flottemesch, Anubhav Jain
<https://doi.org/10.1002/pip.3575>

Secret 2: Modules aren't flat

- IAM measures Isc vs. angle.
- **Isc driven by substring with the highest Isc.**
- **Pmp driven by substring with lowest Isc** (for small changes)
- Since modules are often not flat (they sag under their own weight or have built-in curvature), this leads to errors either when measuring one cell in a module or when measuring the whole module.
- For example, curvature of just 1 degree between the left and right substrings in a module can lead to a 2% error in IAM at 50 degrees.

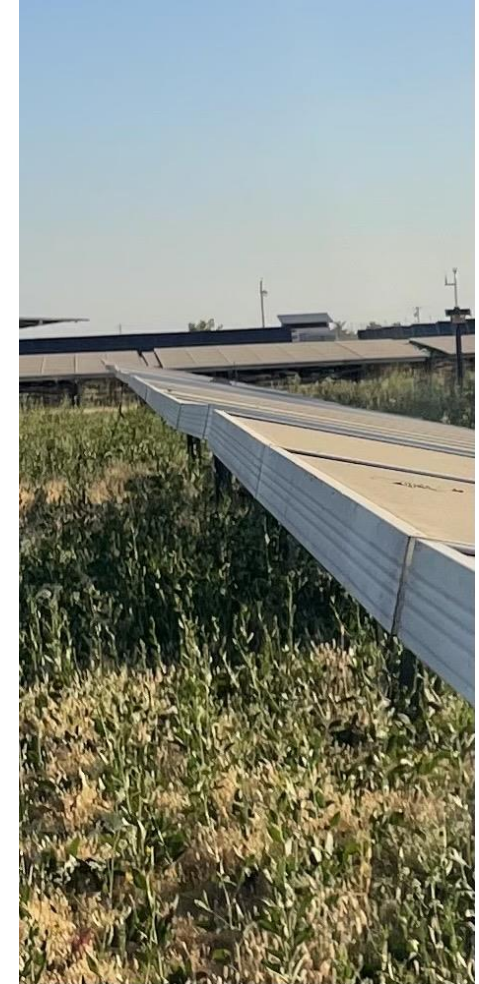


Estimate of IAM error caused by measuring a full module's Isc when the left and right substring differ in angle.



Secret 3: Tracker tables aren't flat

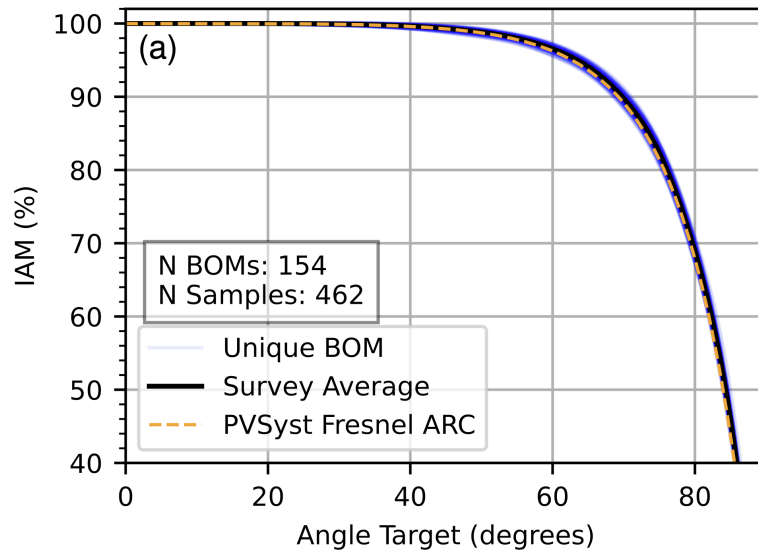
- Mounting irregularities, or torque tube twisting mean modules in a tracker aren't all in the same plane (even when mounted to a standard torque tube).
- Energy models should not assume the table is flat!
- Up to a few degrees variability is typical across an array.
- **Difference in Isc at 60 and 61 degrees is roughly 3.5%!**
- Maybe table flatness should be a settable parameter in PV system models.



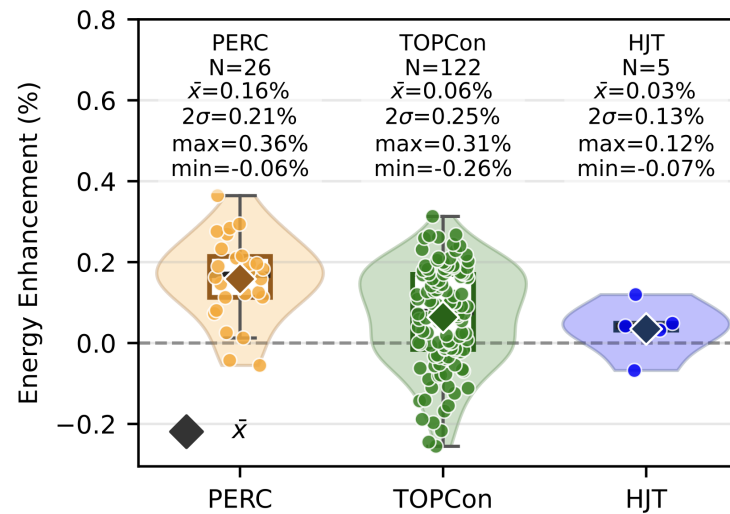
Images from PVUSA

Conclusions

- Using the **most-accurate IAM test method yet reported on full-size modules**, we found **small variability** in a survey of modern commercial modules.



- Best to worst** IAM variation changes energy yield by **0.4%**: there are meaningful differences between modules.



- New **fleet average** and upper/lower bounds provided for energy modelers

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85	45.902	2.090	43.747	43.080	50.287
90	0.000	0.000	0.000	0.000	0.000

Want a preprint? Contact me!

Extra slides

Magnitude of Nonlinearity

