



Technical Considerations for Commercializing Perovskite Photovoltaic Modules – A review of observations from the PACT Center

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2022 DOE Performance Targets for Perovskite PV Modules



Revised Performance Target Matrix:

Configuration	Aperture Area PCE ¹	Total Module Area ²	Durability	Sample Population Requirements
Single Junction	18% PCE	>=500 cm ² with at least 4 interconnected cells	Pass IEC 61215 Module Quality Test (MQT) 10, 11, 13 and 21 and ISOS-L-2 at specified durations with <10% relative performance loss per test ³	>1 kW total, at least 20 modules for outdoor testing ⁵
PVSK-only Tandems	24% PCE			
Hybrid Tandems	27% PCE		6 months continuous outdoor testing with <3% relative degradation overall and <1% degradation in the final 3-month span ⁴	



What is PACT?

PV accelerator for commercial technologies (PACT) is an independent validation center that is **developing methods** to objectively **evaluate** the **performance and reliability** to improve **understanding** of and confidence in fielded performance and **failure modes** of emerging PV technologies.

We can test your perovskites, tandems, OPV etc
Services include:

- Field testing
- Indoor preconditioning protocol development
- Indoor accelerated testing (in support of qualification test protocol development)
- Detailed root cause failure analysis

- Jinsong Huang, UNC
- Chengbin Fei, UNC
- Xiaoqiang Shi, UNC
- Prem Rana, UNC
- Zhaoning Song, UToledo
- Michael Heben, UToledo
- Yanfa Yan, UToledo
- Tao Zhu, UToledo
- Devin MacKenzie, UW
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- David Ginger, UW
- Reinhold Dauskardt, Stanford
- Austin Flick, Stanford
- Abby Carbone, Stanford
- Wanyi Nie, LANL
- Ralph Romero, B&V
- Rob Foree, B&V
- Cara Libby, EPRI
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- Jim Crimmins, CFV
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- James Richards, CFV
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Leadership Team



Joshua Stein
Director, Sandia



Laura Schelhas
Deputy Director,
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Bruce King
Performance Lead
Sandia



Academic, Lab, Industry Partners

University of Toledo (Past) University North Carolina (Past) CFV Labs (Past)
University of Washington (Past) Stanford University/SLAC (Past) EPRI (Past)
Black and Veatch (Past) Los Alamos National Lab (Past) + many unnamed companies

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- Ingrid Repins, NLR
- Nick Irvin, NLR
- Rachael Arnold, NLR
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- Angelique Montgomery, Sandia
- Charles Robinson, Sandia
- Dan Riley, Sandia
- Norman Jost, Sandia





Highlights



- Over 980 modules received by PACT to date
 - 171 Batches: no known or intentional differences
 - >500 University/labs, >480 industry
 - ~ 360 modules field tested
 - 20 partners supplying modules (10 University/Lab & 10 industry)
 - Including international providers
 - Module size from ~10 cm² to >8,000 cm²
 - Varying compositions/stacks (6 OPVs)
 - Including tandems (MHP/Si, MHP/MHP)
 - 2T (93), 4T (48)

“Developing a Stress Testing Protocol for >1 Year of Outdoor Operation for Metal Halide Perovskite PV Modules” Michael Owen-Bellini et al., **Thursday 10:45 AM Area 6: Perovskite Stability and Commercialization session**

Test locations: Sandia (New Mexico, USA) – Latitude-tilt & two-axis tracking
NREL (Colorado, USA), –Seasonally-adjusted fixed tilt

Partners

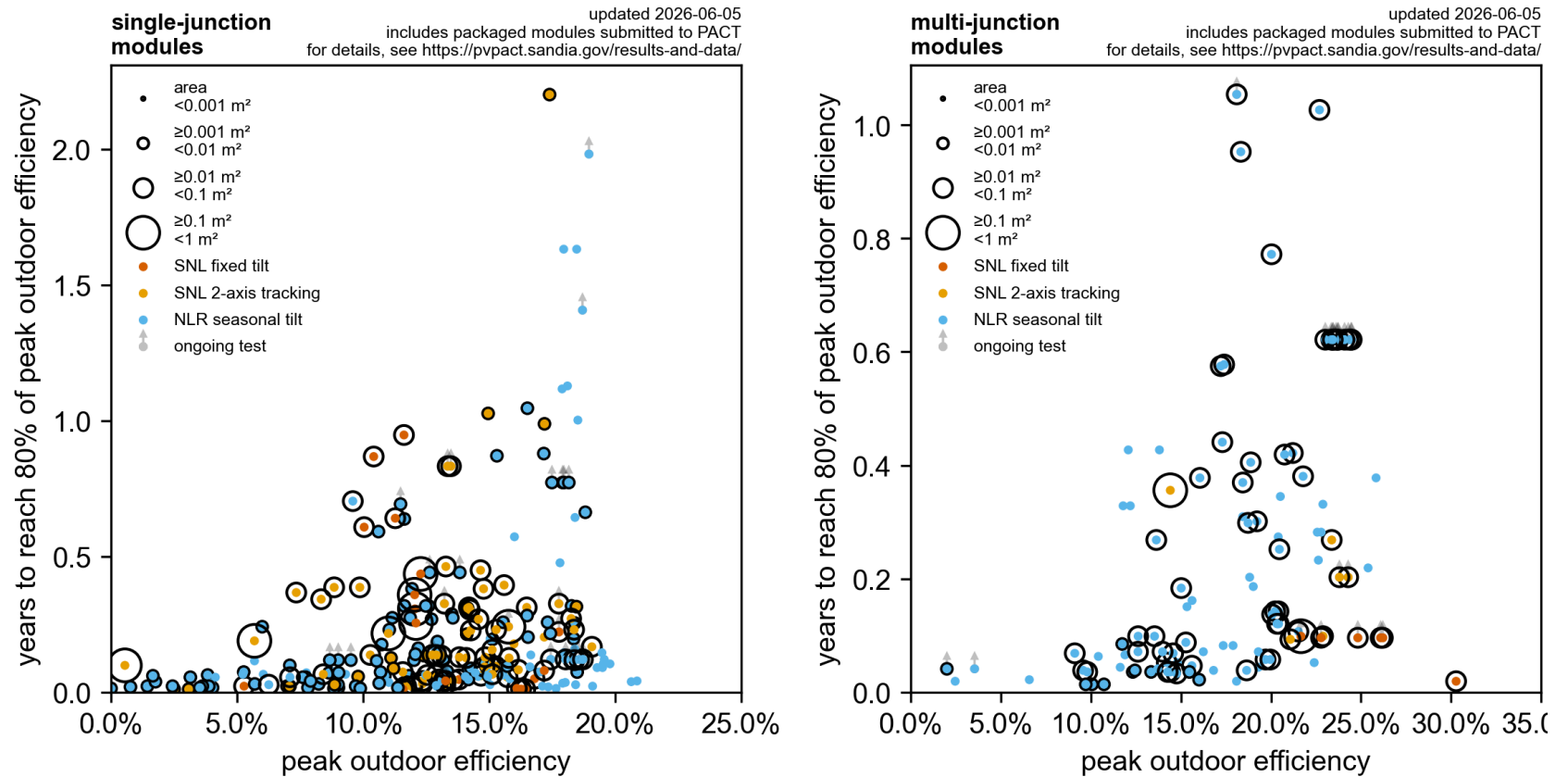


Total of 20 partners (8 of which have chosen to share that they are testing with PACT)

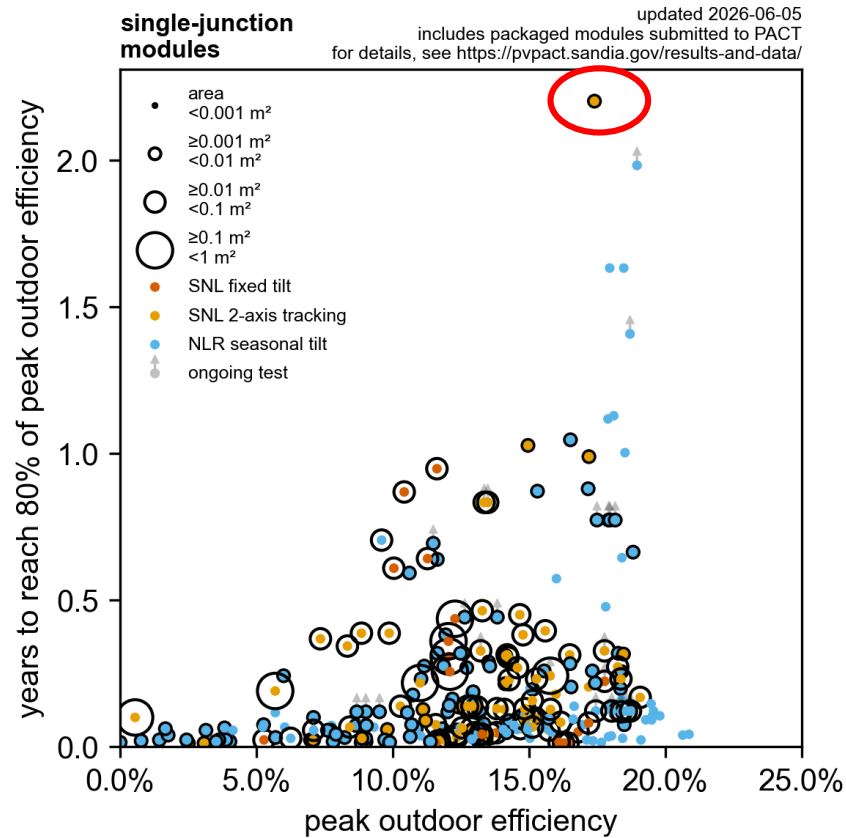




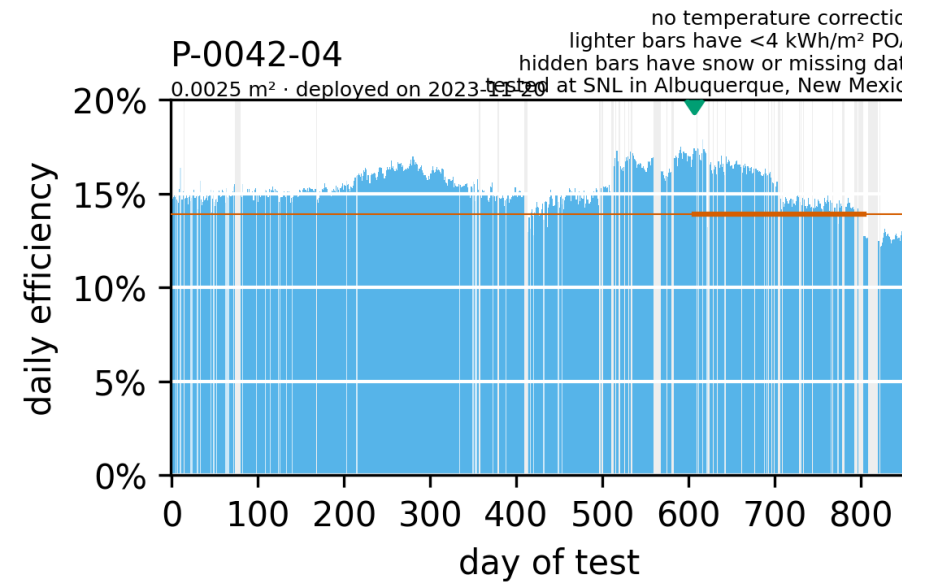
The PACT "bubble" plots



Single Junction Highlights

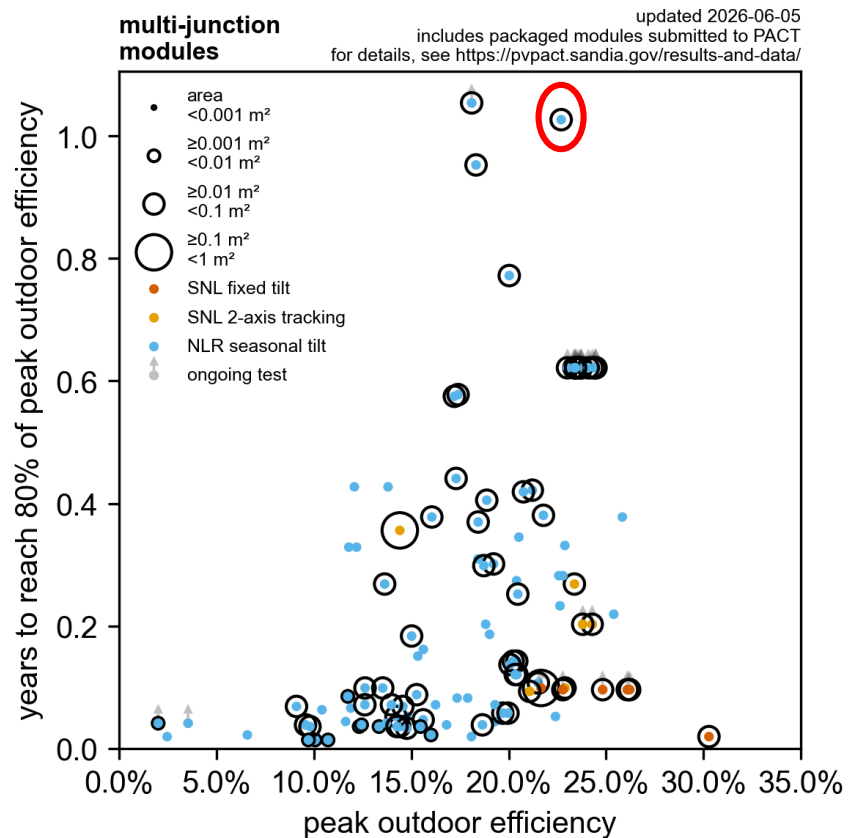


Over 2 years in the field

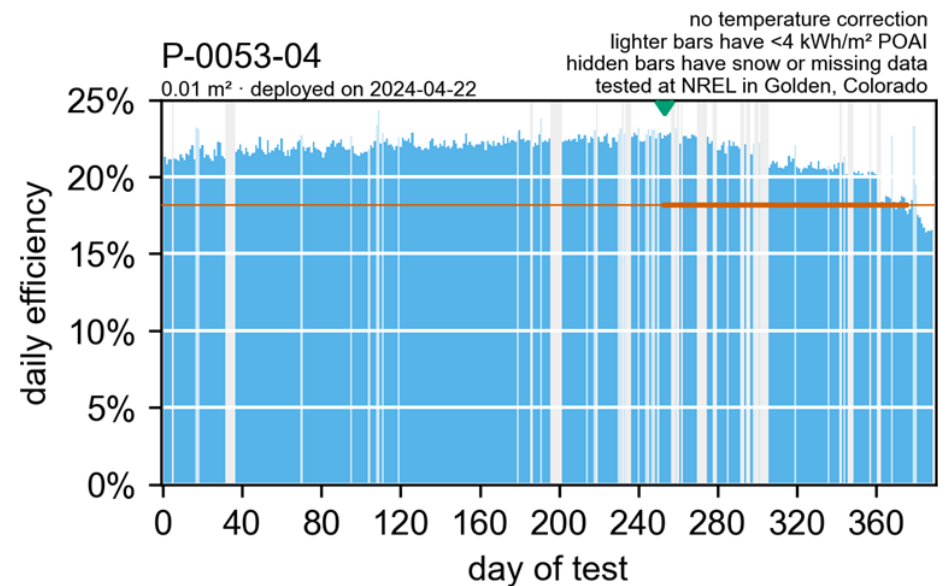


Seasonal trends are significant
Reached peak efficiency during 2nd summer

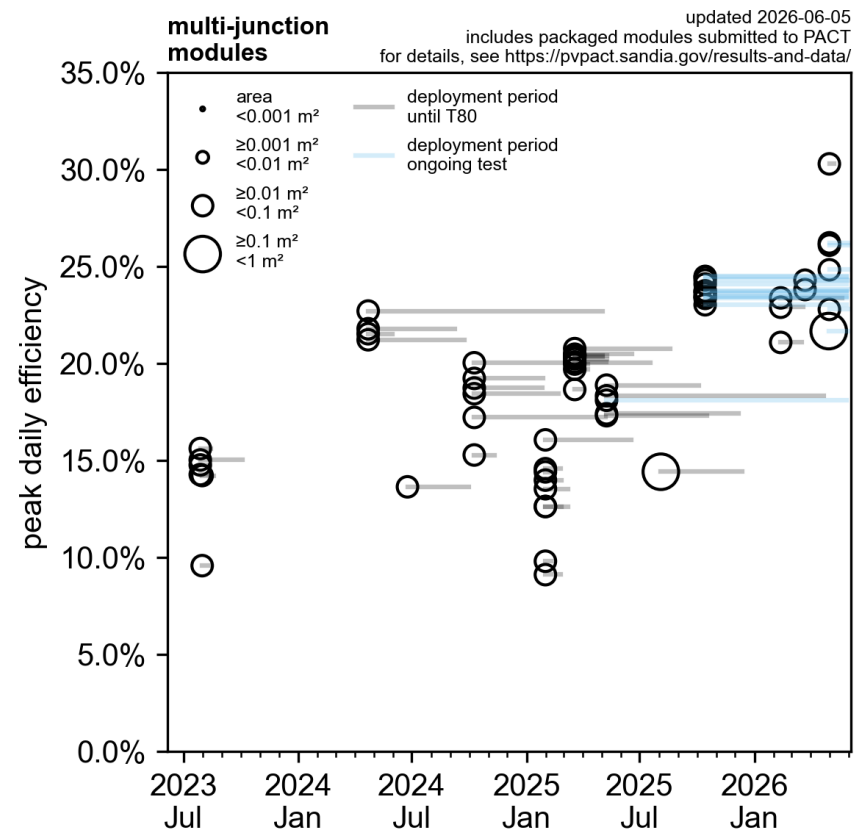
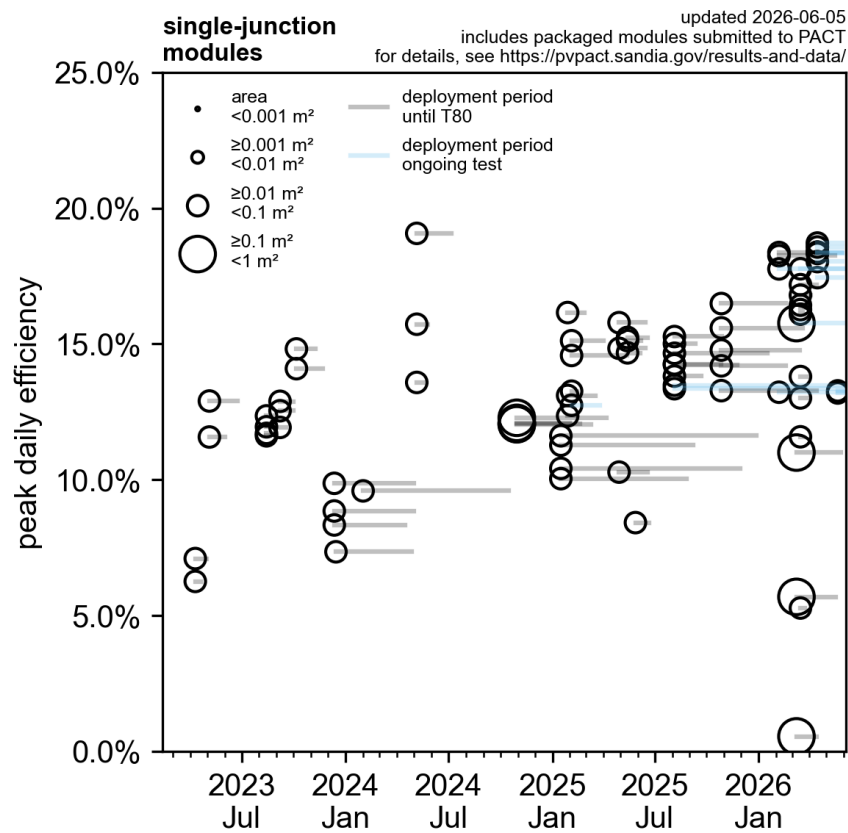
Multi-Junction Highlights



Multi-junction module reaches a year



Module Efficiency and Lifetimes are Improving





PACT

Newport

MODULE CONSISTENCY

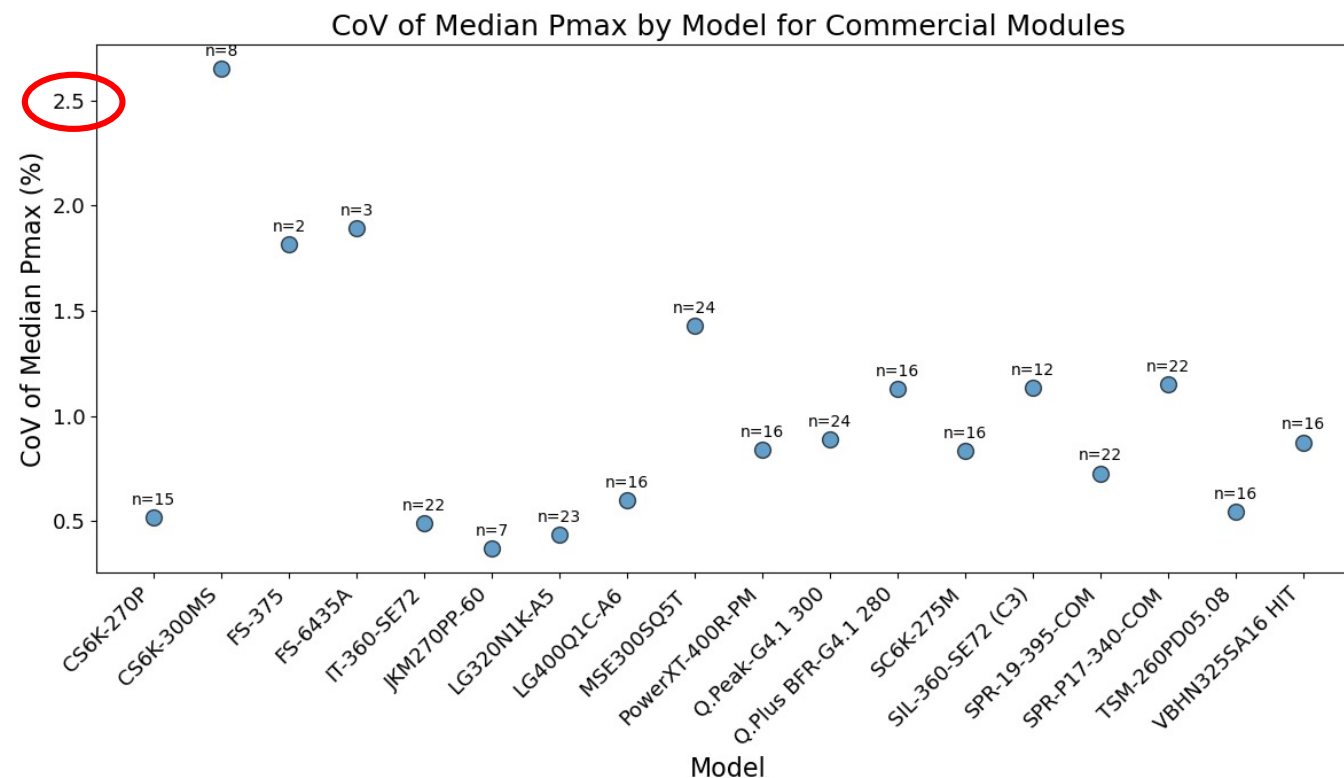
How similar are modules within a batch?

How do PACT modules compare with commercial modules?

Module Consistency (Sample commercial modules)



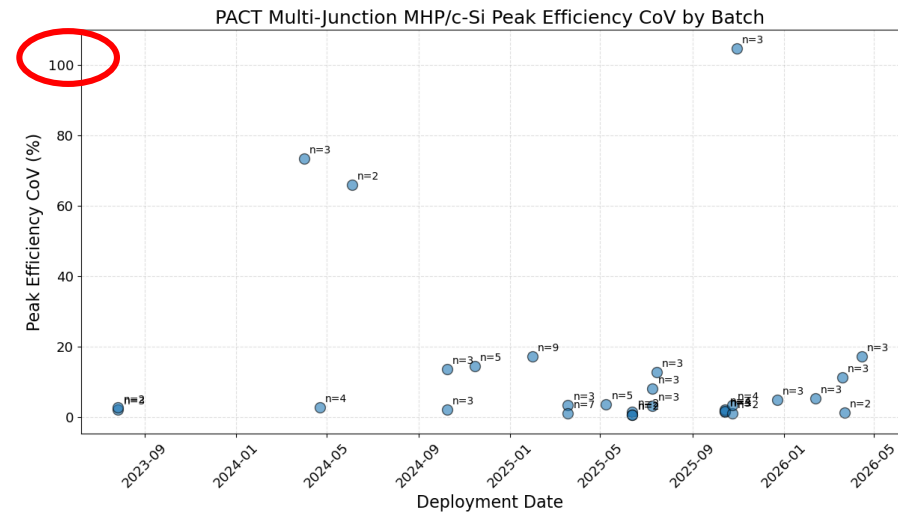
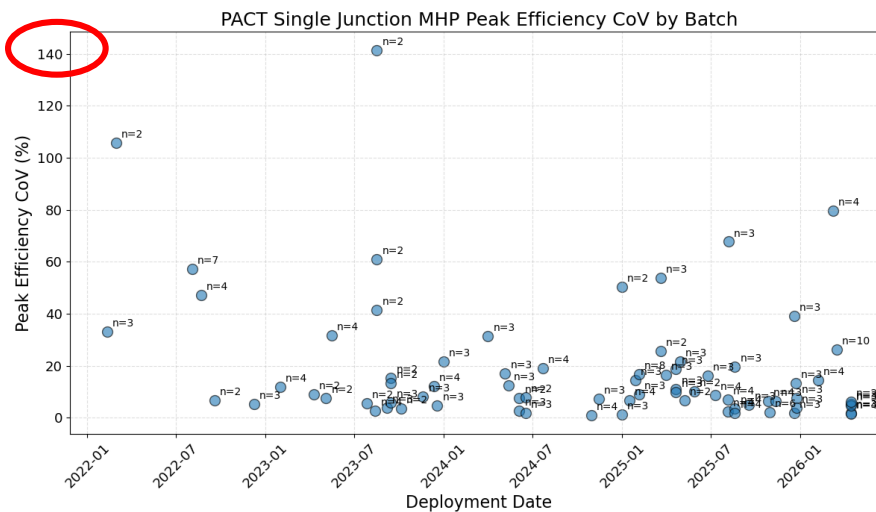
- Modules fielded outside at Sandia and flash tested each year. Data is from 2026 flash tests
- Coefficient of variation of module Pmax measured on a flash tester at Sandia by model
- Most modules vary by less than 2% within a batch (power bin)



Consistency of Peak Efficiency for MHP Modules at PACT



- COV is much higher for MHP (single and multi-junction) modules at PACT.
- Most modules vary by less than **20%** within a batch.
- A few batches appear to be quite consistent!
- Important caveat:
 - PACT modules are R&D samples not commercial products.



Commercial Module Characteristics vs. State-of-the-Art MHP Modules



Characteristic	Commercial Modules	MHP
Efficiency	Current records for c-Si: 26.2% & CdTe: 20.3%	- Current records: Sj: 22.1%, tandem: 31.1% (submodule) - PACT outdoor efficiencies are mostly <20% (STC values should be a bit higher).
Reliability	25-40 year warranty	11 out of ~360 PACT modules have lasted over 1 year.
Consistency	Power bins are very consistent (Cov<2%)	PACT module batches exhibit significantly more inter-batch variability. Most modules >20% CoV
Testability	- Flash simulator (1 sec) - Preconditioning protocols exist	- Continuous simulator - Preconditioning protocols need validation
System integration	- String voltages $\leq 1500V$ - Flexible MPPT	Unknown if MHP arrays will be compatible with standard inverters
Performance	- Predictable in different climates and system designs - Model parameters apply to all modules of the same module model	- Models need to be developed and validated. - Metastability is important



"Developing a Stress Testing Protocol for >1 Year of Outdoor Operation for Metal Halide Perovskite PV Modules" Michael Owen-Bellini et al., **Thursday 10:45 AM Area 6: Perovskite Stability and Commercialization session**

Thank you!
Questions?

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