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Field experience with perovskite mini-modules

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Agenda

1. **Where is UC Merced?**
2. **Analyzing perovskite mini-modules at UC Merced**
   - Cleaning outdoor data can be challenging
   - Methodology to compare modules of different electrical configuration
3. **Perovskite mini-modules showed stable performance for several months!**
   - Mini-modules sustained >80% of the rated power for 120 days.
   - Performance ratio results different from commercial Silicon technologies
4. **Takes aways for measuring perovskites mini-modules in real outdoor conditions**

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Where is UC Merced?

- Collaboration between UC-Merced and Caelux Corporation to test tandem perovskites mini-modules.
- Merced area is known for hot sunny summers and mild winters
  - During the last heat wave (September 2022) we reached a record high of 115 °F!
- UC Merced has an outdoor testing facility to measure IV parameters for long periods at a fixed tilt.

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Experiment configuration

- **Modules mounted on test rack**
  - 35° tilt south-facing
  - Cleaned two (2) times per week
- **IV Curve Monitoring with Daystar multi-tracer**
  - IV curves taken every 5 mins the using 4-wire method
  - Modules held at MPP between IV curves
  - BOM Temperature with T-type thermocouples
- **Ambient conditions tracked**
  - Irradiance, ambient temperature, wind speed, relative humidity
- **----- Perovskite Modules and ------- Silicon reference Module (presented data from this module)**

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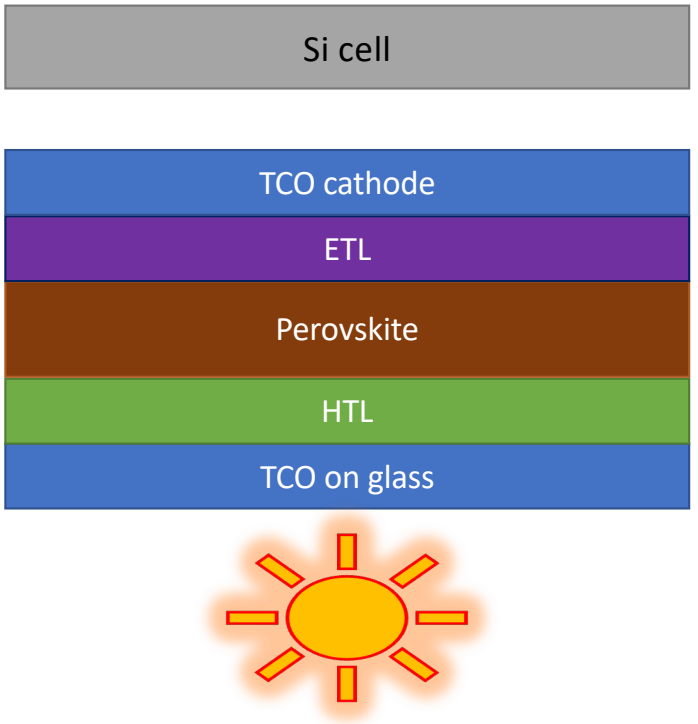
PV mini-Modules tested

- **Caelux provided mini-modules with different electrical configurations.**
  - General composition: MA chemistry with additives; Rev. B generation chemistry and encapsulation.
  - Bandgap ~1.65eV
  - Active area: 256 cm^2
  - **111** is a Tandem Mini-module (4 terminal: PVSK over Si) only perovskite measured
  - **47** is a stand-alone PVSK mini-module



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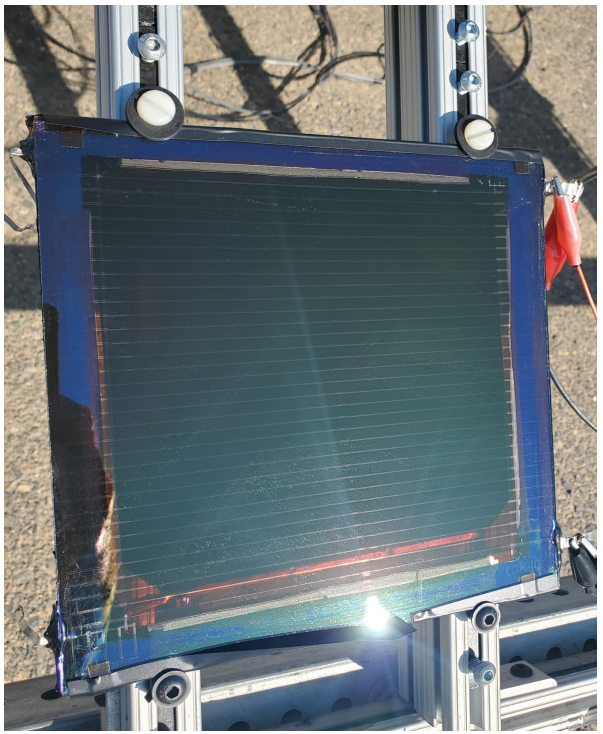
Experiment details

Experiment duration	Module ID	**111**	**47**
	Start date	2/1/2022	1/31/2022
	Days on sun	121	121
First outdoor measurement at 1 sun	BOM Temp (°C)	43	43
	Voc (V)	33.4	15.95
	Isc(A)	0.10	0.24
	FF(%)	0.55	0.42
	Pmax(W)	1.85	1.62



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Data cleaning and filtering

- **As any outdoor experiment, some of the data from the experiment turned out messy. We applied some cleaning and filtering to facilitate the data analysis and comparison of the performance.**
  - Selected measurements with irradiance values between 900-1020 W/m2 (closer to 1 sun) for temperature coefficient analysis,
  - Daily Pmax > 80% initial measurement values,
  - All the measurements before 132 days of exposure (due to material degradation),
  - Other standard data cleaning procedure (e.g., filtering outliers, disconnection, un-intentional shading)
- **We also included some of the low-irradiance data to understand the diurnal transient of the electrical parameters and the performance ratio.**

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Electrical parameter normalization

- **All electrical parameters were normalized for comparison across module configurations by using the first outdoor measurement and applying a correction for irradiance.**
  - We applied these normalization equations to all measurements extracted from the IV curve.

Measured voltage

Reference voltage

$$\bar{V}_{oc,i} = \frac{V_{oc,i}}{V_{ref}}$$

Measured current

Reference current

Reference irradiance

Measured irradiance

$$\bar{I}_{sc,i} = \frac{I_{sc,i}}{I_{ref}} \times \frac{G_{ref}}{G_i}$$

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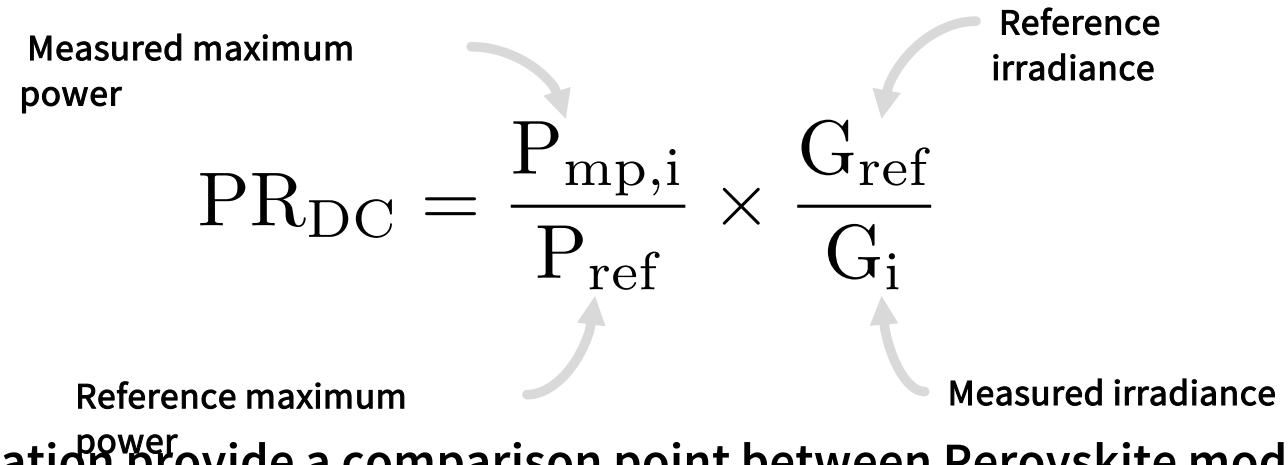
PV module performance ratio

+ The Performance Ratio (PR) calculation gives a relative efficiency for the module and helps us compare between modules of different cell configurations



+ The PR calculation provide a comparison point between Perovskite modules and Si technologies

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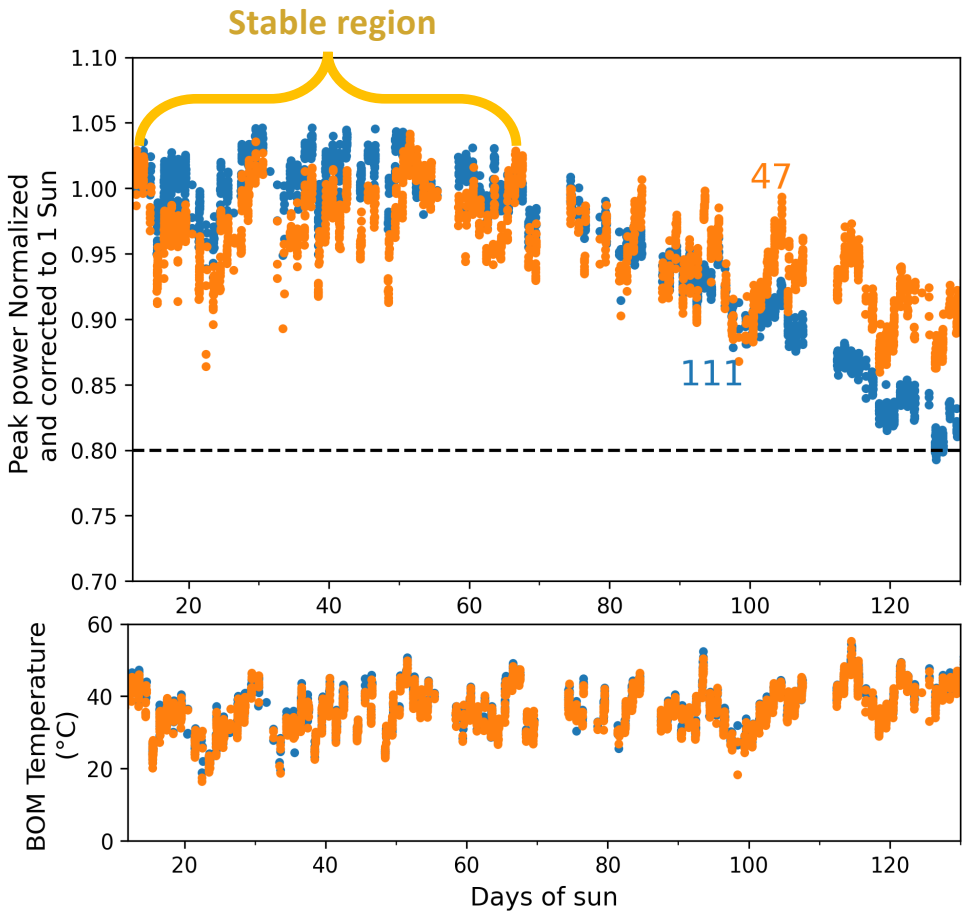
Results

Observed degradation trends

- **Modules maintained >80% of Pmax for more than 120 days of exposure**
  - Stability observed during first 60 days for both samples
  - Mini-module 111 degraded faster than 47
- **Degradation of the material made it difficult to analyze all days.**
  - We selected the 60 days (stable region) to calculate the temperature coefficients
- **Note that: Stable region has a lower ambient temperature**



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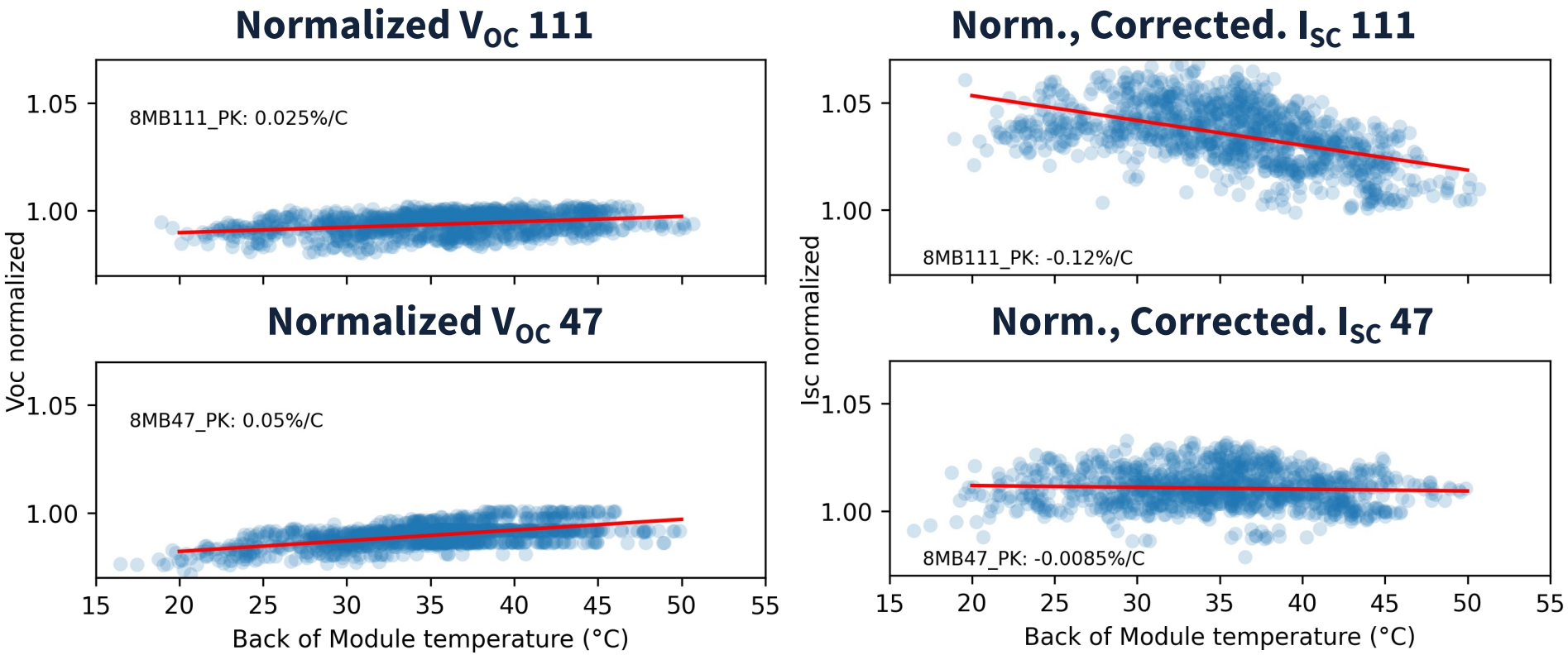
Temperature coefficients V_{OC} and I_{SC}



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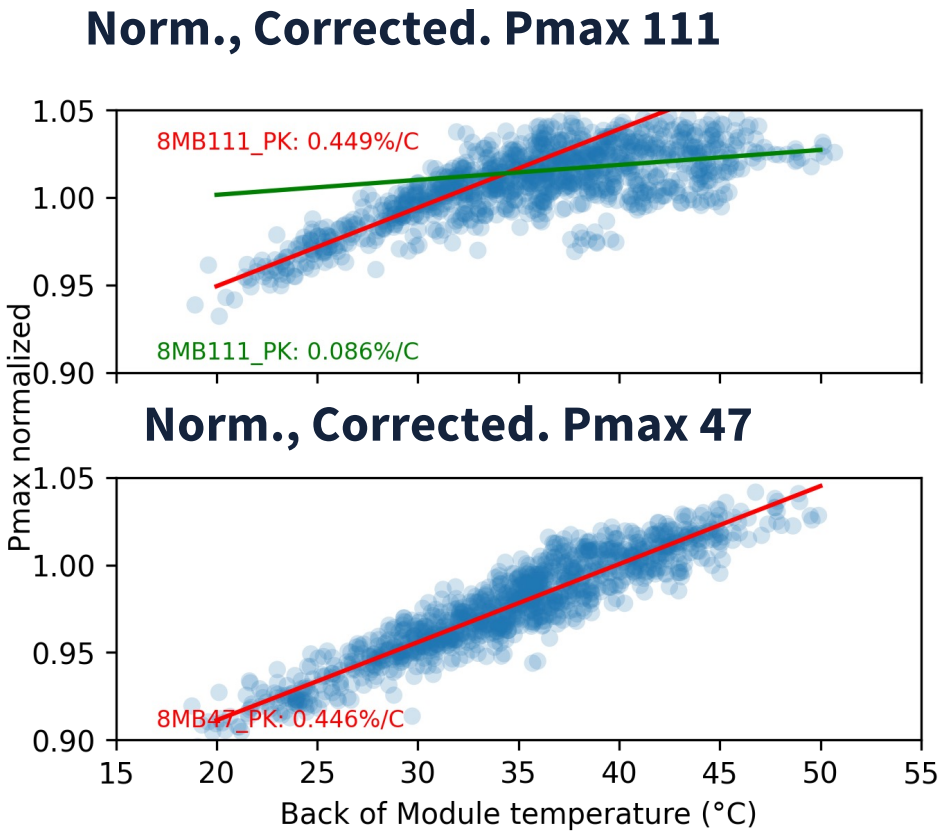
Temperature coefficients: PMAX

- Single perovskite and tandem modules have temperature coefficients contrary to silicon modules:

	Si	Pk
Voc	-	+
Isc	+	-
Pmax	-	+

- 111 and 47 has the same Pmax coefficient for low temperature and different for high temperature



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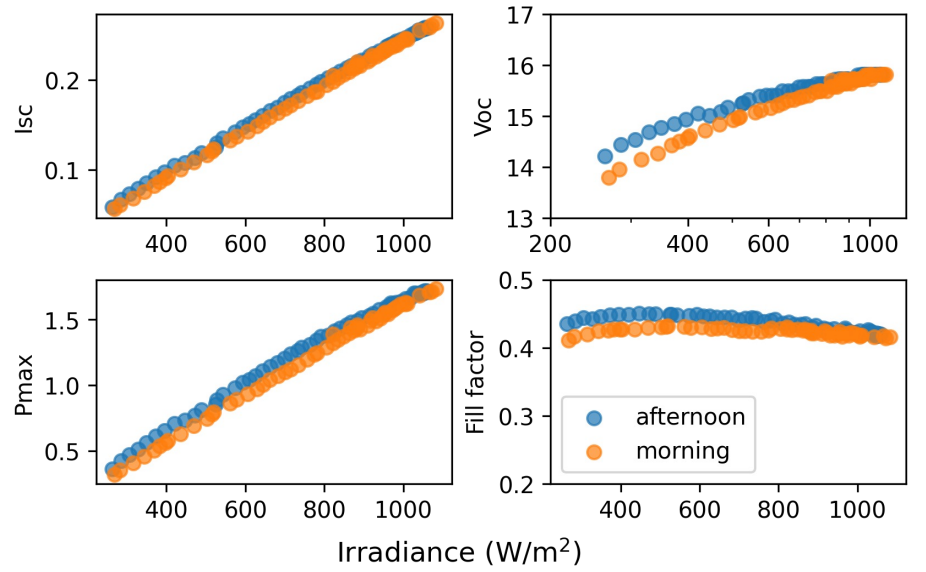
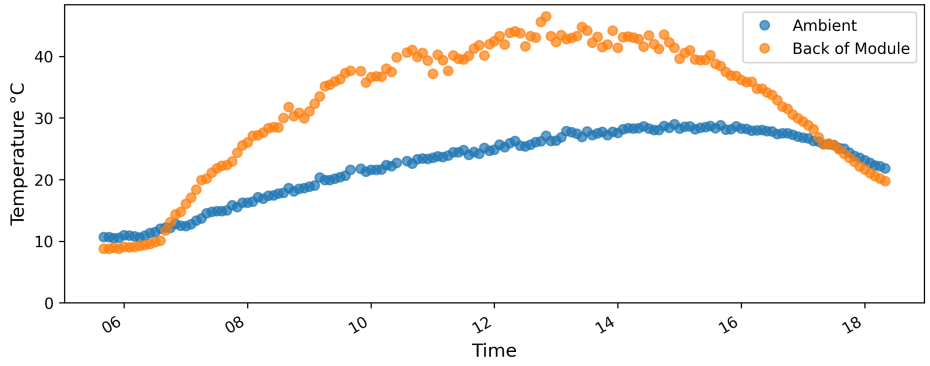
Diurnal electrical performance: March 24th, 2022

- **Module 47 (Single Perovskite)**
- **I_{sc} and Pmax showed linear dependence with the irradiance while V_{oc} has a logarithmic dependence**
  - FF is less affected by the irradiance
- **The performance of the Pk mini-module is *slightly* higher during the afternoon than during the morning.**
  - This trend is true for multiple days as it degraded.





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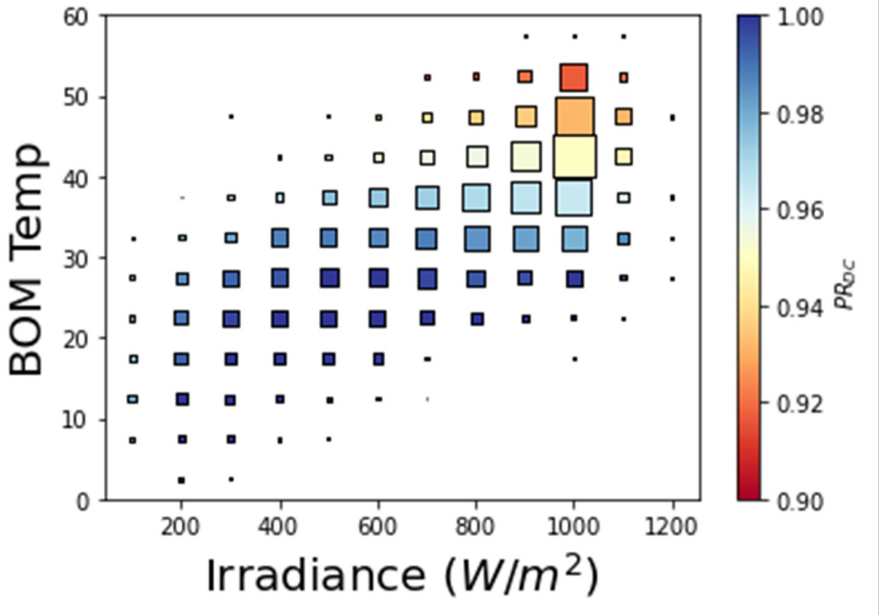
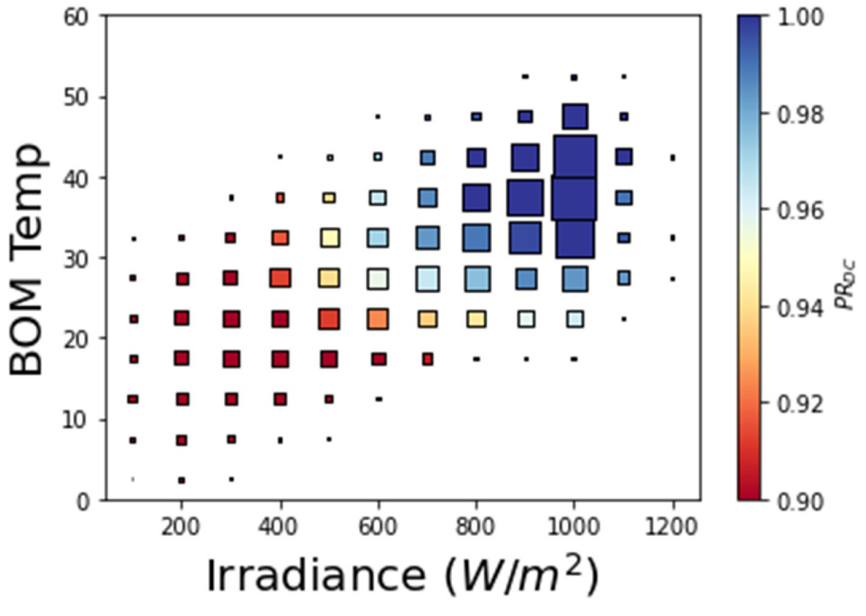
Performance ratio (matrix method)

Silicon



Perovskite



Performance ratio for Perovskite Behaves Differently than Silicon!

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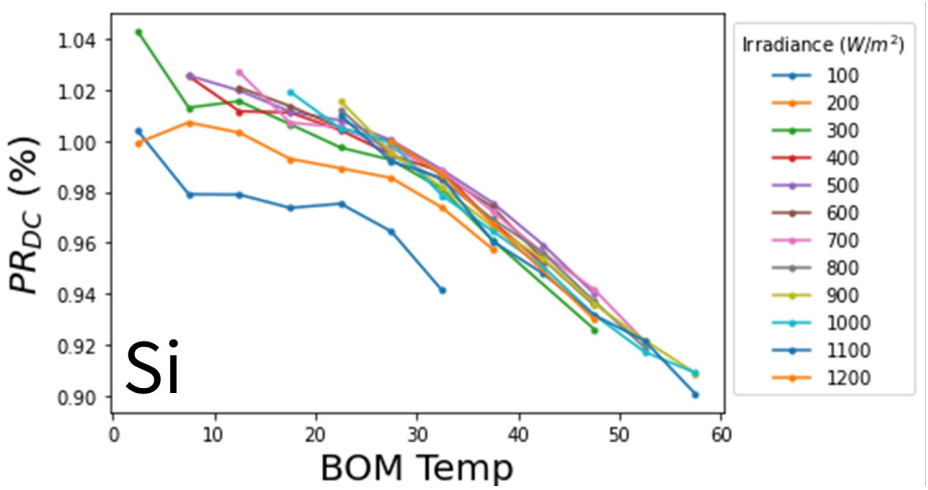
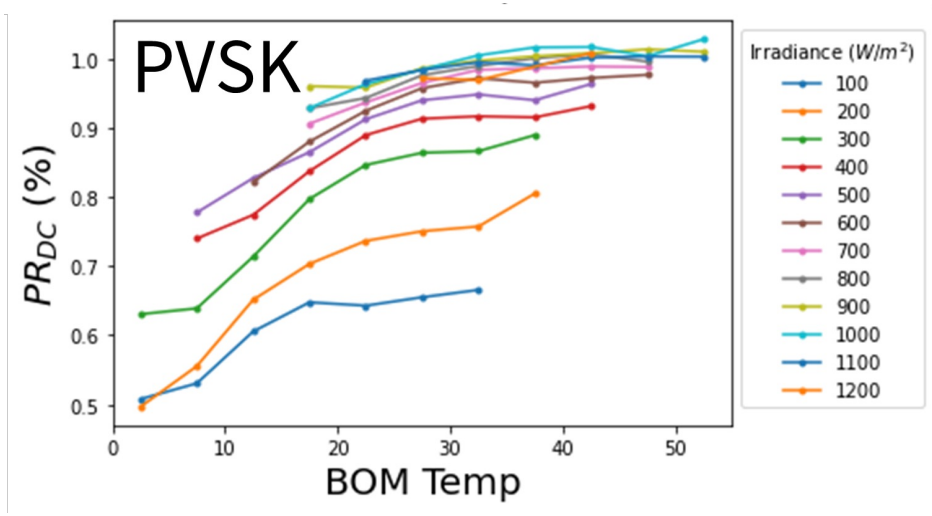
Matrix Method Results





Si PR decreases with temperature while PVSK PR increases

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Take aways

- **We were able to take “good” measurements of the perovskite material that allowed us to estimate the temperature coefficients**
  - This was during the region where modules were stable for 60 days on sun.
- **Performance ratio of the perovskite material behaves differently than Silicon!**
  - We obtained a higher performance at high temperatures opposite to typical Silicon
  - Perovskite improves at higher irradiance
  - Perovskite performance is better in afternoon than in the morning (mainly due to the Voc and the FF)
  - This results are consistent with those results presented by Mark Khenkin

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Thank you!

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