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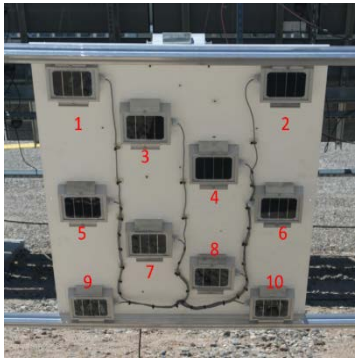

The Disruption of Future PV Developments

Joshua S. Stein Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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PV is a Disruptive Technology

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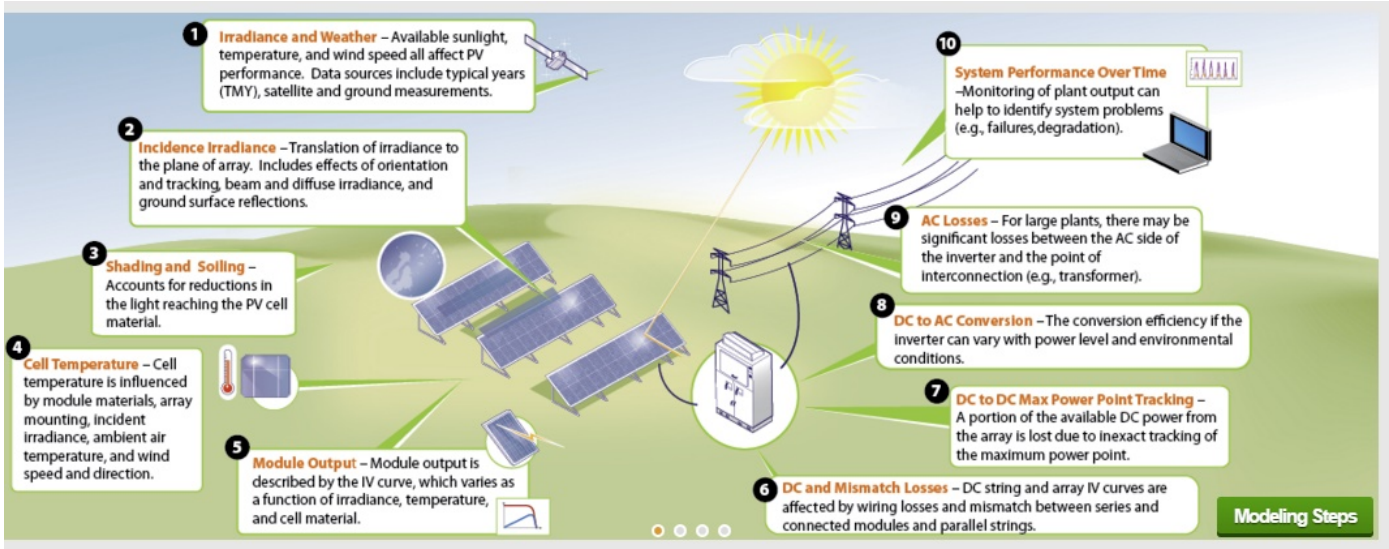
- Steven Sinofsky defines four "Stages of Disruptive Technologies"

1. ***Disruption of Incumbent***
   - PV cells and modules offer "clean" and "free" energy but production costs are initially very high – Focus on small, off-grid systems & first adopters. PV's reliability "black eye" in the 1970's and early 1980's
2. ***Rapid Linear Evolution***
   - Efficiencies rise, reliability and durability increases, production costs fall. Modules treated as a commodity.
3. ***Appealing Convergence***
   - PV is cheapest form of electricity! Integration challenges remain (e.g., energy storage, market structure, demand response, etc.)
4. ***Complete Reimagination***
   - Solar roofing (e.g., Tesla) and BIPV
   - Solar Transportation (e.g., Toyota is aiming for: 70% of cars, 50 GW/yr. 8% GHG reduction) – ships, trains, etc.
   - Solar roads, vertical bifacial, internal tracking (MOSAIC), adaptive shade response, conformable PV, lightweight, and much more beyond what we can now imagine…

Future PV products will have many different characteristics from today's modules. We need to be ready to characterize and model tomorrow's PV technologies.

Measuring and Modeling PV Performance



Factors that Affect PV Performance

- Irradiance (intensity, uniformity, spectrum, variability, reflection, soiling, albedo)
- Temperature (uniformity, effects of air temp, irradiance, wind, RH, etc.)
- IV Behavior (LID, linearity, metastability, mismatch)
- MPPT (string-module-cell level, DC/AC>1)
- System Performance over time (degradation, variability)

New PV technologies will require new ways of characterization and modeling.

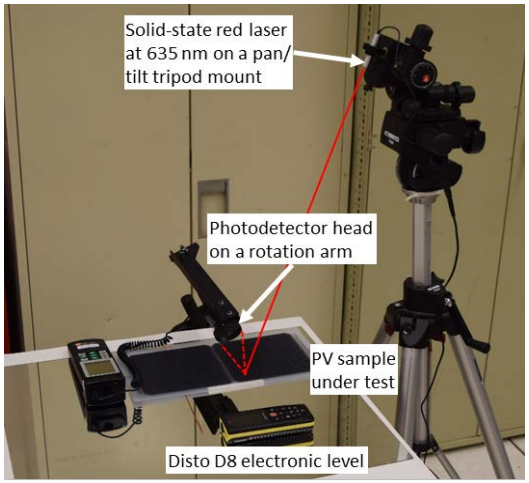
Strategies for Improving PV Performance & Value

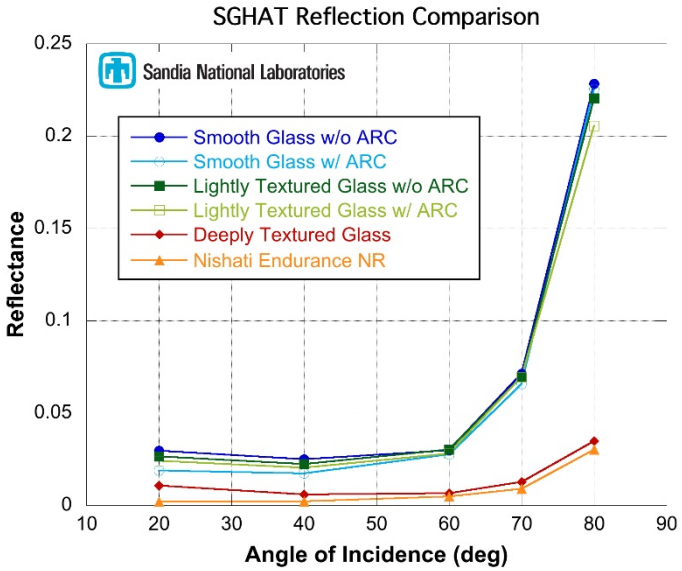
- **Increase effective irradiance**
  - Reduce reflection losses and soiling (coatings, texturing)*
  - Bifaciality*
  - Increase active area (e.g., shingled cells)
- **Decrease operating temperature**
  - "Spectral cooling": selective absorption and emission properties (up to 10° C temperature reduction possible)
  - Increasing thermal conductivity of backsheets*
- **Manage electrical mismatch**
  - Module and Sub-module power optimizers
- **Added value deployments**
  - PV + *"blank"* (e.g., Roofing, facades, agriculture, transportation, etc..
  - Features such as weight, flexibility, form factor, shade tolerance become important.
- **Increase lifetimes**
  - Can we build an affordable 50 yr module?
  - Need for new testing protocols

Reducing Reflections from PV (e.g. Nishati)

- Nishati makes rugged, glass-free solar panels designed for extreme environments (e.g. military deployments).
- They are working with Sandia (SBV Program) to evaluate reflective properties of design variations of their modules.
- Initial results show that reflections are significantly reduced compare with conventional modules with glass top-sheets.
- Such modules would be less visible and may be appropriate for installations near airports or in tactical environments.
- Can they last 20+ yrs?

Nishati-us.com





Bifacial Photovoltaics

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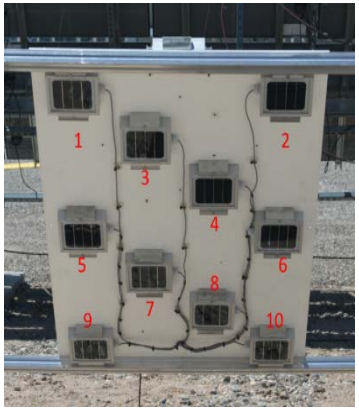
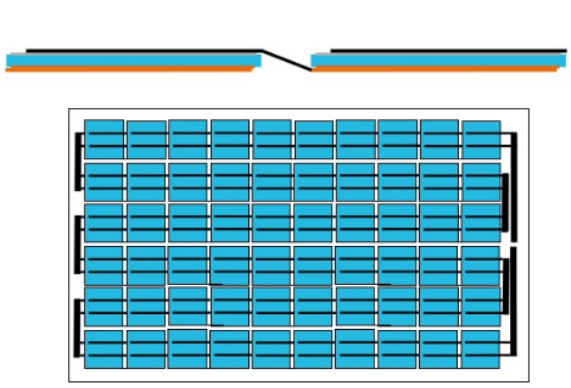


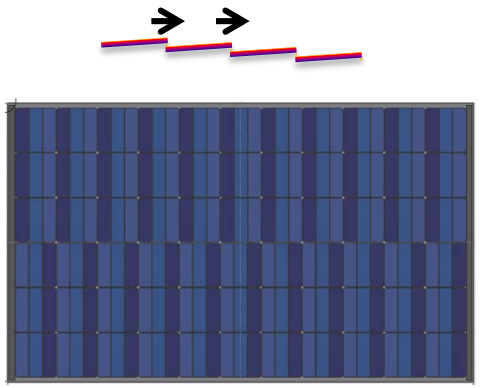
- Bifacial PV offers a means to increasing the output of PV systems by up to 10-20% with little additional costs (~3% cost increase for adding bifacial to 1-axis tracking (Source- PV magazine).
- Sandia and NREL project goal is to build and validate bifacial PV performance models, generate performance data, and develop rating standards.
- Our approach has been to deploy test systems, measure performance & backside irradiance, and develop prediction models.
  - Backside irradiance is affected shadows from modules, racking, and other objects.
  - Backside irradiance is spatially variable.
- Modeling has focused on ray-tracing and view factor approaches.
- Open-source models are available:
  - https://pvpmc.sandia.gov/pv-research/bifacial-pv-project/

This project is a collaboration between Sandia, NREL and the Univ of Iowa

Increase Active Area: Shingled-cell PV Modules

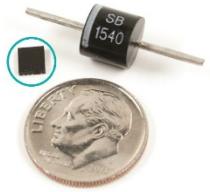
- SunPower recently acquired SolarWorld Americas to build shingled P-Series modules in the US.
- Shingled modules interconnect shingled cells with conductive adhesives.
  - Maximizes the active area in the module
  - Eliminates solder bond cell-cell interconnections (common point of failure)
- These modules require certain changes to modeling assumptions, such as the angular response function, which is directional due to the cell stacking and can include shading effects.
- Conductive adhesives can affect series resistance.
- Are there different failure and degradation modes?





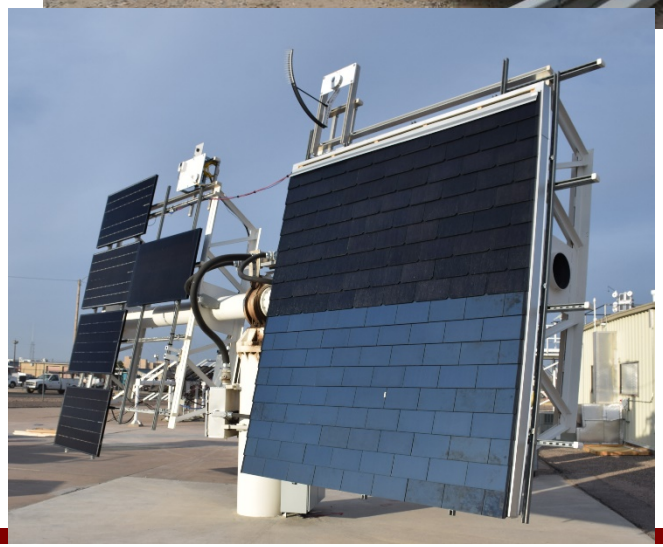
Reduce Electrical Mismatch

- Power optimizers allow modules (or cell strings) with different irradiance levels to be combined in series with minimal losses.
- Maxim Integrated is testing its optimizers at the Regional Test Centers
  - Allows for closer row spacing (higher GCRs)
- Future applications may include:
  - Bifacial modules
  - Curved or conformable arrays
  - Applications with partial shading



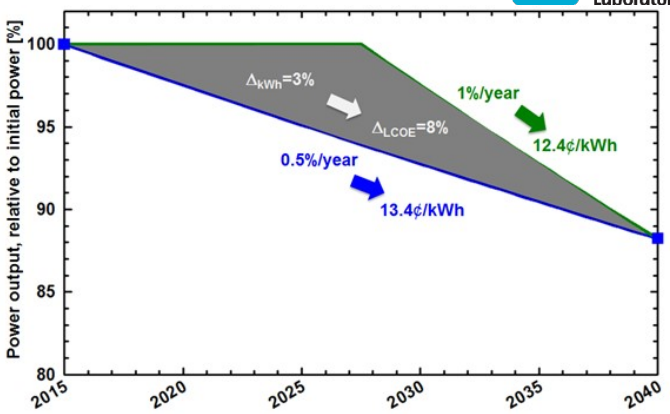
Added Value PV Deployments

- PV modules that produce energy AND provide another value, such as …
  - Protect building from elements
    - Roof, windows, façades
  - Reduce evaporation on reservoirs
    - Floating PV
  - Allow more varied crops to be grown
  - Reduce fuel needs (remote grids, solar cars, ships
- **Value is more than energy**
  - Appearance, weight, physical properties are all important.

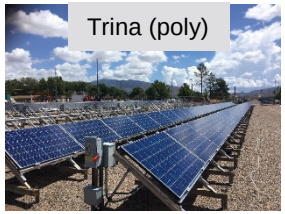


Increase PV Lifetime

- Degradation rates and profiles affect LCOE.
- PV Lifetime Project
- Challenges include:
  - Keep out moisture
  - Minimize effects of thermal cycling & mechanical stress
- Possible solutions include:
  - Glass-glass modules
  - Eliminate junction box
  - Eliminate cables and connectors
  - Wireless charging technology?



New Mexico PV Lifetime Systems



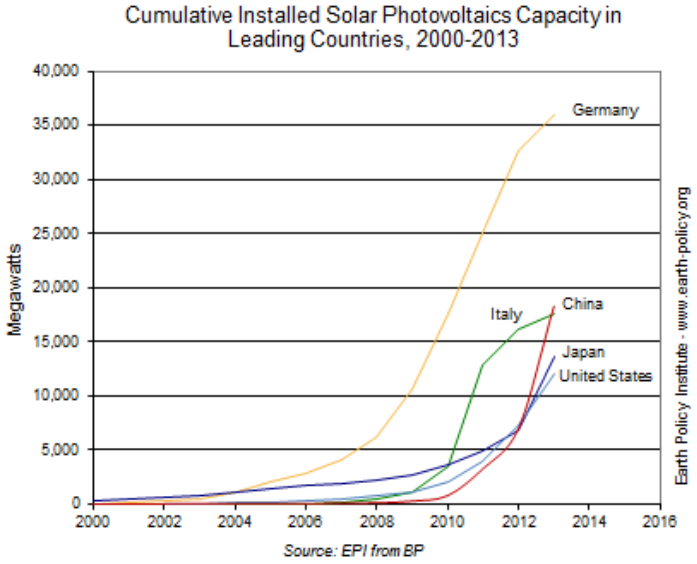
Colorado PV Lifetime Systems

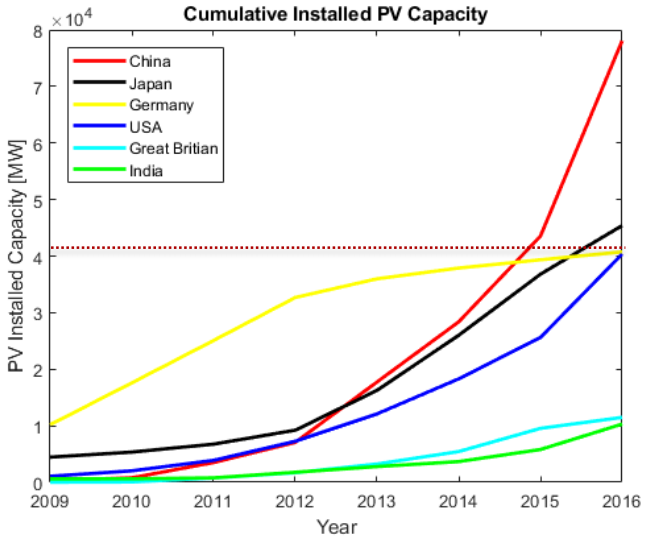
Collaboration is Very Important

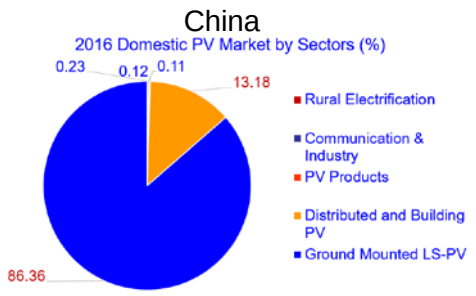
- The PV Performance Modeling Collaborative (PVPMC) facilitates sharing of new methods, data, and information.
  - Website: https://pvpmc.sandia.gov (over 10k visits per month)
  - Open-Source Software (PVLIB, and more)
  - International Workshops
    - Last one was: 9th PVPMC Workshop in Weihai, China 12/2017
    - We are in discussions for repeating this event annually (Stay tuned).
  - PV is global – witnessing the fastest growing PV market in the world is valuable for the US PV industry.

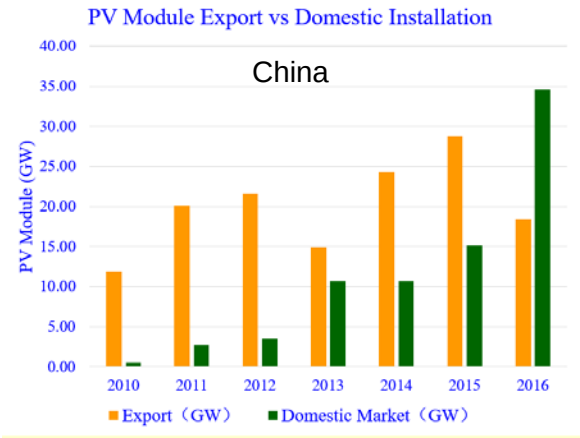
From Germany to China

- In 2009, when I started in PV, Germany was the world leader in PV technology.
  - US sent fact-finding missions
- China is now emerging as a world leader in PV (and RE) technologies
  - 2018 NSF Report: China is world's largest producer of scientific articles
  - Chinese PV innovations are growing fast
  - Increased technical engagement with China's universities, labs, and PV industry is warranted.









Data from EPIA, IEA, CPIA (Wang Sicheng, 2017)

Final Thoughts

- PV is a disruptive technology and is starting to be completely reimagined.
  - Early prototypes are always expensive but their multi-use value might be underestimated.
  - Refocusing from cost to value may open up new innovation opportunities.
  - DOE's national laboratories serve the nation and provide unique capabilities to help the US take full advantage of what PV has to offer our future –clean, renewable, and abundant energy.

Thank you!

- Special Thanks to **CFV Solar Test Laboratory!**
  - CFV organized the logistics for this workshop
  - Kathleen Conners (CFV) deserves special recognition for her dedication to quality and attention to detail.

Upcoming Events

- bifiPV Workshop 2018 in Denver, CO (September 10-11, 2018)
  - Bifacial cells, modules, systems, modeling, and characterization

Slido.com - #PV2018

- We are trying out a new technology called Slido.
- Go to Slido.com and enter “PV2018”
- **Questions:** Enter questions for speakers
- **Ideas:** Free form idea sharing
- **Polls:** We will be asking the audience a series of focused survey questions during breaks and discussion sessions. Please participate!
- Participants can ***promote*** (“*like*”) questions or ideas so that the most popular ones appear at the top of the list.
- This feedback will be used to help guide future PVPMC activities.