High-Accuracy Measurement of the Incidence Angle Modifier on PV Modules

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Outline

- Why care about Incidence Angle Modifier (IAM)
    - IAM is difficult to measure.
- Kiwa PVEL's solution
    - Most accurate IAM tester yet reported.
- Survey of Commercial Modules
    - Defining a new default IAM curve
- Energy yield
- Simple optical model
- Issues with IAM

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Intro

Why IAM?

The sun isn't always perpendicular to the module.

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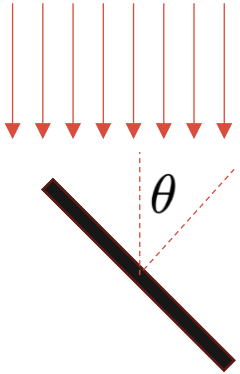
What is IAM?

Perfect Absorber

Absorption proportional to cos(theta)

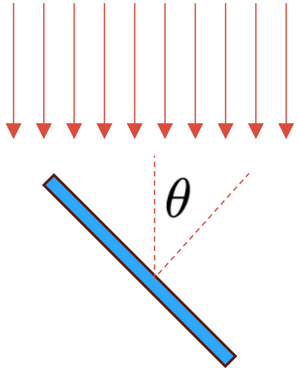


PV Module

Isc proportional to cos(theta) times IAM

$$\mathrm{IAM} = \frac{I_{\mathrm{sc}}(\theta)}{I_{\mathrm{sc}}(0)\ \cos(\theta)}\eta$$

(nonlinerity correction)



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

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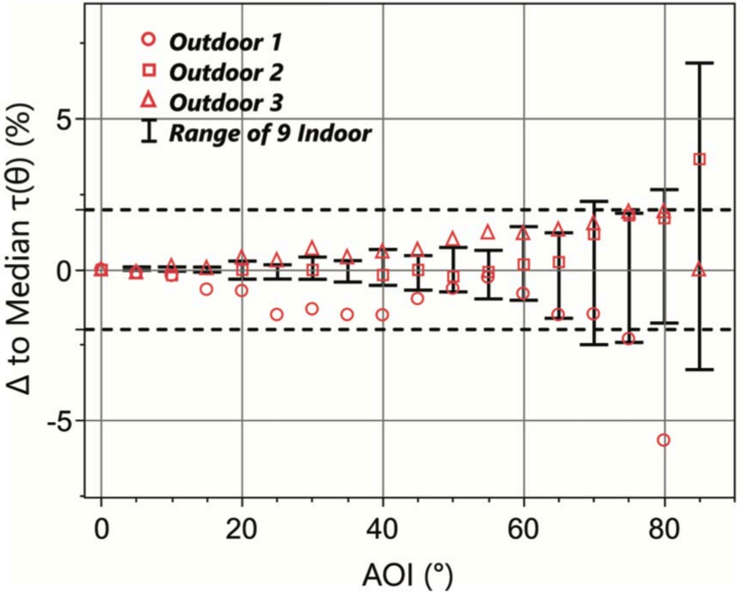
IAM measurements are **notoriously difficult**

- 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

Interlaboratory comparison



Goal: improve the accuracy of the IAM test

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

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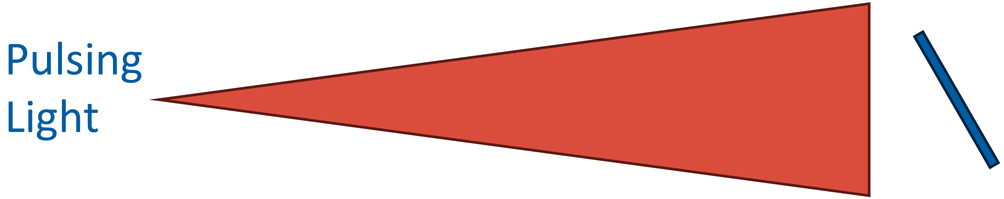
Differential Responsivity

- **Responsivity: Current out / Optical Power In**
- **Differential Responsivity**: the change in Isc divided by the change in input irradiance.
- Established technique, but not commonly used for IAM.



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

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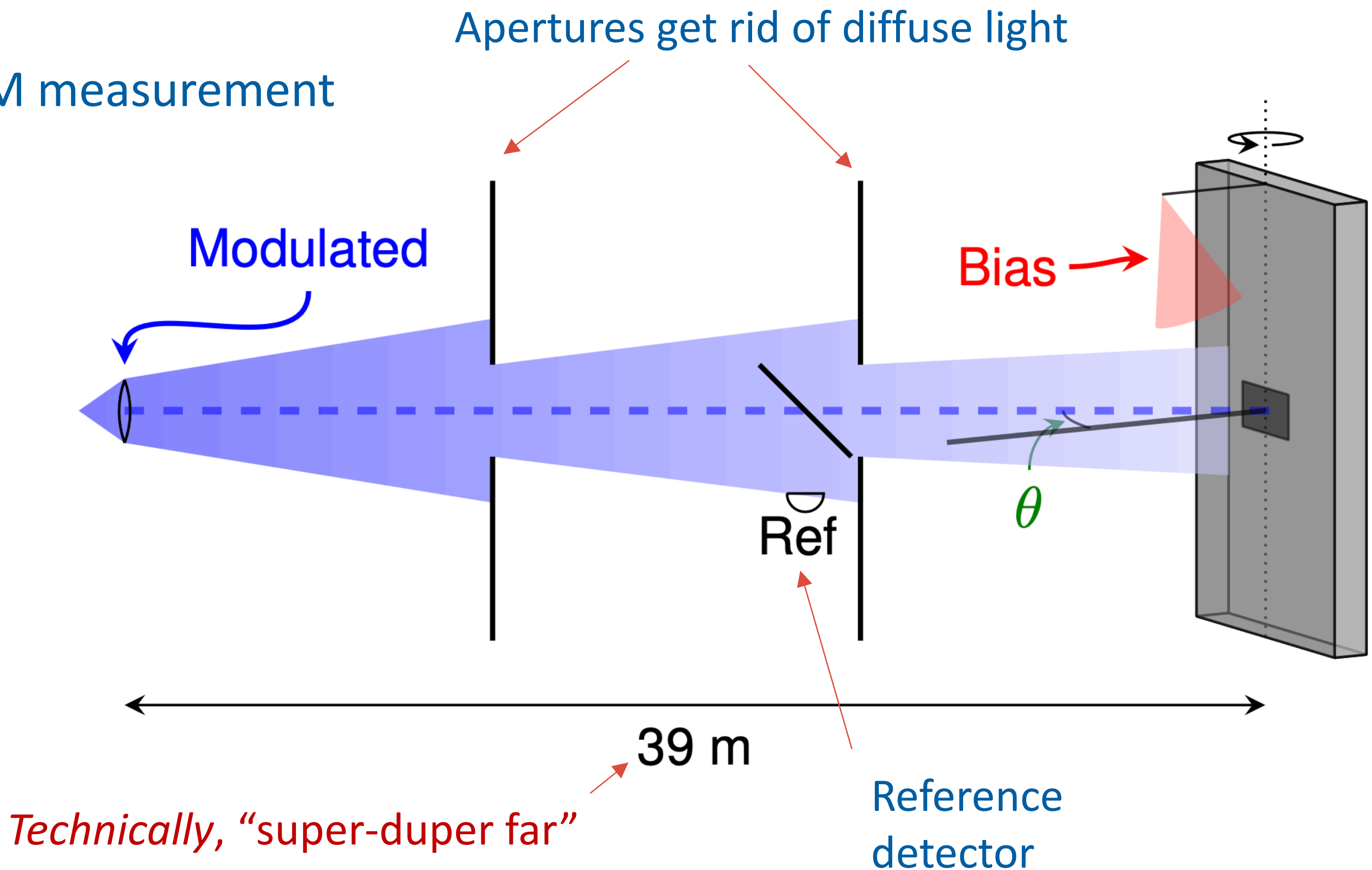
Kiwa PVEL's IAM measurement



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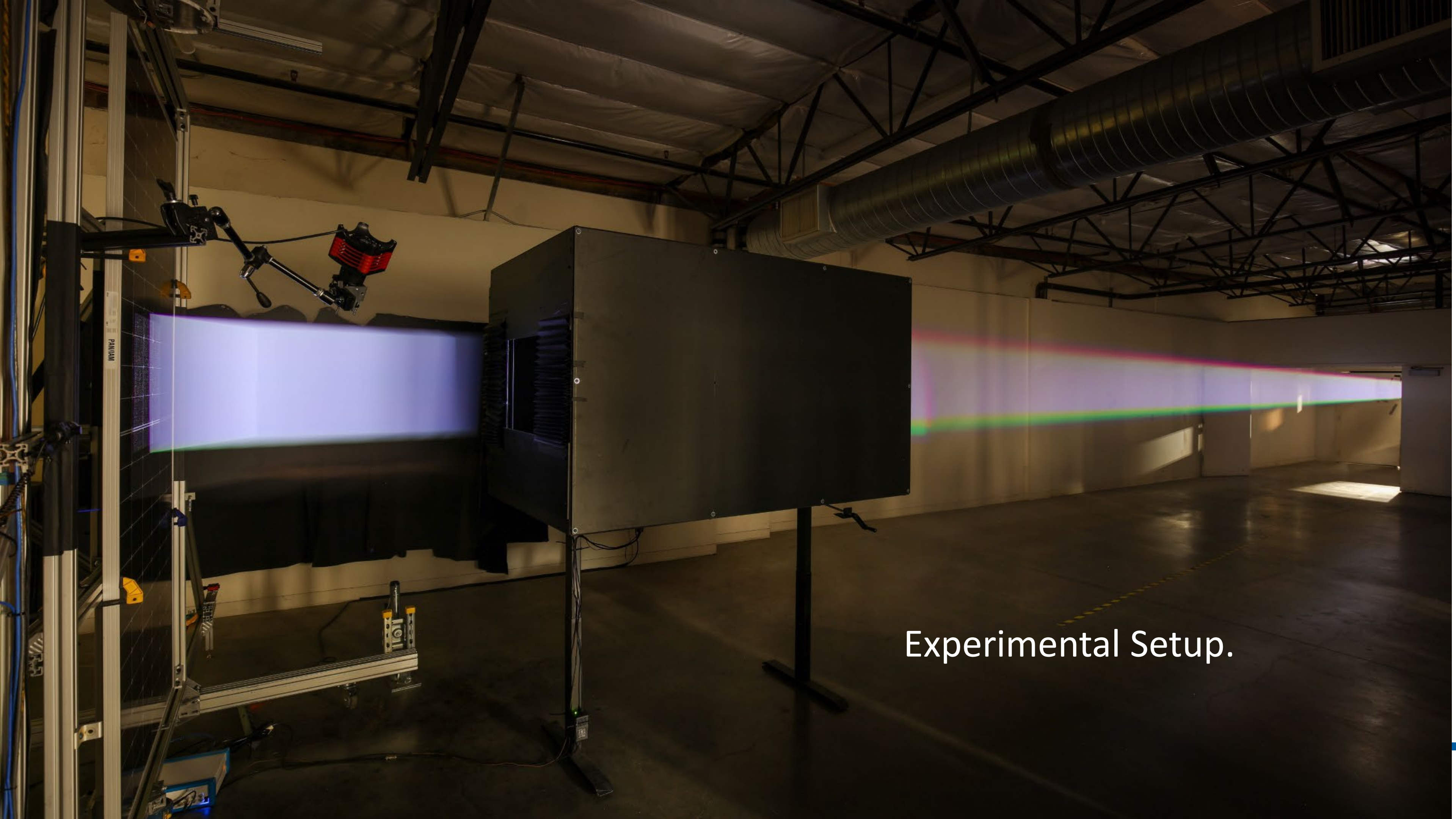
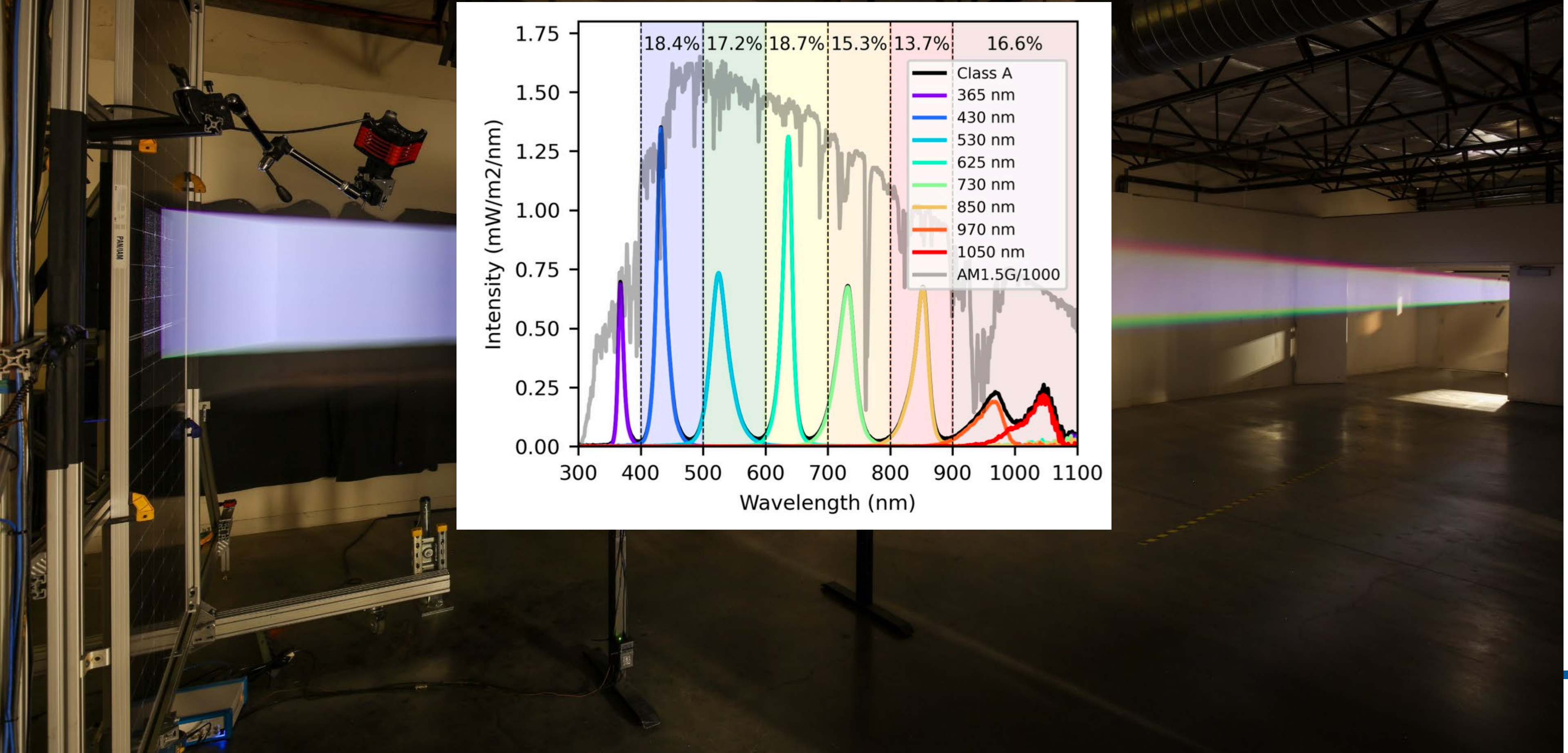


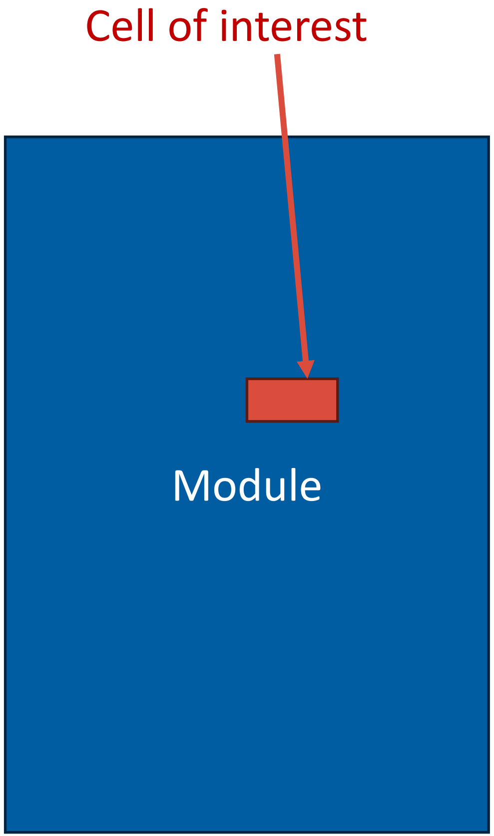
Experimental Setup.

Class A LED Simulator



Kiwa PVEL's IAM protocol

- Tapping procedure (contact a single cell):
  - Single cell tapped near center of module
  - All modules measured indoors on the same tester: glass//glass and glass//backsheet
  - Parallel substring isolated (extremely important)
  - Temperature of cell measured.



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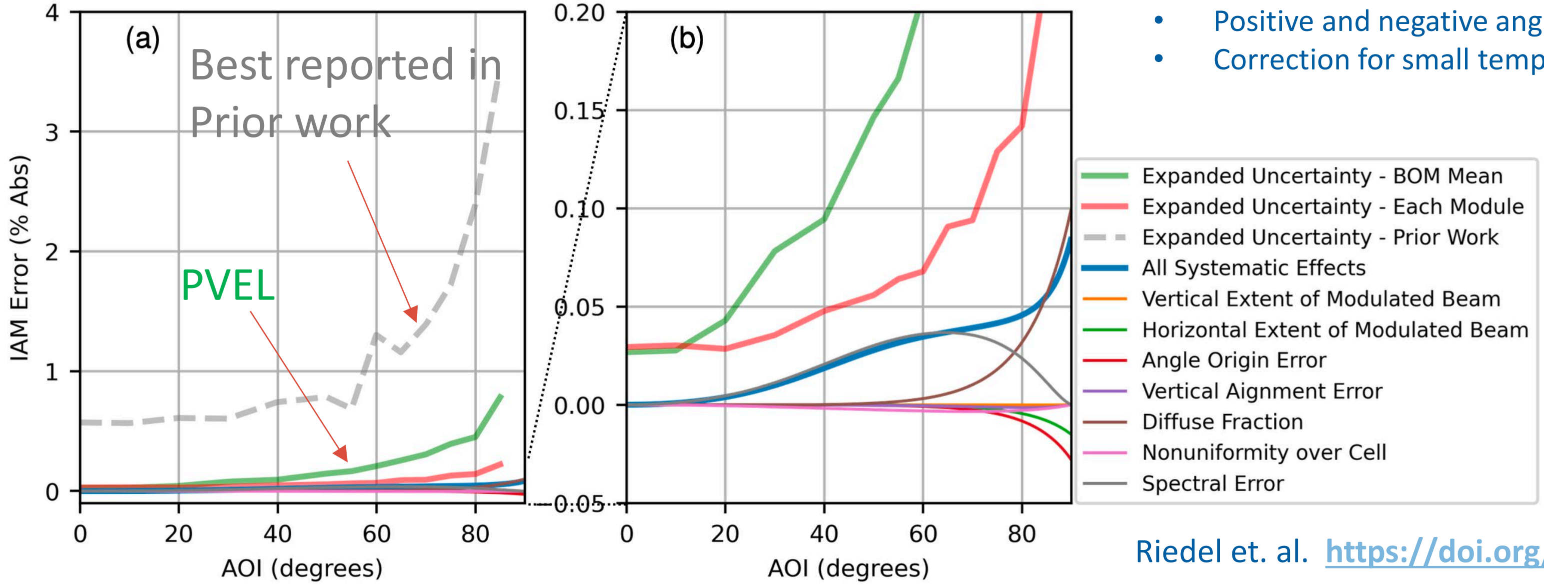
Kiwa PVEL's IAM test is the most accurate yet reported

Reduced IAM uncertainty by an order of magnitude

- **Large effort to reduce uncertainties**.
  - Diffuse light <0.1%
  - High-precision angle measurement: 0.01 deg
  - Address 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
- Error-compensation Analysis:
  - Positive and negative angle averaging.
  - Correction for small temperature changes.



Riedel et. al. https://doi.org/10.1002/pip.3365

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Results

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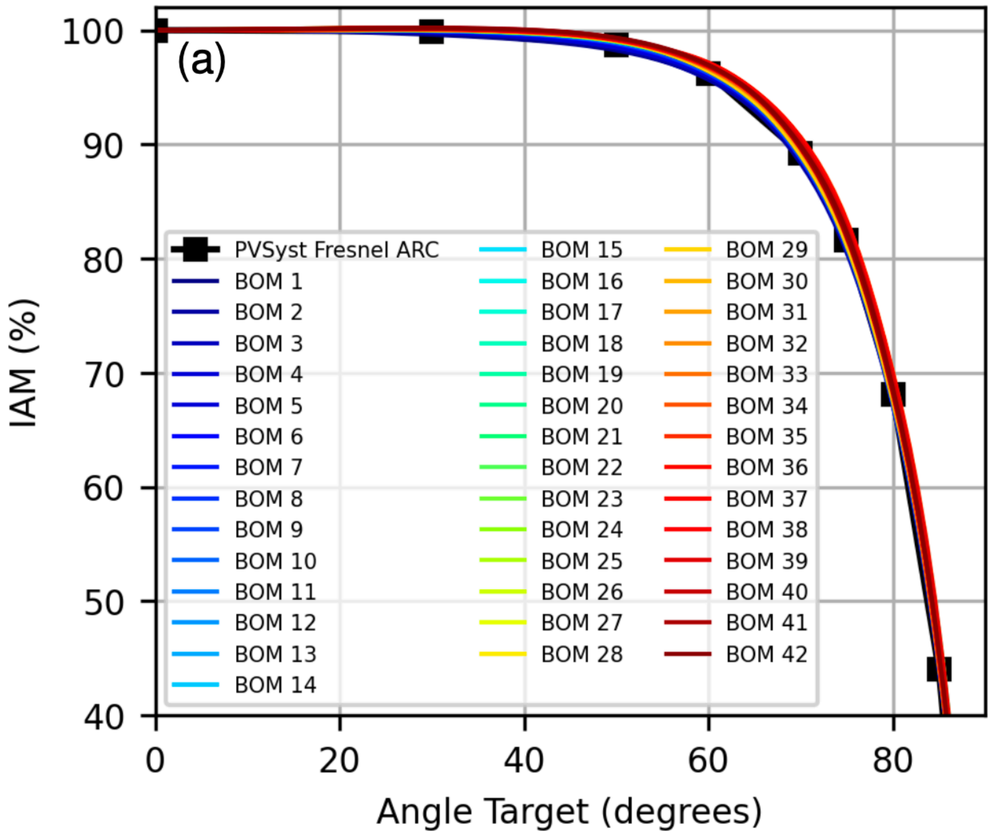
IAM Survey

- **42 unique BOMs** tested (126 mods)
- 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.**



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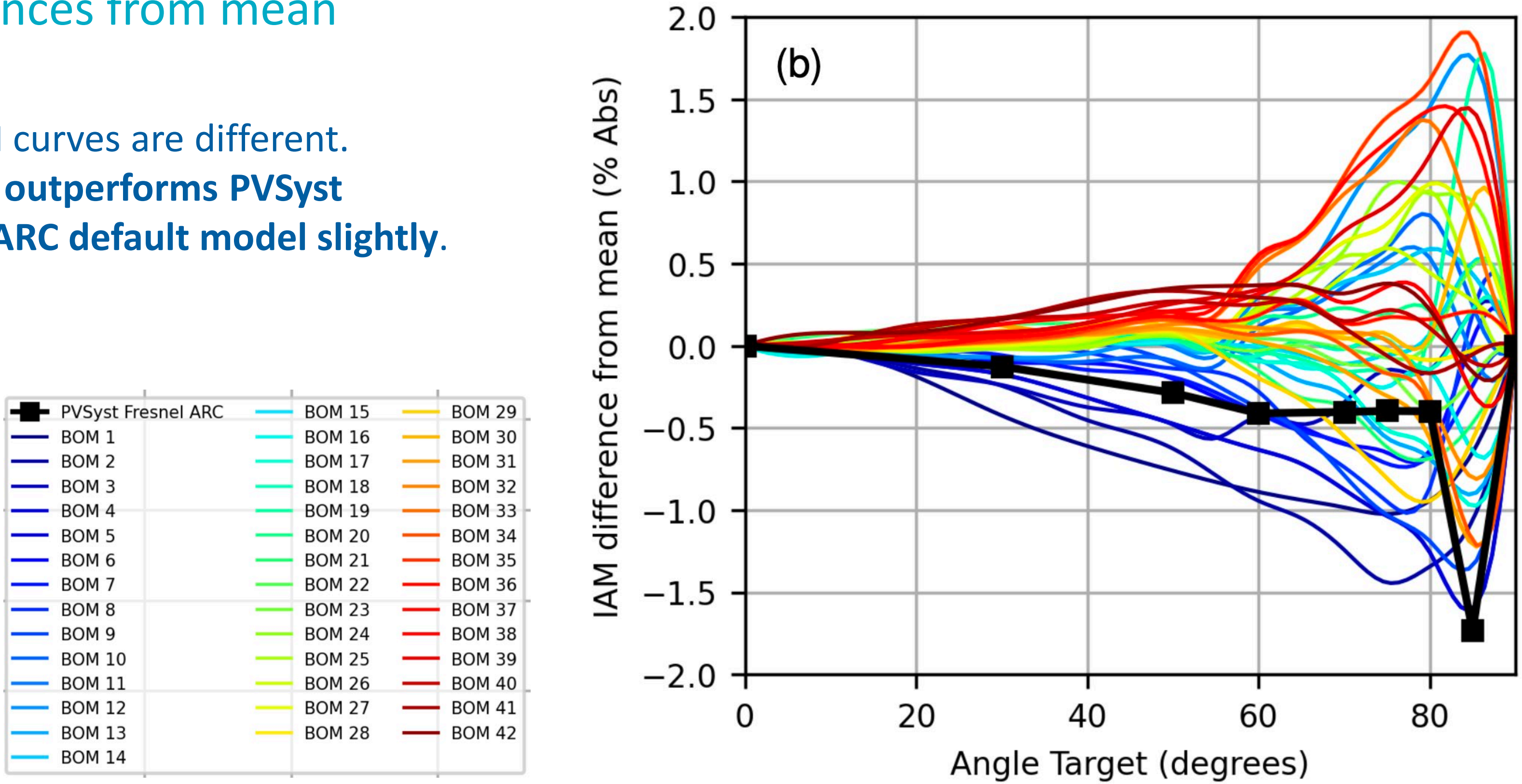
Differences from mean

- But, IAM curves are different.
- **Average outperforms PVSyst Fresnel ARC default model slightly**.



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New Fleet Average IAM curve

- For energy modelers: in the absence of validated IAM data, use the fleet average presented here! (to be published soon)
- **Be wary of IAM measurements that fall above or below the highest and lowest here**.

AOI (°)	IAM Fleet Average (%)	IAM Fleet 2σ (%)	IAM PVSyst Fresnel ARC (%)	IAM Lowest (%)	IAM Highest (%)
0	100.000	0.000	100.000	100.000	100.000
10	100.026	0.054	-	99.976	100.106
20	100.048	0.139	-	99.860	100.178
30	100.026	0.234	99.900	99.601	100.197
40	99.774	0.360	-	99.163	100.056
50	98.986	0.488	98.700	98.225	99.337
55	98.181	0.397	-	97.618	98.417
60	96.611	0.709	96.200	95.667	97.166
65	94.041	0.864	-	92.992	94.715
70	89.603	1.117	89.200	88.361	90.639
75	81.997	1.412	81.600	80.555	83.388
80	68.499	1.602	68.100	67.155	70.115
85	45.735	1.764	44.000	44.132	47.619
90	0.000	0.000	0.000	0.000	0.000

- To be published soon.

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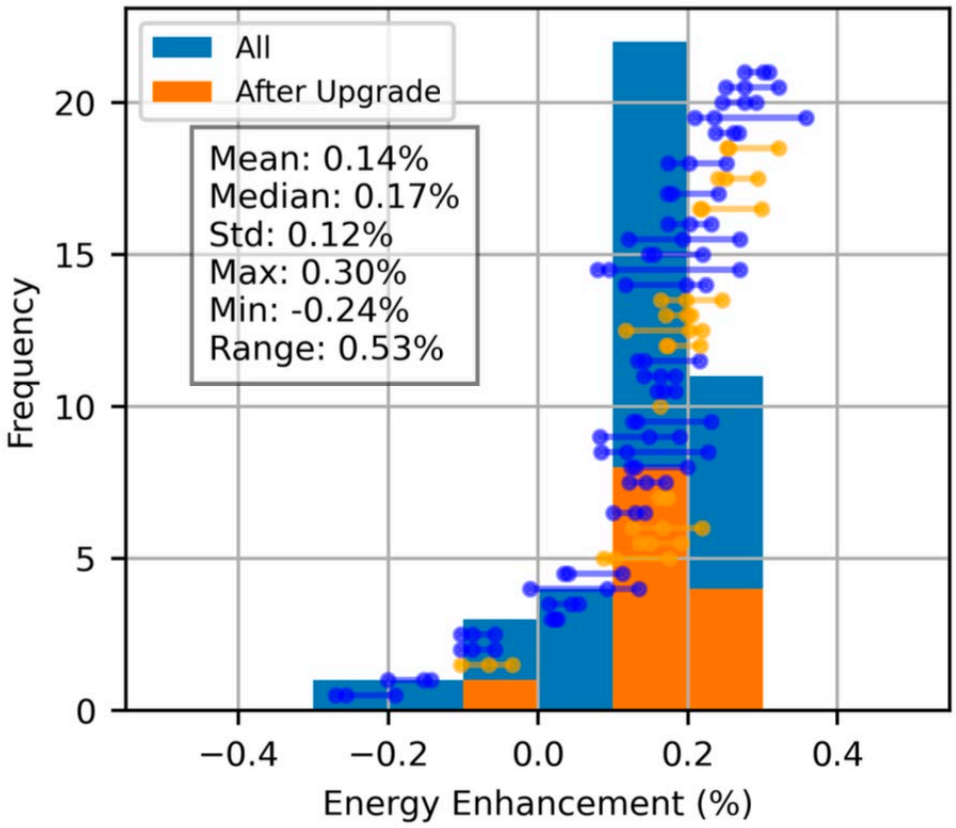
Energy Yield

- Simulations in PVSyst show differences in energy yield between modules.
- **This work**: the full range of energy yield on all *different modules* is less than **0.5%**!
- **Previously**, uncertainty of measurement is high enough that it would be difficult to tell the difference between modules.



Fit to energy yield of SAT system in Las Vegas NV with DC/AC ratio of 0.9 modeled using PVSyst.

$$\text{Energy} \propto f(0°) + 0.920 \cdot f(30°) + 0.479 \cdot f(50°) + 0.185 \cdot f(60°) + 0.059 \cdot f(70°) + 0.010 \cdot f(75°) + 0.011 \cdot f(80°) + 0.006 \cdot f(85°)$$

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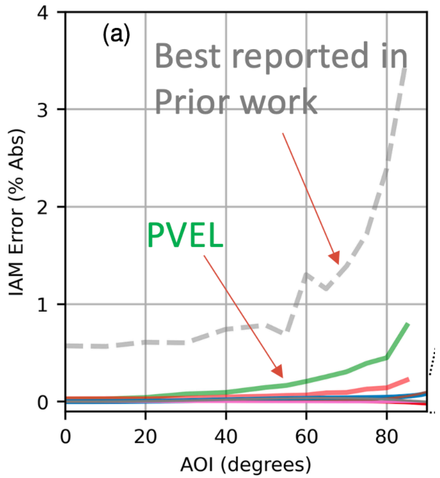
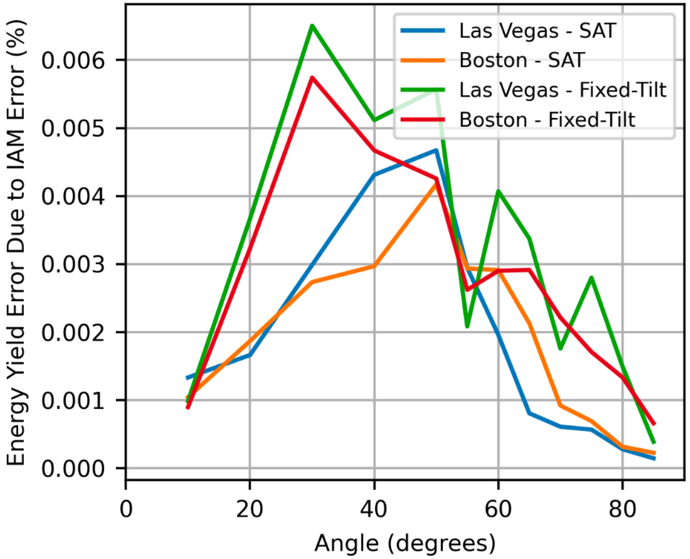
What drives Energy yield uncertainty?

- IAM measurements have greatest uncertainty at 70-85 degrees.



Take home message:
IAM at >80° doesn't matter

But there is not much light there, so **energy yield uncertainty is dominated by uncertainty in measurement at 20-60 degrees.**



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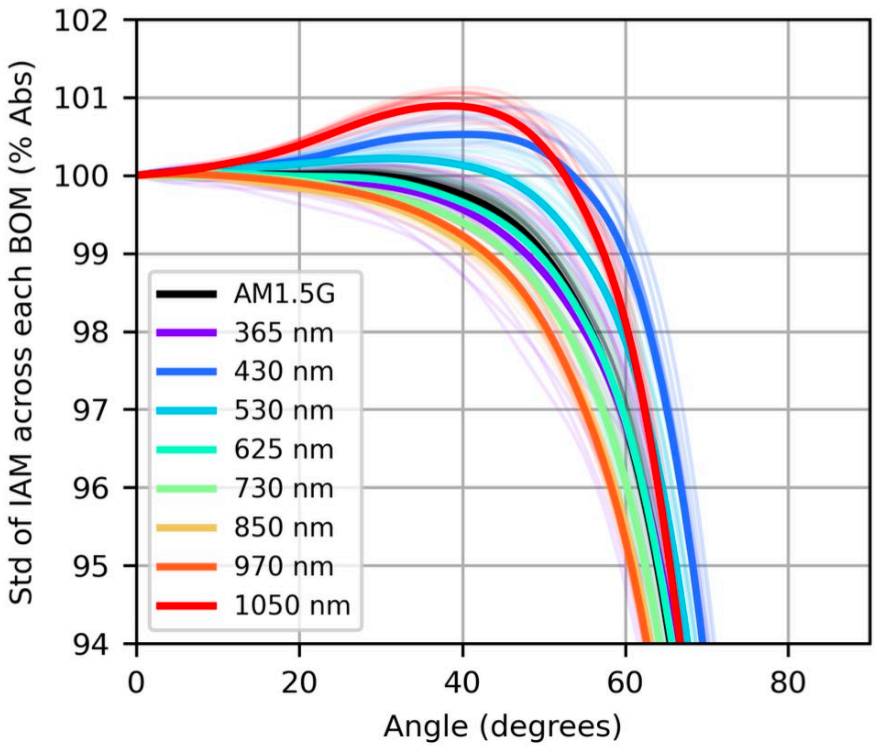
Spectral IAM

- We can measure IAM using each of the LED color individually.
- There is “nowhere” to put this data right now. Energy models cannot accept a spectral IAM.

- [Aside – some people think IAM can’t be bigger than 1.0. It can, and is for certain wavelengths]



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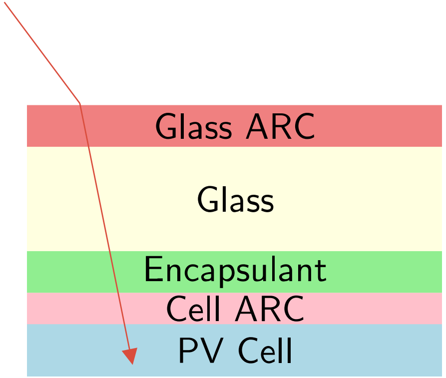
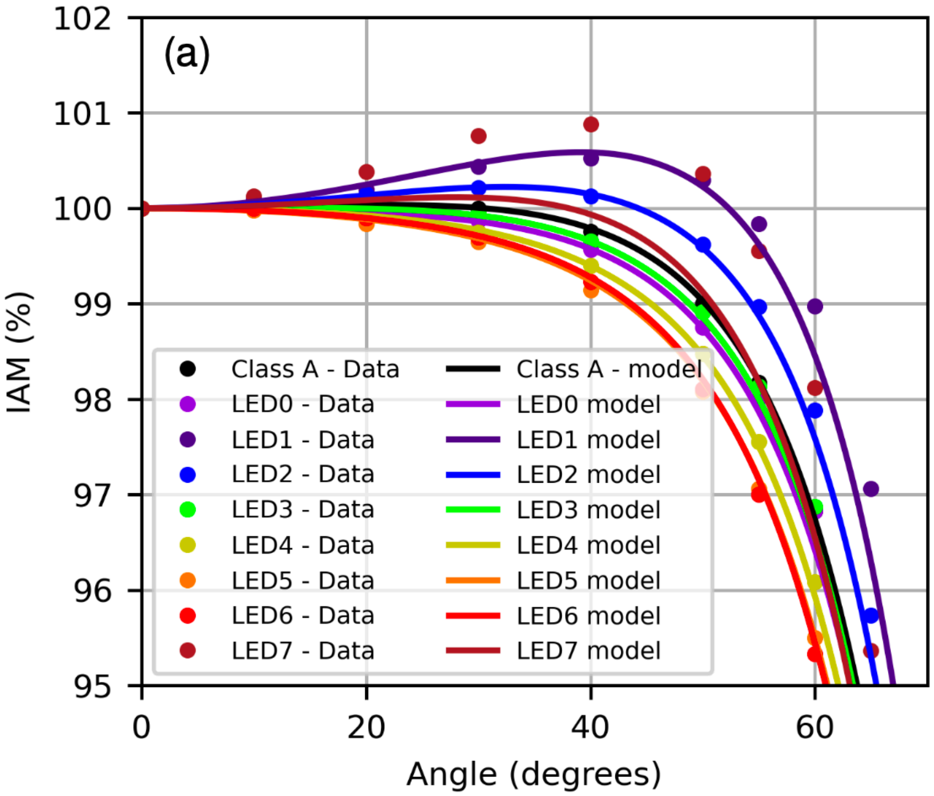
IAM Model

- What's causing this spectral IAM?
- IAM is mostly due to glass ARC.
- Surprising how well a 1D all-optical model fits.





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.

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Issues with IAM

<u>IAM Secret:</u>

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

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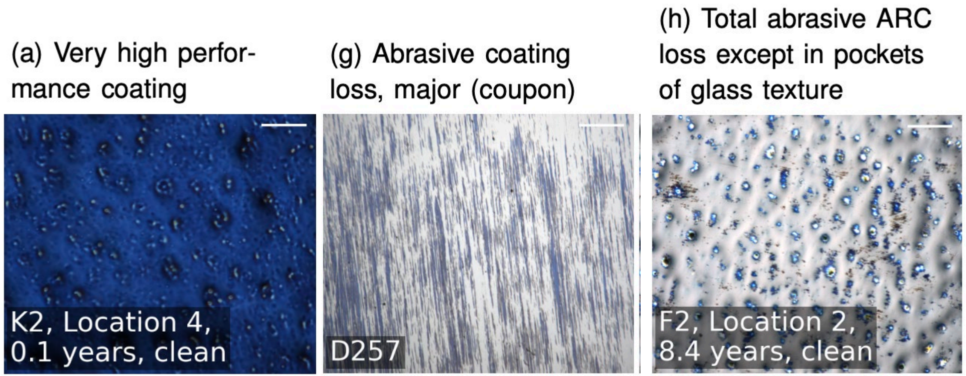
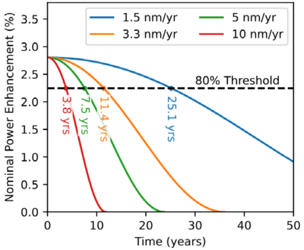
Issue (1) with energy modeling

- “Good IAM” is due to glass coating.
- **But,** coating lifetime can be 7 years (or less) when vigorously cleaned.
- Should have a model where the IAM curve changes with time.
- Responsible for about 3.5% reduction in performance after coating is removed.





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

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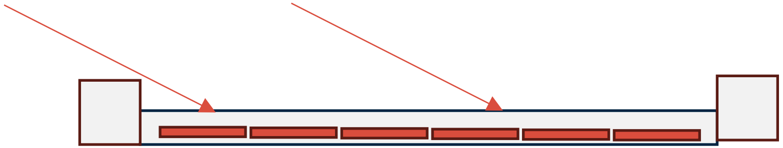
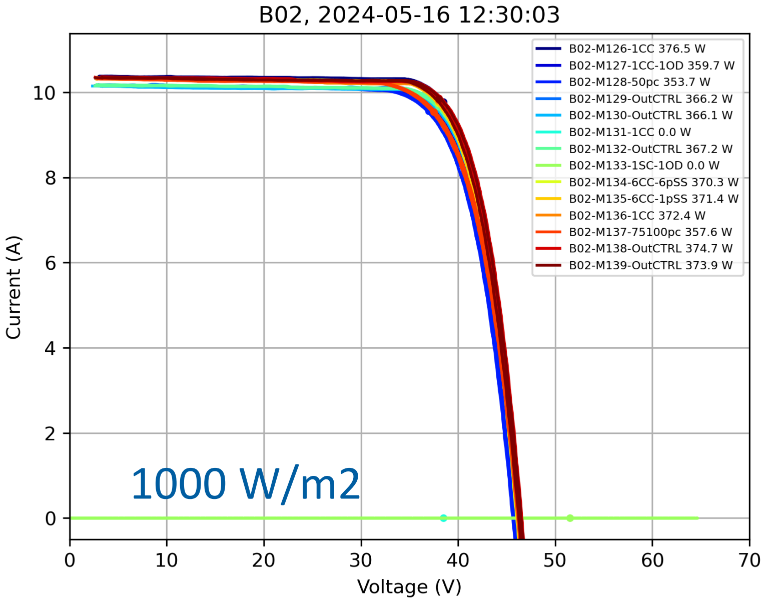
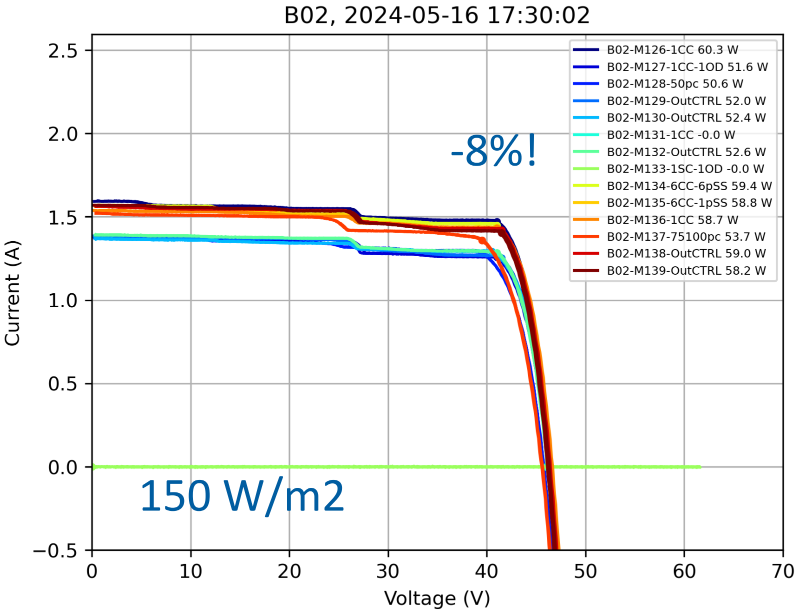
Issue (2) with IAM for energy modeling

IAM measures Isc of the "best" cell in the module, but we actually care about power, which also depends on the Isc of all the other cells in the module.







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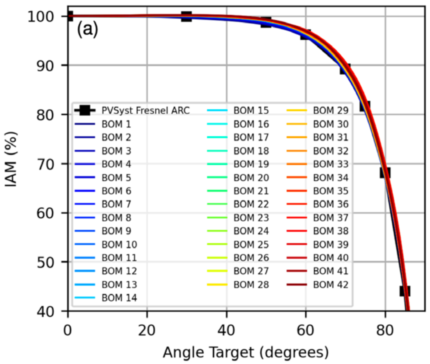
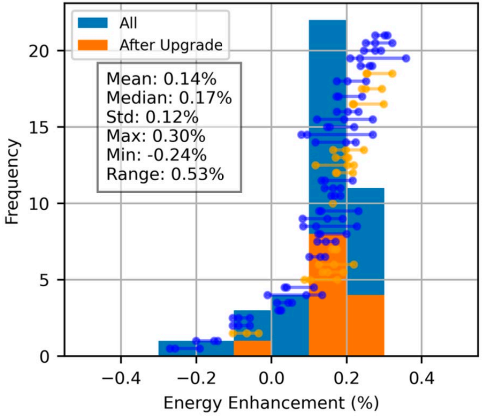
Conclusions

- Using the **most-accurate IAM test method yet reported**, we found small variability in a large survey of modern commercial modules.
- **Best to worst** IAM variation changes energy by 0.5%, so there are differences between modules.
- New **fleet average** and upper/lower bounds for energy modelers





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