Perovskite PV Accelerator for Commercializing Technologies (PACT): Importance of Field Testing

Joshua S. Stein PhD., Sandia National Laboratories

2023 Spring MRS, San Francisco, CA

https://pvpact.sandia.gov

SAND2023-02109C

Acknowledgements

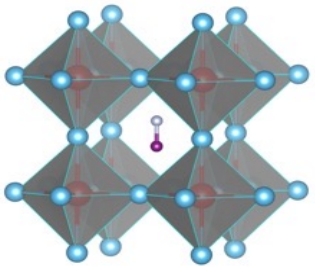
- This material is based upon work supported by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office Award Number 38050.
- The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

- **PACT Team:**
  - **Laura Schelhas[2], Bruce King[1], Wanyi Nie[3], Ralph Romero[4], Jim Crimmins[5], Cara Libby[6], Angelique Montgomery[1], Charles Robinson[1], Christa Torrence[1], Marios Theristis[1], Joseph Berry[2], Timothy J Silverman[2], Michael Owen-Bellini[2], Ingrid Repins[2], Dana Sulas-Kern[2], Michael G. Deceglie[2], Robert White[2], Kirsten Perry[2], Paul Ndione[2], Nikos Kopidakis[2], Jack Schall[2], Rob Foree[4], Daniel Zirzow[5], James Richards[5], Colin Sillerud[5], Wayne Li[6]**
    - *[1]Sandia National Laboratories, United States*
    - *[2]National Renewable Energy Laboratory, United States*
    - *[3]Los Alamos National Laboratory, United States*
    - *[4]Black & Veatch, United States,*
    - *[5]CFV Labs, United States,*
    - *[6]Electric Power Research Institute, United States*

What are Perovskite Photovoltaics?

- "Perovskite" refers to a crystal structure.
- Metal Halide Perovskite PV has a range of chemical compositions:

ABX_3



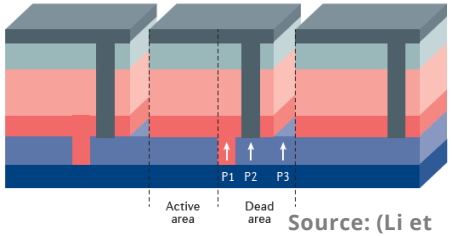
A= Pb, Sn, Ge, Bi, Sb, …
X=halides (Cl, Br, I)
B= Organics or metal (Cs)

- To make things even more complex, alloys are possible.

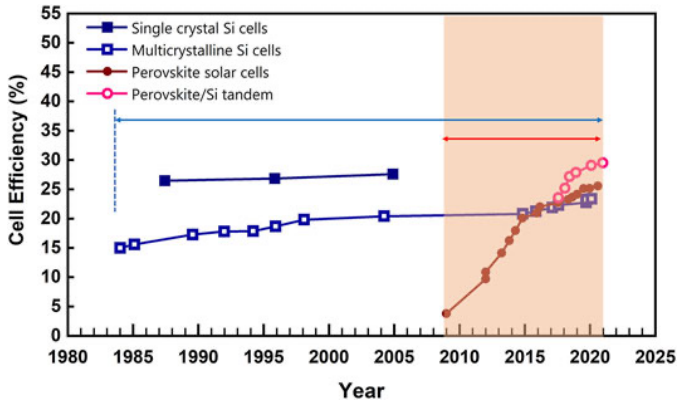
History

- First perovskite PV cell reported in 2009
  - <3% PCE (power conversion efficiency)
- PCE has risen fast
  - >= 25.7% single junction cell. (limit – 33%)
  - It took 40 years to achieve this PCE for c-Si.
- Promise of low cost manufacturing
  - Low temperature
  - Solution processing
  - High speed manufacturing

Monolithic module integration



Source: (Li et al., 2018)

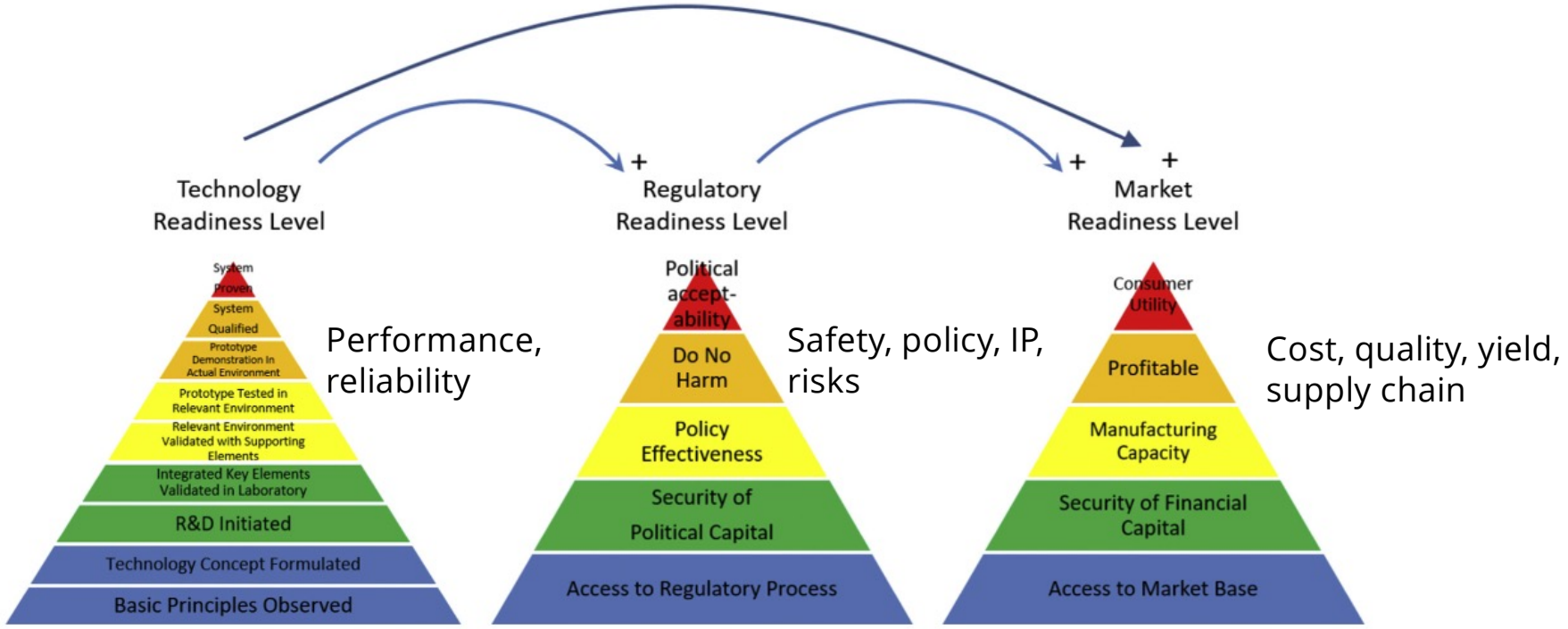


Zhang et al., 2022

PACT

Where are we on the development roadmap for perovskite PV modules?

Commercial Readiness is more then just technology



Technology Readiness Level (1-9)
'Can we build it?'
'Does it work?"

Regulatory Readiness Level (1-5)
'Can we accept it?'

Market Readiness (1-5) Level
'Will they adopt it?'

Kobos et al., "Timing is everything: A technology transition framework for regulatory and market readiness levels", 2018

Technology Readiness Levels

PACT

TRL Description

1. Basic principles observed
2. Technology concept formulated
3. Experimental proof of concept
4. Technology validated in lab
5. Technology **validated** in relevant environment (industrially relevant environment in the case of key enabling technologies)
6. Technology **demonstrated** in relevant environment (industrially relevant environment in the case of key enabling technologies)
7. System prototype demonstration in operational environment
8. System complete and qualified
9. Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

- ***Perovskite PV modules*** are currently between TRL 4 & 5.
- In order to solidly meet TRL 5, modules must be able to ***operate and survive outdoors*** for many many weeks to months.
  - These results need to be:
    - **Independent** – tests run by parties external to the developer
    - **Repeatable** – similar results on many samples from different batches and testing parties
    - **Relevant** – environment should be similar to expected operational conditions
- TRL 6 will require modules to consistently ***survive outdoors for at least a year or more***.

Fraunhofer ISE TRL Stages for PV Cells

- On this scale, perovskite PV is between TRL 2 & 3
- Current effort is focused on:
  - Increasing reliability and lifetimes
  - Reducing cell-to-module losses in minimodules
  - Working on reproducibility
- Higher TRL levels focus on manufacturing and quality.

Process TRL	Description process TRL
TRL 0	Process simulation, functionality and economical potential demonstrated
TRL 1	Laboratory process, functioning and reproducible on small areas
TRL 2	Laboratory process, efficiency potential demonstrated potential on small areas
TRL 3	Laboratory process, functional and reproducible on industrial standard large and full areas*
TRL 4	Laboratory process, efficiency potential demonstrated on industrial standard large and full areas*
TRL 5	Process demonstrated as pilot process in environment suitable for production (throughput)
TRL 6	Process used as pilot process on tools suitable for production, > 1000 cells manufactured, sample modules manufactured and certified
TRL 7	Process used in pilot production with 6 hours/7 days on production tools
TRL 8	Process used in mass production with 24 hours/7 days on production tools
TRL 9	Process used in mass production with 24 hours / 7 days on production tools, production experience > 2 years

* industrial standard large area = (125x125 mm² or 156x156 mm²)

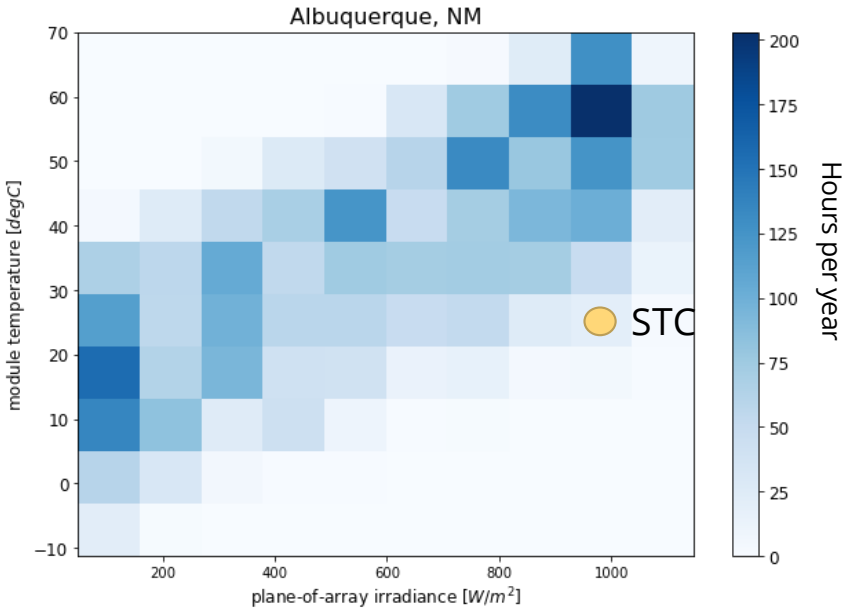
PACT

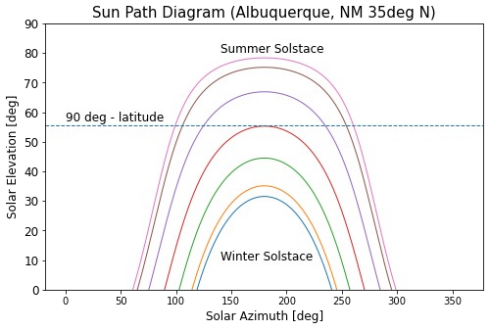
Baliozian et al., 2016, "Photovoltaic development standardizing based on roadmaps and technology readiness levels.

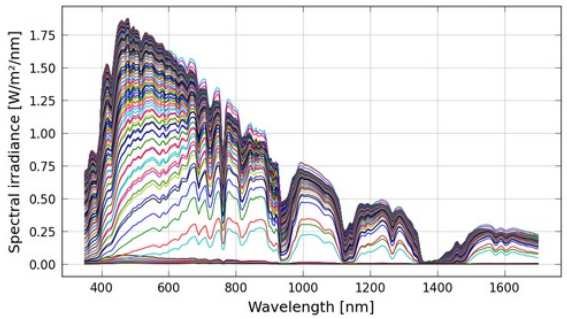
8

Typical Outdoor Environment for PV

- 2D Histogram of operating conditions over 1 year for c-Si PV modules in Albuquerque, NM.
- Standard testing conditions (STC) are rarely encountered in the field.
- Modules spend much more time at higher temperatures and somewhat lower irradiance values.
- Modules experience diurnal irradiance and temperatures that change with season.
- Indoor tests that expose a module to constant illumination for 1000+ hours may not provide information that is relevant for operation in the outdoor environment.

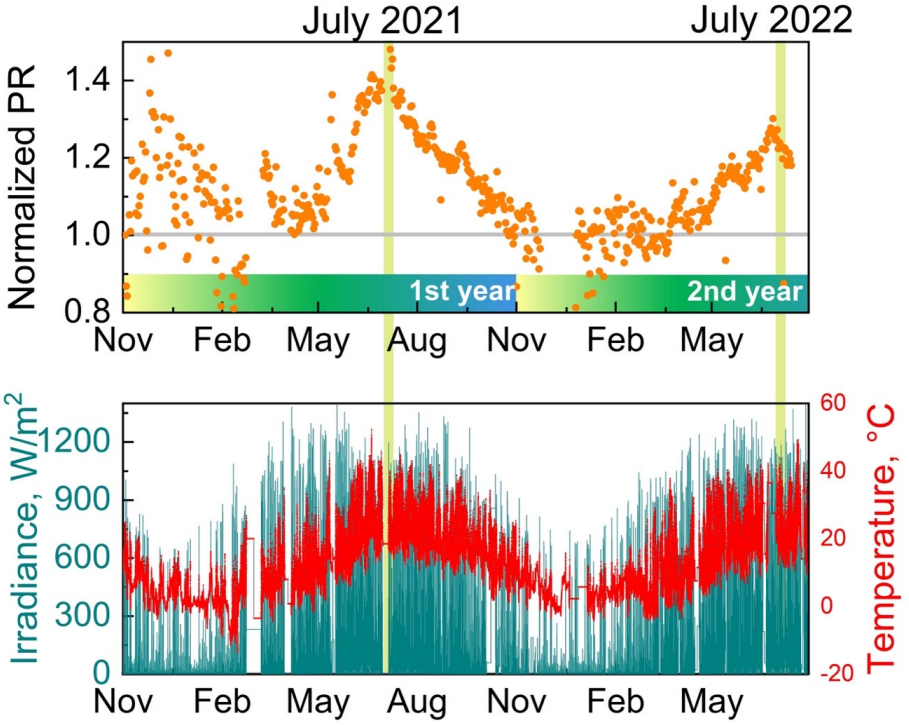






Outdoor Data from Perovskite Cells

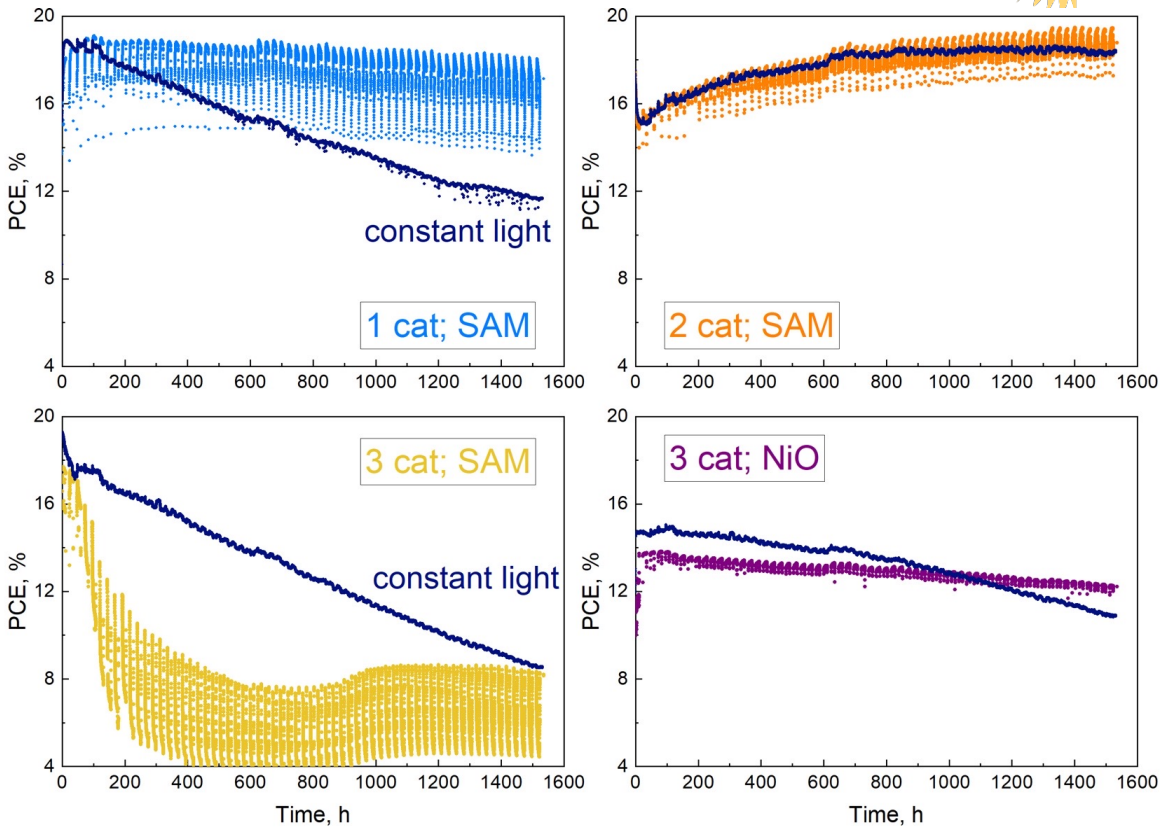
- Mark Khenkin has measured long-term outdoor performance of many perovskite PV cells in Germany (some for as much as two years).
- He and others have observed large seasonal fluctuations in performance ratio.
  - THIS IS NOT EVIDENCE OF A POSITIVE TEMPERATURE COEFFICIENT!!
    - Indoor controlled measurements prove that PSC temperature coefficients are negative.
  - Source of this behavior is still a mystery.
    - Small part is likely due to spectral response
    - Other factors may include metastability from the combined effect of temperature and changes in the length of the day/night.



Plot from Mark Khenkin (Helmholtz-Berlin)

Metastability Behavior for Cells and Appropriate Testing

- Most PSC researchers test their cells under constant illumination.
- Constant illumination tests may be misleading.
- Behavior can be very different when light is cycled.
  - Strongly dependent on device architecture.

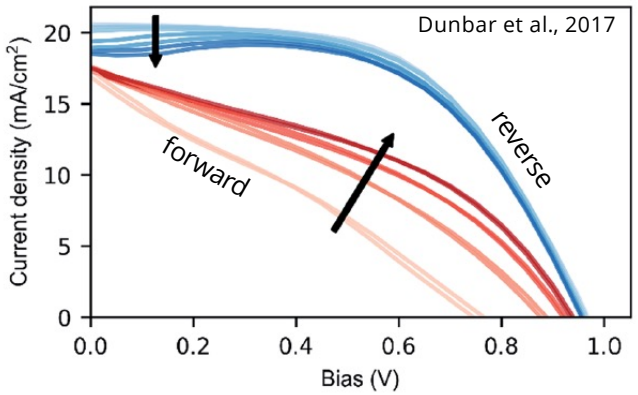


Plot from Mark Khenkin (Helmholtz-Berlin)

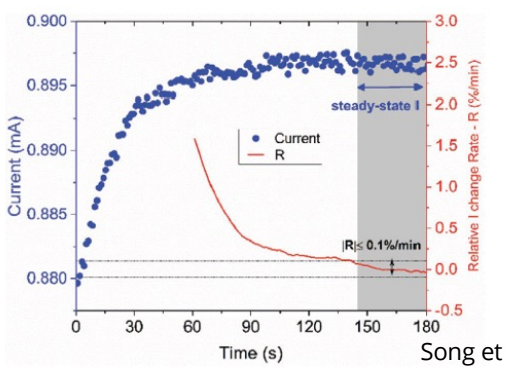
SAM – Self-assembled monolayer used as a hole-selective contact

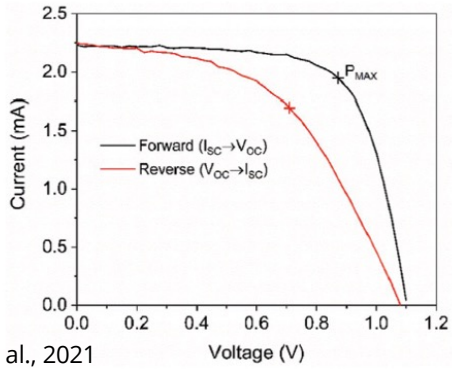
Unique Performance Characteristics

- Much of what we "know" about performance characteristics of perovskite PV is affected by the high diversity of formulations.
  - Not all PSCs are the same and some are much more stable than others.
- Common observations
  - **IV hysteresis** – difference between forward and reverse IV scans.
  - **Scanning rate** affects resulting IV curve.
  - Stable measurements currently require a ***continuous solar simulator*** and either MPPT or asymptotic IV curve (proposed by NREL) – ***SLOW!***
- This presents a problem for manufacturers – How to characterize modules inline during production?
  - Requires measurements to be made in <1 sec for conventional technologies.



IV curves from a PSC.
Arrows point to decreasing scan speed





Song et al., 2021

PACT

Wow, this is really interesting behavior!

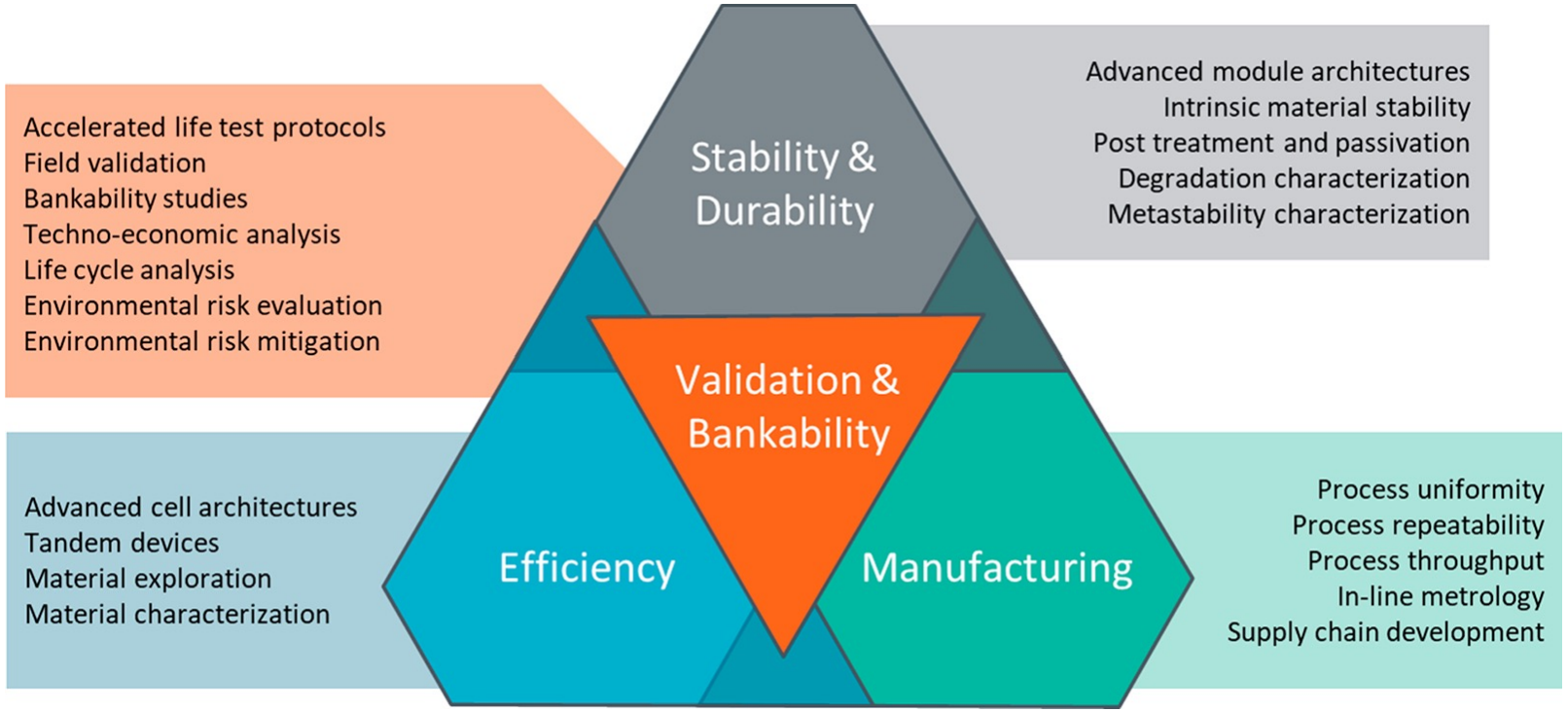
Perovskite metastability looks interesting to study!

Unfortunately……

Bankable PV Technology Should be Boring!

- Investors and financers want BORING PV technologies.
  - Sunlight in, predictable power out. (linear performance is a plus)
  - Easy and quick to characterize
  - Stable, predictable outdoor performance
  - Slow, predictable degradation
- Metastability is no necessarily BAD, but need to be predictable, repeatable and well understood.
- Rapid degradation is very BAD
- Unique testing requirements might be BAD if unique equipment is required or the tests take too much time to complete.

Technical Challenges Facing Commercialization



ACS Energy Lett. 2022, 7, 1728−1734

Perovskite PV Performance Targets in the US

- DOE SETO has set performance targets for perovskite modules
  - Higher efficiency
  - Larger areas
  - Durability
  - Manufacturing scale

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] 6 months continuous outdoor testing with <3% relative degradation overall and <1% degradation in the final 3-month span[4]	>1 kW total, at least 20 modules for outdoor testing[5]
PVSK-only Tandems	24% PCE			
Hybrid Tandems	27% PCE			

Source: SETO

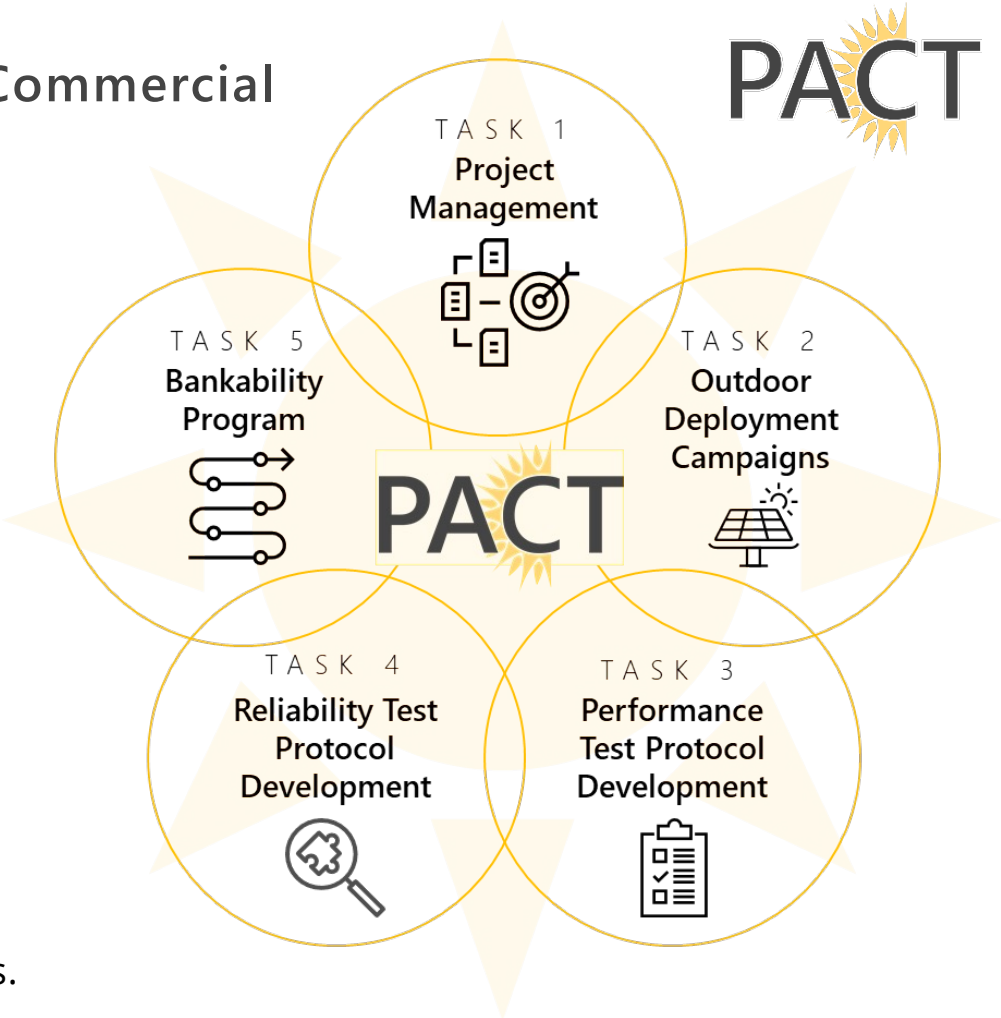
How to Support Commercialization?

- We need a common set of testing protocols (performance, reliability)
  - Tests should represent/reproduce **relevant** conditions/failures seen in the field.
  - For example: Light and elevated temperature testing appears to be important. Extended STC testing gives a false impression of reliability.
- Industry needs to demonstrate that high efficiency, reliable perovskites can be scaled to larger sizes, be made using commercial manufacturing equipment and economically reasonable materials and produced at a rapid rate.
  - No spin coating
  - No gold, no SPRIO, etc.
- More outdoor testing, demonstrations, and independent validation.
- Support new companies with testing, manufacturing, and bankability services.
- More research on sustainability potential of perovskite PV.

PACT: Perovskite PV Accelerator for Commercial Technologies

- Since July 2021, Sandia is leading a multilab validation center (Team includes NREL, LANL, EPRI, Black & Veatch, and CFV Labs). https://pvpact.sandia.gov

- We are partnering with four universities to supply perovskite mini-modules for test development.
  - University of North Carolina
  - University of Toledo
  - University of Washington
  - SLAC/Stanford University
- We are starting to test modules from industry.



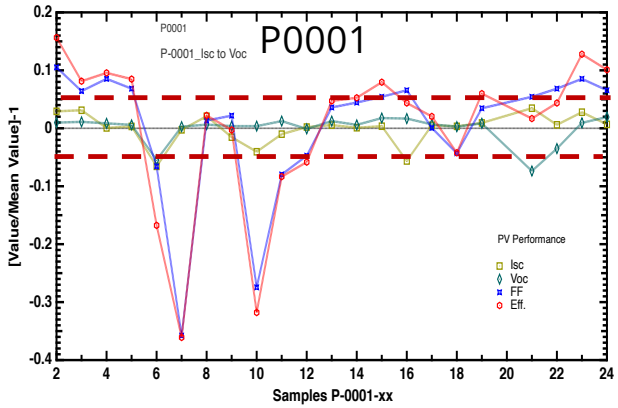
So far we have received 12 batches of minimodules (total = 151) from our university and industry partners.

PACT

What have we learned?

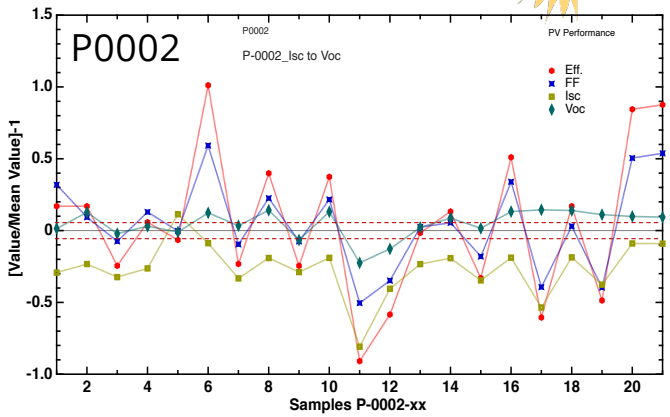
1. Performance repeatability from our initial university modules is quite low and needs improvement. We have not received sufficient samples from industry to comment.

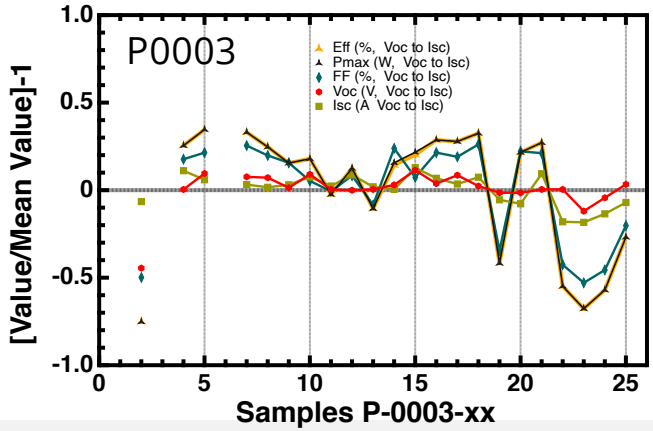
Initial Characterization of PACT University Modules

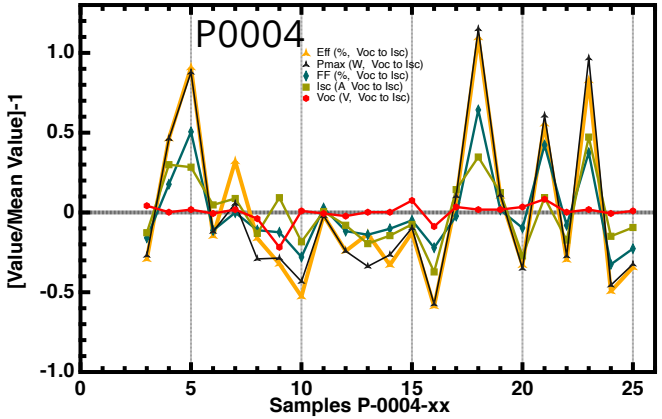


- These are some early examples of variations between modules in a batch.

Why is there so much variation?







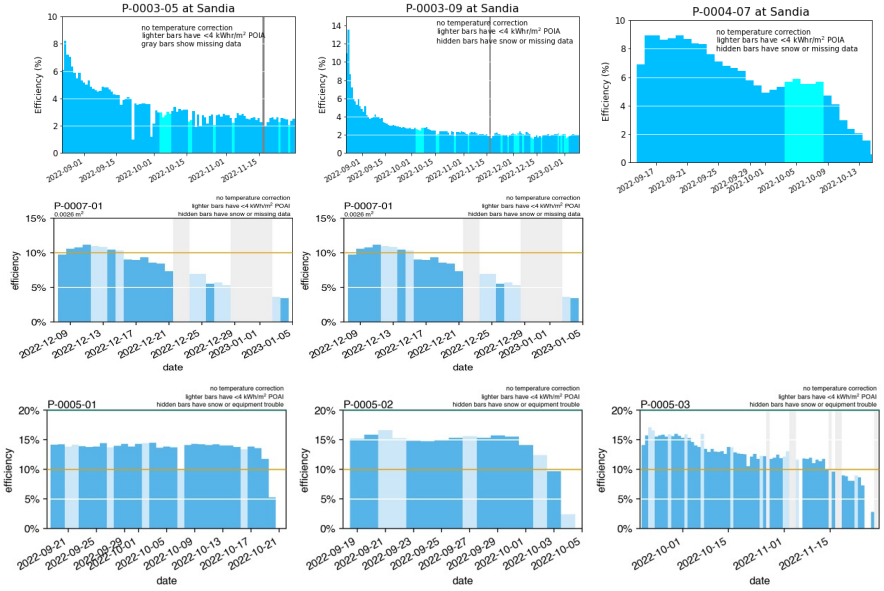
PACT

2. Outdoor performance is not boring. (a) We have observed rapid degradation over days and weeks. (b) Metastability over each day is common. (c) Degradation appears to be related to module interconnects and interfaces.

Example PACT Outdoor Data

- Field testing is being done at three sites
  - Sandia - 2-Axis tracker
  - NREL – Fixed tilt
  - CFV Labs. - Fixed tilt for industry modules

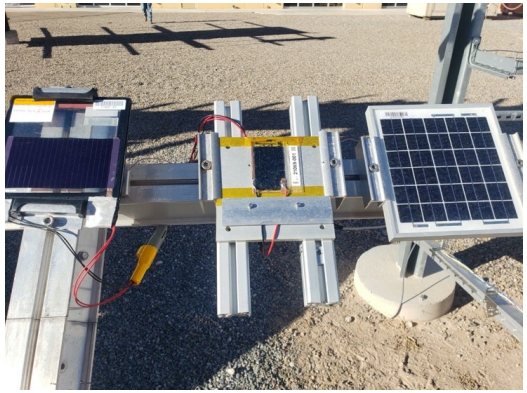
Example Results



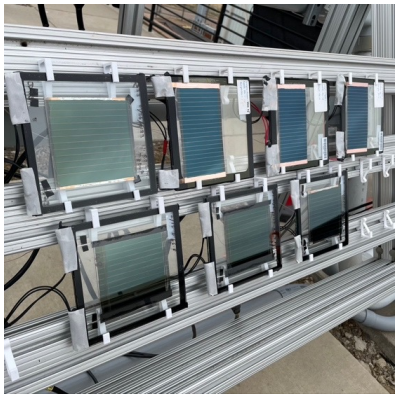
CFV Labs Custom MPPT/I-V Hardware

Sandia Field Testing

CFV Labs Testing

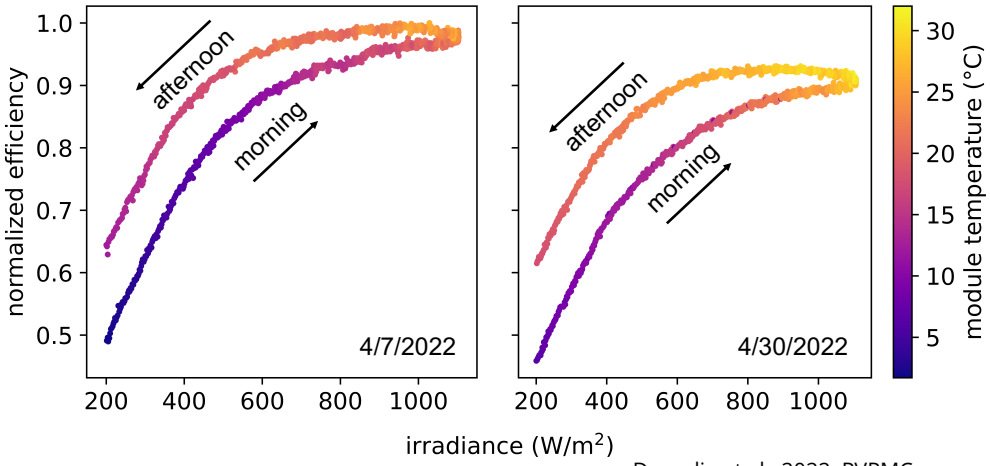


NREL Field Testing



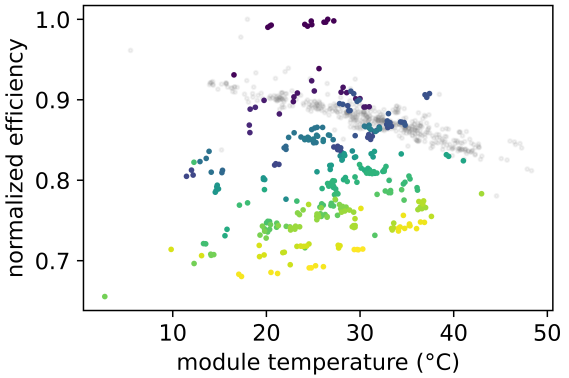
Outdoor Metastability in Modules

- Many modules tested at PACT show metastable behavior each day
  - Efficiency increases over the day
  - Resets the next morning
  - Plots to the right show two clear day examples.



Deceglie et al., 2022, PVPMC Workshop, "Existing Field Performance Models Cannot Describe Perovskite Modules"

- Efficiency vs. module temperature shows evidence of degradation and varying and unexpected trends.



Gray points are for c-Si module

Considerations for Outdoor Testing

- Maximum power point tracking (MPPT) algorithms need to be slowed down and adjusted for the perovskite modules that we have seen.
  - Working recommendations (should be validated for new samples):
    - Initial start voltage set to 70% of Voc (measured dynamically)
    - MPPT voltage step = 1% of Voc
    - MPPT time interval = 1 sec (this is very slow!)

} These are PACT default settings

  - During "nighttime" periods (defined by sun elevation < 2 deg) – depends on site
    - Set module to be short-circuited. (There is no universal consensus on this)
  - Module variability makes it difficult to validate these settings.
- Measure back of module temperature (TC or RTD)
- Measure plane-of-array irradiance with a pyranometer
- Nice to also measure a c-Si module at MPPT for reference and comparison.

More Information about PACT

Many documents are available on the PACT website (https://pvpact.sandia.gov)

- Legal agreements
- Data management plan
- Module packaging guidelines
- Module stress test protocol
- Preconditioning protocol

Publications and Protocols

PACT is working on the first versions of performance and reliability test protocols for perovskite PV technologies. Once they are complete they will be available on this page.

- PACT Module Preconditioning Protocol Version 0.1 (219 downloads) (3/30/2022)
- PACT Recommended Packaging Procedure – version 4 (149 downloads) (3/29/2022)
- PACT Module Design Acceptance Criteria (Research) V. 1.0 (128 downloads) (3/14/2022)
- PACT Module Design Acceptance Criteria (Industry) V 1.0 (181 downloads) (2/24/2022)
- PACT Nondisclosure Agreement (99 downloads) (2/24/2022)
- PACT Materials Transfer Agreement (89 downloads) (2/24/2022)
- PACT Perovskite PV Module Stress Testing Protocol Version 0.1 (180 downloads) (3/14/2022)
- PACT Center Factsheet (145 downloads) (11/3/2021)
- PACT Data Management Plan (142 downloads) (10/20/2021)

PACT

SUMMARY

- Technology, Regulatory, and Market Readiness are all important to consider.
- Surviving outdoor testing is required to move to TRL 5
- Testing needs to be more representative of deployment conditions (light cycling, elevated temperature, etc.) – Outdoor testing is the gold standard.
- Early university modules have widely varying initial performance. Process repeatability is an issue.
- Early university modules tested outdoors have degraded rapidly (days to weeks) and display significant diurnal metastability.
- We need to remain focused on the goal of commercialization.
  - Successful perovskite modules will be commodities not high-performance custom devices.
  - We seek predictable, "boring" performance and reliability.

Thank you!

Joshua S. Stein
jsstein@sandia.gov

U.S. DEPARTMENT OF ENERGY · Sandia National Laboratories · NREL Transforming ENERGY · Los Alamos NATIONAL LABORATORY · BLACK & VEATCH · EPRI ELECTRIC POWER RESEARCH INSTITUTE · CFV Labs · UNIVERSITY of WASHINGTON · THE UNIVERSITY of TOLEDO · THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL · SLAC · Stanford University

Industry Challenge #1

- Milestone to justify PACT providing a bankability program:
  - PACT measures a perovskite PV module (masked aperture area >100 cm^2) from industry that after at least 10 weeks of outdoor exposure at MPPT has an outdoor one-hour measured efficiency of >12% (>16% if a Si-perovskite-tandem module). No temperature and spectral corrections.

  - Due by September 30, 2023 (module needs to be installed in the field by **early July**)
  - Please contact me if you would like to enter a module (or more)