Panel

- What are differences in testing cell level vs module level?
    - Cells are relative tests. For example, results might be framed as 20% improvement over what they have seen before. This approach is used to show that they continue to make progress. But ultimately, in the end you need to compare against silicon modules, use absolute numbers, and compare against years in the field.
        - Researchers should try to make transition from relative testing to comparing against existing established products and years in the field.
    - Data density is a lot higher for cells (mm^2, can test a lot of them on one substrate that came from same process run, etc). Scale up + module size means you can't test as many per unit time. Cycles of learning slow down significantly on larger scale. But the scale up can contain a lot of things that you don't see at small scale--process defects, series resistances, etc.
        - Cell level and module level are two critical and challenging phases of develop, but very different in the cycles of learning.
        - Consider your schedule when you start planning.

- What type of reliability testing conditions should emerging solar startups adopt, especially when they want to convey their product stability to their first customers?
    - Companies should know what their own problem area is and test for that. When you're showing your reliability to your customers, it does help to have UL certification. Lifetime data beyond that is also good. Going to need something certified before you start talking to customers.
    - Your early adopter customers are really on your side. Something First Solar did was trust early partners and worked with them. It was okay to show all the defects/deficiencies because the synergies mean faster learning cycles. Open/trusting engagements are good, but remember to protect your IP. Having key partners is good.
    - Get things outdoors ASAP. Outdoor data is more important than chamber testing. NREL and Sandia will be offering outdoor testing services and lab test services for perovskite devices through Perovskite PV Accelerator for Commercializing Technologies (PACT).

- Is IEC really the gold standard for customers? Why or why not? Are there other qualifications researchers should pay attention to?
    - IEC is like a drivers license test. You need it to get on the road but it does not mean you are a good driver. They are for early failure mechanisms or for relative comparisons.
        - IEC certification does not mean your product will last 25-30 years. Example of this is the AAA polyamide backsheets. It was a new backsheet type, hadn't tested before. Did not know they needed mechanical stress + weathering. The backsheets ended up failing after about 5 years.
        - PID was also a surprise. As system voltages grew, did not realize that Na was going to migrate in from the glass and affect the cell. As technology changes, new things will come up.
    - One misconception is that the IEC test proves long term reliability. That's not what they're designed to do. They're designed for finding early failures (5-10 years). To assess long term reliability, you need to understand the failure mechanism physics (and usually more than one). Need to understand acceleration factors and the science behind the degradation mechanism. That will be unique to your product, how it's packaged, and the

environment it will exist in. That will require a lot of internal R&D. You can get some support at National Labs.
    - When there are modules that have passed certification testing but failed in the field, it's usually because there are multiple stressors on a module that is hard to replicate in a chamber. Hardest stressor to replicate is UV, it’s really difficult to get UV into a chamber. You can only irradiate one module at a time in a chamber. You can only ask so much from laboratory testing for anticipating lifetime. Really need to get it out in the field.

- How do you suggest solar researchers balance performance while managing reliability?
    - Your company needs to survive into the next round of funding. A lot depends on what you're going to be raising money off of—that's generally performance. But you can get in a bad place where you start making choices where you choose materials that are too expensive, or you end up doing something that is unreliable. You need to pay due attention to reliability and should ramp up reliability testing as the product becomes more advanced. Obviously there are difficulties of a small company and there is only so much time. You need to know what you need to do to raise the next round of money.
        - There is a cautionary tale there. CIGS community was very good at raising the next round of money, but not addressing the hardest question which was may have been manufacturability. Maybe didn't address biggest bottleneck in that community. Very little CIGS is left, most of it left is small portable products.
        - Perovskites are starting in a harder place than CIGS and CdTe. For CdTe the initial challenge was will this ever be as efficient as silicon. But for perovskites the efficiencies are fantastic, there's hardly a tradeoff. The big bottlenecks are manufacturability. In perovskite you could be raising money against the reliability/durability of your device because the efficiency is already promising.
            - Reliability data can be used as a selling or marketing tool, despite the difficulty in directly monetizing it in terms of average selling price
                - Ex: wafer cracking in silicon is big deal (hail). First Solar is marketing their CdTe cell technology as a more robust alternative to silicon since it is less prone to fracture.

Q&A

- What time frame really matters for reliability? Obviously the products have to outperform the warranty time period, but for many PPA's the first 5-7 years have the highest return bundle, does that mean that timeframe means more for bankability?
    - Customers are concerned about first few years. Need to be proactive with resources. The experience of your customer with your technologies will dictate returns. As they learn more they'll be more tolerant with issues (e.g. blemishes on the module)
    - A project developer may have a more detailed answer to this

- How do you assess and maneuver when things go wrong?
    - You have to have people in facilities and resources at the ready to respond to the customer. Customers will be in panic and put all your sales on hold. They want an answer in weeks, not months or years. Hopefully all your proactive research has allowed you to identify most problems and give a really good explanation. Sometimes you need to do research on the fly. Need to know how to test your product properly. Need the place, resources, people to do this research. This experience can work in your favor if

you build trust and work through the problem with the customer. You can give them confidence that you handle challenges well.

  - For failure analysis (FA) testing, if you pull a module in the chamber and it went bad, how do you know it went bad? You can look at electrical characteristics first (current, voltage, FF). You can do IR imaging, relatively inexpensive, and can see if there are hot spots on the module. Also do EL, some cells will indicate that there's something wrong with them.
    - In general you have a Failure Analysis person that goes through set protocol on every failed module and assign a failure mode. Sometimes that works and sometimes that doesn't.
  - There are resources available at National Labs to help early stage companies for things like failure analysis. Everyone at National Labs is accessible by emails. They really value collaborating with industry and welcome those emails. It is great to open a line of communication and explore possibility informally.
    - If it looks like there is a larger examination needed, then they would try and set something up (agreement) or participation in one of the DOE programs.
    - If they want do one exploratory measurement they can do that and get someone on their way. Can also set something up more formalized.

- What specific tests (and passing criteria) should a company do on a cell level before making modules? Could you share some of these experience in CdTe or CIGS?
  - You need to distinguish between true degradation and metastability. You'll get answers in field. Metastable would be reversible changes in performance (electronic traps, ionic drift in either drifting, hysteresis behaviors, polarization). Metastable can behave seasonally/diurnally. True degradation is 1 way process--corrosion, built in drift, etc
  - CIGS, the cell is moisture sensitive so it will degrade over a period of several days. Rarely did bare cell measurements. Would often do simple package between glass. In that single cell module, then they would do every test. Would follow up with doing full module tests. Would do a lot of single cell tests because it's easier to make cells than modules. Should be first pass when doing any first studies in testing chambers.
    - Note that CIGS is moisture sensitive, more so than CdTe but less so than perovskites. Perovskite sensitivity may be new regime of packaging. Silicon mfgs will boil cells as a test. Need to think about what range of behaviors we're talking about when we're talking about packaging/moisture.
      - There are a lot of assumptions that we can put perovskite in glass/glass with thick edge seal and it'll be okay. Might not be true. There are still has points of entry for moisture and also you don't want give up efficiency to super thick edge seal.

- Would Si/Perovskite tandem testing still need to go through all the years of testing, as compared to pure Si devices
  - Even more so. We have some ideas about silicon reliabilty. We have a lot of question about perovskite reliability/mfgability. Lions share of questions would be solved if you solve reliability in separate. But when you combine them there may be new behaviors/interactions.
    - Great start will be establishing the perovskite reliability separately. But then think about what new failure modes come with the tandem.

- Also, for reliability of Perovskites, especially since the overall technology still has issues. What is the best way to think about modules at this time?
    - Personally, thinks that as soon as you can, make a module ASAP. Even if it's bad efficiency, you will learn problems that'll occur during scale up. Better to get an idea of what those problems are before you perfect the cell. Start studying scale up effects.

- What's the minimum cell to module efficiency drop before you consider the module tests? When do you know the lessons are translatable? Is there a floor in performance you'd suggest?
    - If you can make a mini module that is at least half the efficiency of your all-star cell, that's probably worth doing. You wouldn't be looking for efficiency/reliability problems, but more thermomechanical type problems like delamination, chemical interaction with encapsulants, that sort of thing. More emblematic of the package and the cell interactions and get an early start on that. Would be less concerned of great module efficiency. Would be interested in learning about nonefficiency related parameters.
    - You may have to re-do it when you go from 10% module to 20% module. To get an early start and avoid catastrophe is a good thing. May not be a bad thing if difference in efficiency is because things aren't optimized yet (e.g. laser scribing). Engineering problem is okay. Same thing with edge seals and such. You might understand why the efficiency is low and it's okay.
    - Put an upper bound in module size during early research, probably don't need to make a mini module that's more than about a square foot. Diminishing returns. Probably don't want to make a 2mx1m module when you're still in the R&D phase.

- In thin films, is there a minimum physical cell or module size required for early reliability testing to ensure that it captures most (if not all) failure modes at scale?
    - You can learn a lot from a 10 cm x 10 cm mini module workhorse. Used a lot at First Solar.
    - You want to have a few cells in series in a small module to test interconnection. Easier to handle something that you can pick up and move around.

- Are there hidden problems for perovskites in a non-glass packaging?
    - If you look where flexible CIGS tried to go, there is a cost issue there. To make a flexible transparent package (non glass), you need very low water vapor transition rates. You need a stacked ALD deposited layer. Gets expensive. To think about doing that for utility scale solar, that gets rough. To get rid of front glass, need real innovation in non glass front sheet low water vapor transport rates. Need a really great moisture barrier.

- For perovskites...with degradation still being an issue. Does commercialization make sense for now...or is it too ealry?
    - If it's degrading, you won't find a big market. You might find a small market, but you wouldn't put it in a utility scale field. Fix the degradation.
    - Application dependent as well. For example, highway signs might be a potential beachhead. Get indirect bankability and get it out in the field.

- Given the scale of the problems, do they have to be tackled in a company setting or academic lab setting? Do you think the challenges that you were trying to overcome in your companies, would they be better handled in academic R&D or a company with focus on the problems.

- For work done at First Solar, it would have been impossible to do much of this outside of a company environment. You need that profit motive/excitement of the technology/large production/large deployment to start learning what the real problems are. Even National Labs are talking about kW scale deployment in testing
- The particulars matter. Have to do the reliability/durability on your cell, academic lab would do slightly different cell. Understanding degradation mechanisms in academic setting is useful learning, but would have to redo many of those studies when you move to the cell you're actually making. In the CIGS world, NREL did contribute significantly with round robin testing, and expert analysis of cells sent in from US manufacturers. Everyone's cells are different, and they all have different problems, but it was useful to have a group of experts who had a good overview of everyone's problems.