Commercialization of Perovskite PV - Current Status and Future Challenges

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https://pvpact.sandia.gov

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PACT

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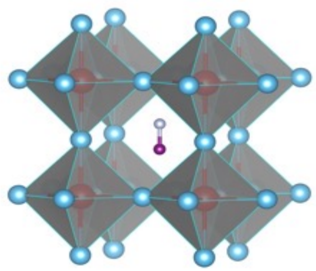
What are Perovskite Photovoltaics?

- "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 made in 2009
  - <3% PCE (power conversion efficiency)
- PCE has risen fast
  - >= 25.6% today at the cell level (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
- Defect tolerance is high compared with c-Si.
- New result from NREL led team (Jiang et al. 2022):
  - Perovskite solar cell with PCE>25%
  - Reactive surface engineering breakthrough – electric field helps to stabilize and boost efficiency.
  - Retained 87% of initial PCE after over 2,400 h (1000 W/m^2 and 55℃ in air (encapsulated))

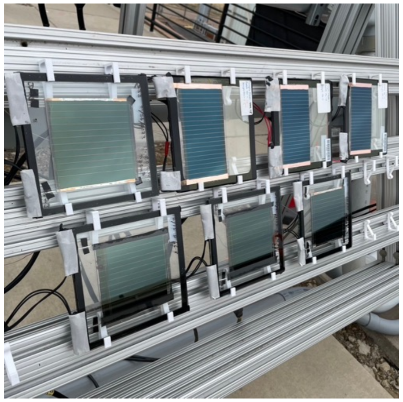
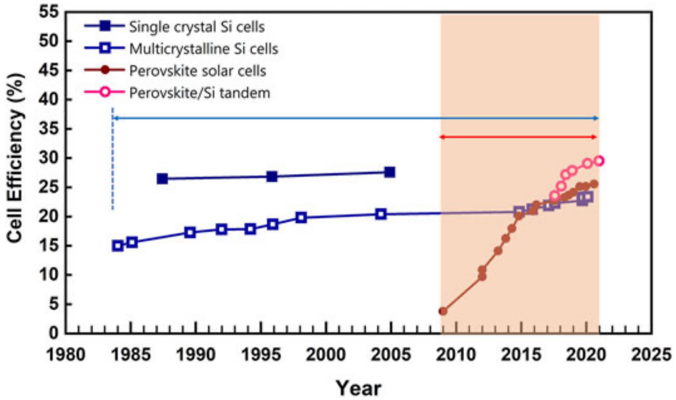


Photo NREL



Zhang et al., 2022

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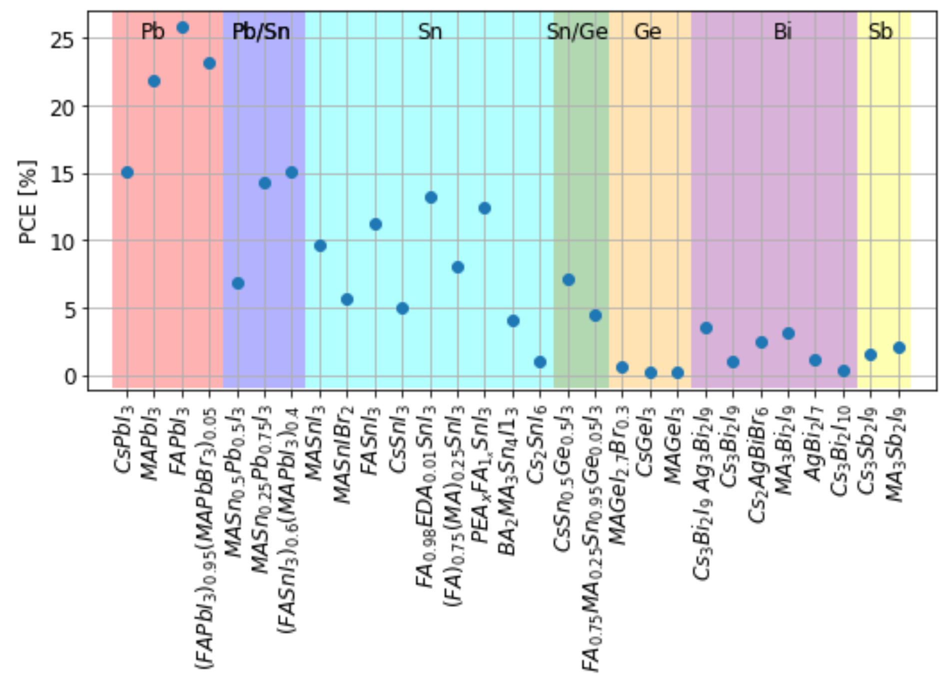
Compositional Diversity

- 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 a class of one material may not affect other materials.

Examples of PCSs using different metals

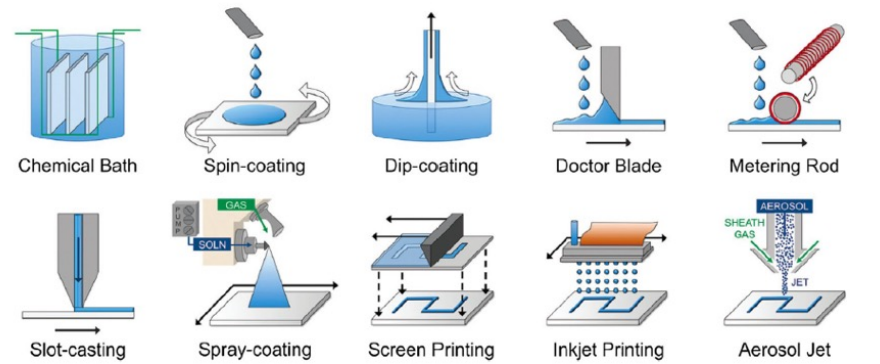


* https://doi.org/10.1016/j.egyr.2020.07.029

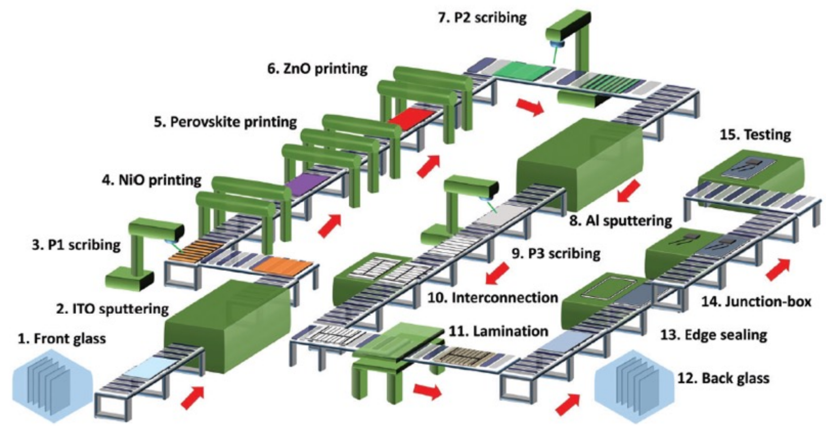
Manufacturing Method Diversity

- There are many solution 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

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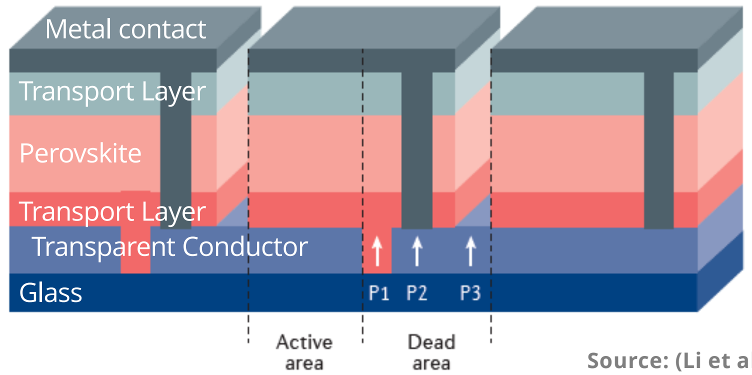
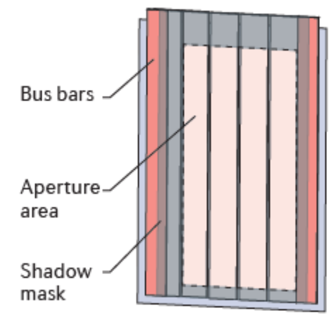
Perovskite PV Modules

- Single junction perovskite modules are made using a series of deposition, scribing, and metallization process steps.
- Some companies are working to develop tandem solutions (e.g., perovskite on c-Si, perovskite on CdTe, or perovskite on perovskite)
- DOE SETO has set performance targets for perovskite modules
  - Higher efficiency
  - Larger areas
  - Durability
  - Manufacturing scale





Source: (Li et al., 2018)

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

1,300 cm^2 perovskite PV module from GCL-Nano in 2019.

Performance Characteristics

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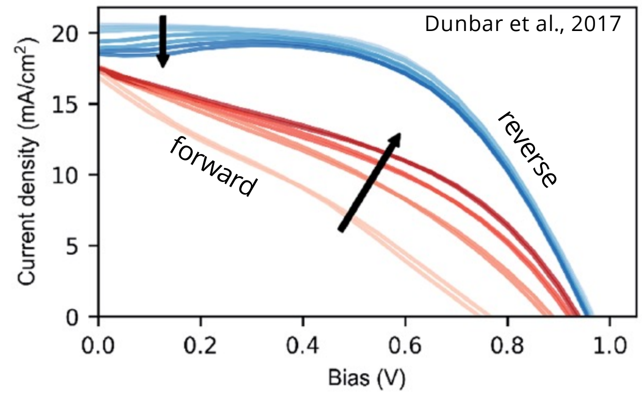
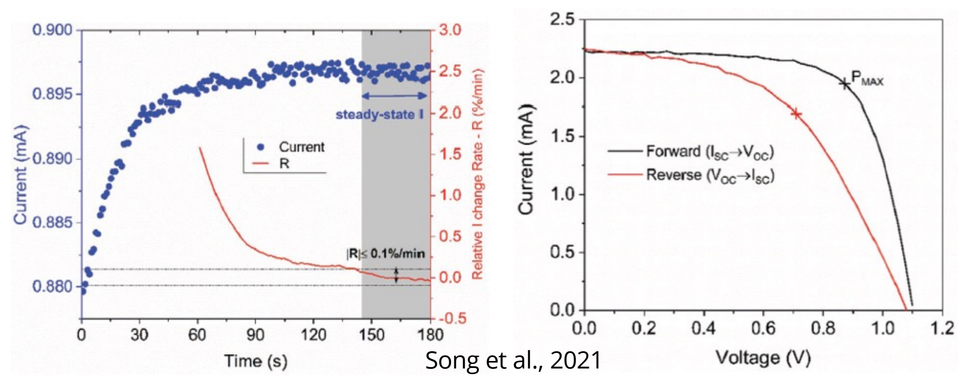
- Much of what we "know" about performance characteristics of perovskite PV is affected by the high diversity of formulations.
  - Not all PSCs are the same and some are much more stable than others.
- Common observations
  - **IV hysteresis** – difference between forward and reverse IV scans.
  - **Scanning 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 in line during production?
  - Requires measurements to be made in <1 sec



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

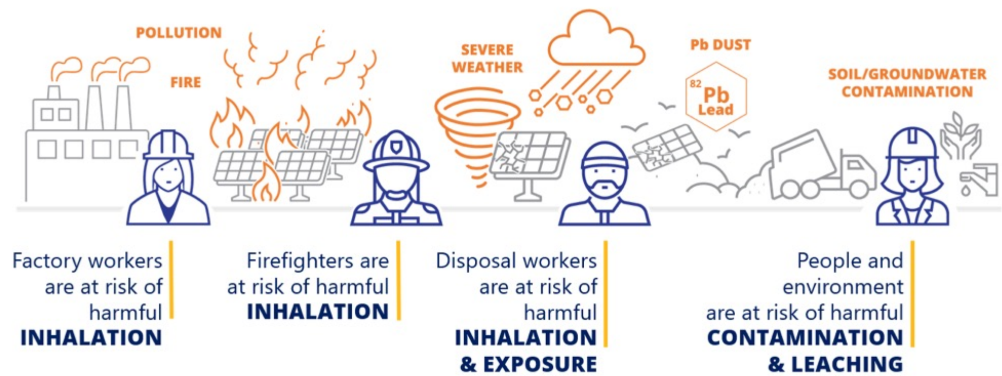


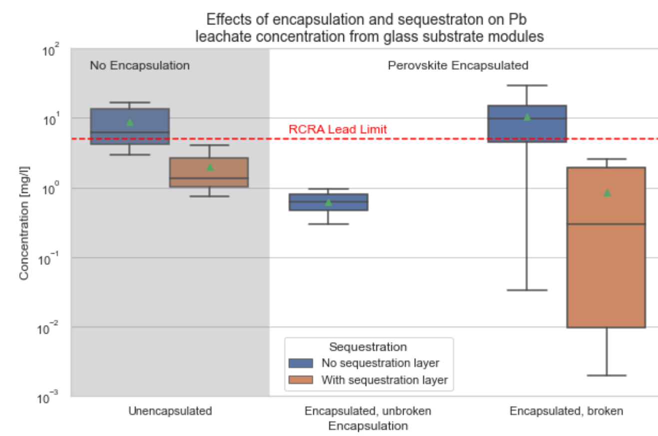
Song et al., 2021

Toxicity Concerns

- Most promising perovskite formulations contain **lead in a highly soluble form**.
- The amount of lead in a perovskite module per watt will likely be less than or equal to that in a c-Si module (solder bonds)

- 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, Libby, and Stein (2022) In Review

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Comparison Between Perovskites and c-Si

	Perovskites	C-Si
Material purity	>99% - High defect tolerance?	99.999%
Estimated module cost*	\$38.69 per m^2	\$62.90 to \$79.31 per m^2
Energy payback time**	0.35 yrs (0.09 yrs with recycling!)	1.52 yrs
Electrical response	Slower response (continuous simulator)	Fast response (flash testing)
Module lifetime	Months so far	20-40 years
Factory size	Small footprint	Large manufacturing facilities (ingot, wafer, cell, module)
Contacts	Contact resistance and adhesion can be challenging. High temps can damage materials.	Robust, high temp metallization

* Sofia, S.E. et al., (2020). DOI: 10.1039/C9SE00948E

***Sci. Adv.* 2020, DOI: 10.1126/sciadv.abb0055, Tian et al., 2021

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 produced at a rapid rate.
- Support new companies with testing, manufacturing, and bankability services.
- More research on sustainability potential of perovskite PV.
  - Chen et al., 2021: Demonstration of module recycling of lead and transport materials
  - Tian et al. 2021: Life-cycle assessment of perovskite PV recycling → 72% decrease in energy payback time and GHG emissions

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PACT: Perovskite PV Accelerator for Commercial Technologies

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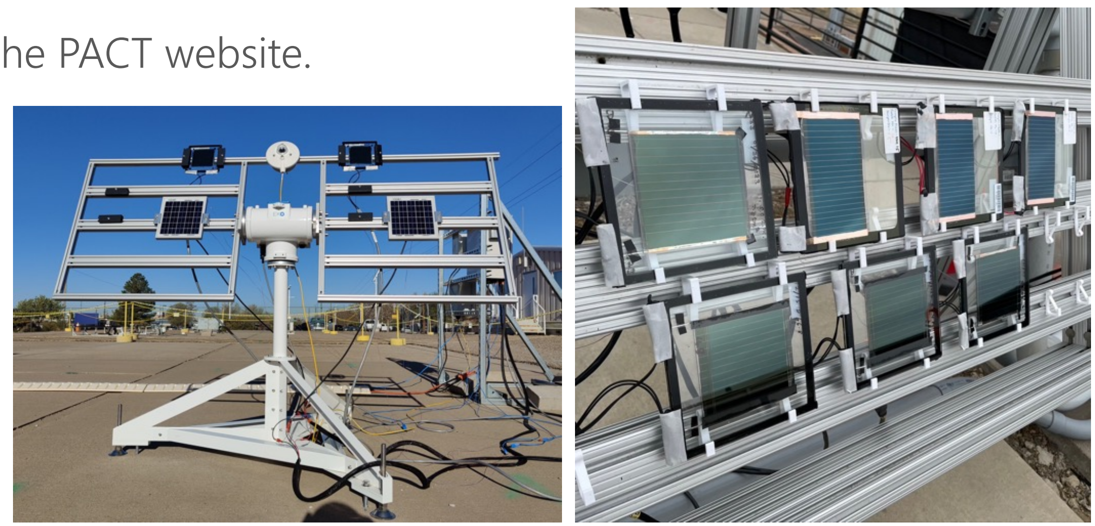
- Sandia is leading a multilab validation center (Team includes NREL, LANL, EPRI, Black & Veatch, and CFV Labs). https://pvpact.sandia.gov
- We are working with four universities to supply perovskite mini-modules for testing.
    - University of North Carolina, University of Toledo, University of Washington, and SLAC/Stanford University
- Version 1 of test protocols are available on the PACT website.
- 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.



Outdoor testing of modules at Sandia and NREL

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PACT Outdoor Testing

- Commercialization of perovskite PV modules will require lots of outdoor operational data in a variety of climates.
- Initially we are testing in New Mexico and Colorado. We plan to add more climates later.
  - Validate ability to model the performance.
  - Validate accelerated testing protocols
    - Do failures from testing match failures outdoors???

16-channel load/measurement box from CFV labs.

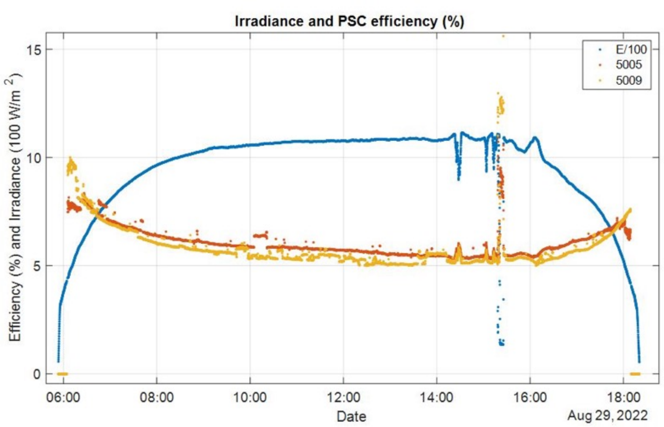
Outdoor Monitoring at CFV Labs

2-axis tracker at Sandia

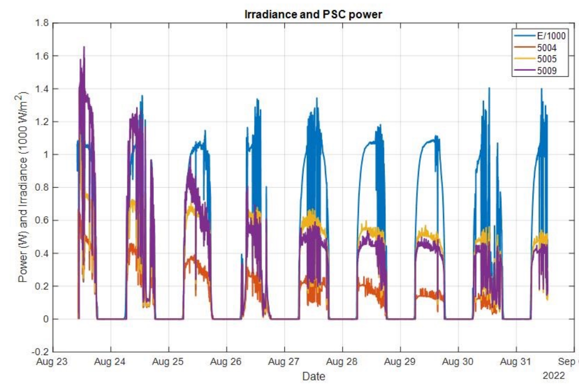
Tim Silverman at NREL

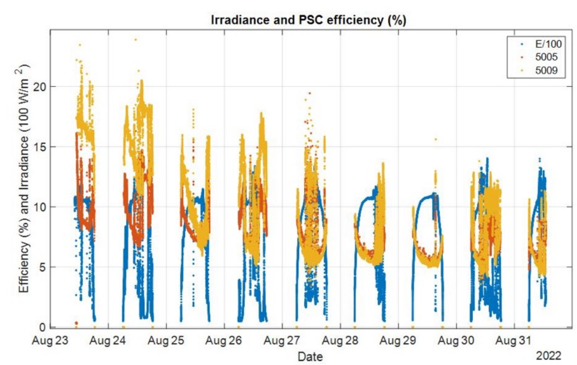
P0003 Field Testing

- 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)



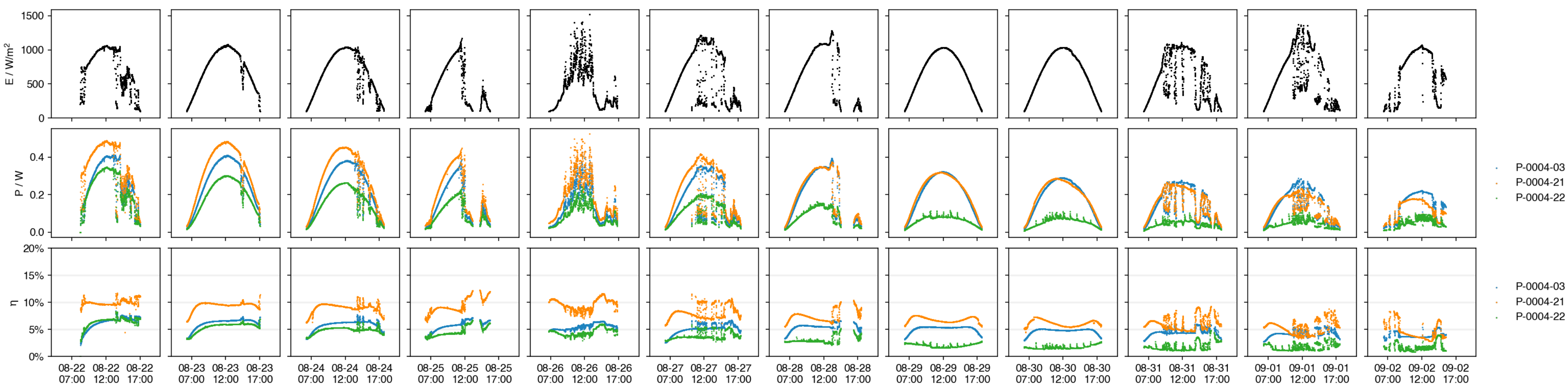
P0003 Module in Field in NM





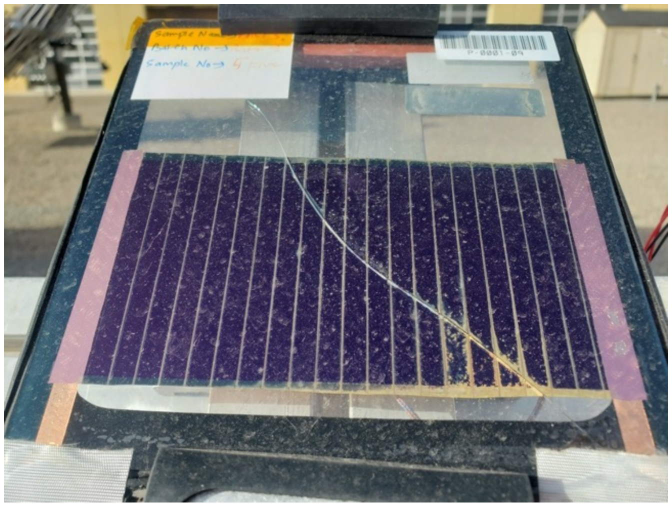
Rapidly declining performance precludes performance model characterization.

P-0004 Preliminary Field Data From Colorado



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

Degradation due to Cracked module



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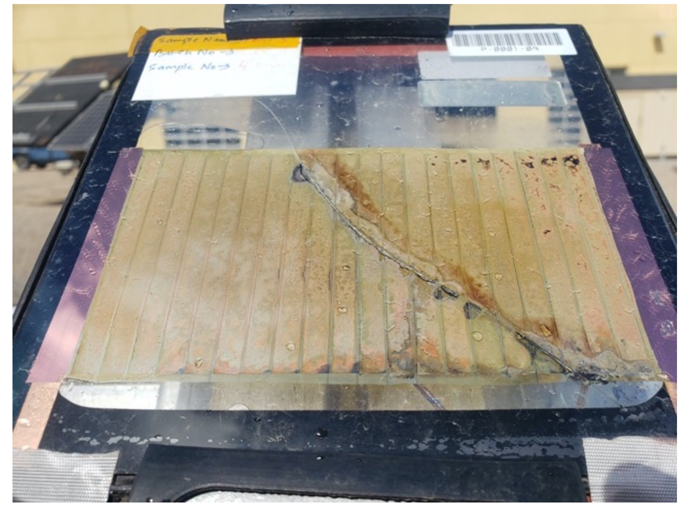
March 18



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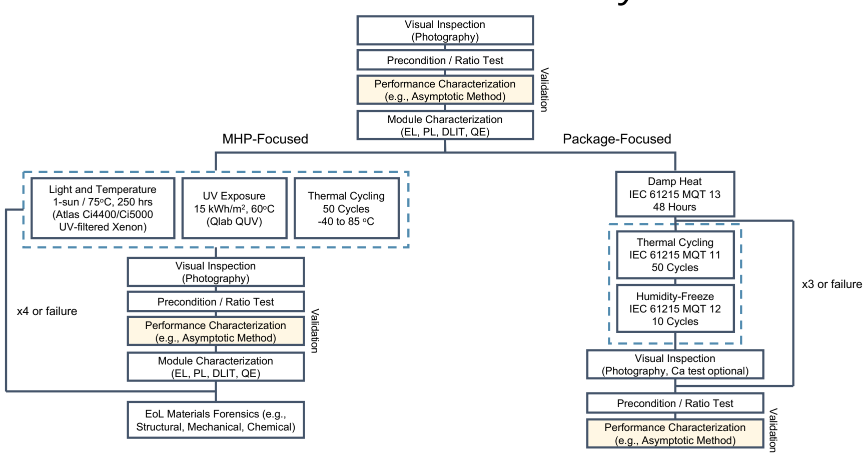
Once the module cracks, the perovskite absorber reacts readily with water to form lead iodide, which is very easy to observe (note these modules are glass-glass with no encapsulant).

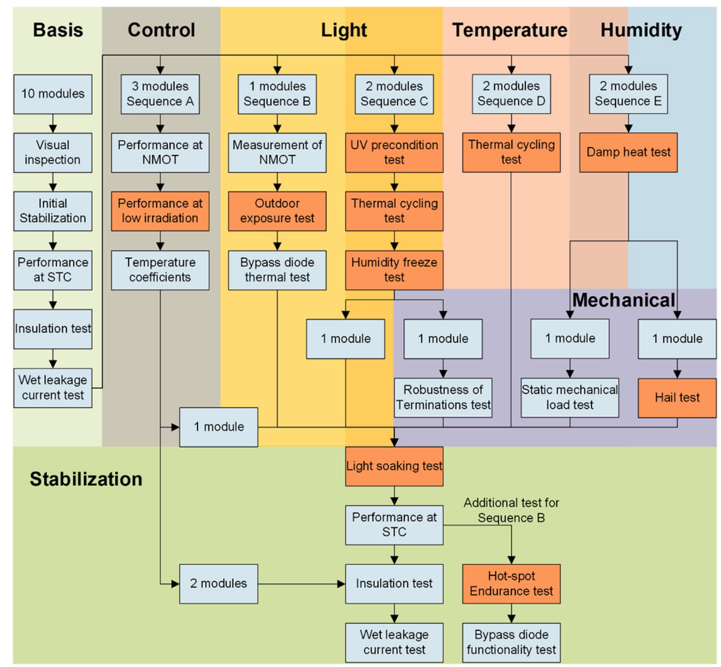
Accelerated Tests Need to be Adapted to Perovskites

- 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



IEC 61215 Test Sequence



https://doi.org/10.1038/s43246-022-00281-z

PACT is developing test protocols for perovskites to match observed field failure modes.

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Summary and Conclusions

- The ease of making perovskite solar cells and the sheer diversity of options for commercializing this technology (composition & process) distract from the few groups that are making significant progress in bringing this technology to market.
- Scale-up in size and speed of production are proving quite challenging.
- Environmental and health risks from lead need to be addressed.
  - Lead sequestration materials show promise for reducing the mobility of lead to the environment. More testing is needed including fire testing.
- More data on failure and degradation modes under realistic conditions is needed.
- PACT is an effort to help support US perovskite PV manufacturers by developing testing protocols, fielding modules, and providing bankability services.