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PEROVSKITE PHOTOVOLTAICS: CHALLENGES OF COMMERCIALIZING A NEW TECHNOLOGY

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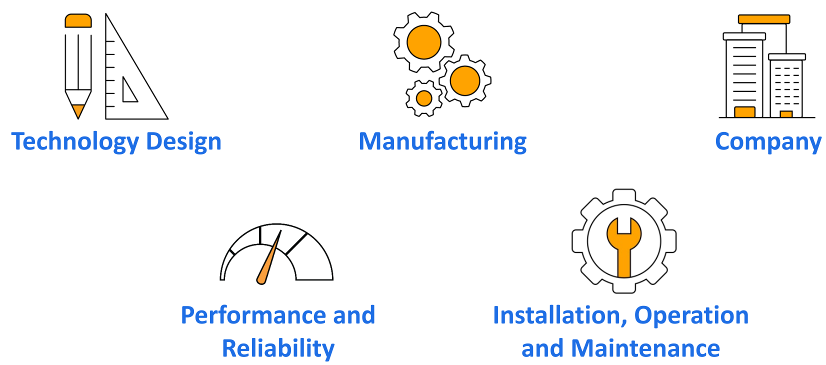
INTRODUCTION

- Brief timeline on the history of photovoltaic cell and module technology
  - 50+ years of conventional PV technology development (crystalline silicone (c-Si))
  - 16 years of perovskite PV technology development
- What are the hurdles to commercializing perovskite PV?
  - Costs
  - Performance
  - Reliability
  - Quality
  - Testability
  - Risks

Black & Veatch’s Pillars of Bankability



Dr. Angelique Montgomery (Sandia/DOE)

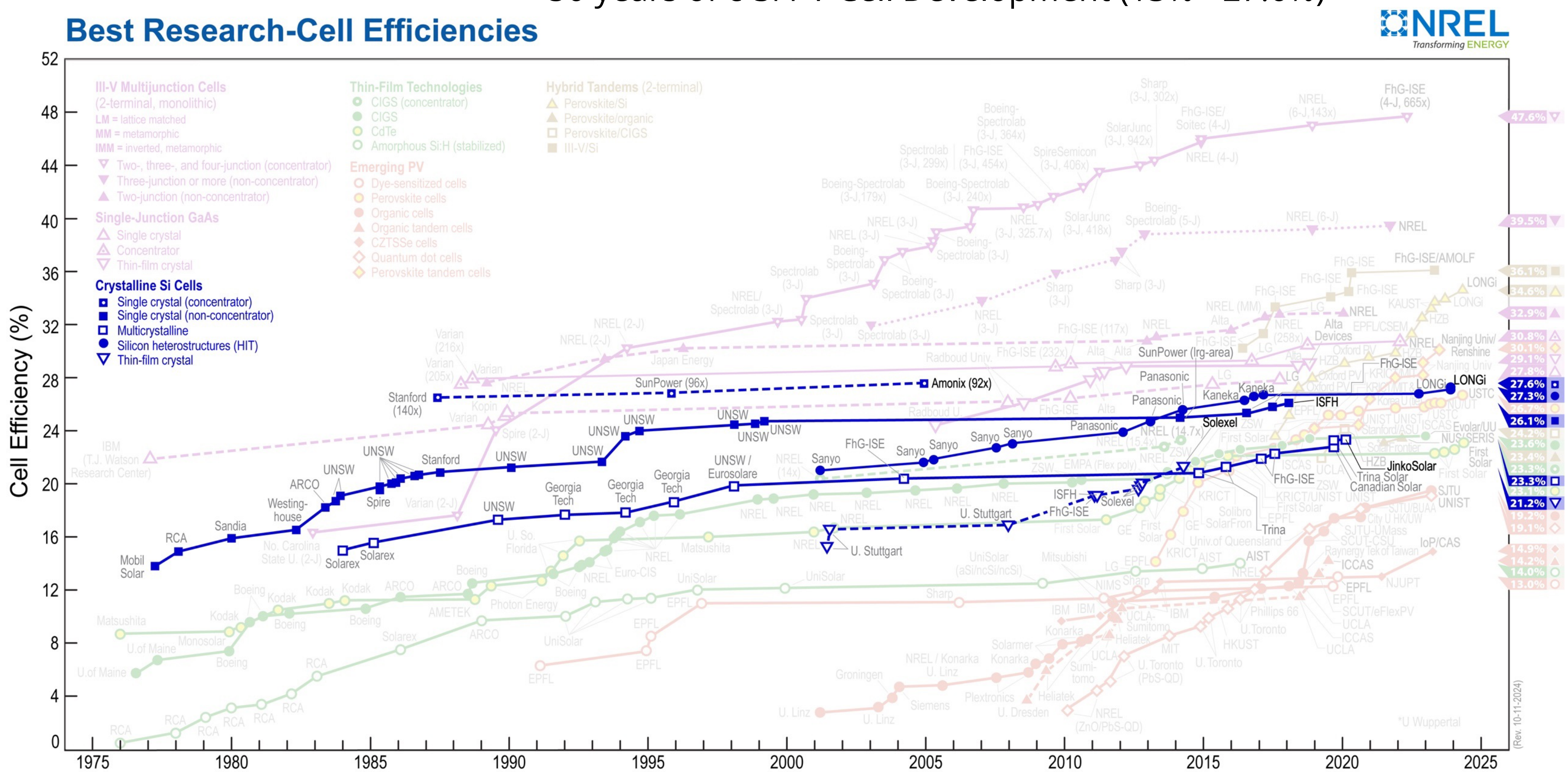
PV CELL TECHNOLOGY TIMELINE

- 1839: First photovoltaic cell developed by Edmond Becquerel (he was 19 years old)
  - Electrode in a liquid solution.
- 1905: Albert Einstein published on photoelectric effect using quantum mechanics.
  - Won Nobel Prize in 1921
- 1954: Bell Labs announce first practical silicon solar cell (~6% efficiency)
- 1963: Sharp Corporation produces PV modules
  - Installed a 242 W PV array on a lighthouse (world's largest array)
- 1974: 1st building heated and powered by solar and wind
  - New Mexico!
- 1977: World PV cell production exceeded 500 kW
- 1983: World PV cell production exceeds 21 MW
- 1985: 20% efficient c-Si PV cells (UNSW)
- 1999 World PV production reaches 1,000 MW
- 2009: Perovskite solar cell (3.8% efficiency) invented in Japan
- 2024: Perovskite solar cell record (26.7% efficiency)

Wikipedia: Timeline of solar cells

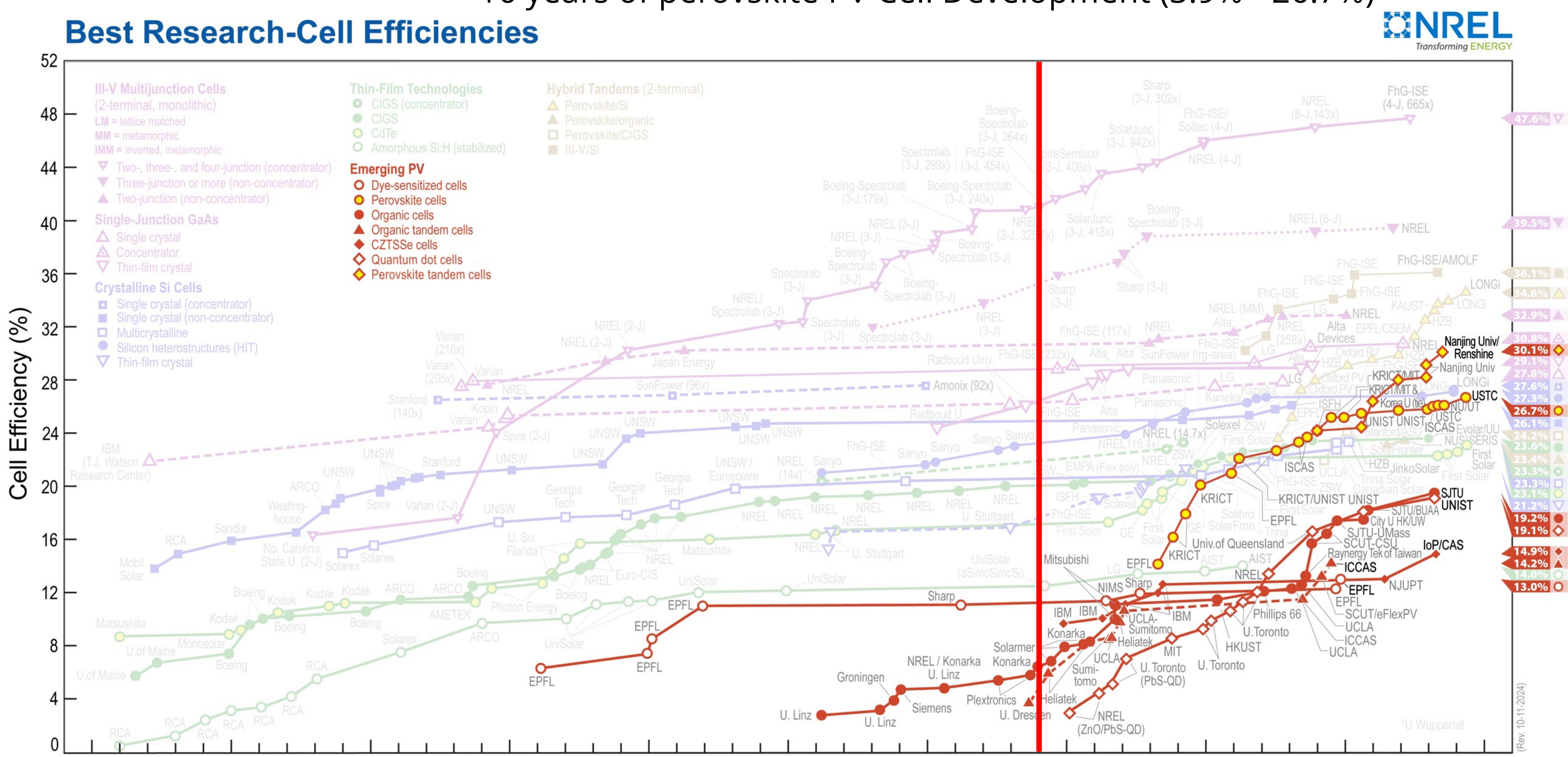
WHY PEROVSKITES?

~50 years of c-Si PV Cell Development (13% - 27.6%)



WHY PEROVSKITES?

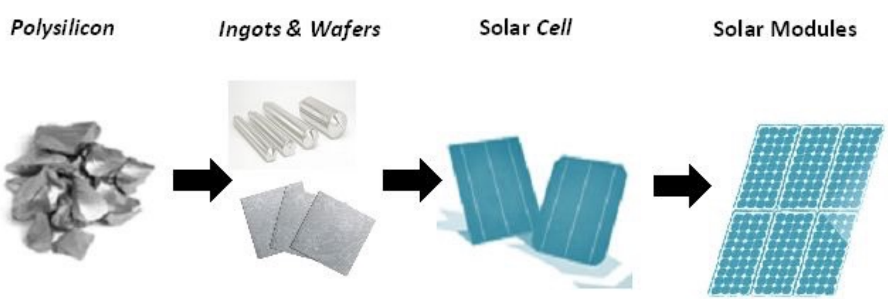
~16 years of perovskite PV Cell Development (3.9% - 26.7%)



WHY THE INTEREST IN PEROVSKITE PV?

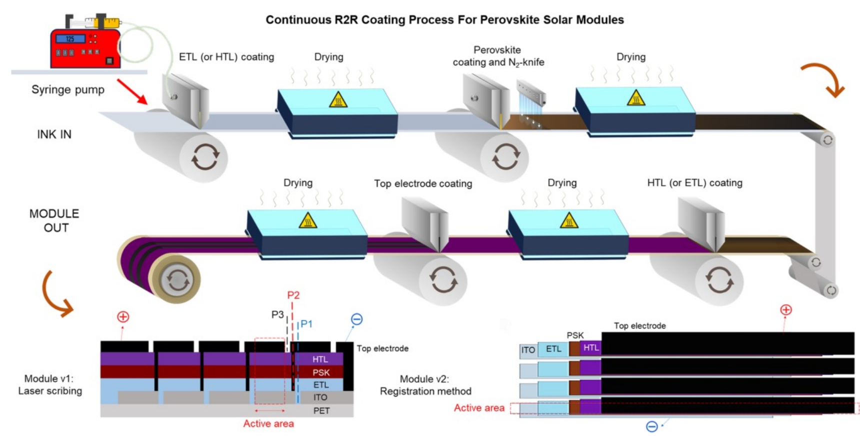
Crystalline Silicon PV

- High temperature (1414 °C) process
- Very high purity of silicon needed (99.999999999% pure 7N-10N)
- High capital expense for production
- Ingots are cut into wafers
- Wafers are doped and processed into cells
- Cells are interconnected and encapsulated into modules.



Metal Halide Perovskites

- Cell efficiency has reached or exceeded that of standard c-Si. (record efficiency 26.7%)
- Can be added to c-Si in a tandem configuration. (record efficiency 30.1%)
- Abundant feedstock materials (Pb, halides (I, Br, Cl), electrode (Cu, C).
- Low temperature process (<150 °C)
- Solution processing (i.e. printing)



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HOW TO COMMERCIALIZE PEROVSKITE PV

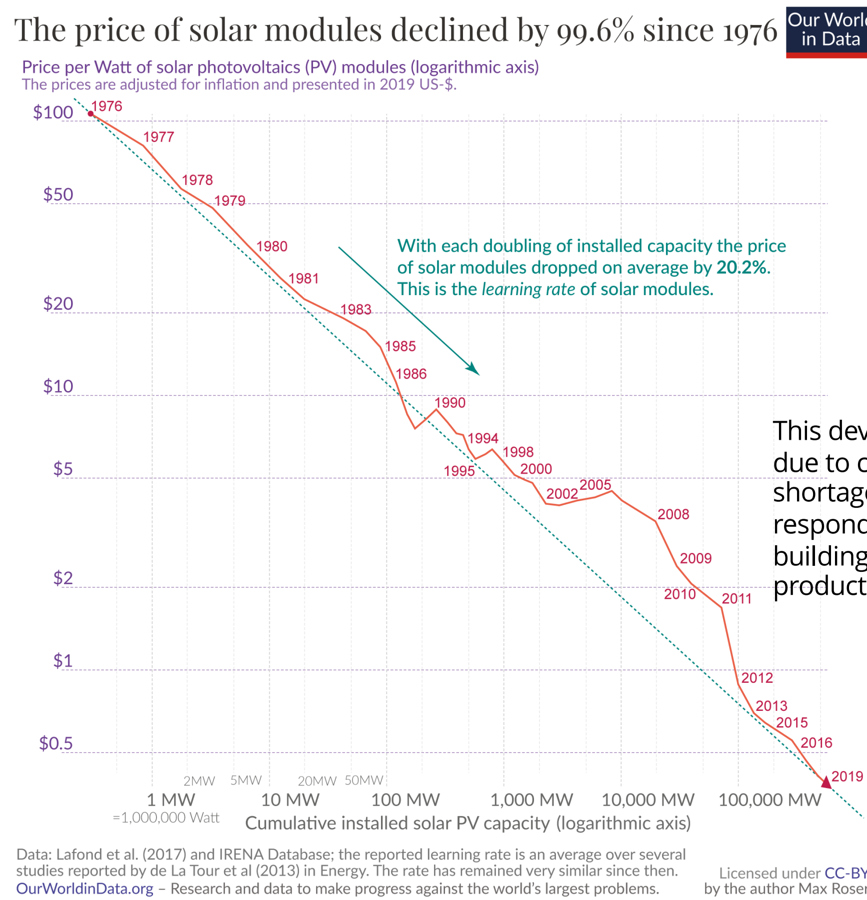
- Costs
- Performance
- Reliability
- Quality
- Testability
- Risks

COSTS: PV LEARNING CURVE

- Learning curves are a way to understand how scaling up production can lead to lower costs/prices. ("Economy of Scale")
- Every time the total amount of PV installed in the world (installed capacity) doubles the price reduces by ~20.2%
  - Will this continue?

- What does this mean for a new PV technology?
  - The cost of the conventional technology keeps getting lower.
  - Hard for new technologies to compete.

- Recent technoeconomic studies have suggested that perovskite-silicon tandem PV modules can me made for ~$0.35/W in the US.

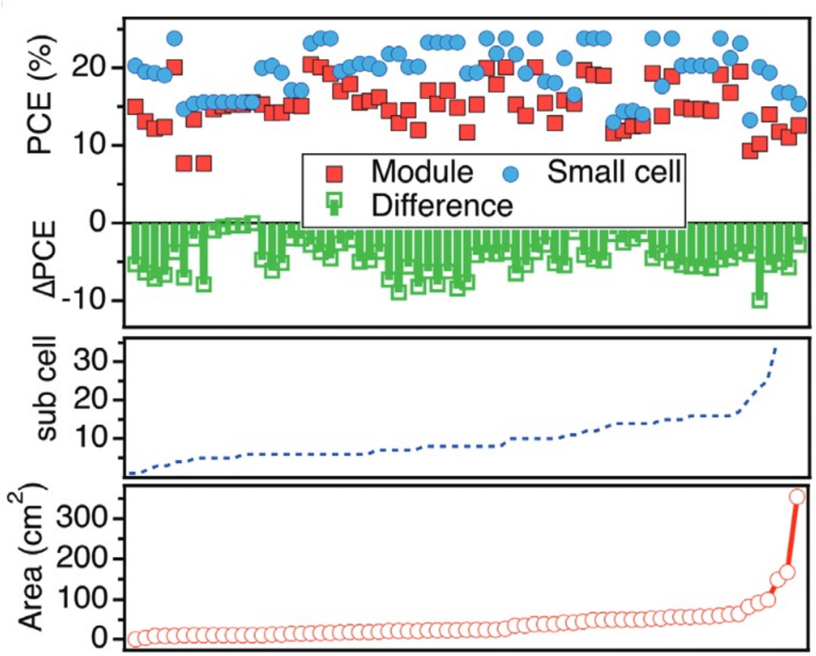


This deviation was due to c-Si shortages. China responded by building our production.

PERFORMANCE: CELL TO MODULE LOSSES

- Modules are made by interconnecting PV cells in series and parallel to increase size and voltage, which reduces electrical losses.
- Modules (i.e. "solar panels") are considered the commercial product goal.
- Cell to module losses in efficiency are significant (5-10% absolute). Much higher losses than c-Si.
  - Dead space
  - Electrical resistance
  - Spatial variability
  - Other reasons…
- Module areas are also still very small.

Efficiency decrease from cells to modules from literature survey



https://doi.org/10.1002/aelm.202300093

EARLY LARGE PEROVSKITE MODULES

The Chinese are world leaders in scaling up production of new PV technologies.

Microquanta α-series modules are advertised.

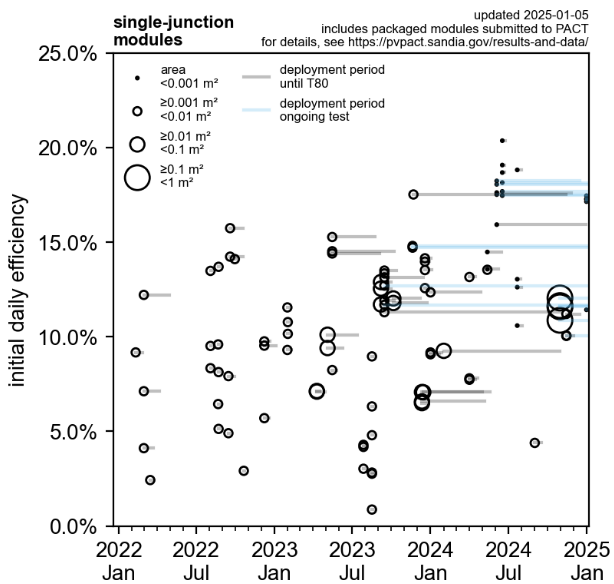
- They are ~12% efficient
- 1.2 x 0.64 m (small compared with c-Si)
- Rating of 95W (compared with ~500W for c-Si)

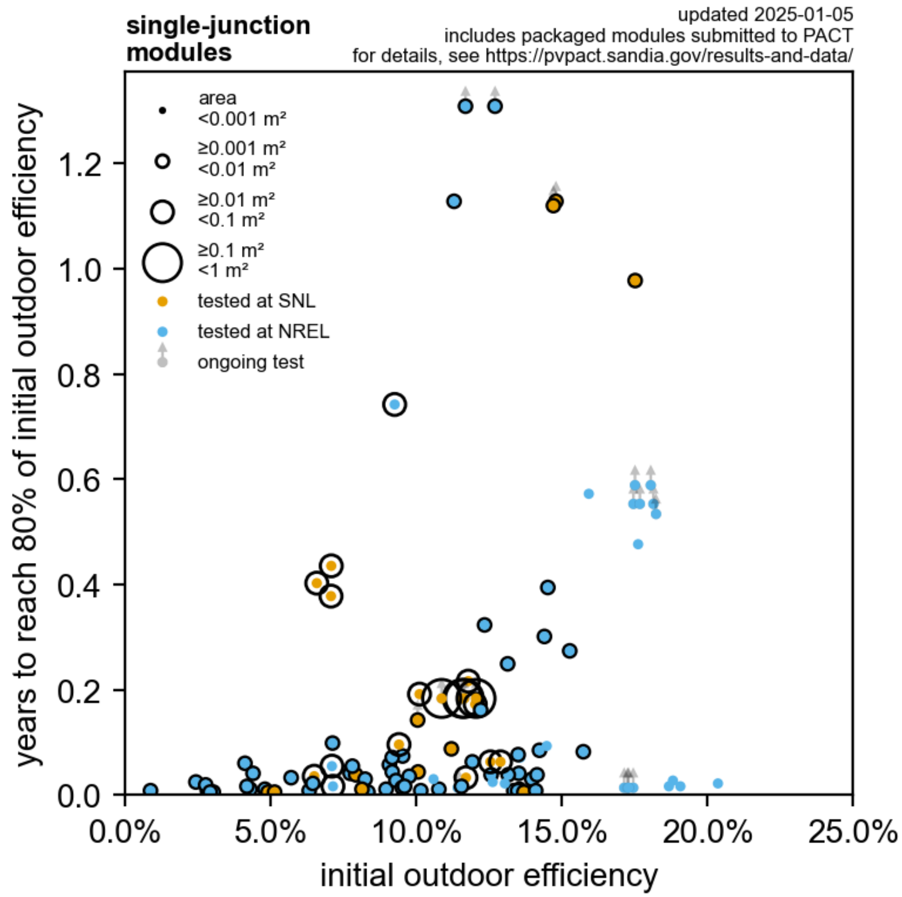
Question: Can larger modules with higher efficiencies ~20% be produced?

RELIABILITY/STABILITY OF PEROVSKITE PV

- Conventional PV modules last for 30-40 years.
- PACT has tested hundreds of perovskite modules outside.
- To assess reliability, we define the metric: "T80" – Time to reach 80% of initial efficiency outdoors.
- Most modules have very low T80 values (<10 weeks)

Slight improvement over time in performance and reliability





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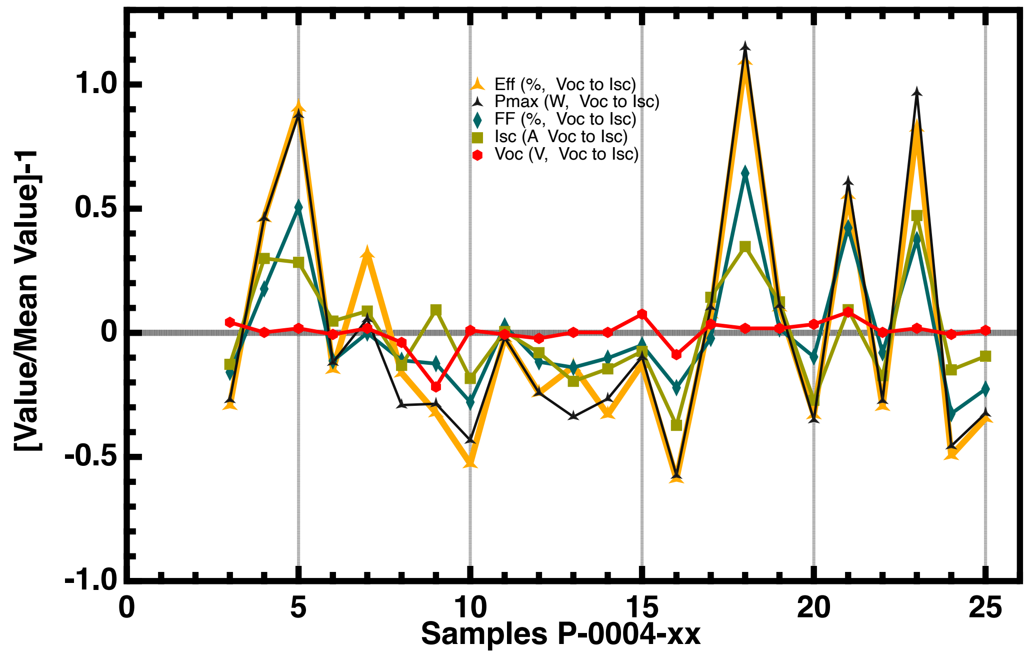
QUALITY

- PV moules are almost considered commodities.
- Expectation is that consistency between different modules is very high (+/- 1-2%)
- Initial batches of minimodules received at PACT varied by as much as 100% or more.
- Very little data is available for modules nearer to commercialization.



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TESTABILITY

- Conventional PV modules are tested on a pulsed solar simulator (flash tester).
  - Flash tests are performed on each module several times during manufacturing.
  - Module are binned into power classes.

- Perovskite PV modules **do not respond fast enough** to be tested this way.
  - They require a continuous solar simulator and several minutes to stabilize for each test.
  - Uncertain how this will impact volume manufacturing. ← slow the process!
- Most commercial test labs do not have equipment to test perovskite PV modules.

RISKS

- Most perovskite PV cells are based on lead iodide compounds.
- Lead is highly toxic and regulated. No safe exposure levels.
  - Manufacturing
  - Operations
  - End of life (recycling)

Factory workers are at risk of harmful **INHALATION**

Disposal workers are at risk of harmful **INHALATION & EXPOSURE**

People and environment are at risk of harmful **CONTAMINATION & LEACHING**

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WHAT ARE WE DOING?

- DOE Performance Metrics
- Offering free testing to industry
- Developing new test protocols

DOE PERFORMANCE METRICS

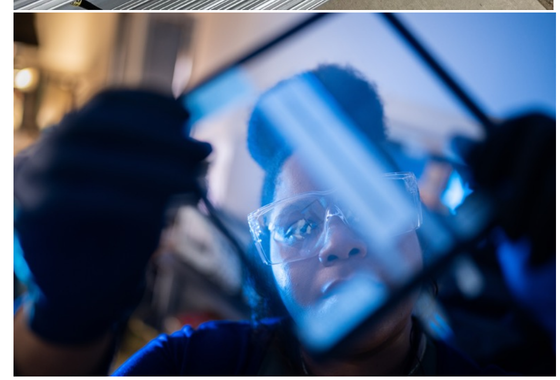
Revised Performance Target Matrix:

<table>
<tr><th>Configuration</th><th>Aperture Area PCE[1]</th><th>Total Module Area[2]</th><th>Durability</th><th>Sample Population Requirements</th></tr>
<tr><td>Single Junction</td><td>18% PCE</td><td rowspan="3">>=500 cm^2 with at least 4 interconnected cells</td><td rowspan="3">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]</td><td rowspan="3">>1 kW total, at least 20 modules for outdoor testing[5]</td></tr>
<tr><td>PVSK-only Tandems</td><td>24% PCE</td></tr>
<tr><td>Hybrid Tandems</td><td>27% PCE</td></tr>
</table>

PACT PROGRAM

- Joint test program between Sandia and NREL.
- Started in 2021.
- PACT has received ~600 single junction and tandem minimodules for testing.
- Modules come from nine companies and six research labs and universities.
- Outdoor testing for reliability
- Indoor test protocols:
  - How to screen for early failures (qualification tests)
  - How to stabilize performance after accelerated testing to get repeatable results (preconditioning testing).



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STUDENT INTERNSHIPS AT DOE NATIONAL LABS

- All DOE national laboratories have summer internship programs.
  - Wide range of technical areas, many are geared for undergraduates.
  - Located across the country
- Sandia has many internship programs (e.g., FORCEE)
  - https://www.sandia.gov/careers/career-possibilities/students-and-postdocs/internships-co-ops/
- NREL has the STAR (Student Training in Applied Research) program
  - https://www.nrel.gov/docs/gen/fy23/84267.pdf
- Search other labs websites for even more opportunities.
- Learn to use and develop your professional network.
  - Ask professors, friends, and career centers for help
  - Be willing to try and learn new things – be open to working in an area you know little about.
  - Focus your resume on skills (e.g., software, coding), accomplishments (e.g., projects), interests.

Thank you!
Questions?

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