Technical Barriers to the Commercialization of Perovskite Photovoltaics: How Do We Overcome Them?

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https://pvpact.sandia.gov

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- The views expressed herein do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

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What are Perovskite Photovoltaics?

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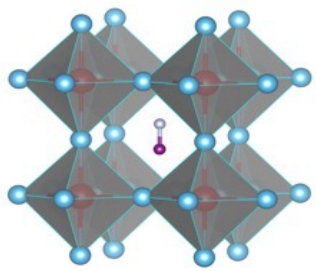
- "Perovskite" refers to a crystal structure.
- Metal Halide Perovskite PV has a range of chemical compositions:

ABX_3



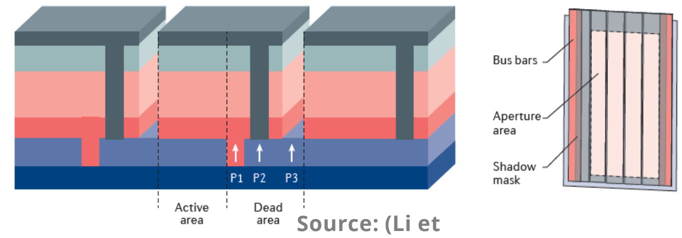
A= Pb, Sn, Ge, Bi, Sb, …
X=halides (Cl, Br, I)
B= Organics or metal (Cs)

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

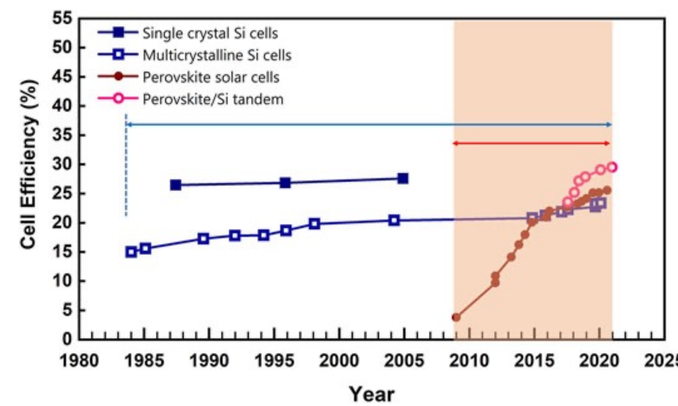
History

- 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

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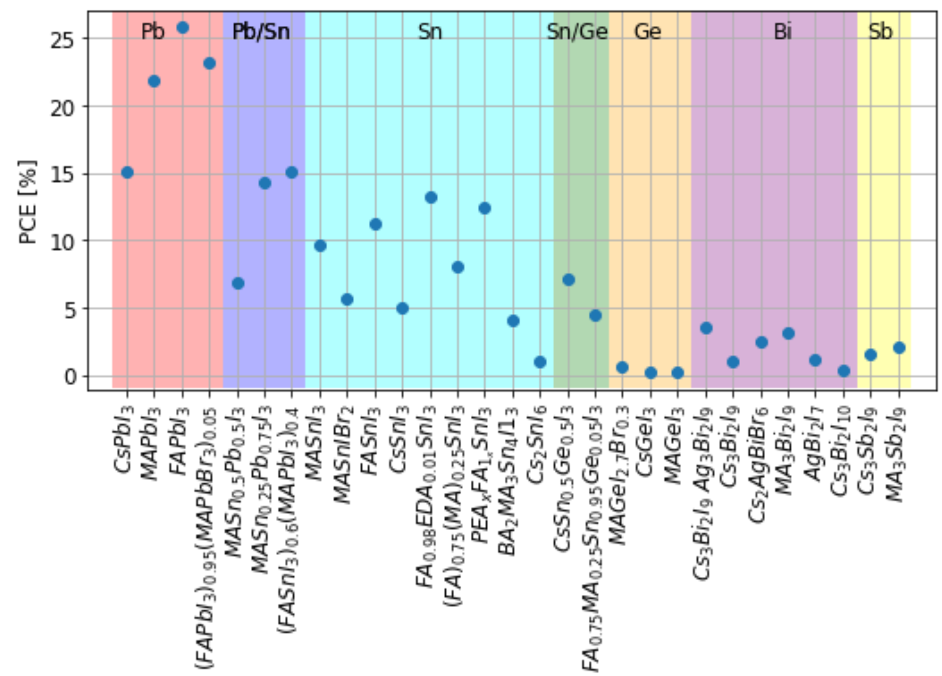
Compositional Diversity

- Unlike many existing commercial PV technologies, perovskite PV composition can be quite varied.
  - This leads to many published papers.
    - 6,581 papers found between 2009-2018*
  - Good for academics, creates some confusion!
- Why is this important?
  - A few formulations are proving to have high PCE, and *relatively high reliability durability*.
  - Most formulations are terrible solar cell materials.
    - Low efficiency, unstable, degrade in light and/or typical operating temperatures, etc.
  - Problems suffered by one material may not affect other materials.

Examples of PCSs using different metals



[* https://doi.org/10.1016/j.egyr.2020.07.029](https://doi.org/10.1016/j.egyr.2020.07.029)

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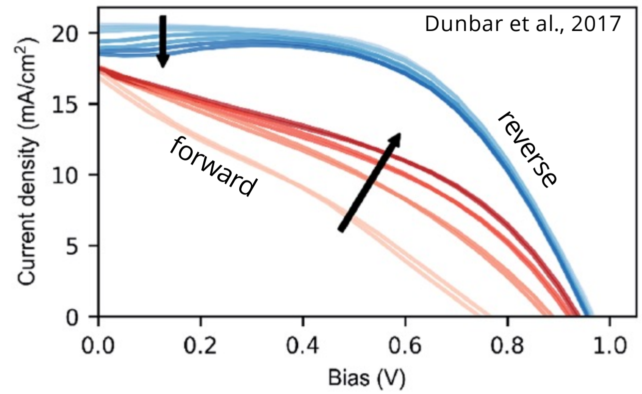
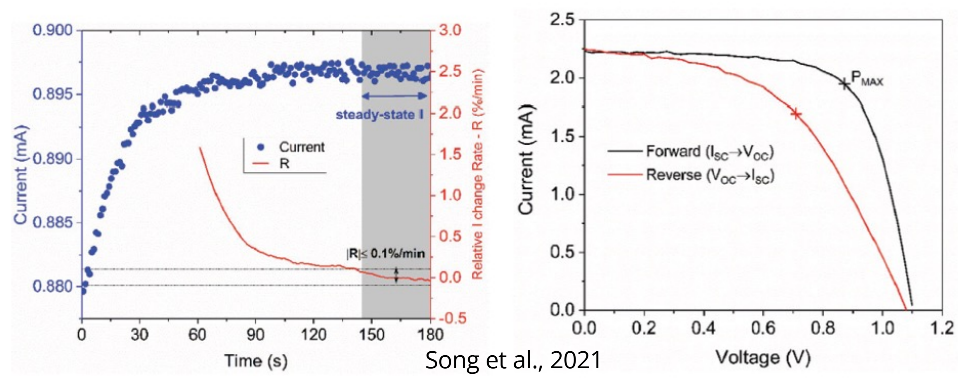
Performance Characteristics

- 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

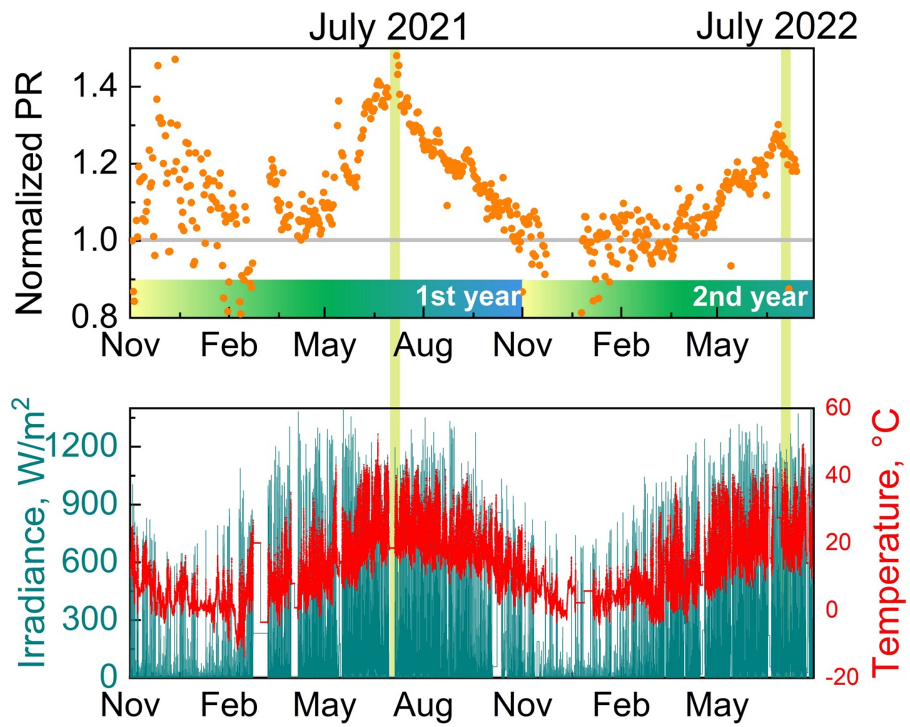


IV curves from a PSC.
Arrows point to decreasing scan speed



Importance of Field Data

- 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 and Appropriate Testing

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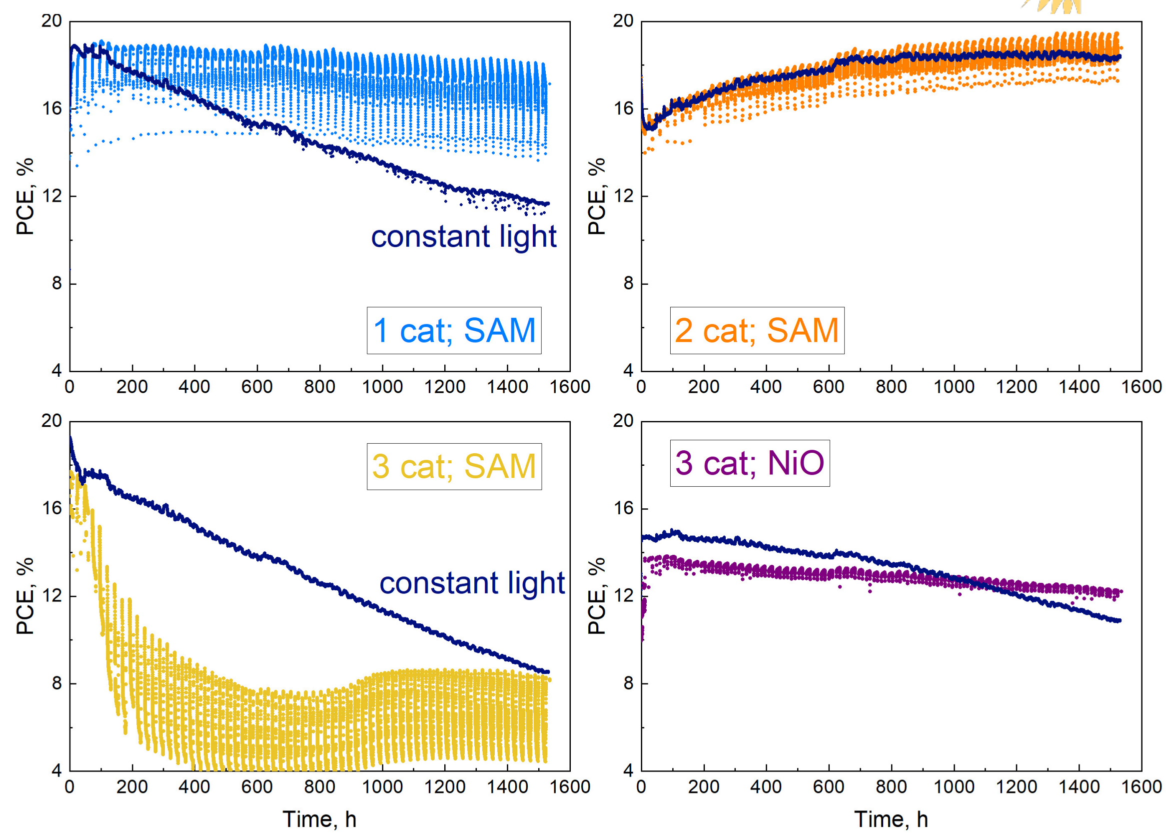
- Most PSC researchers test their cells under constant illumination.
- Constant illumination tests may be misleading.
- Behavior is different when light is cycled.
    - Strongly dependent on device architecture.

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



Plot from Mark Khenkin (Helmholtz-Berlin)

Manufacturing Method Diversity

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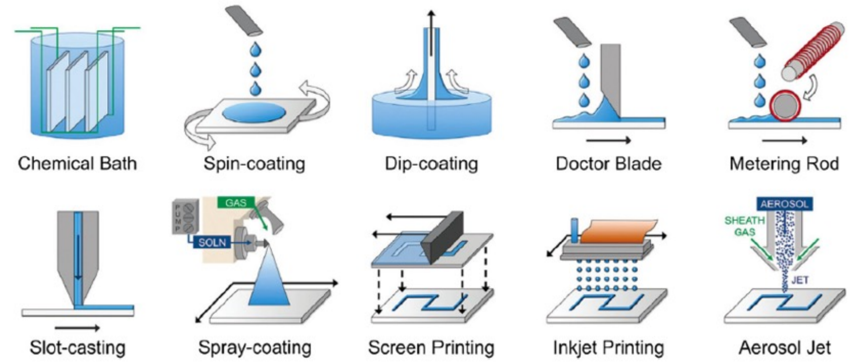
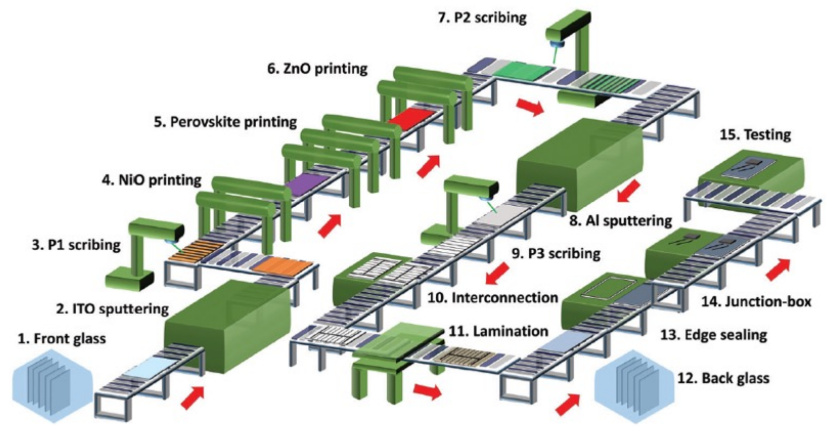
- There are many solution/vapor processing application methods that are being investigated.
- Variety comes with benefits and challenges.
  - Variability between different perovskite PV manufacturers is far larger than for c-Si.
  - Many options for overcoming problems
  - Fewer opportunities for sharing best practices.
- Perovskite PV manufacturing footprint is relatively small compared with c-Si.
  - Glass in….. Modules out
- Perovskite PV should be much more straightforward to recycle than c-Si.



Source: Chilvery et al., 2016



Source: Song et al., 2017

Technical Challenges Facing Commercialization

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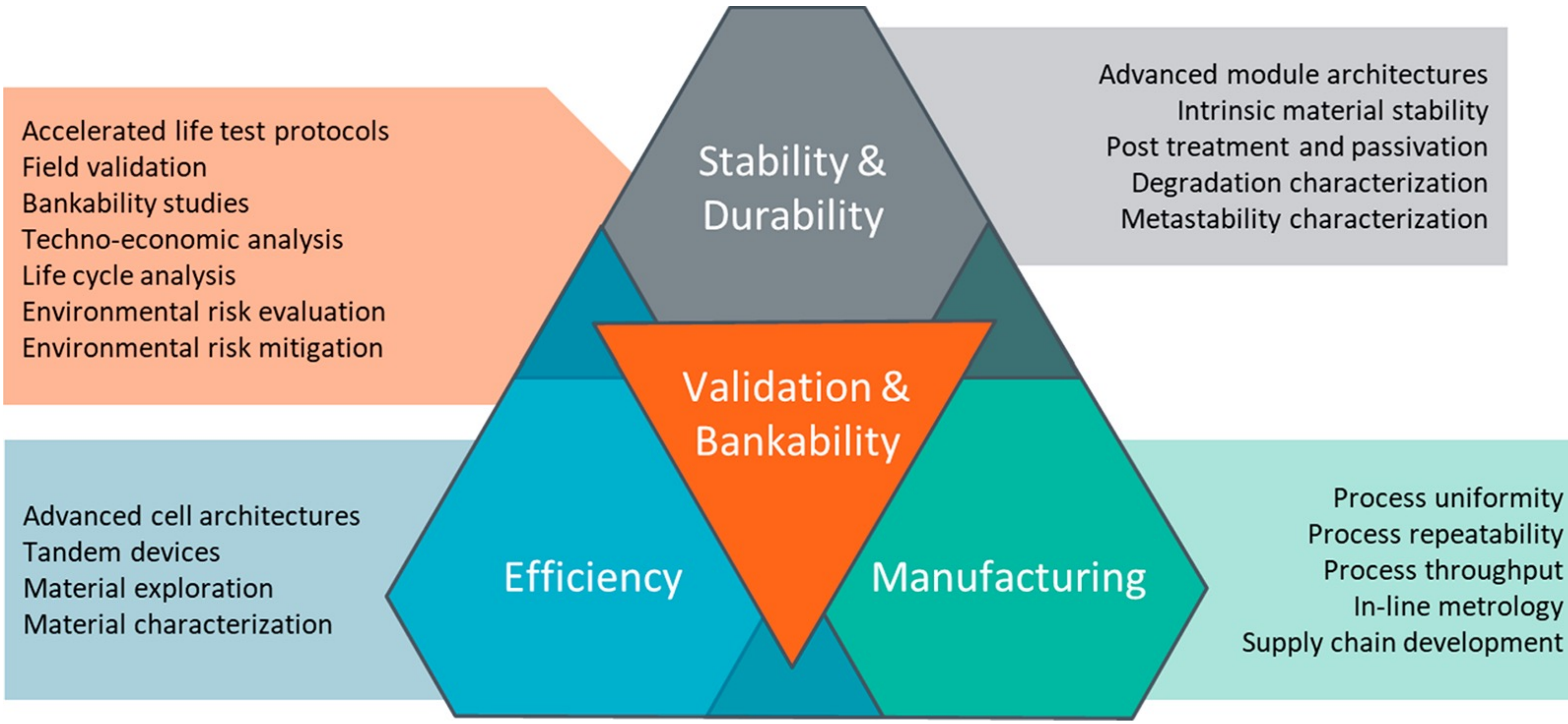

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Perovskite PV Performance Targets in the US

- 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]	>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]	

Source: SETO

How to Support the Commercialization?

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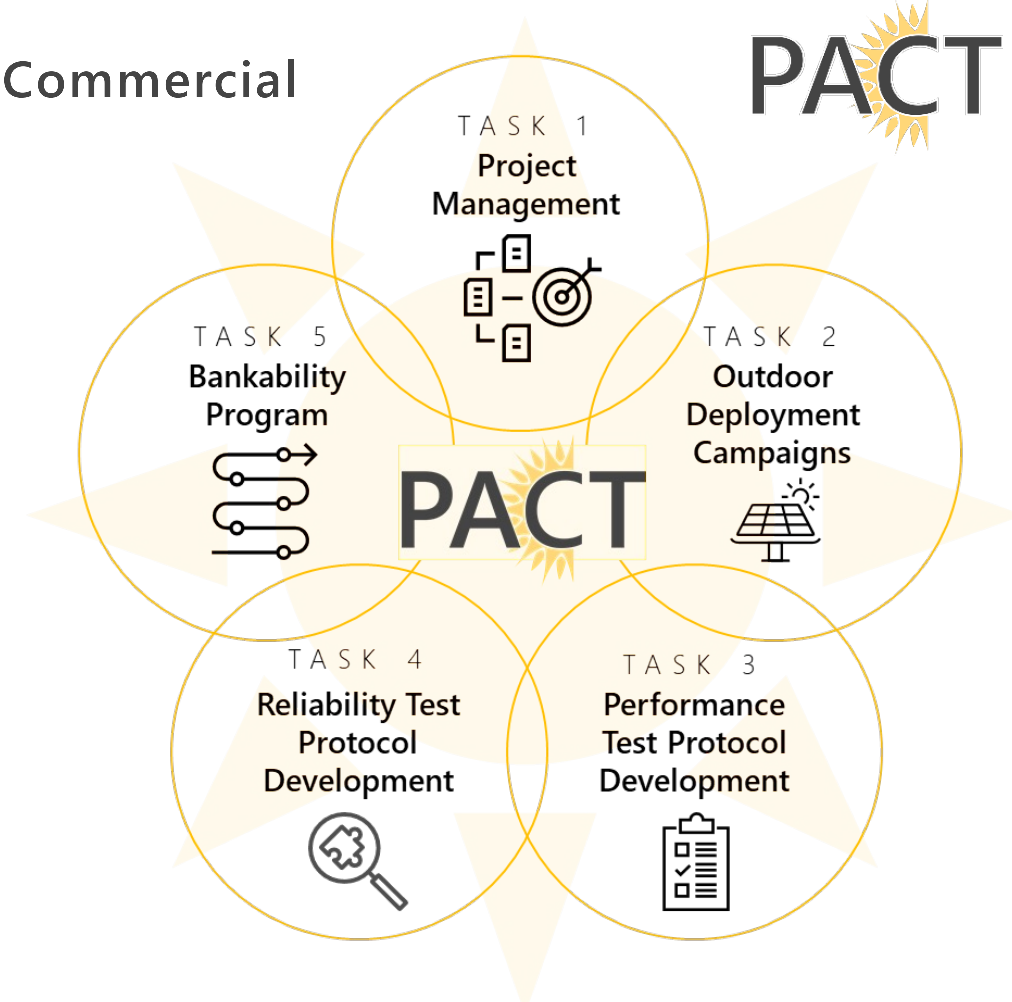
- We need a common set of testing protocols (performance, reliability)
  - Tests should represent/reproduce **relevant** conditions/failures seen in the field.
  - For example: Light and elevated temperature testing appears to be important. Extended STC testing gives a false impression of reliability.
- 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.
- Support new companies with testing, manufacturing, and bankability services.
- More research on sustainability potential of perovskite PV.

PACT: Perovskite PV Accelerator for Commercial Technologies

- 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 testing.

  - University of North Carolina
  - University of Toledo
  - University of Washington
  - SLAC/Stanford University



PACT Module Testing Status

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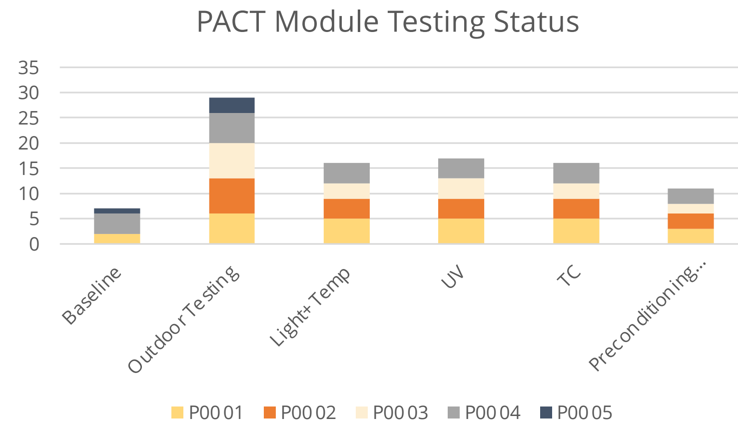
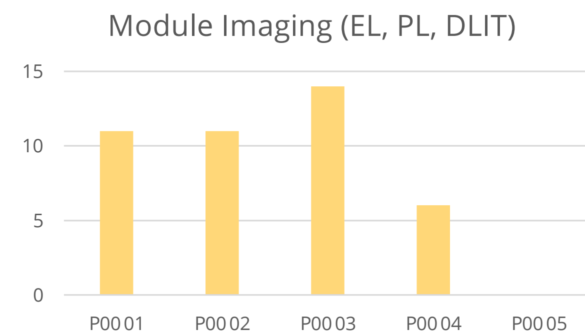
- We have received >100 modules from our university partners.
- Distributed to
  - Baseline and controls (7)
  - Outdoor testing (29)
  - Light and elevation temperature (16)
  - UV (17)
  - Thermal cycling (16)
  - Preconditioning development (11)
- Module imaging (42)





Initial Characterization of PACT Modules

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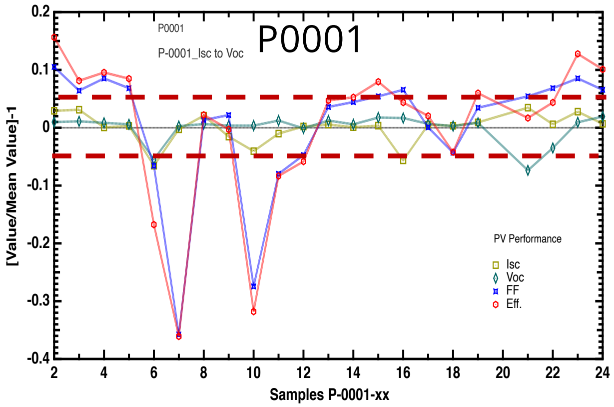
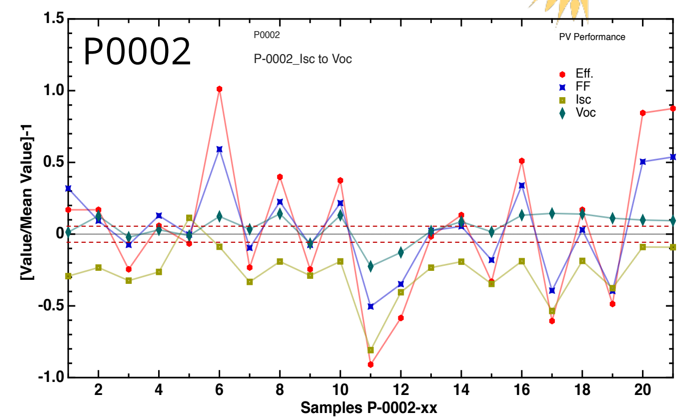
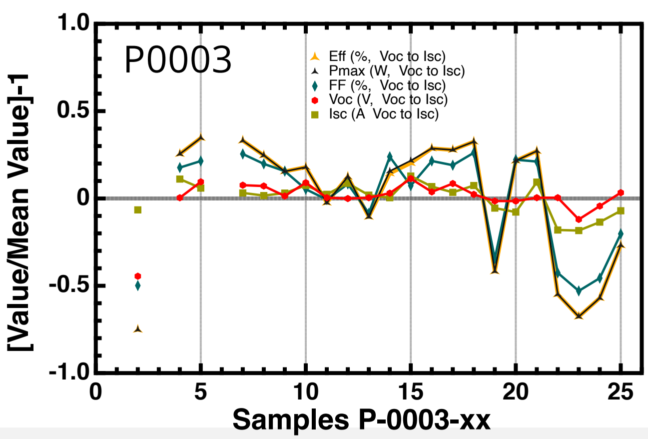
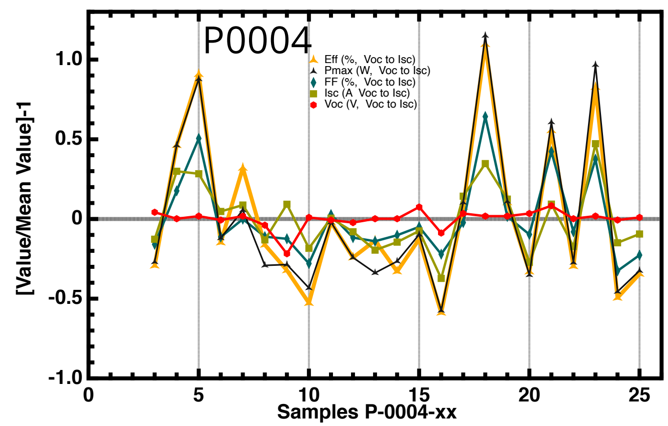




Variations between modules in a batch is a major issue.





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PACT: Outdoor Testing

- Early field tests have had mixed results.
  - Some modules fail in days
  - One module has "lasted" for months
  - Failures appear to be related to manufacturing issues and not failure of the perovskite absorber layer.
- PACT is actively reaching out to perovskite startup manufacturers to begin helping them develop their products for the market.

2-axis tracker at Sandia

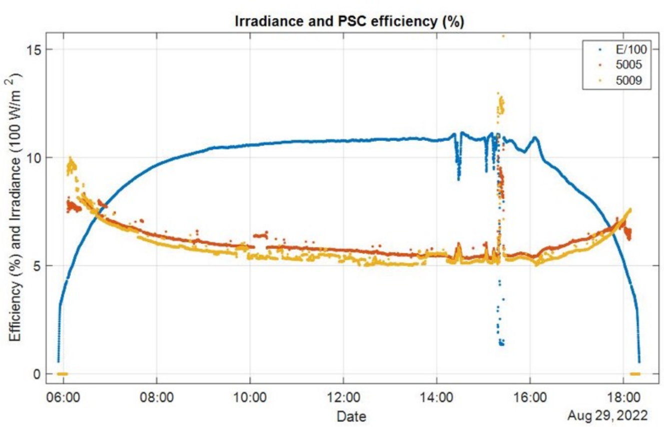
16-channel load/measurement box from CFV labs.

Outdoor Monitoring at CFV Labs

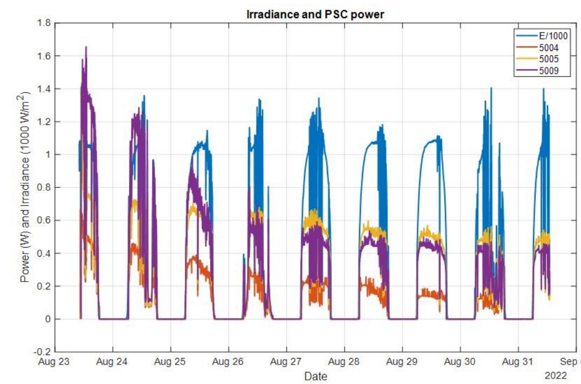
Fixed-tilt test rack at NREL

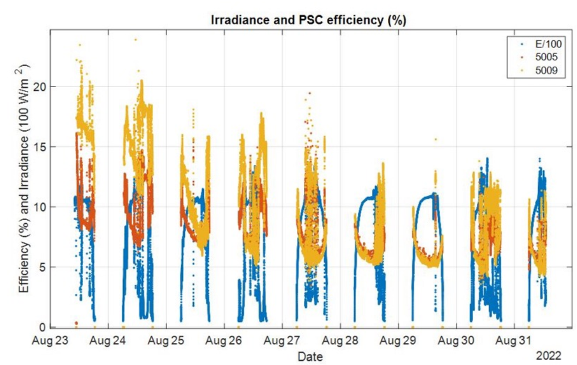
P0003 Outdoor Testing

- All modules saw rapid degradation and then somewhat stabilized after three days.
- Efficiency over the day shows some interesting patterns
    - Declines from ~17% to ~6% over time.
    - Highest in morning and evening
    - Lowest in midday (likely caused by high Rs)



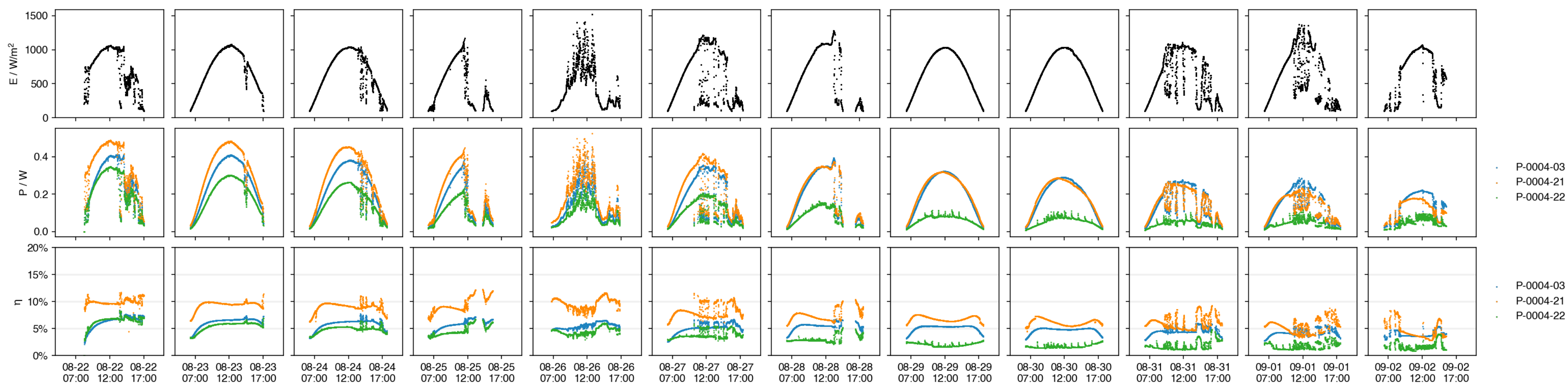
P0003 Module in Field in NM





Rapidly declining performance precludes performance model characterization.

P-0004 Outdoor Testing



- Champion module performing at about 10%
- Modules fairly stable over the first week though low starting efficiency
- Losing ~50% power over 12 days.
- Not showing the same Rs issues we see with P-0001/P-0003

Accelerated Tests Need to be Adapted to Perovskites

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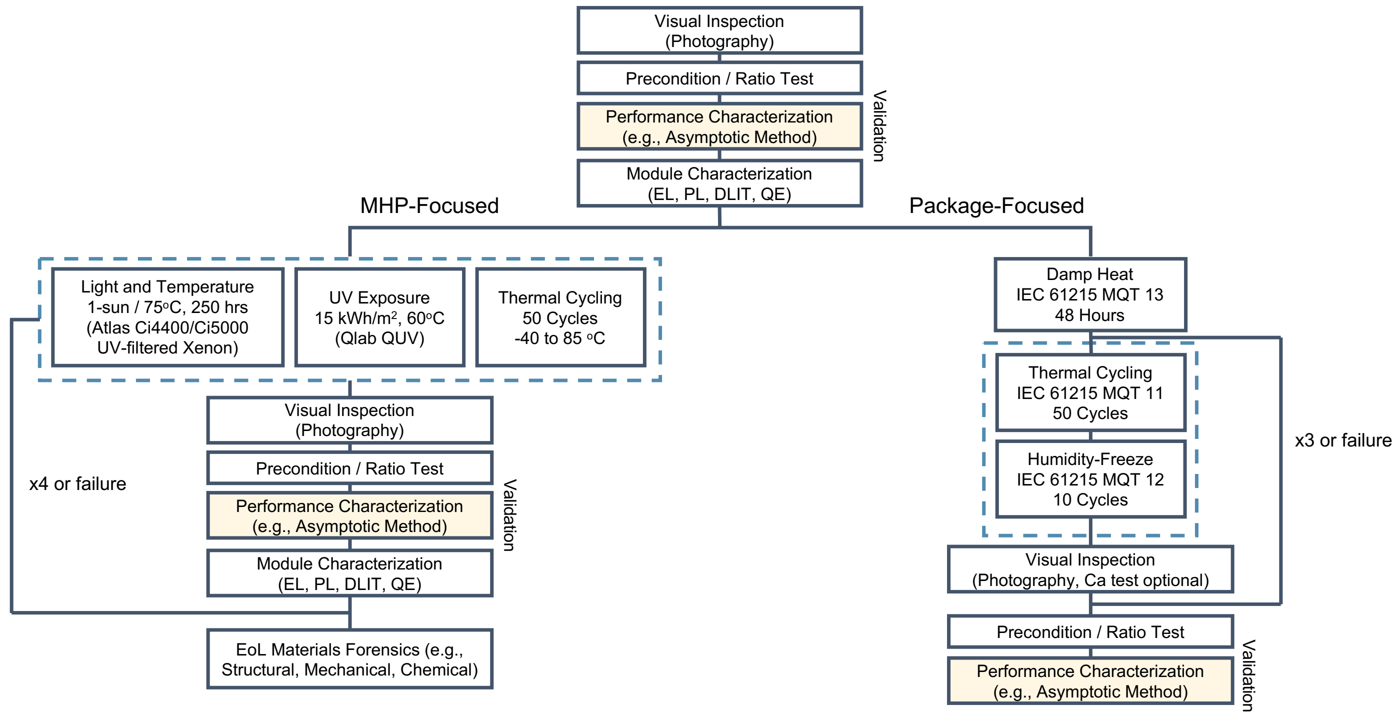
- Qualification tests (e.g., IEC 61215) help to provide confidence that modules will initially survive outdoor deployment – they do not test long-term reliability.
- These tests are modified for different PV technologies (e.g., c-Si, a-Si, CdTe, CIGS, etc.)
- Tests should demonstrate realistic observed field failures.

Initial PACT Accelerated Reliability Protocol



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Bankability of Perovskites – Lead Risks

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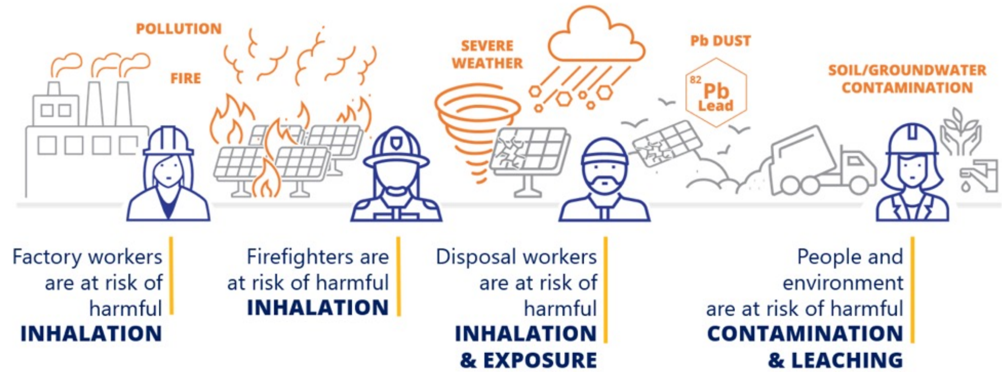
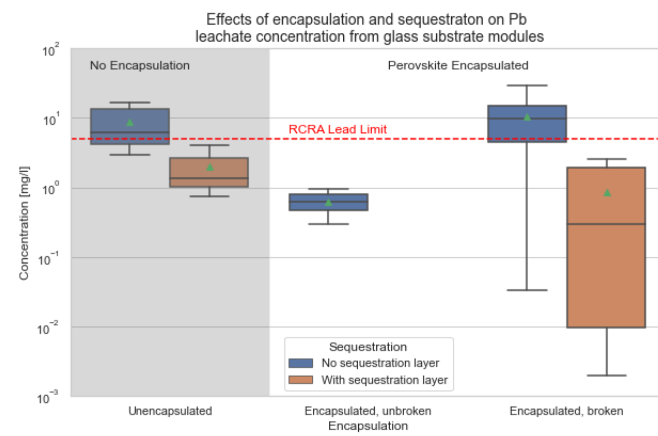
- Most promising perovskite formulations contain **lead in a highly soluble form**.
- Risks of lead toxicity present challenges for bankability of this technology
  - Leaching, fire, disposal, etc.

- How much lead will leach out if module breaks and exposed to water?
- Researchers are investigating materials to sequester lead inside the module.
  - We reviewed 35 leaching experiments comparing the effects of encapsulation and sequestration materials.
  - All samples with sequestration materials added passed the RCRA Lead Limit (5 mg/l)





Torrence et al., 2022 - Accepted

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More Information about PACT

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)

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SUMMARY

- Composition diversity of perovskite PV is both a blessing and a curse for commercialization.
- Efficiency records are fine, but consistency and variations in a batch may be more important.
- Focus should be on devices that have a chance of being commercialized (materials, manufacturability, scalability, etc.)
- Testing needs to be more representative of deployment conditions (light cycling, temperature, etc.)
- We need to remain focused on the goal of commercialization.
  - Successful perovskite modules will be commodities not a high-performance custom devices.

Thank you!

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