Perovskite PV: How to Support the Commercialization of this Exciting New Technology?

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https://pvpact.sandia.gov

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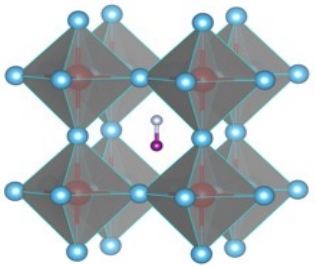
What are Perovskite Photovoltaics?

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

ABX_3

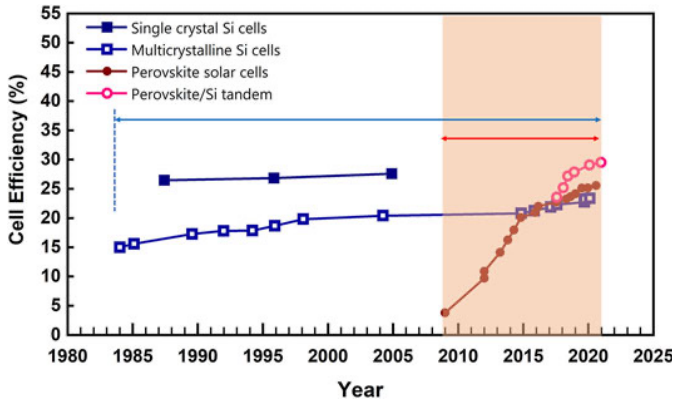


A= Pb, Sn, Ge, Bi, Sb, …
X=halides (Cl, Br, I)
B= Organics or metal (Cs)

- 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



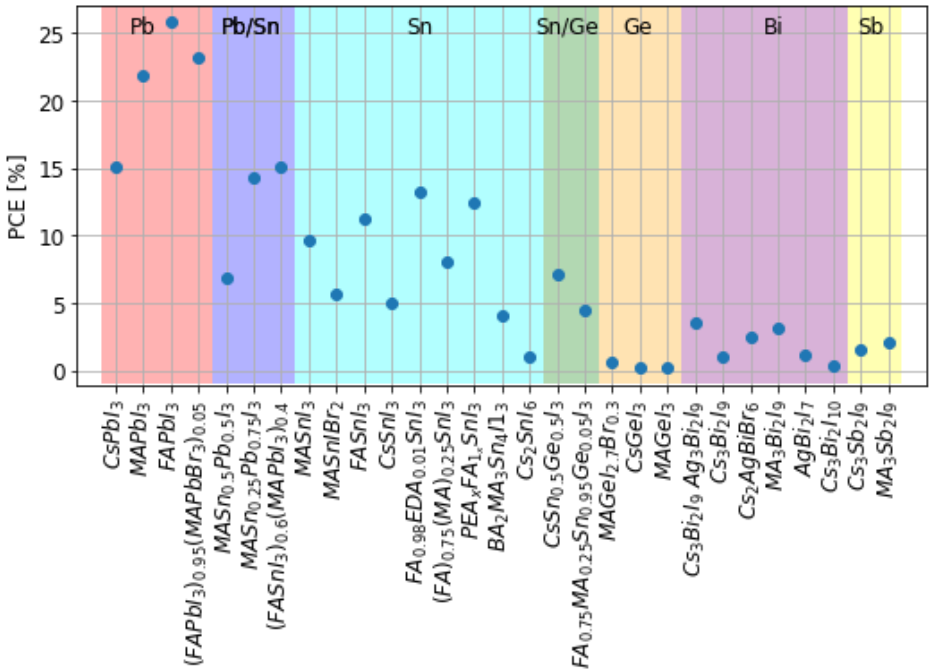
Zhang et al., 2022

Reference:.

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 stability, and durability.
  - Most formulation 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

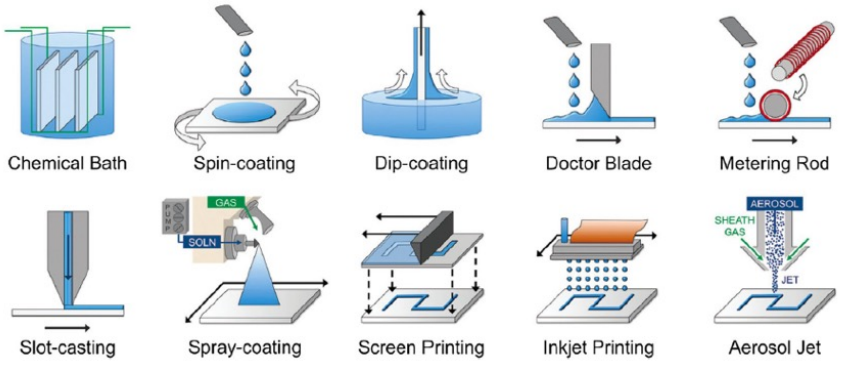


* https://doi.org/10.1016/j.egyr.2020.07.029

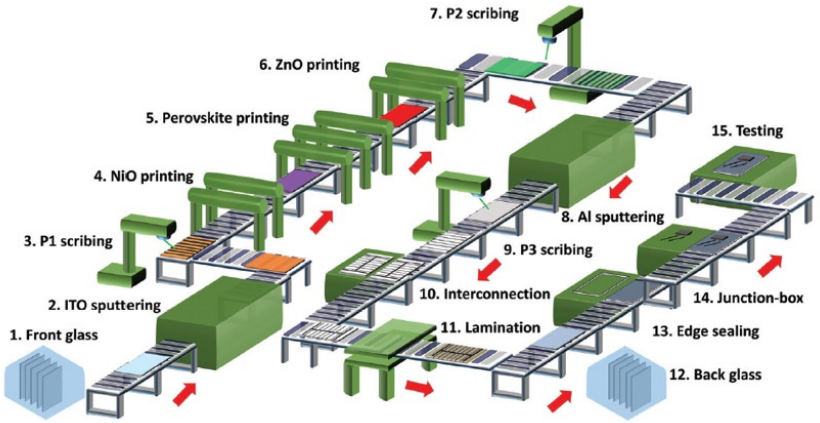
Manufacturing Method Diversity

- There are many solution processing application methods that are being investigated.
- Variety comes with benefits and challenges.
  - Many options for overcoming problems
  - Only a few work on a single method

- Perovskite PV manufacturing footprint is relatively small compared with c-Si.
  - Glass in….. Modules out



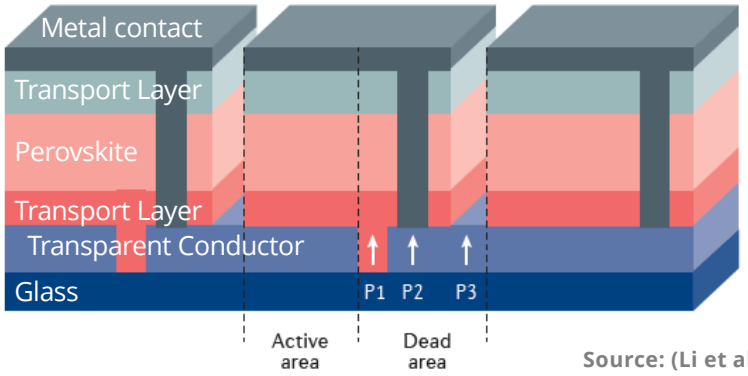
Source: Chilvery et al., 2016

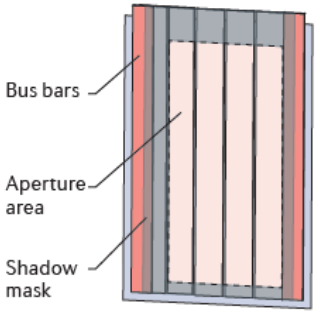


Source: Song et al., 2017

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:

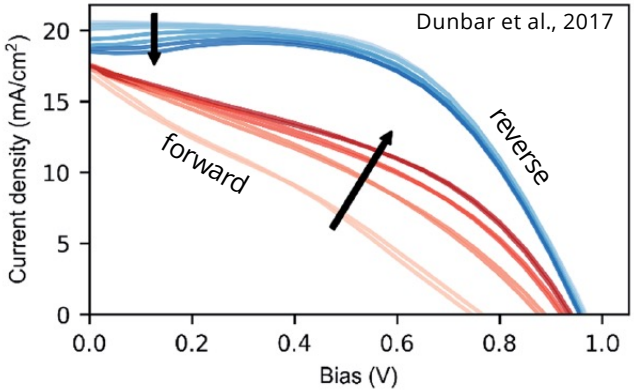
Configuration	Aperture Area PCE[1]	Total Module Area[2]	Durability	Sample Population Requirements
Single Junction	18% PCE	>=500 cm^2 with at least 4 interconnected cells	Pass IEC 61215 Module Quality Test (MQT) 10, 11, 13 and 21 and ISOS-L-2 at specified durations with <10% relative performance loss 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

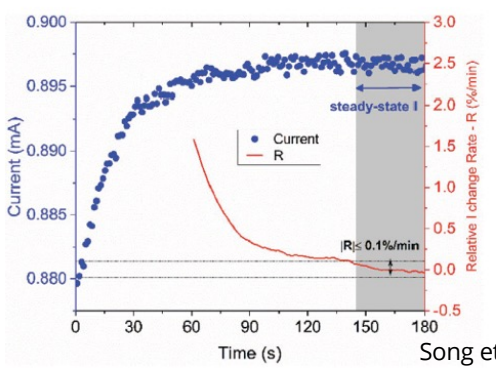
1,300 cm^2 perovskite PV module from GCL-Nano in 2019.

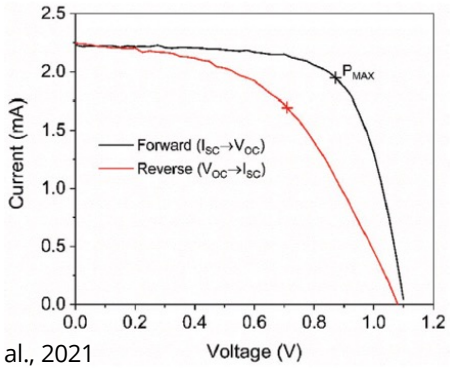
Performance Characteristics

- 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 scanning of voltage
  - IV testing can cause temporary changes in performance.
  - Scanning rate affects resulting IV curve.
  - Stable measurements 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?



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



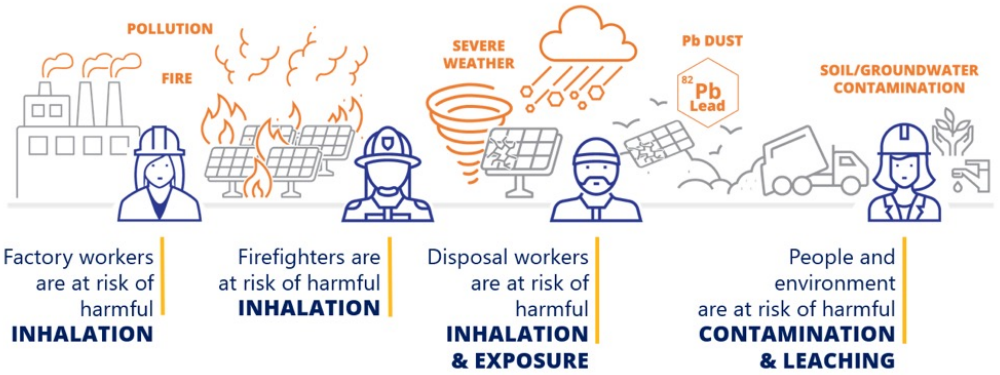


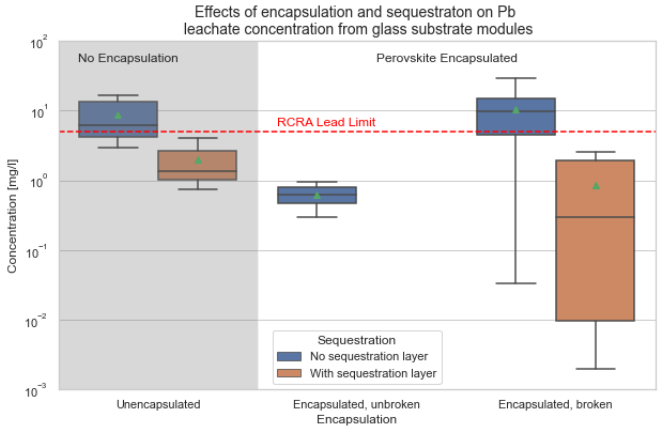
Song et al., 2021

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 can leach out if module breaks?
- 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

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
Contacts	Contact resistance and adhesion can be challenging	Robust, high temp metallization

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

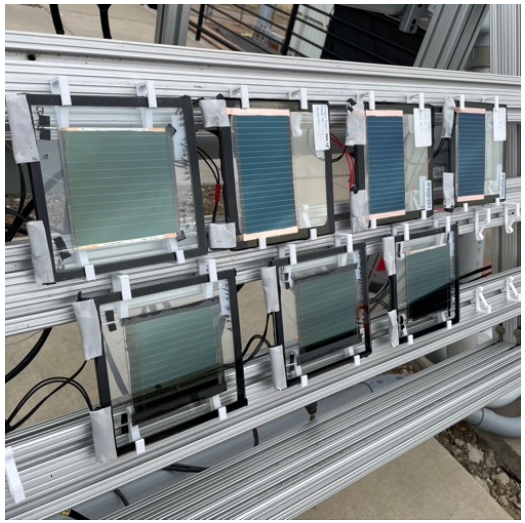
**Sci. Adv.* 2020, DOI: 10.1126/sciadv.abb0055, Tian et al., 2021

How to Support the Commercialization?

- Develop a common set of testing protocols (performance, reliability)
  - Tests should represent/reproduce **relevant** conditions/failures.
- Encourage module pilot lines – Industry needs to demonstrate that high efficiency, stable perovskites can be scaled to larger sizes and be made using commercial manufacturing equipment.
- Deploy perovskite PV modules in the field and monitor performance and reliability.
- Support companies with testing, manufacturing, and bankability services.
- Encourage studies to demonstrate 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

PACT: PEROVSKITE PV ACCELERATOR FOR COMMERCIAL TECHNOLOGIES

- Sandia is leading a multilab, $14M (4-yr) 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 Stanford University
- Version 1 of test standards 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.



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Summary and Conclusions

- Perovskite PV is a promising early stage solar PV technology.
- 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.
- Enforcing standard testing protocols will help to weed out low performing technologies.
- Methods for rapid in-line performance characterization of modules are needed.
- Lead sequestration materials show promise for reducing the mobility of lead to the environment.
- Studies of the recyclability of perovskite PV are very encouraging.
- PACT is an effort to help support US perovskite PV manufacturers by developing testing protocols, fielding modules, and providing bankability services.

Questions?