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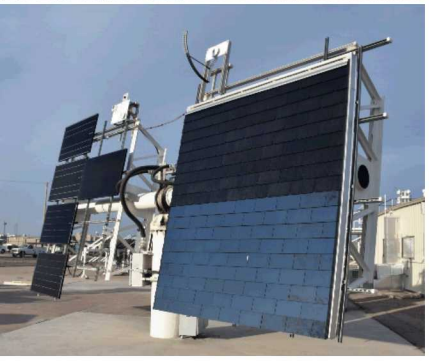


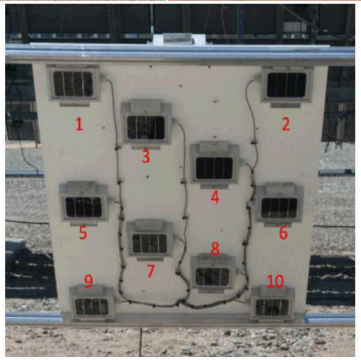

Opportunities for New and Innovative Photovoltaic Modules and Systems

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U.S. DEPARTMENT OF ENERGY NNSA

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PV as a Disruptive Technology

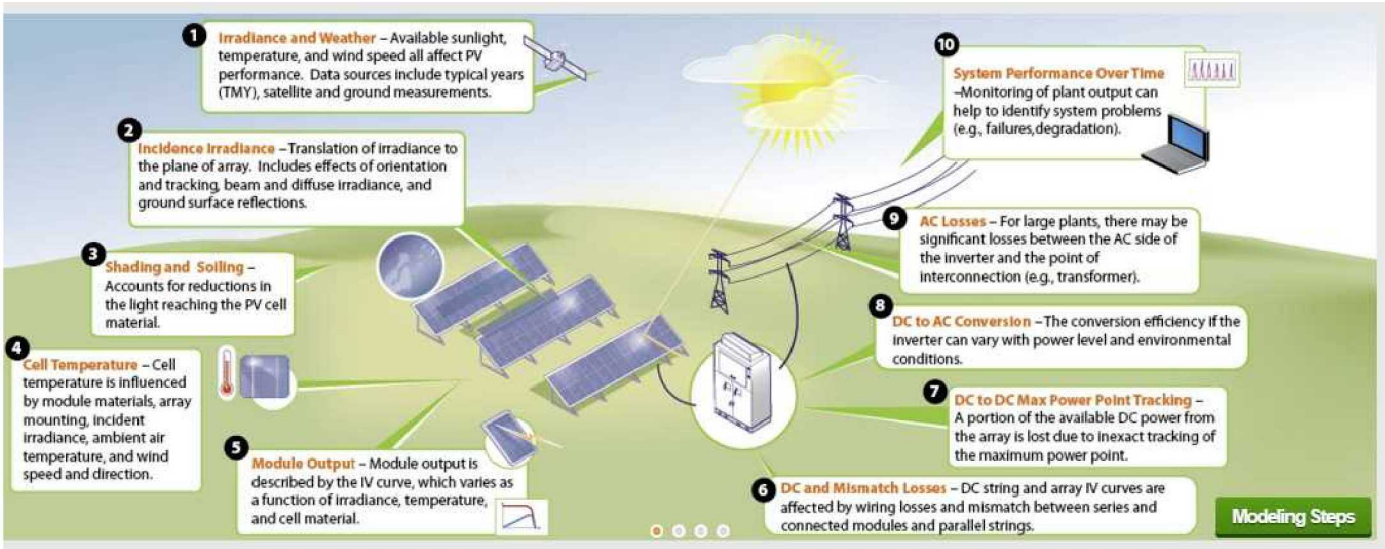
- Steven Sinofsky defines four "Stages of Disruptive Technologies"

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***
   - Beyond the PV module
   - Solar roofing (e.g., Tesla) and BIPV
   - Solar-driven cars (Toyota is aiming for: 70% of cars, 50 GW/yr. 8% GHG reduction)
   - Solar roads, vertical bifacial, internal tracking, adaptive shade response, conformable PV, etc.

Future PV products will likely have many different characteristics from today's modules. Sandia provides capabilities to characterize and model tomorrow's PV technologies.

Measuring and Modeling PV Performance

For the past 40+ years Sandia National Laboratories has developed new methods for measuring and predicting 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, shading)
- MPPT (string-module-cell level, DC/AC>1)
- System Performance over time (degradation, variability)

In this talk I will show several examples of Sandia's work aimed at better understanding the performance and reliability of new PV technologies.

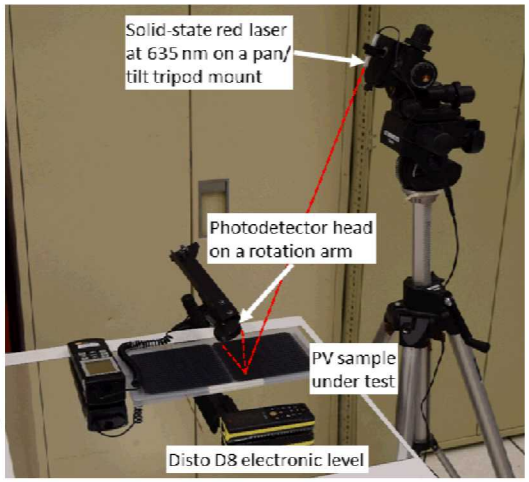
Strategies for Improving PV Performance

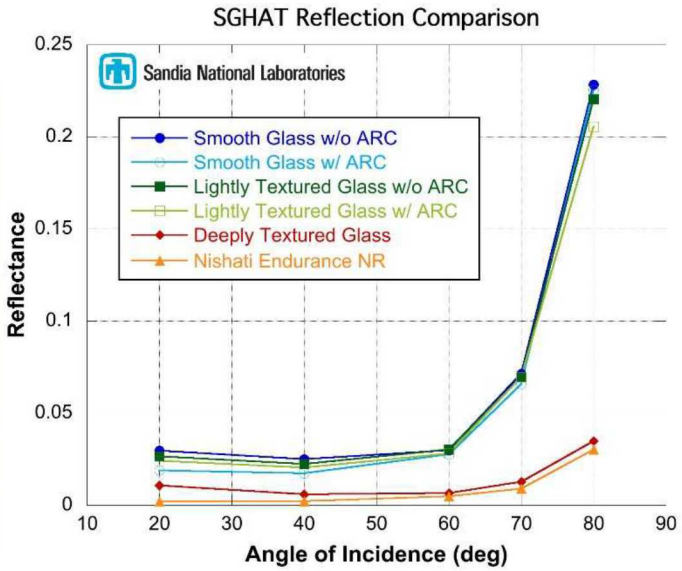
- Increase effective irradiance
  - Reduce reflection losses
  - Bifaciality
- Increase active area
  - Shingled cells
- Manage electrical mismatch
  - Module and Sub-module power optimizers
- Dual or Multi Use Deployments
  - PV Roofing
- Increase lifetimes
  - Hard to measure
- New hardware and software needs
- Future challenges

Reducing Reflections from PV (e.g. Nishati)

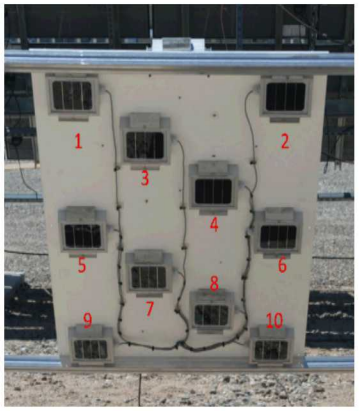
- Nishati makes rugged, glass-free solar panels designed for extreme environments (e.g. military deployments).
- They are working with Sandia (SBV Program) to evaluate reflective properties of design variations of their modules.
- Initial results show that reflections are significantly reduced compare 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

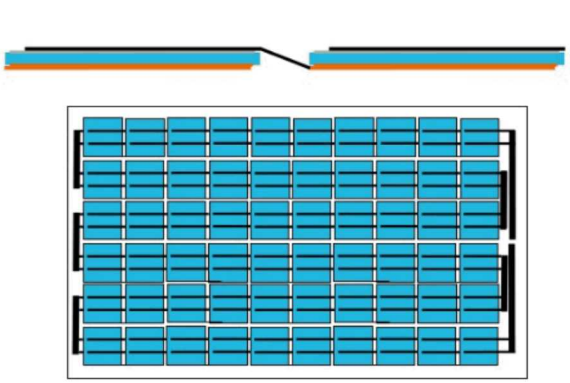


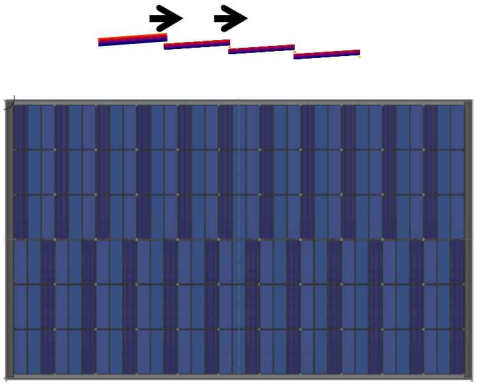
- Bifacial PV offers a means to increasing the output of PV systems by 10-20% with little additional costs.
- Sandia and NREL project goal is to build and validate bifacial PV performance models, generate performance data, and develop rating standards.
- Our approach has been to deploy test systems, 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/
  - Datasets will be made available at the end of the project.

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

Increase Active Area: Shingled-cell PV Modules

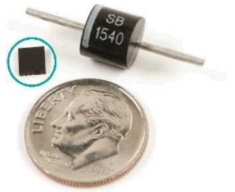
- SunPower, Tesla, and others are making modules with shingled cells interconnected with conductive adhesives.
  - Maximizes the active area in the module
  - Eliminates solder bond cell-cell interconnections (common point of failure)
- These modules require certain changes to modeling assumptions, such as the angular response function, which is directional due to the cell stacking.
- Conductive adhesives can affect series resistance of cells too.





Reduce Electrical Mismatch (e.g, Maxim Integrated)

- 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 that have significant backside irradiance variability

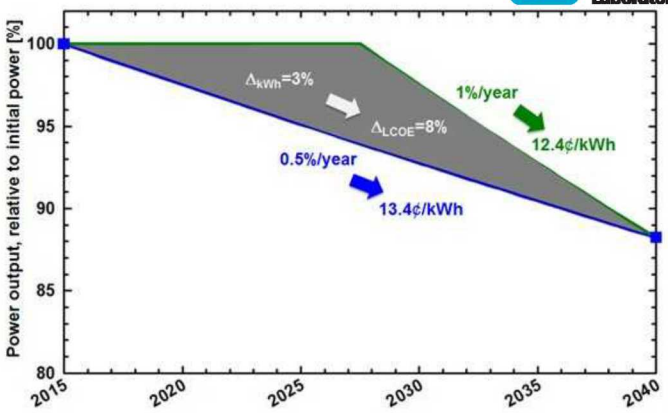


Multi Use PV Deployments

- 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
- **Value is more than energy**
  - Appearance, weight, physical properties are all important
- We have worked with several PV roofing developers. Most recently, Tesla's Solar Roof.
- Outdoor, large-scale testing capability is necessary
  - Sandia's outdoor 2-axis trackers are able to run performance characterization on full-sized roof mockups.

Increase PV Lifetime

- Degradation rates and profiles affect LCOE.
- PV Lifetime Project
  - Sandia and NREL are deploying representative PV systems (~10-15 kW) in NM, CO, and FL.
  - 100% module flash testing initially
  - Annual retesting of samples
  - Automated string-level IV tracing every 30 min.
  - >700 modules currently in program
    - 7 manufacturers (4 of the top 10), 10 different module models
  - Data from these modules and systems will be made available after analysis is complete.



New Mexico Systems

Colorado Systems

New Monitoring Hardware

Sandia has helped to develop some new hardware solutions for monitoring PV performance.

- 140A Series II: 8-32 Channel In-Line String-Level I-V Tracer
  - Developed jointly by Pordis LLC and Sandia (available for purchase from Pordis)
  - >20 units to be deployed in the field in NM, CO, and FL.
  - Traces are triggered from ref cell, Modbus signals (e.g. irradiance, temperature) or by time.
  - String is automatically disconnected from inverter, trace is scanned, and then reconnected.
  - Extremely linear temperature response (-10° to +50 ° C)
- Irradiance Variability Datalogger
  - Developed jointly by Pordis LLC and Sandia
  - Measures and stores irradiance at 1 sec intervals
  - Communicates via cellular modem, Wifi, or serial.
  - Onboard leveling, GPS
  - Records irradiance ramp rate distributions
  - Parts cost <$100

Open-Source Modeling Tools

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Open-source software allows the National Labs to share new methods with industry stakeholders. Some Examples….

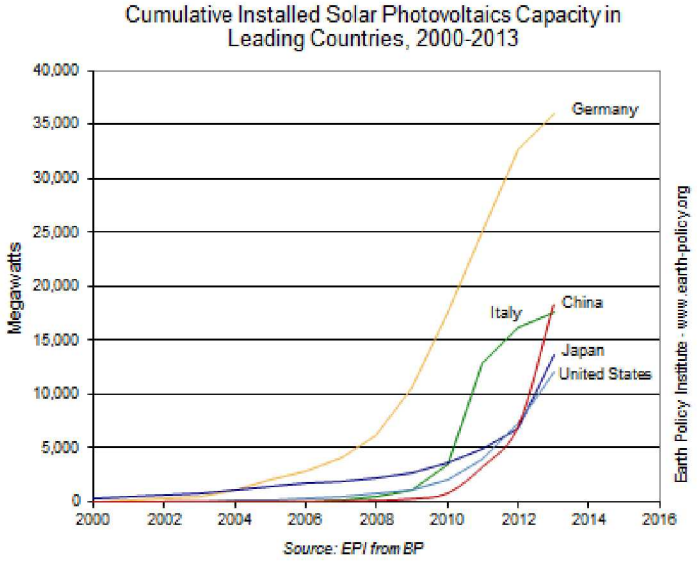
- **PVLIB Toolbox** (Matlab and Python) – Set of over 50 functions that allow users to build their own sophisticated PV performance models. (Sandia)
- **System Advisor Model (SAM)** – Performance simulations for many RE technologies. Recently released as open source (C++) (NREL)
- **Bifacial_radiance** – Ray-tracing software for bifacial (NREL)
- **BifacialVF** – 2D view factor code (Python) for bifacial (NREL)
- **GridPV Toolbox** (Matlab) – Models and simulates the impacts of PV on the distribution grid. (Sandia)
- **Wavelet Variability Model** – Simulates geographic smoothing of irradiance variability over a PV plant footprint. (Sandia)

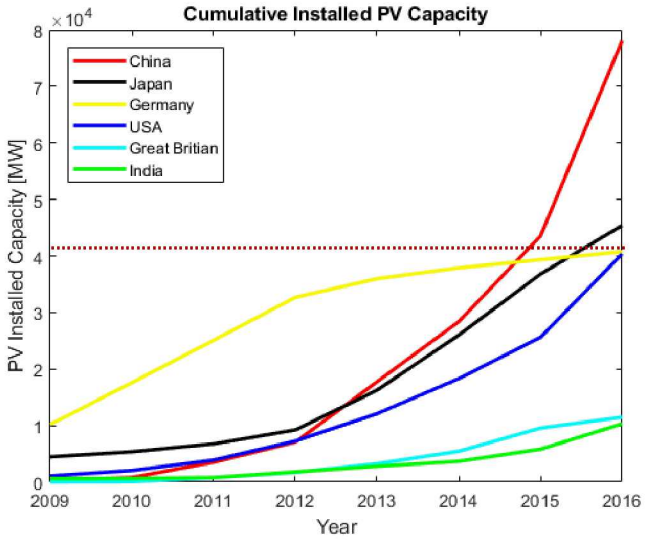
Collaboration is Very Important

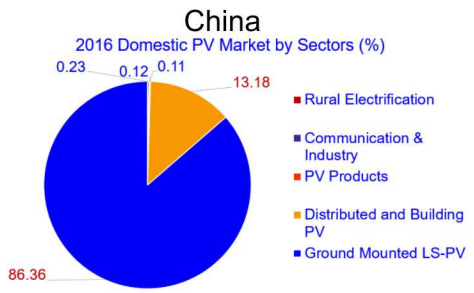
- The PV Performance Modeling Collaborative (PVPMC) facilitates sharing of new methods, data, and information.
  - Website: https://pvpmc.sandia.gov (over 10k visits per month)
  - Open-Source Software (PVLIB, and more)
  - International Workshops
    - 9th PVPMC Workshop in Weihai, China 12/2017
    - Next workshop (the 10th) is in Albuquerque, NM **May 1-3, 2018**
- Sandia and NREL also collaborate internationally with IEA PVPS, PVQAT, and other groups.

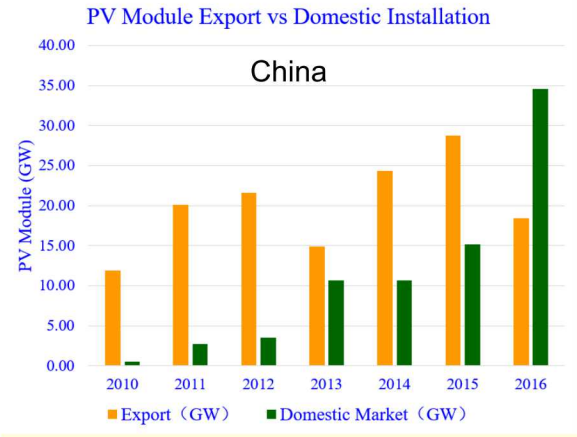
From Germany to China

- 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
  - Increased technical engagement with China's universities, labs, and PV industry is warranted.





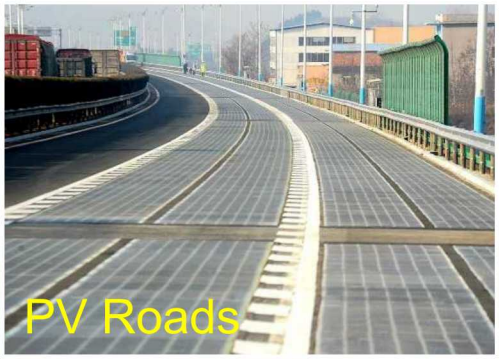


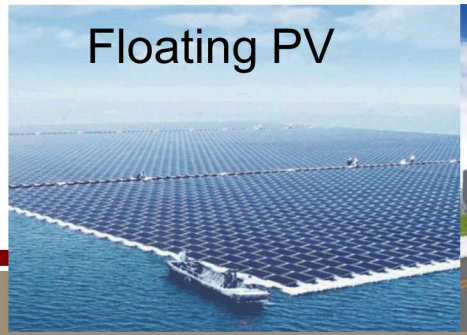


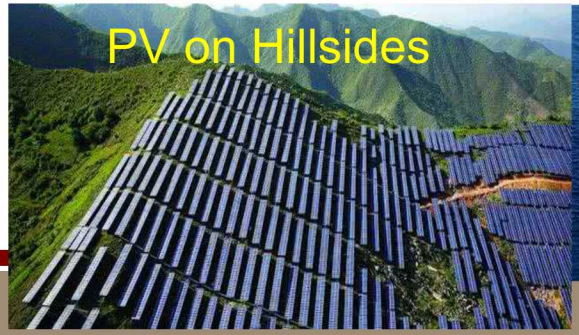
Data from EPIA, IEA, CPIA (Wang Sicheng, 2017)

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!

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Upcoming Events

- 2018 PV Reliability Workshop, Lakewood, CO (February 27-March 1)
  - PV Materials (DuraMAT), Modules, and Systems Reliability
- 10th PV Performance Modeling Workshop in Albuquerque, NM (May 1-3, 2018)
  - PV Measurement, Modeling, Monitoring and Integration
- bifiPV Workshop 2018 in Denver, CO (September 10-11, 2018)
  - Bifacial cells, modules, systems, modeling, and characterization