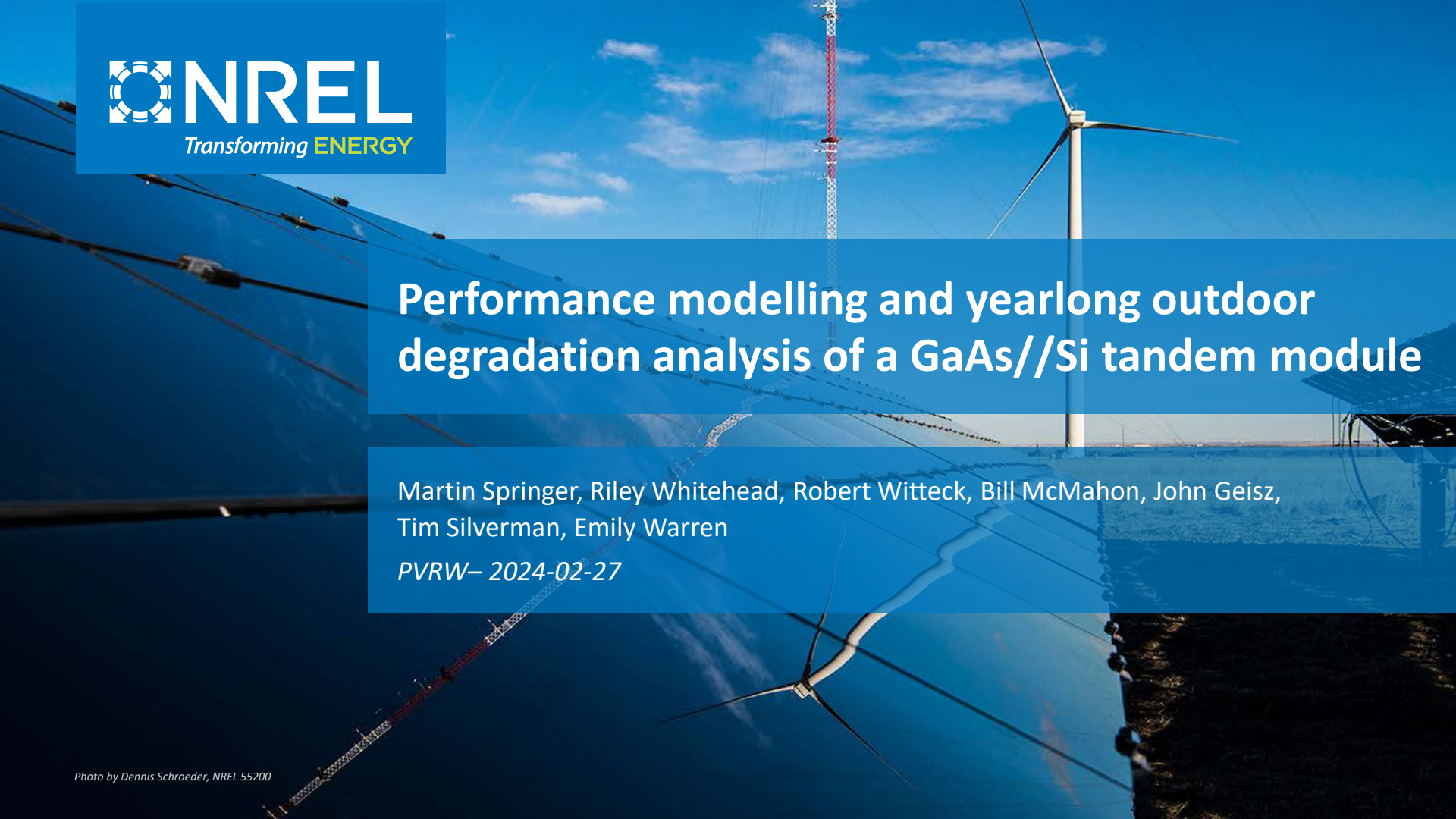


Performance modelling and yearlong outdoor degradation analysis of a GaAs//Si tandem module

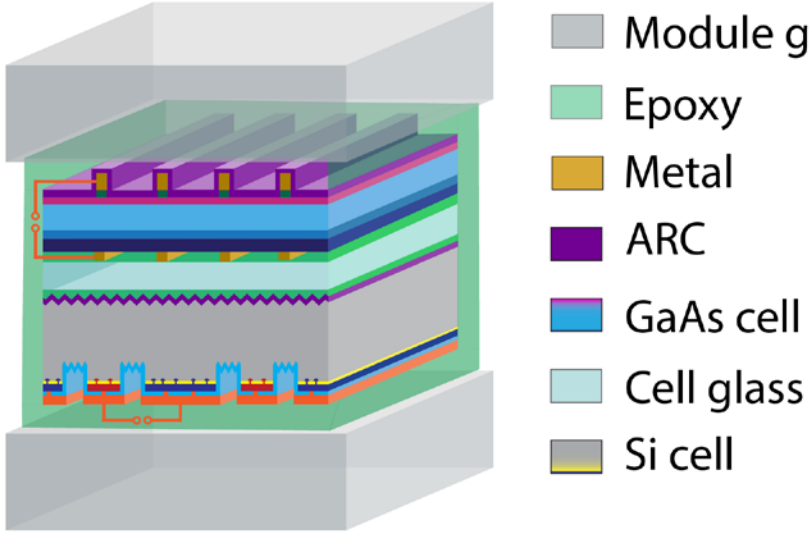
Martin Springer, Riley Whitehead, Robert Witteck, Bill McMahon, John Geisz, Tim Silverman, Emily Warren

PVRW– 2024-02-27

Photo by Dennis Schroeder, NREL 55200

Motivation

Assess the long-term, outdoor performance of a GaAs//Si module



Configuration of the GaAs//Si four-terminal, rear heterojunction tandem solar module.

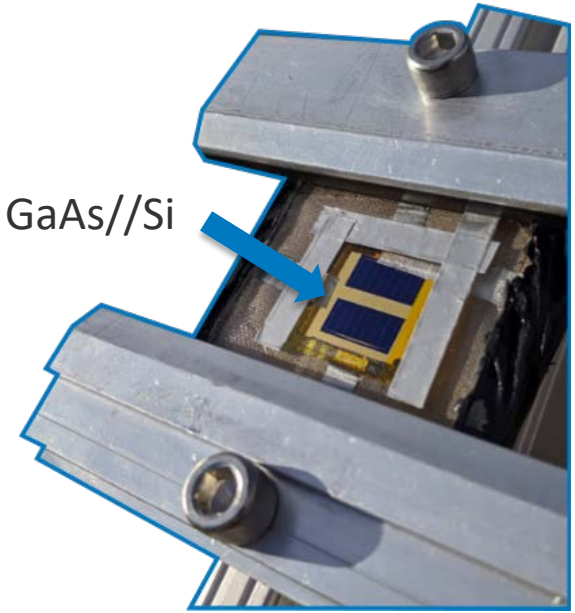


Image of fixed tilt mounting configuration

Outline

Outdoor deployment

filtering around standard test conditions

Performance metric

translation to STC and normalization

Degradation analysis

determine performance loss rate

Performance modelling

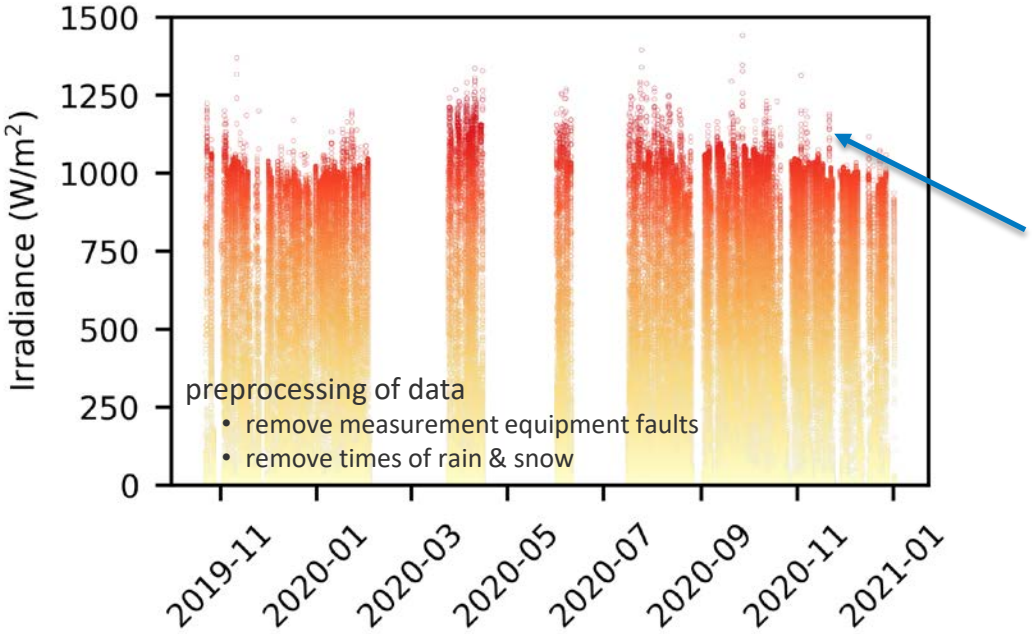
confirming failure mode hypotheses

Outdoor deployment

Outdoor Test Facility, NREL, Golden, Colorado | 40° south, fixed tilt

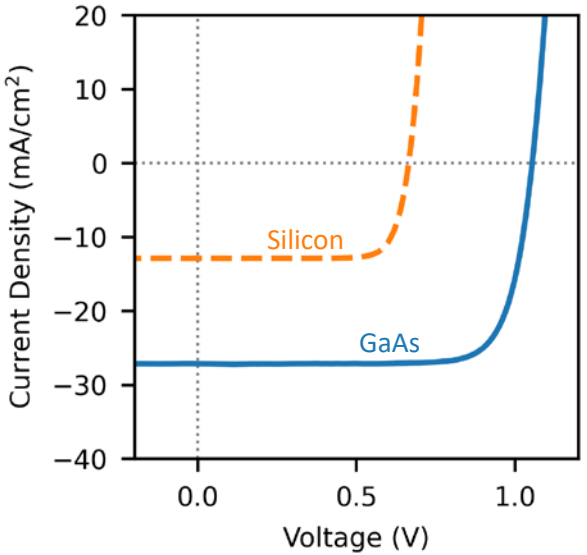
Observation timeframe

slightly over 1 year



I-V sweep nominally every 5 min

GaAs top & Si bottom cell



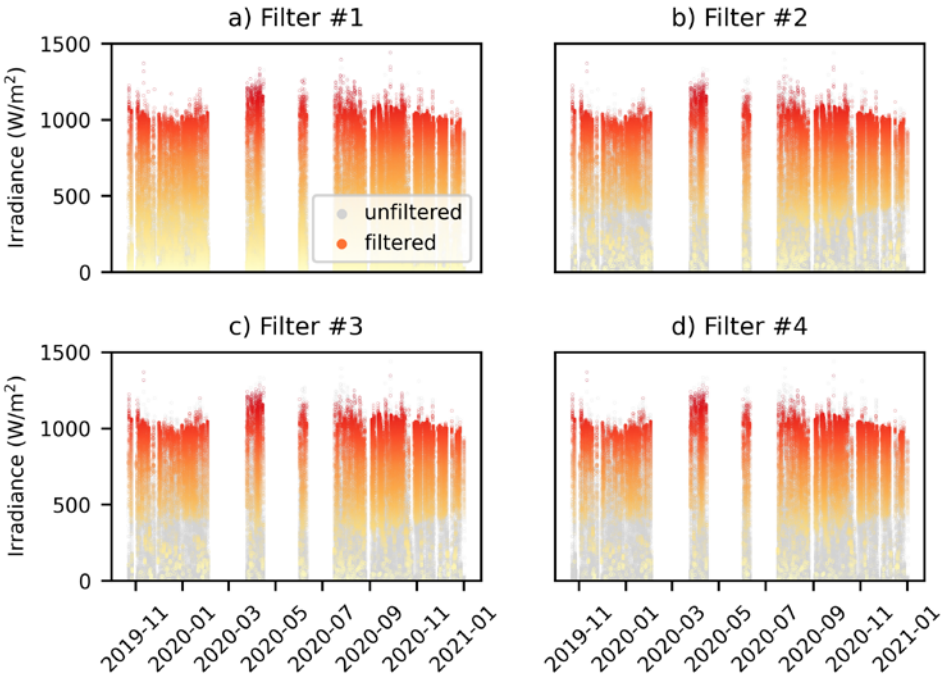
Filtering data close to STC

Reference filter set [Steiner and Siefer, 2023]

- Proposed for translation of outdoor tandem PV module I-V measurements to a STC power rating

Nr.	Filter parameter	Restriction
1	GTI variation before-after I-V sweep	≤ 1%
2	GTI min-max variation 10 min	≤ 10%
3	GTI min-max variation 30 min	≤ 40%
4	Average wind speed	0.5 – 5 m/s

GTI … Global Tilted Irradiance (W/m^2)



[Steiner and Siefer, 2023, Translation of outdoor tandem PV module I–V measurements to a STC power rating]

Filtering data close to STC

Reference filter set [Steiner and Siefer, 2023]

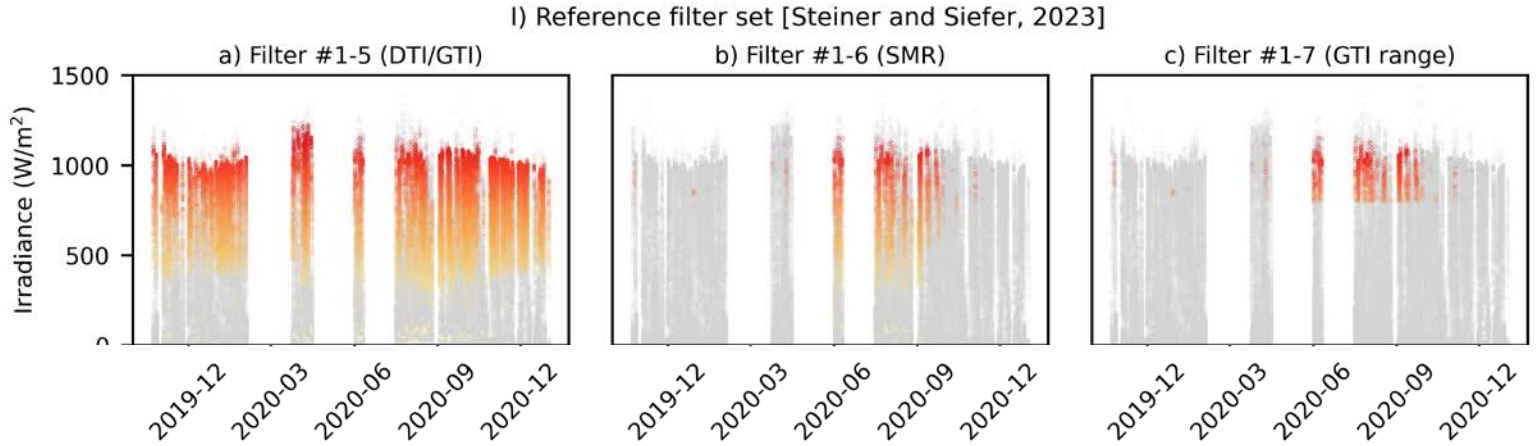
Nr.	Filter parameter	Restriction
5	DTI / GTI	> 0.8
6	Spectral Matching Ratio (SMR)	1 ± 0.03
7	GTI range (W/m²)	800-1200

GTI … Global Tilted Irradiance (W/m²)
DTI … Direct Tilted Irradiance (W/m²)

Problem with reference filter set

- filter #6 seems too strict for Golden, Co
- remaining data localized around summer/fall

Note: Reference filter set was developed for a tracked system in Freiburg, Germany.

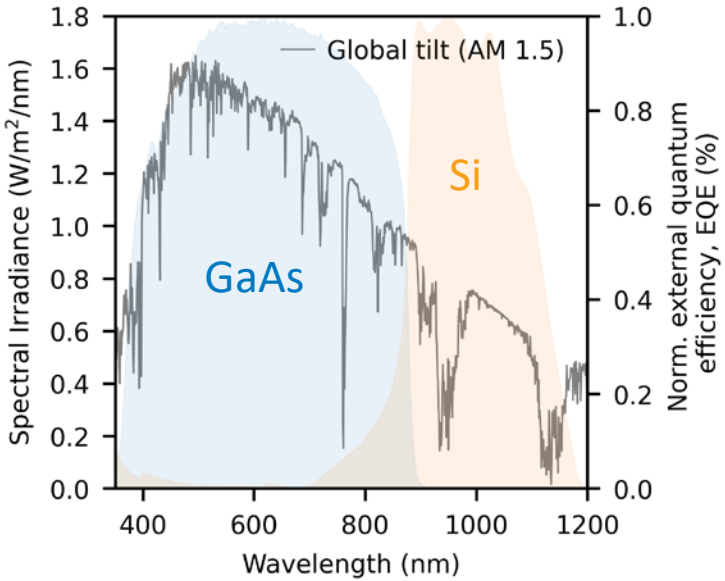


Spectral Matching Ratio (SMR)

used to quantify the impact of different spectral irradiance composition on the power output

$$\mathrm{SMR} = \frac{J_{\mathrm{sc,top}}}{J_{\mathrm{sc,bot}}} \frac{J_{\mathrm{sc,bot,ref}}}{J_{\mathrm{sc,top,ref}}}$$

measured current output current output at reference spectral irradiance (AM1.5G)

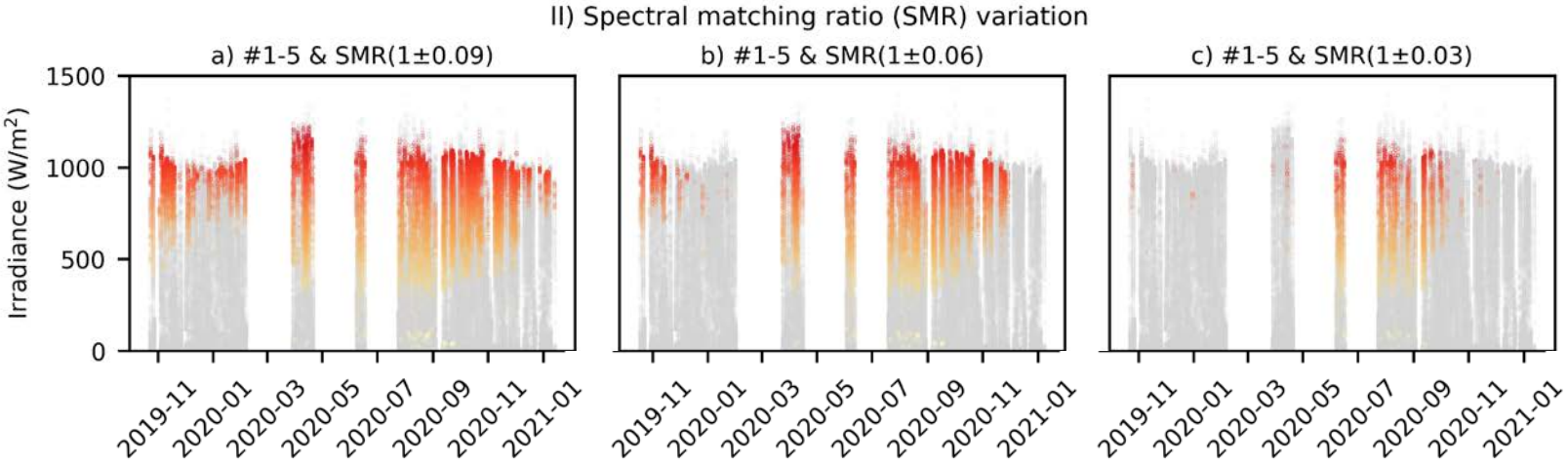


Spectral Matching Ratio (SMR)

used to quantify the impact of different spectral irradiance composition on the power output

$$\mathrm{SMR} = \frac{J_{\mathrm{sc,top}}}{J_{\mathrm{sc,bot}}} \frac{J_{\mathrm{sc,bot,ref}}}{J_{\mathrm{sc,top,ref}}}$$

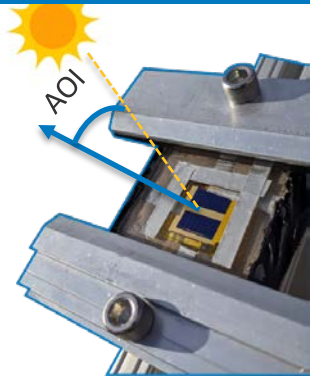
measured current output current output at reference spectral irradiance (AM1.5G)

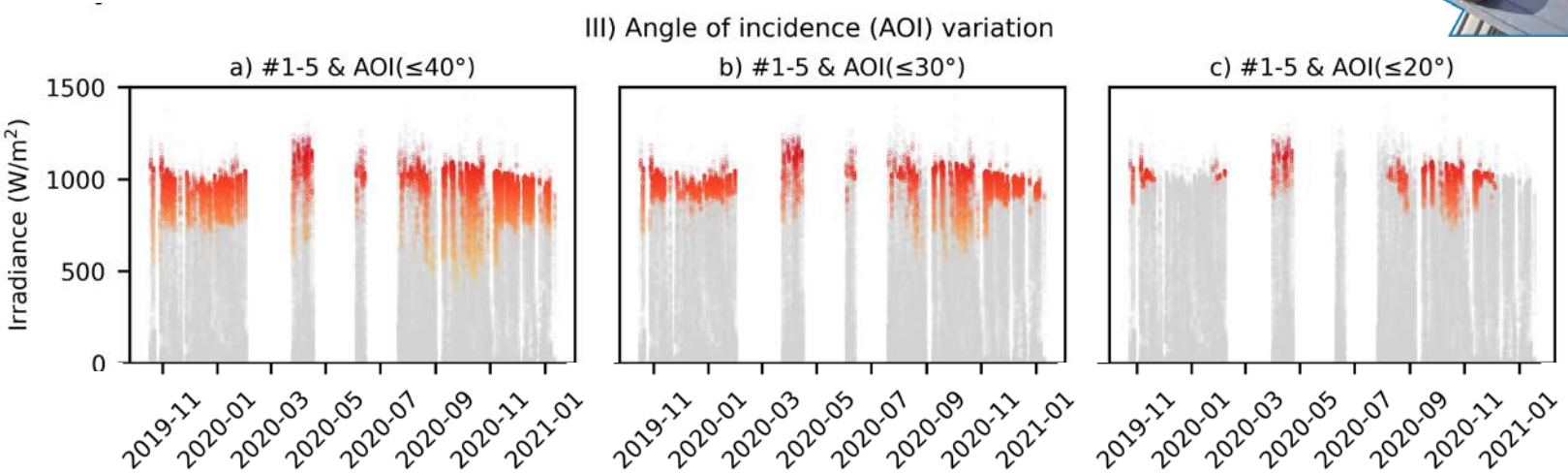


Angle of Incidence (AOI)

Reference filter set does not account for AOI

- reference filter set was developed for tracked system
- our tandem module is deployed on fixed tilt racking

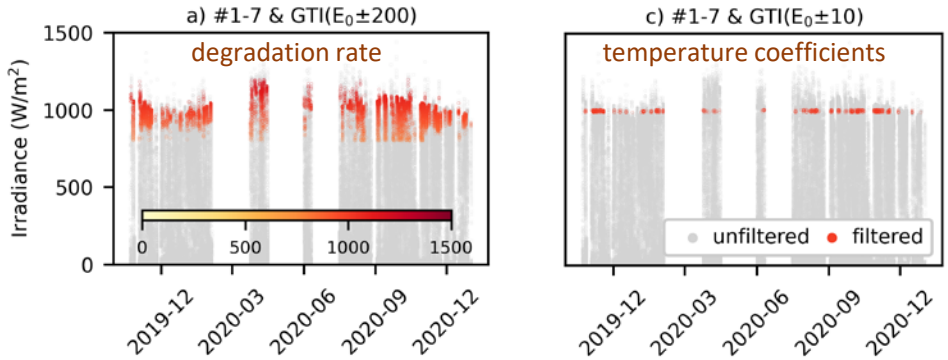


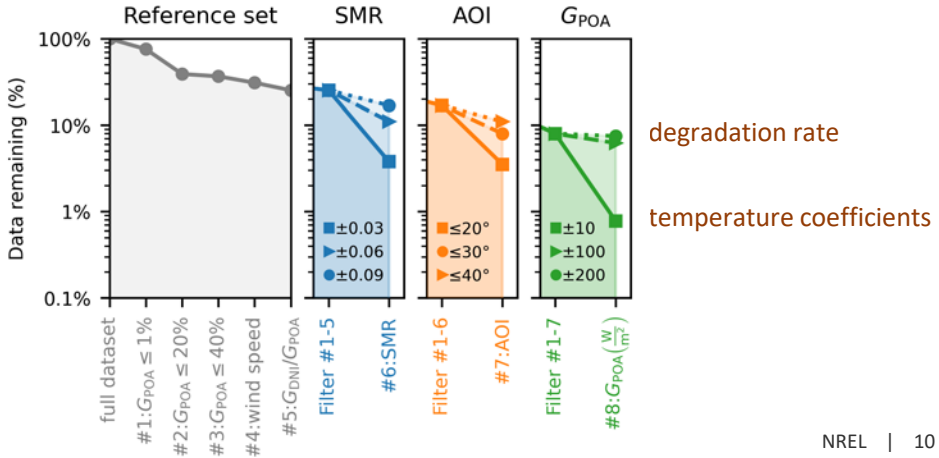


Filter set for fixed tilt system

Modified filter set

Nr.	Filter parameter	Restriction
1	GTI variation before-after I-V sweep	≤ 1%
2	GTI min-max variation 10 min	≤ 10%
3	GTI min-max variation 30 min	≤ 40%
4	Average wind speed	0.5 – 5 m/s
5	DTI / GTI	> 0.8
6	Spectral Matching Ratio (SMR)	1 ± 0.09
7	Angle of Incidence (AOI)	± 30°
8a	GTI(temperature coefficients)	E_0 ± 10
8b	GTI(degradation rate)	E_0 ± 200





Outline

Outdoor deployment

filtering around standard test conditions

Performance metric

translation to STC and normalization

Degradation analysis

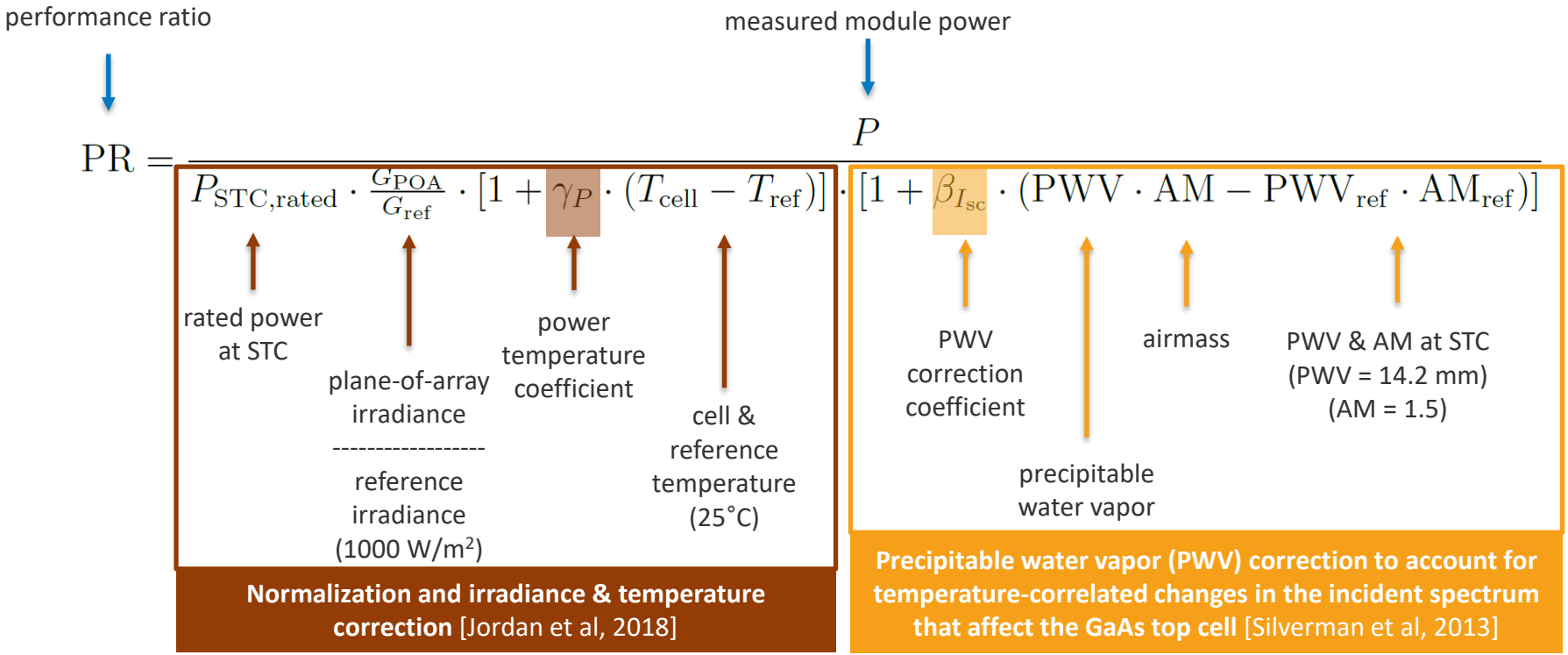
determine performance loss rate

Performance modelling

confirming failure mode hypotheses

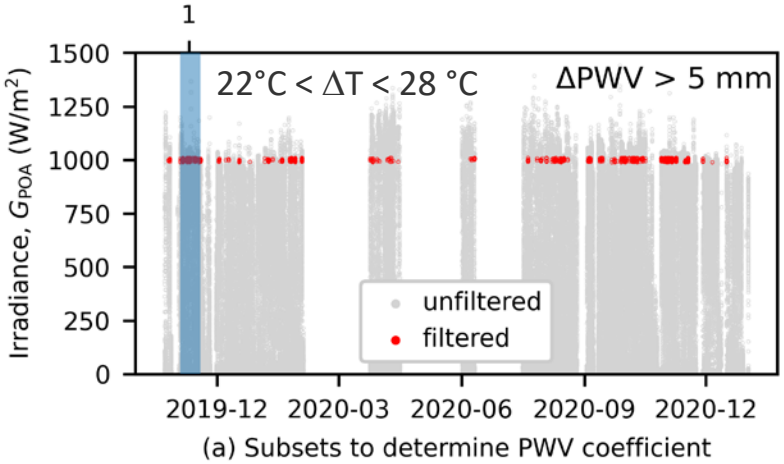
Performance metric for degradation analysis

unitless performance ratio (PR)

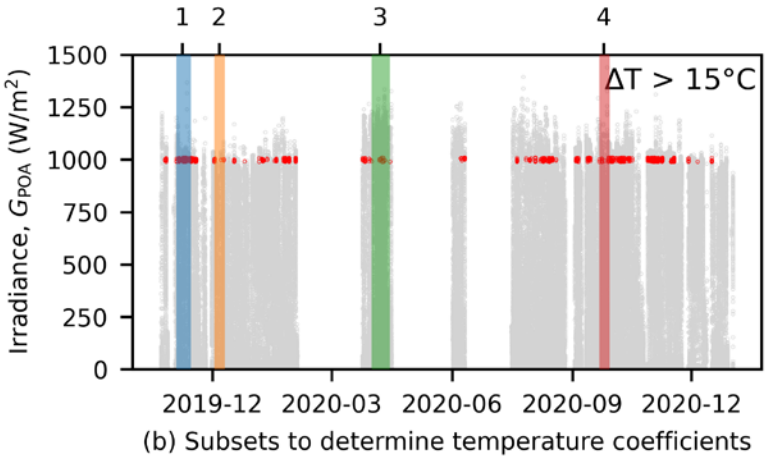


Temperature & spectral correction coefficients

Challenges	Solutions
• dedicated thermal transient measurements not available	• coefficients calculated from outdoor time-series data
• spectral effects and temperature effects need to be decoupled	• used a simple correction based on precipitable water vapor (PWV) and airmass (AM)
• device degradation must not affect coefficient determination	• use subsets with sufficient variation to determine the coefficients

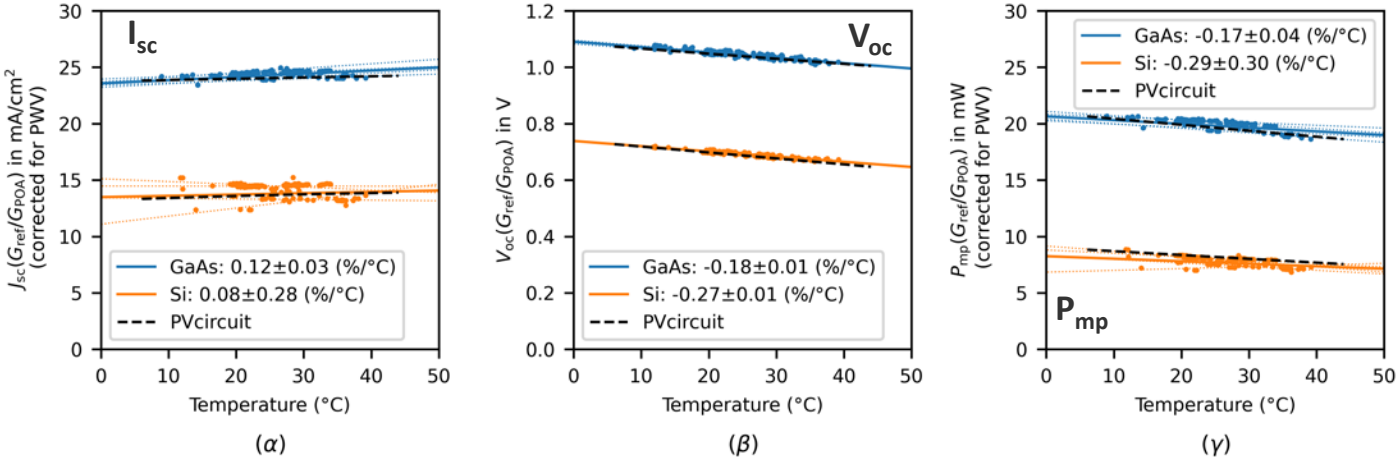


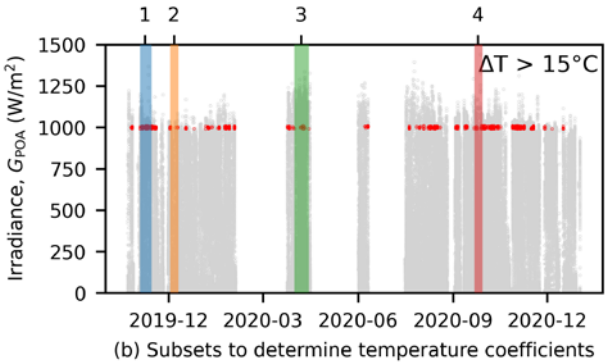
(a) Subsets to determine PWV coefficient



(b) Subsets to determine temperature coefficients

Temperature coefficients





	GaAs		Si		
	Outdoor	Model	Outdoor	Model	Units
$\alpha_{I_{sc}}$	0.12±0.03	0.05	0.08±0.28	0.11	%/°C
$\beta_{V_{oc}}$	-0.18±0.01	-0.17	-0.27±0.01	-0.30	%/°C
$\gamma_{P_{mp}}$	-0.17±0.04	-0.17	-0.29±0.30	-0.30	%/°C
β_{PWV}	0.15	N/A	-0.05	N/A	%/mm

Outline

Outdoor deployment

filtering around standard test conditions

Performance metric

translation to STC and normalization

Degradation analysis

determine performance loss rate

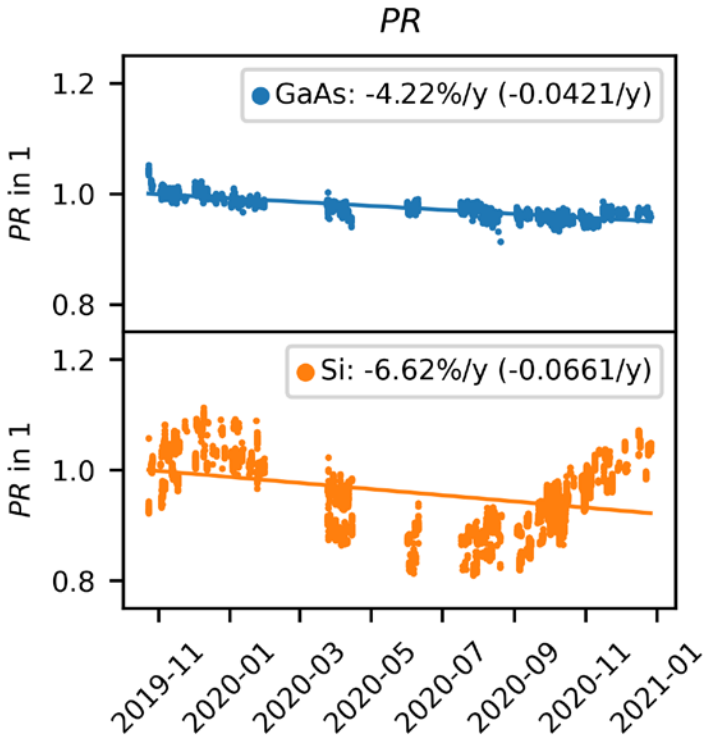
Performance modelling

confirming failure mode hypotheses

Performance loss rate

Regression analysis

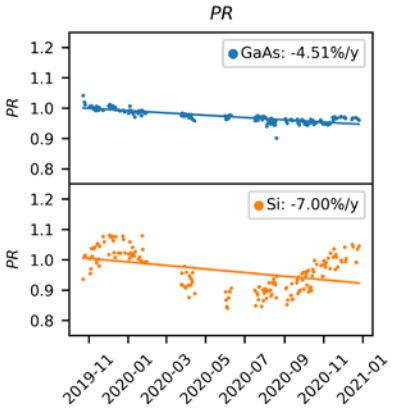
- Theil–Sen estimator
- fit over whole observation time frame

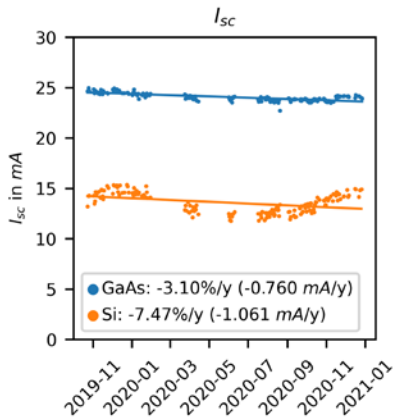


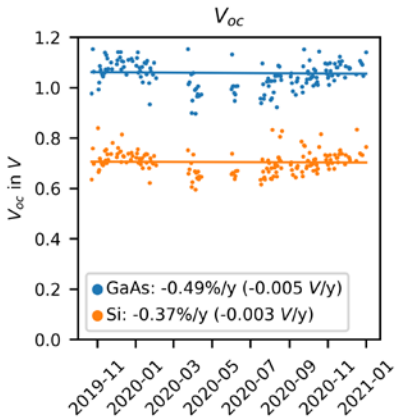
Aggregated degradation analysis

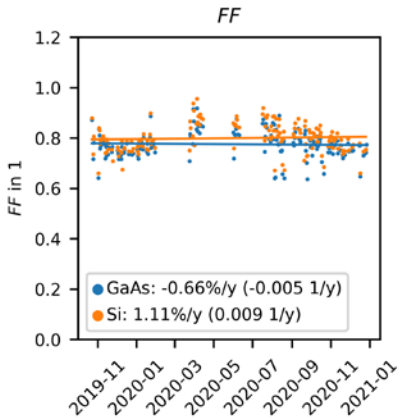
Improvements

- 1-day insolation weighted aggregation of data





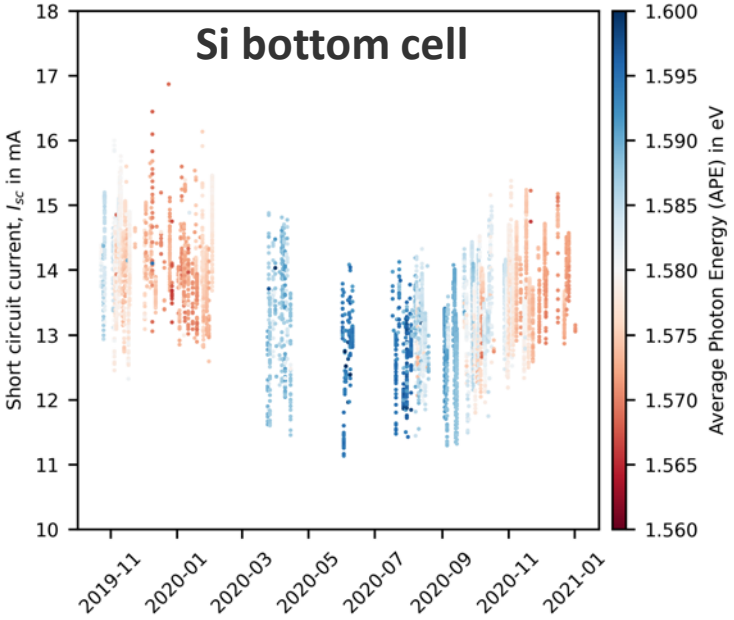




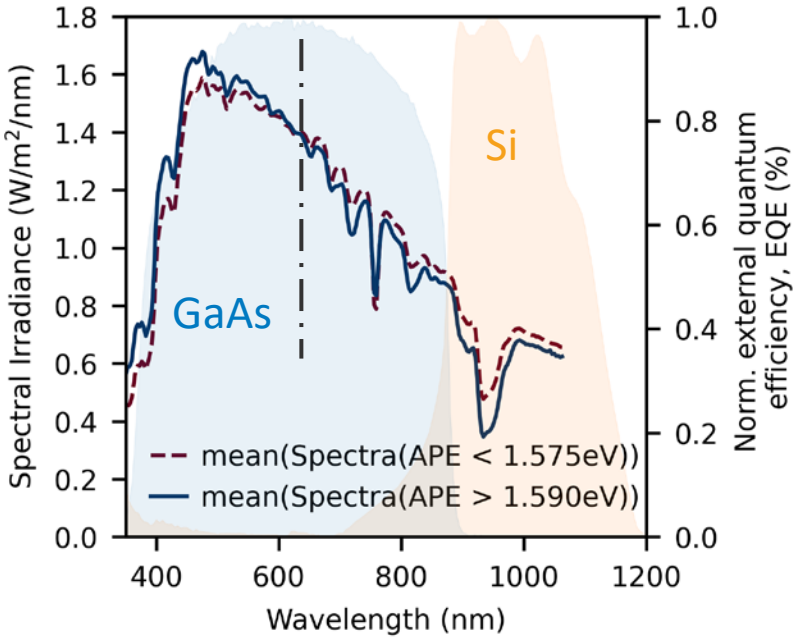
RdTools

Seasonal spectrum change

blue-shift during summer



"mean spectra summer / winter"



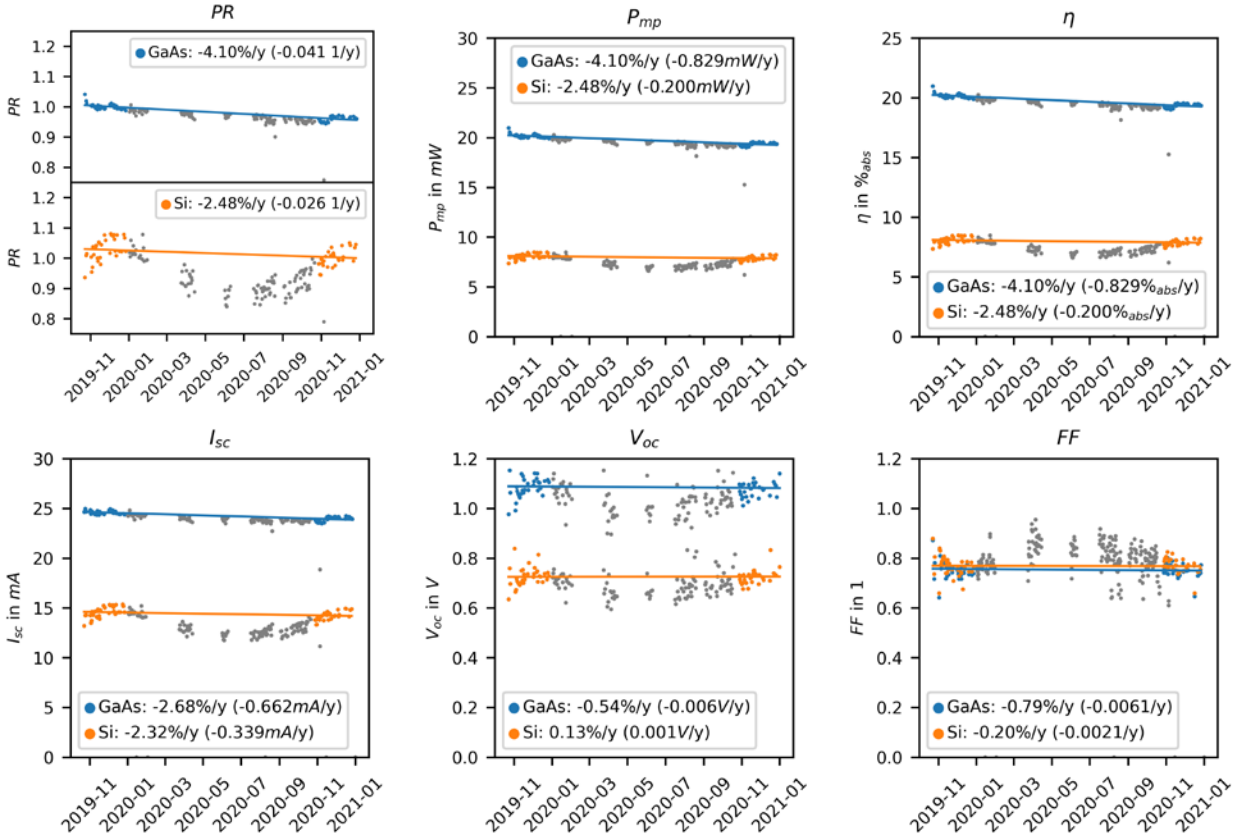
Aggregated degradation analysis

Improvements

- 1-day insolation weighted aggregation of data
- mask the overlapping month in 2019 & 2020

→ *"winter degradation rate"*

Degradation hypothesis
→ delamination in module packaging



Outline

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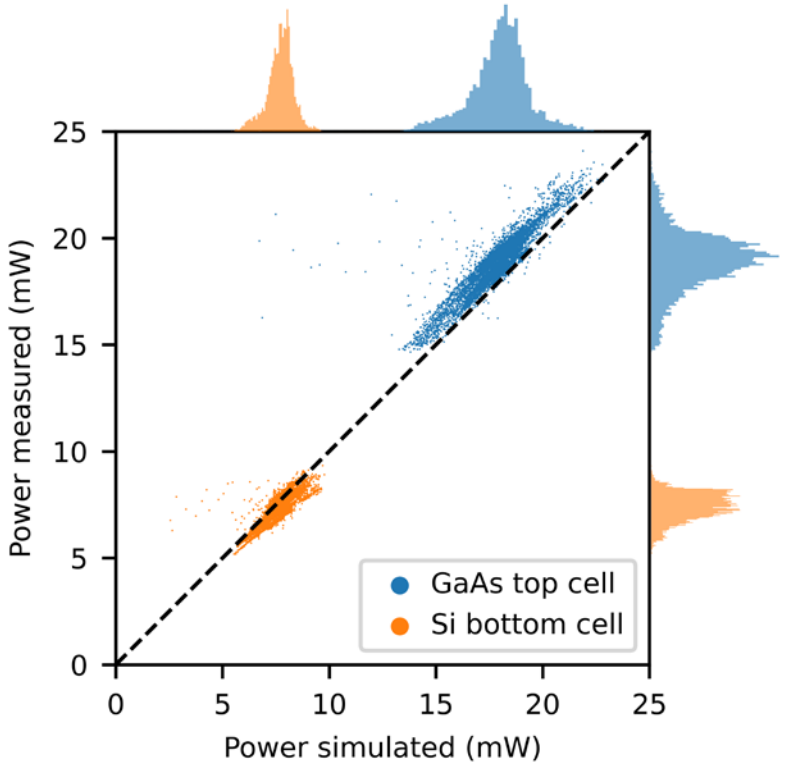
Performance modeling

PVCircuit

open-source Python library for optoelectronic modeling of tandem/multijunction solar cells

- measured J_{sc} data as model input
- cell or packaging degradation not accounted
- simulated and measured power data are in good agreement

→ **reduction in the J_{sc} explains performance degradation**
→ **aligns with the identified delamination failure mode in the module packing that reduces J_{sc}**



Conclusion

Summary

- GaAs//Si tandem module deployed outdoors for **14 month**
- filtered data for outdoor conditions close to STC
- corrected for irradiance, temperature, precipitable water vapor, air mass
- still ended up only with a "***winter degradation rate***"

Takeaways

- **2+ years of outdoor data** would be optimal for degradation analysis
- *(or better spectral correction)*

Manuscript in preparation

Springer et al. "Performance modelling and yearlong outdoor degradation analysis of a GaAs//Si tandem module"

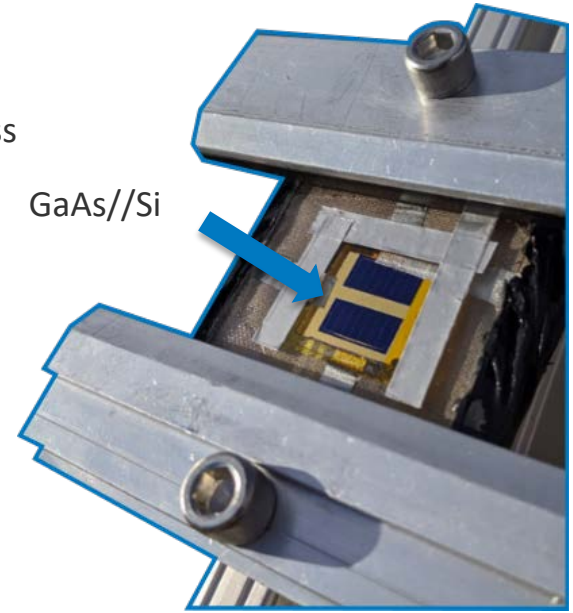


Image of fixed tilt mounting configuration

Thank you!

Contact: Martin Springer | Martin.Springer@nrel.gov

NREL/PR-5K00-89010

Acknowledgements

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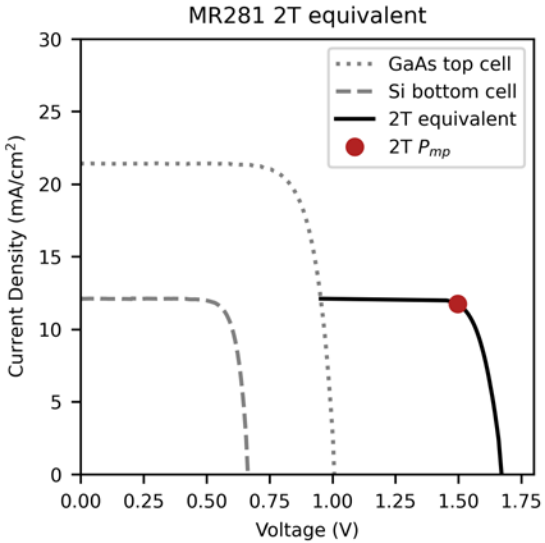
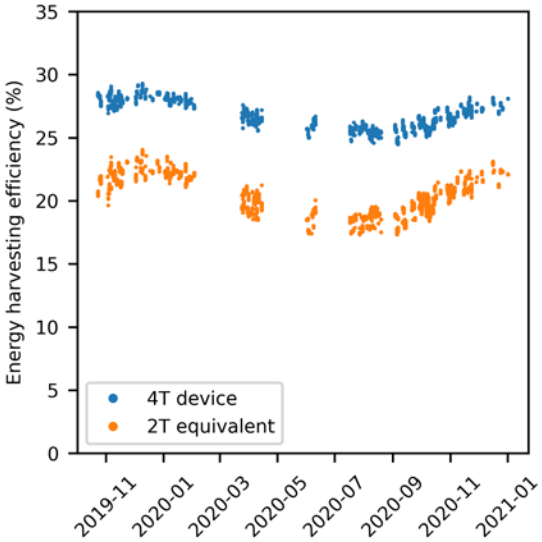
Appendix

Energy harvesting efficiency 2T vs. 4T

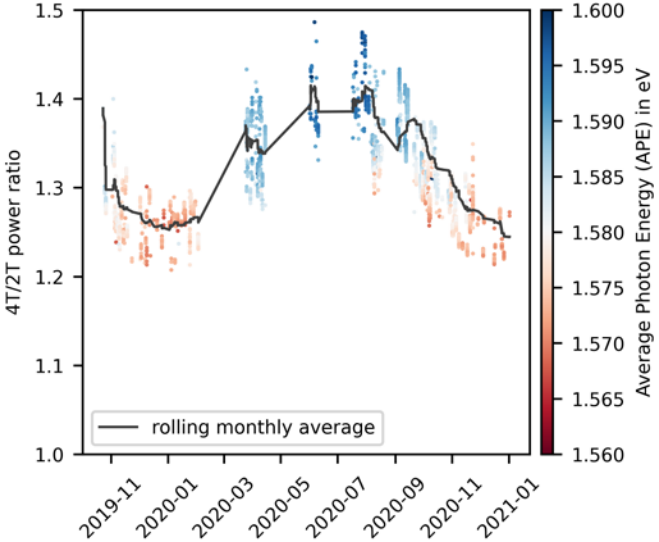
2T equivalent JV



EHE



Power ratio



Spectral Matching Ratio (SMR)

used to quantify the impact of different spectral irradiance composition on the power output

SMR can be obtained from

1) component cell* measurements

$$\mathrm{SMR} = \frac{J_{\mathrm{sc,top}}}{J_{\mathrm{sc,bot}}} \frac{J_{\mathrm{sc,bot,ref}}}{J_{\mathrm{sc,top,ref}}}$$

measured current output

current output at reference spectral irradiance (AM1.5G)

**component cells are defined as cells, which are optically (absorption and transmission) equivalent to the whole multi-junction cell but electrically behaving as one of the multi-junction's sub cells.*

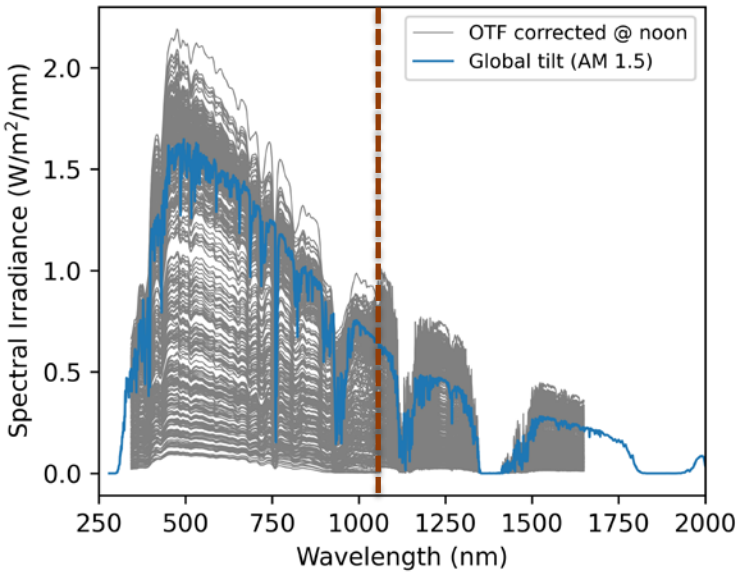
2) spectroradiometer readings

$$\mathrm{SMR} = \frac{\int E(\lambda)\,\mathrm{SR}_{\mathrm{top}}(\lambda)\,\mathrm{d}\lambda}{\int E(\lambda)\,\mathrm{SR}_{\mathrm{bot}}(\lambda)\,\mathrm{d}\lambda} \frac{\int E_{\mathrm{ref}}(\lambda)\,\mathrm{SR}_{\mathrm{bot}}(\lambda)\,\mathrm{d}\lambda}{\int E_{\mathrm{ref}}(\lambda)\,\mathrm{SR}_{\mathrm{top}}(\lambda)\,\mathrm{d}\lambda}$$

**only the Global 40-South Spectral Data (OTF) spectroradiometer readings were available for the investigated time frame. This sensors cuts off at 1050 nm.*

OTF Spectrometer correction

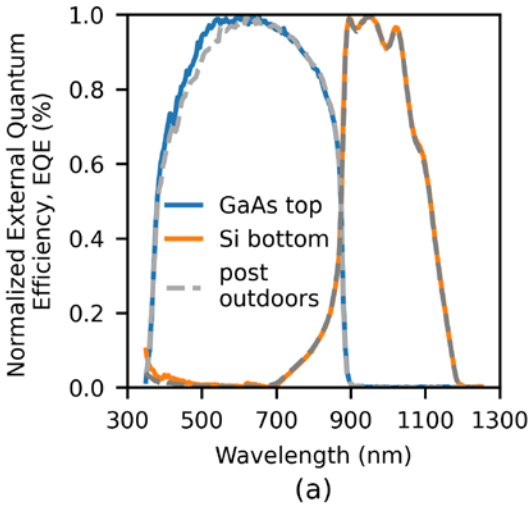
The new SRRL Global 40-South sensor makes this correction obsolete for time series analysis after 04/28/2022.



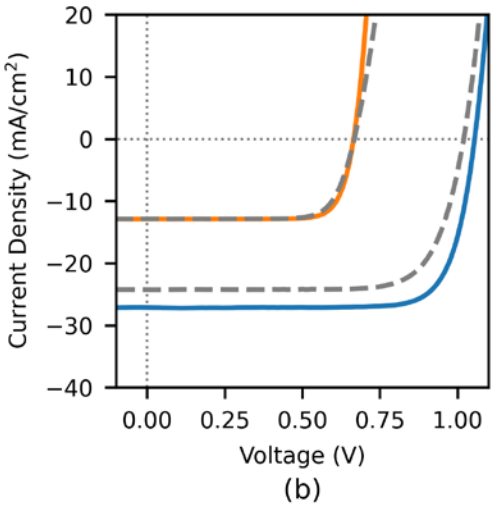
Simulator performance characterization

Module measured at one-sun under the AM1.5G spectrum

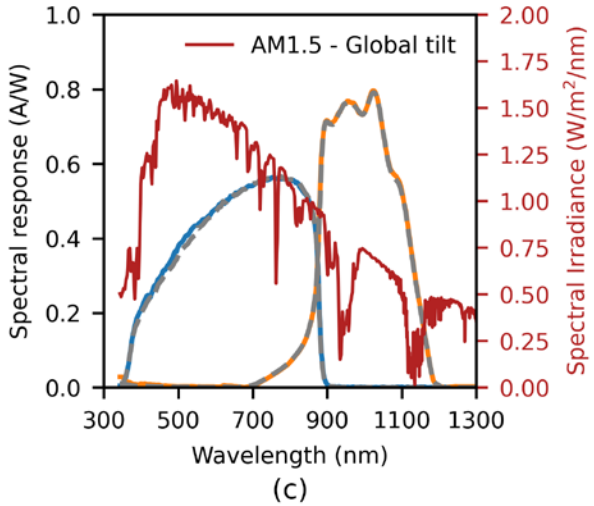
EQE



J-V



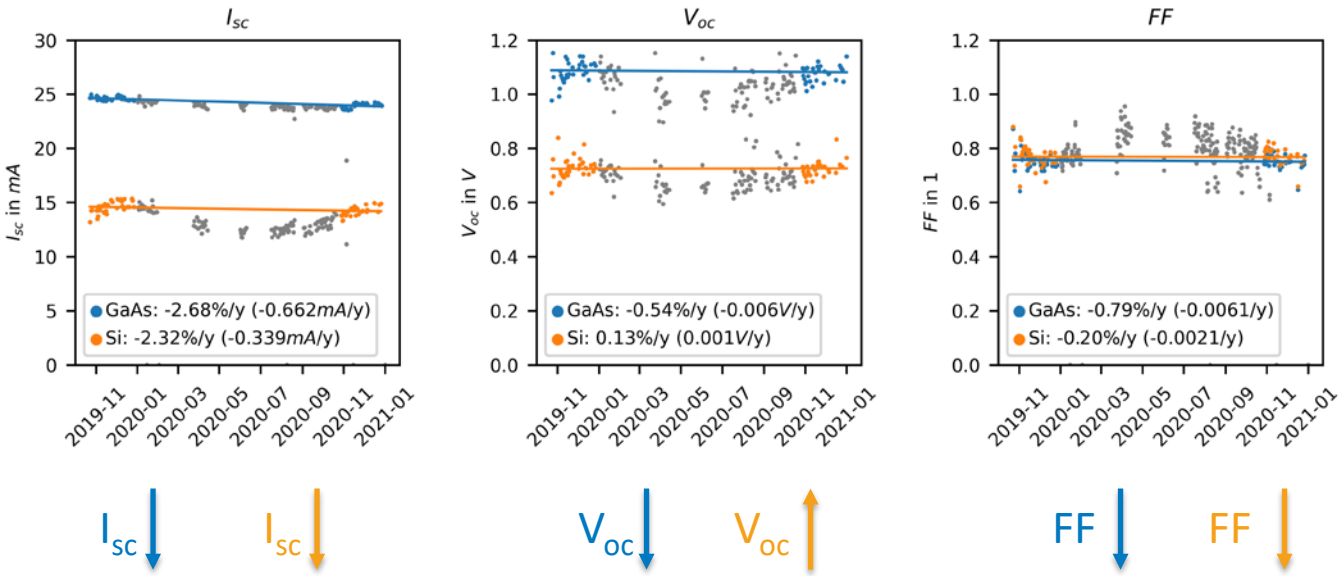
SR



$$\mathrm{SR} = \frac{q\lambda}{hc}\mathrm{EQE}$$

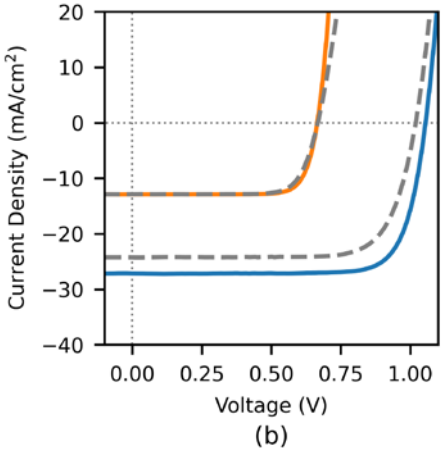
Comparison outdoor analysis vs. simulator

Outdoor analysis



I_{sc} ↓ I_{sc} ↓ V_{oc} ↓ V_{oc} ↑ FF ↓ FF ↓

Lab measurements



trend ✓