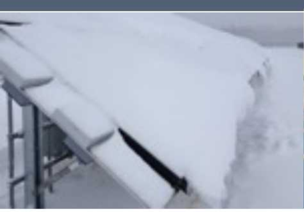
Sandia National Laboratories

SAND2020-3642PE

Snow as a Factor in Photovoltaic Performance and Reliability



Laurie Burnham

IEA Task Force 13 Meeting

25 March 2020

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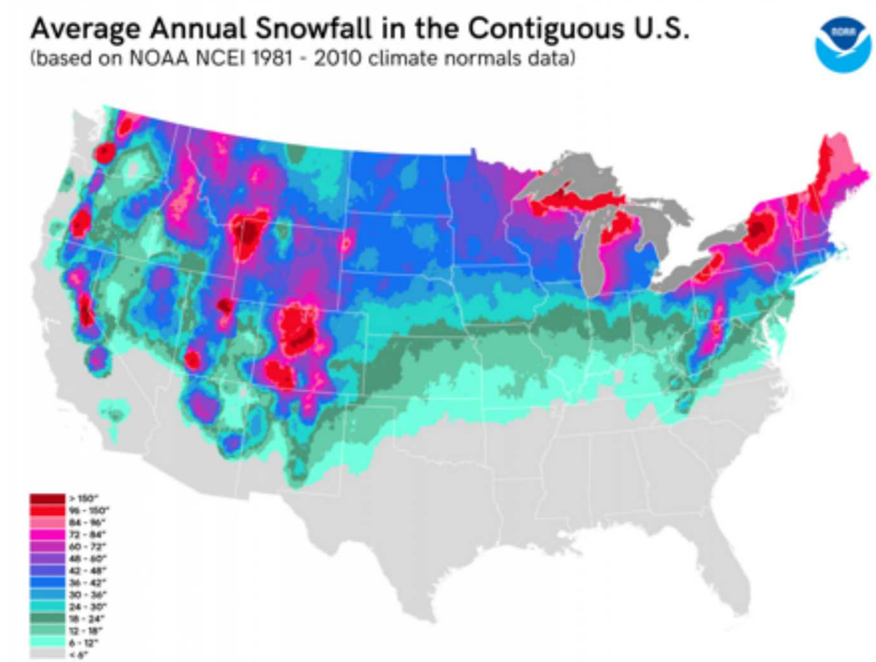
SAND2019-11284 C

US Snow Facts

- Snow occurs in all 50 states
- More than 30% of the US sees significant snow.
- Extreme snow and hail events common: Nov 2019 storm dumped snow across the US: CA 49”; CO 15”; MN 25”; ME 12”. 15” in CO and 25” in MN.



Annual average snowfalls US

2019

Winter Storm Brings Snow to at Least 30 States

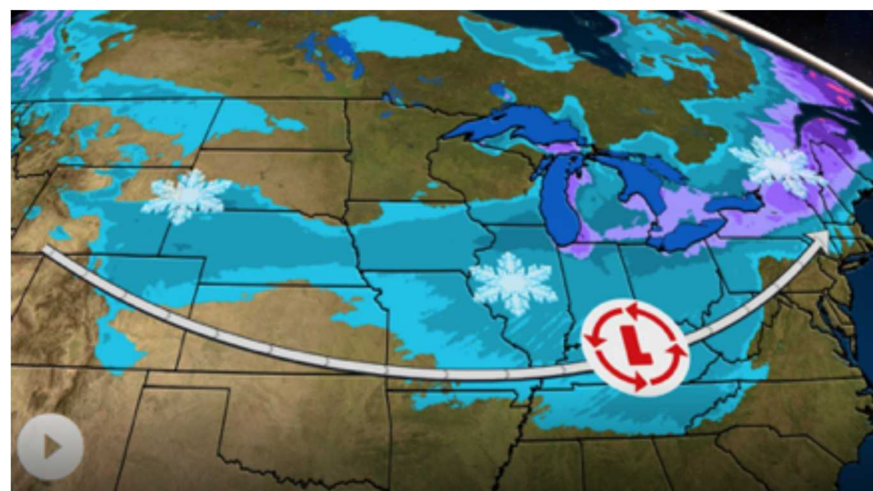
SMARTNEWS *Keeping you current*

Record-Breaking Storm Dumps Four Feet of Snow on Parts of Montana

The September storm broke snowfall and temperature records across several states

Record-breaking hailstone in Colorado: 'Big hail like this can easily kill people'

By Amanda Schmidt, AccuWeather staff writer



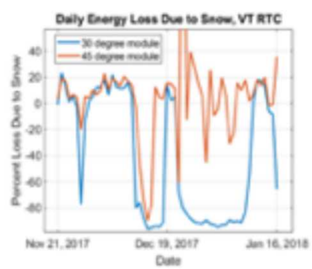
Why Snow Has the Solar Industry’s Attention

Deployment in Northern Regions is Increasing:

- Continued growth: capacity increase of 25% from 2018 to 2019 (2^{nd} biggest year on record)
- New markets opening up: cost drop and solar-friendly policies (GHE goals)
- More geographically distributed
- Impact of climate on performance and reliability increasingly important

Snow Losses Are Significant:

- Snow losses can be large (>90%/month; 2-5%/yr)
- Average irradiance levels are low



Reliability is Poorly Understood:

- Long-term impact of snow loading not known
- Global climate change = extreme weather: record-breaking snow and hail storms

Bottom Line: LCOE calculations hard to calculate!

	Rank		
State	2016	2017	2018
California	1	1	1
Texas	6	4	2
North Carolina	4	2	3
Florida	9	3	4
Nevada	5	9	5
New York	12	12	6
New Jersey	10	11	7
Minnesota	14	6	8
Arizona	7	7	9
Massachusetts	8	5	10

State solar installation rankings 2018, SEIA

Some of some fastest solar growth is in regions with heavy snow

Alaska has 2MW of solar
563kW in Fairbanks

Why Snow is Challenging

- Properties of ice are well-known; **far less is known about snow.**
- Also nothing about snow is constant: depth and density, reflect atmospheric variables and change as snow accumulates and compacts over time.
- Snow can melt and partially reform; distinct layers can be identified.
- Crystalline structure is highly variable, impacting reflectivity and transmissivity.
- Albedo is also not constant
- Snow predictions have large margin of error

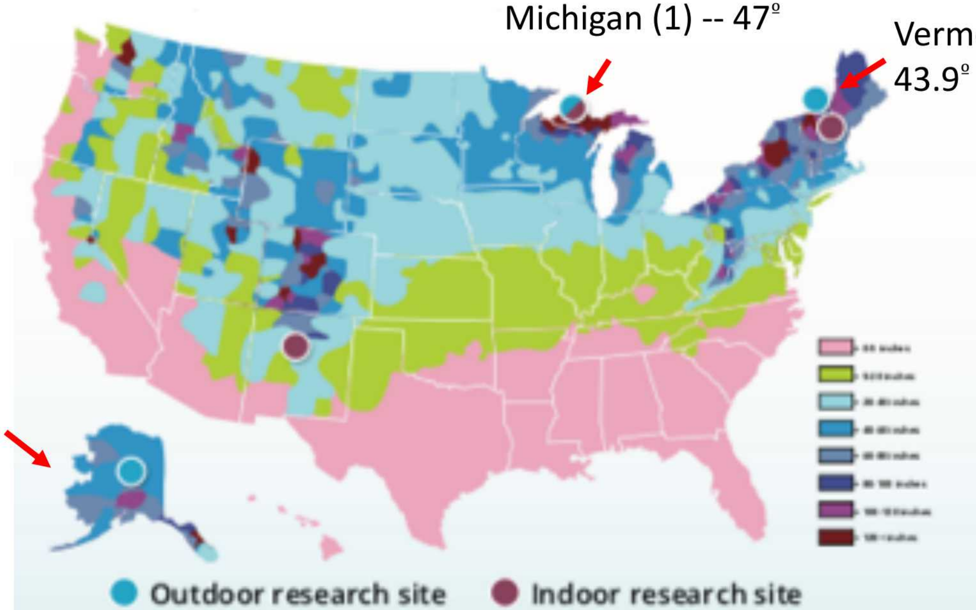
Alexey Kljatov; NOAA

Introduction to Sandia's Snow Project

Three-year, DOE-funded, Sandia-led research project: "Snow as a Factor in PV Performance and Reliability"

Objective:
To further the deployment and optimal operation of PV systems in northern regions by measuring snow losses and demonstrating effective mitigation strategies

"Five" Field Sites:



Average annual snowfall in the US

Four-member project team:

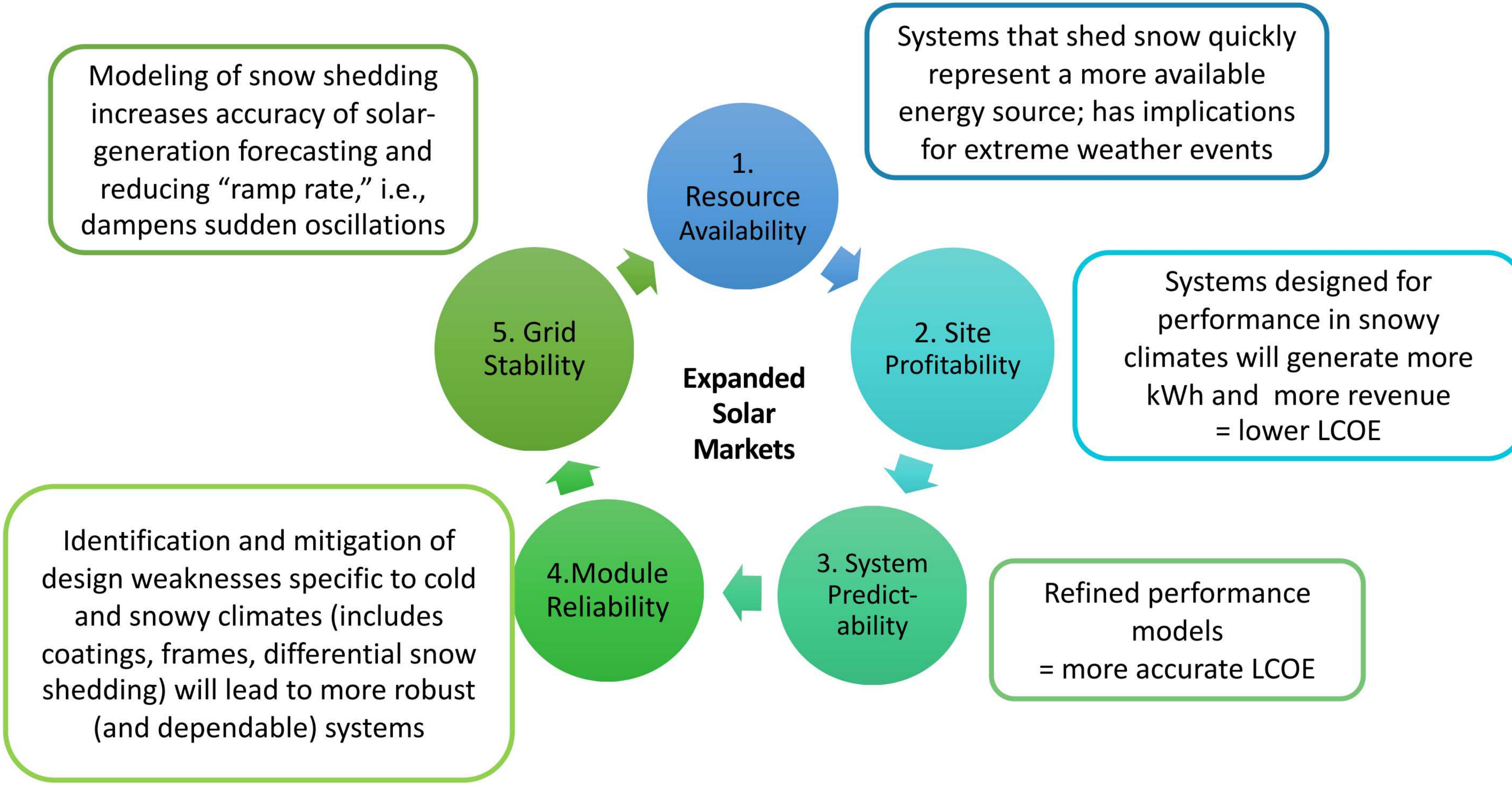
Sandia National Laboratories

Michigan Technological University

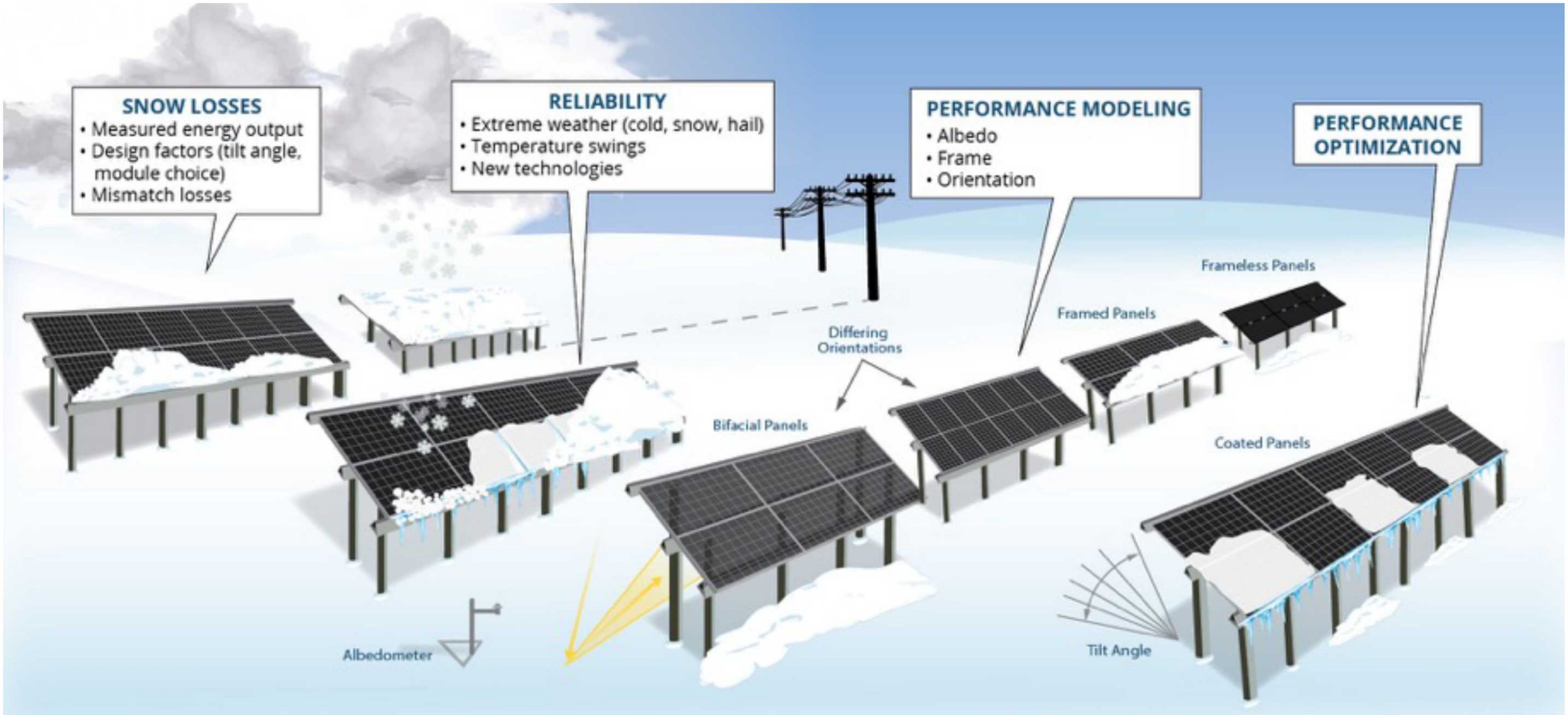
University of Alaska Fairbanks

University of Michigan

Project Has a Multi-Pronged Value Proposition



Four-Part Technical Approach



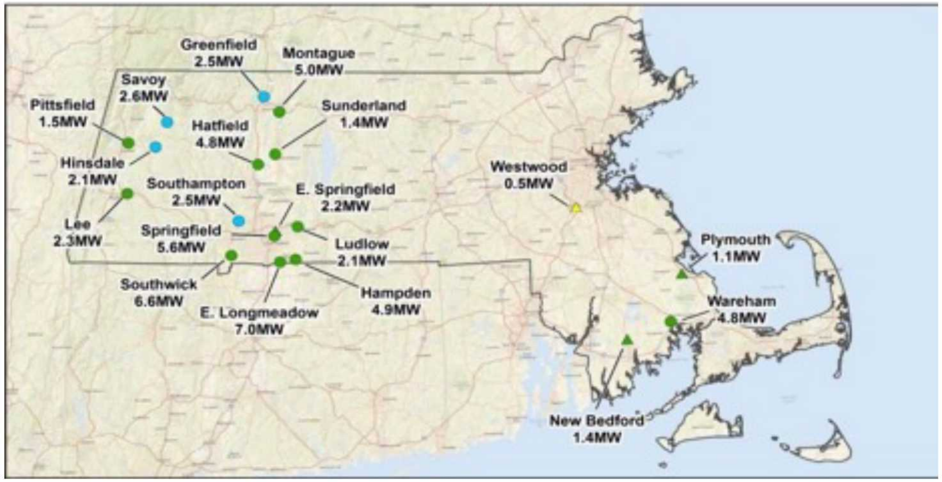
1. Snow Losses:
Utility-scale data analysis

Partnerships with developers and asset owners

Objective: to measure actual snow losses across the northern US and identify contributing factors

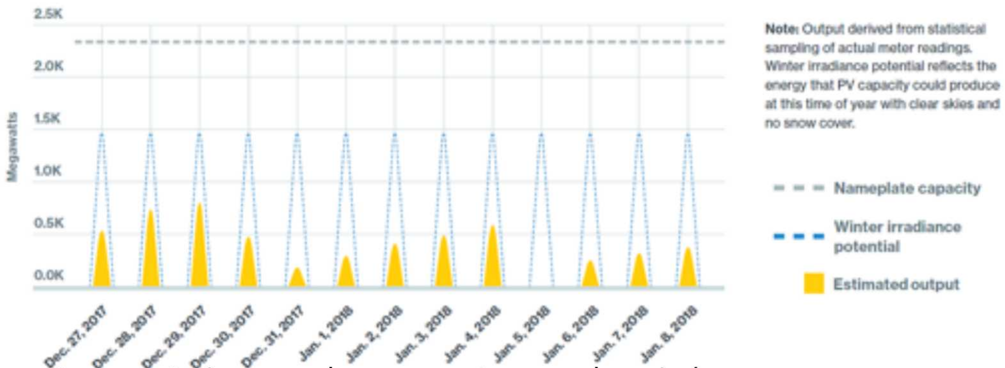
- Data we are collecting:
  - -Inverter power data
  - -Plane of array (POA) irradiance
  - -Ambient air temperature, wind speed and relative humidity; BOM temperature
  - -Images at 15' intervals to provide data on:
    - --Percentage of snow cover
    - --Percentage of energy loss attributable to snow cover
  - -System metadata
- Participation criteria:
  - -Onsite monitoring, including heated pyranometer and meteorological instrumentation
  - -O&M support
  - -Automated access to time-stamped data, including energy data
  - -Site metadata
  - -Willingness to forgo snow-clearing, if routinely done
- Concept is expandable; opportunities for machine learning

Example: Data from Massachusetts Utility



22 sites scattered across MA; large variability in weather. Objective: improve predictive models to include snow coverage losses; track actual snow losses.

Potential vs. Actual Estimated Output from Behind-the-Meter Solar Power During 2017-2018 Cold Spell



Representative snow losses over two-week period

Inconsistent loss factors

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
32.6%	16.1%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	13.5%

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
20.8%	9.8%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	0.5%	5.9%

Snow losses significant and hard to predict

Array soiling losses, two consecutive years

2. Reliability Challenges:

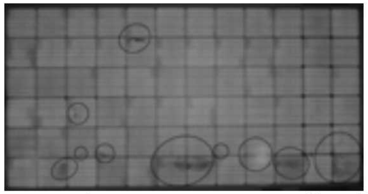
Short and Long-Term Stressors

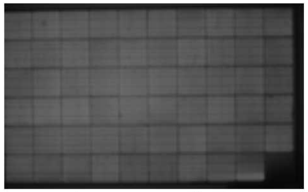
Thermo-mechanical Loading

Objective: measure mechanical loads (module displacement) under different meteorological conditions.

Long-Term Cold Exposure (need for longitudinal studies)

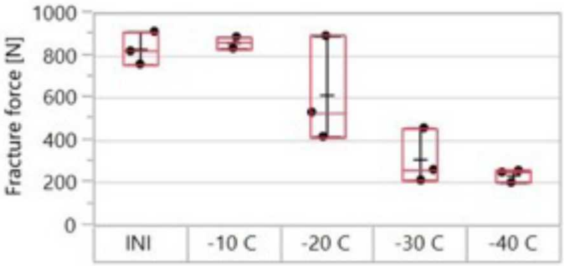
Framed bifacial





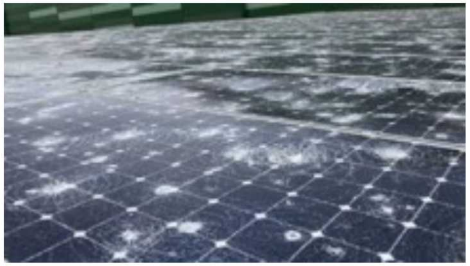
Frameless bifacial

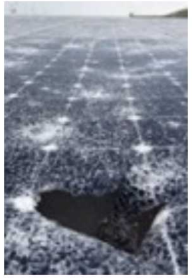
*Objective: correlate patterns of cell cracking with snow load, module and **cell technologies** over time*



Schneller *et al* show less force is needed to induce cell cracking as temperatures drop

Extreme Weather





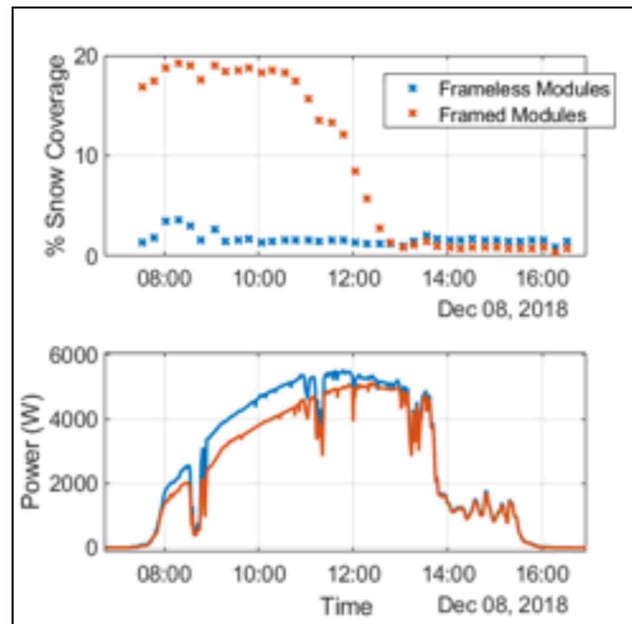
Objective: Track in situ crack formation; mitigation strategies

3. Performance Modeling:

Impact of frame on snow-shedding

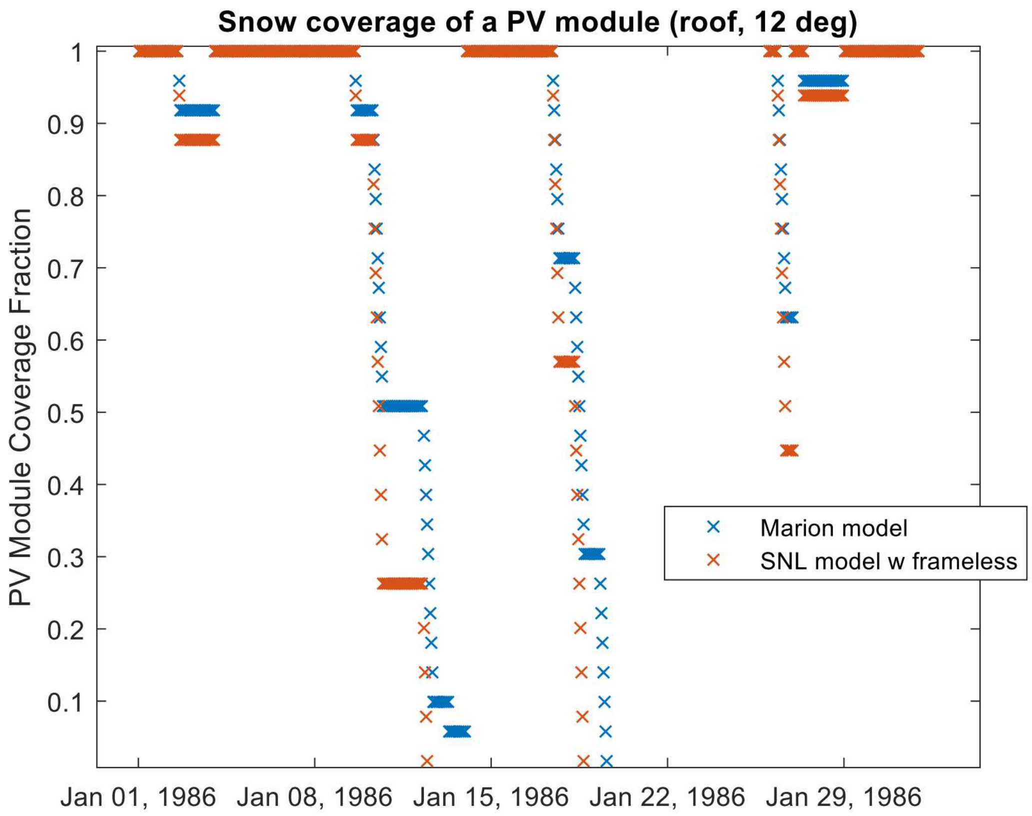
Framed modules on the left; frameless on the right.

- Images taken at 15’ intervals from adjacent CIGS arrays, one framed, one frameless
- Image anlysis showed frameless modules *generally* shed snow 50% more quickly than framed modules
- Energy gains from frameless—relative to framed—were ~ 13% in December, 2018.
- Height of the array needs to be considered to prevent build-up of snow on the ground.



3. Performance Modeling:

Model Development



Estimated coverage of a roof mounted PV module with 12 degree tilt using TMY data from Burlington, VT

3. Performance Modeling:

Albedo

Objective is to:

1) Quantify seasonal and diurnal variation, as a function of:
    - Irradiance
    - Angle-of-incidence
    - Spectral variation
    - Age of snow
    - Depth of snow

2) Refine bifacial performance model to include albedo of snow

Rethinking modeling assumptions: does snow really have an albedo of ~.8?

4. Performance Optimization:
Strategies to accelerate snow-shedding

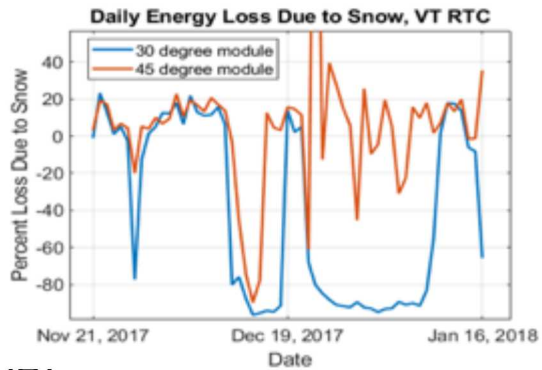
Passive strategies:

- Tilt angle
- Presence of frame
- Module orientation
  (sliding distance relative to frame)
- Module surface (friction coefficient)
- Edge gap
- Module clips
- Module technology (bifacial)
- Adhesive properties of snow

Active strategies:

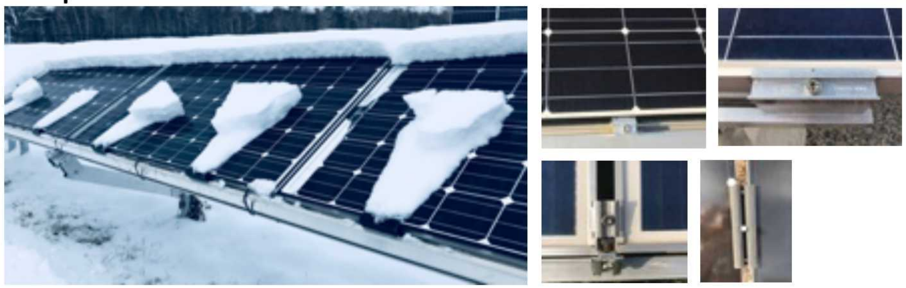
- Snow Removal (rake, blower)
- Adjustable tilt angle
- Reverse-Current Injection

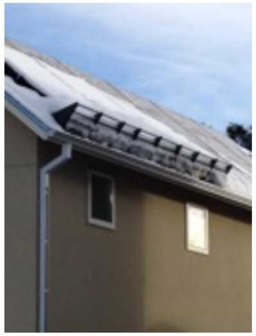
Tilt Angle



Edge Effect

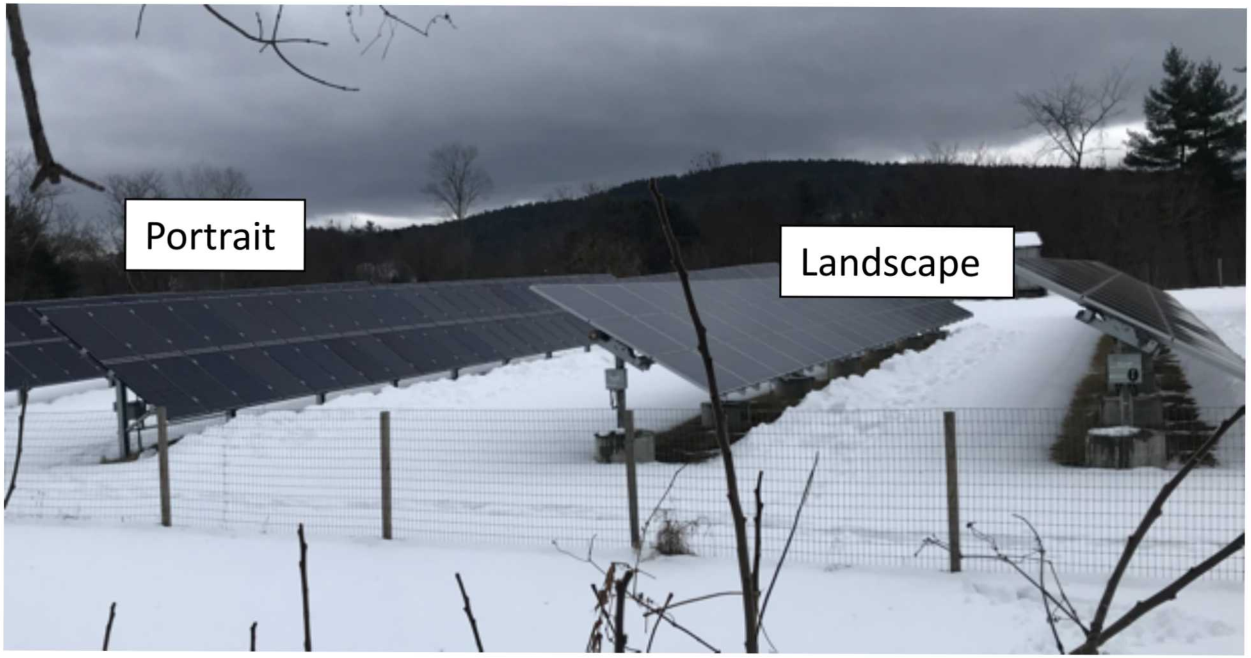
Clip Effect

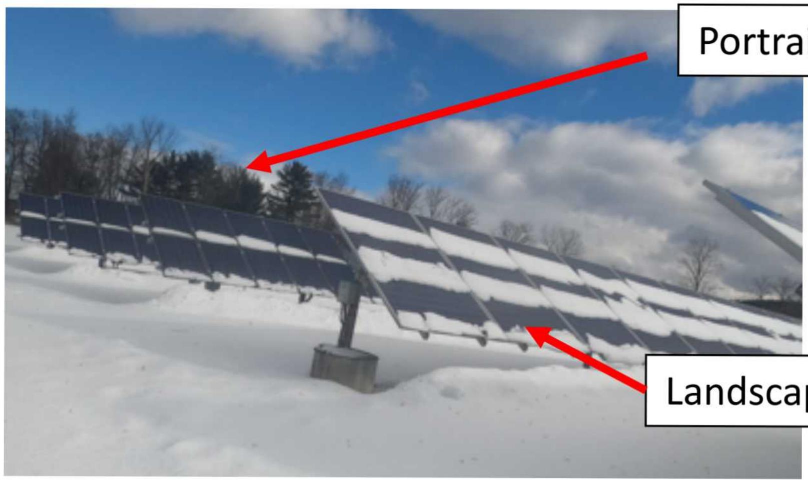




Design Optimization: Module Orientation

Images taken every 5 minutes





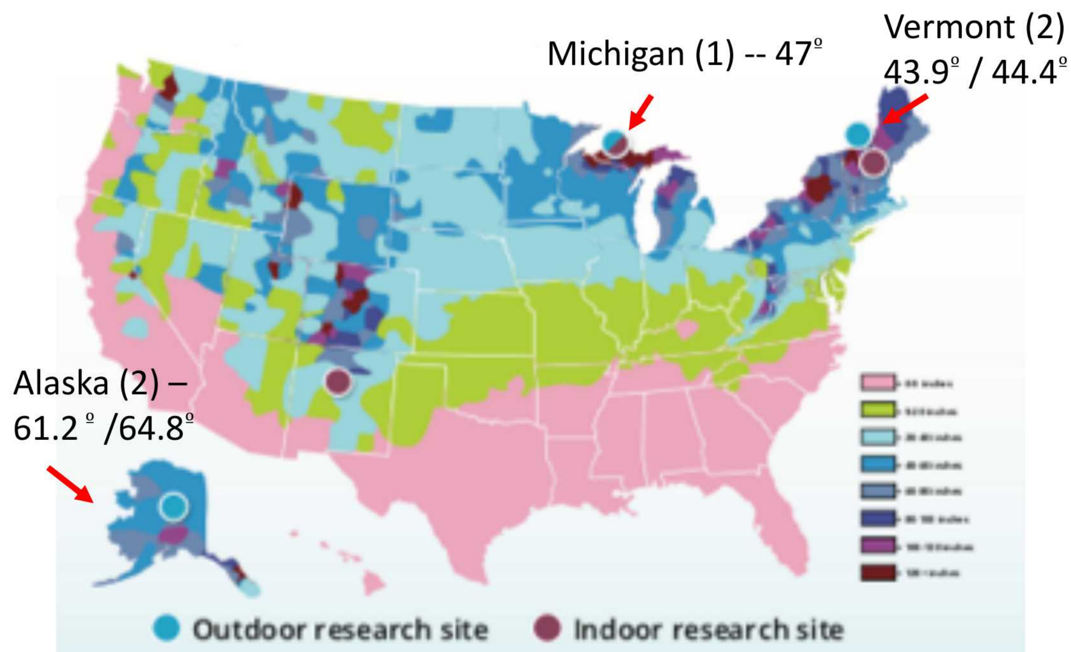
Design Optimization: Snow-phobic Coatings

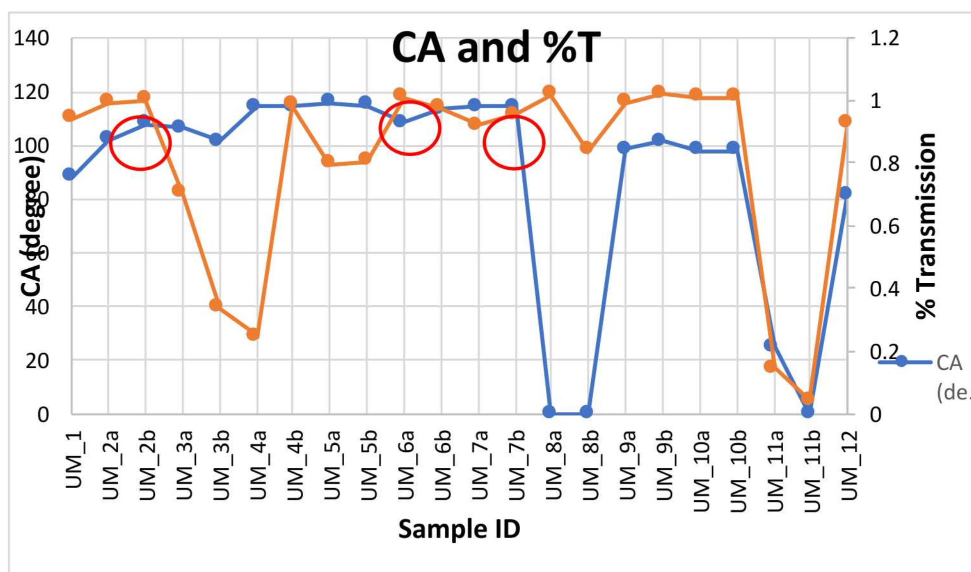
Five Functional Categories

- **Low adhesion to ice** (single vs dual layer)
- **Low interfacial toughness** (allows for easy crack propagation at the ice-coating interface)
- **Low contact-angle hysteresis** (e.g., silanes)
- **Low surface-energy** (omniphobic polymers)
- **Delayed ice nucleation and growth**

Two Applications

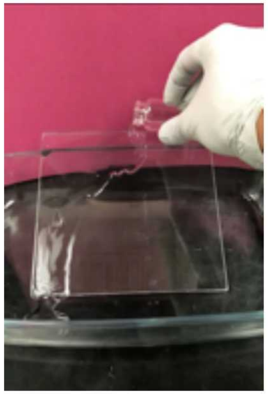
- Coupon-level (N=12) – AK, MI (2)
- Module-level – AK (2), MI, VT

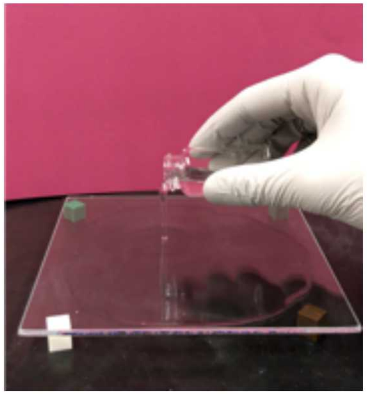




Coupon Analysis – Anchorage, AK

Coated 6”by 6” PV glass coupons mounted at a 45 degree angle

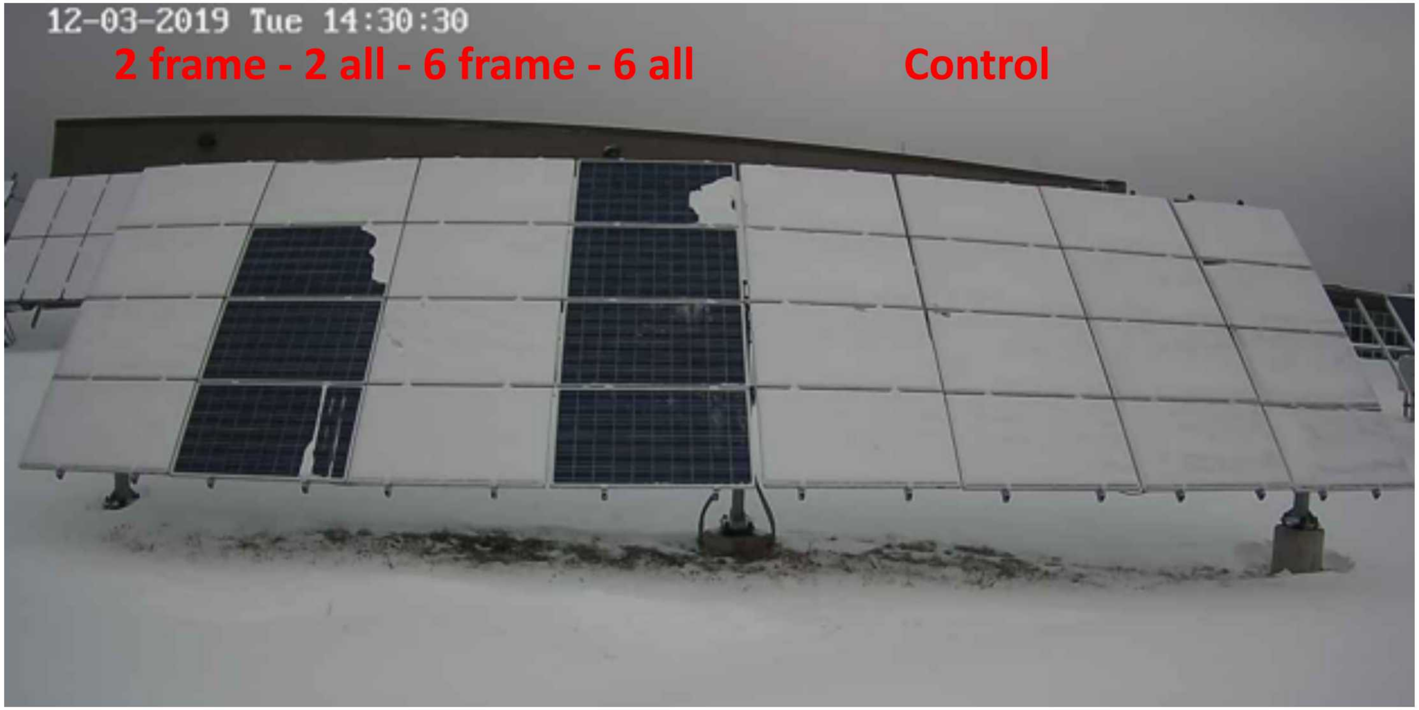




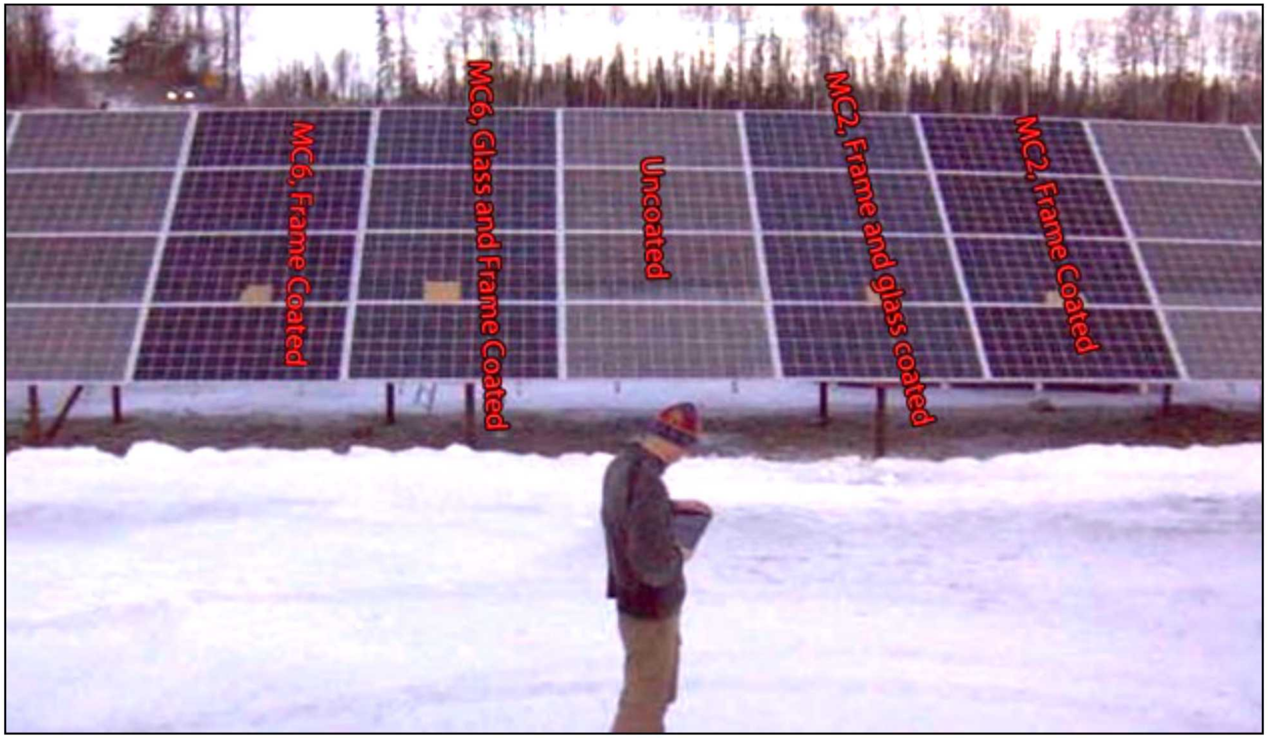
After one significant snowfall (approximately 6”) since deployment, no difference in snow shedding between the coated and uncoated coupons was observed.

Coating Study: Houghton, MI

Two coatings, each applied to glass and frame, frame only and a control



Coating Study: Two Sites in Alaska



Coatings MC2 and MC6 were applied to modules at two sites (Willow and Fairbanks). Modules were removed from the racks and coatings applied indoors on a flat surface, under controlled temperature conditions.

Willow Site

Preliminary results for the Willow array: MC2 and MC6, applied to the module frame and glass, perform differently on different days; investigation of meteorological conditions is forthcoming.

28 December 15:15

15:30

15:45

2 January 11:15

11:30

11:45

The bottom row of photos from 01.02.2020, show a different pattern in shedding for coating MC6 and accelerated shedding for coating MC2. Coatings applied only to the module frames appear to have had no effect on snow shedding.

Coating Study: Bradford, VT

March 6, 2019

Uncoated	UM-1	Uncoated	UM-2	Uncoated	UM-6	Uncoated	NeverWet (frame)	Uncoated	NeverWet (frame *in situ)*	Uncoated	UM-2 *In situ*	Uncoated	UM-6 *in situ*

Experimental layout: coatings were applied indoors under controlled conditions and also outdoors to assess differences in performance and durability.

Preliminary Results: Bradford, VT

March 24, 2019, 0ºC

Next Steps

- Image Analysis of utility-scale sites
- Correlation of coatings results with meteorological conditions; further coatings development in advance of next winter and a repeat of both module and coupon studies
- Analysis of albedo data from MI and AK
- Model development and validation: frameless modules, albedo
- Build-out of experimental site in MI
- Longitudinal studies of cell integrity
- Expanded partnerships with industry
- Development of international collaborations

Summary

- Solar is expanding rapidly across northern regions
- Deployment is outpacing our knowledge of snow losses and reliability issues
- Project hypothesis: significant increases in system efficiency are possible through design optimization
- Specific opportunities for cold-climate optimization include:
  - Frame architectures
  - Module and cell technologies
  - Racking and mounting designs
  - Module and frame coatings
- Our research on all of the above is continuing

Thank you!

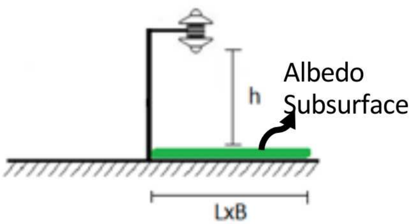
Laurie Burnham

lburnha@sandia.gov

505-845-7354

II. Bifacial Performance

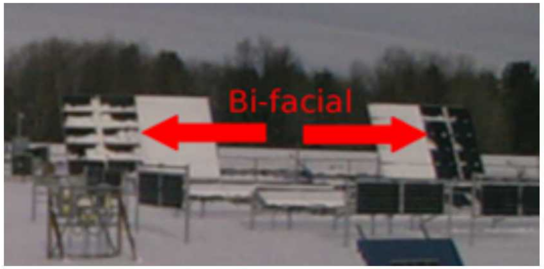
Albedo measurements

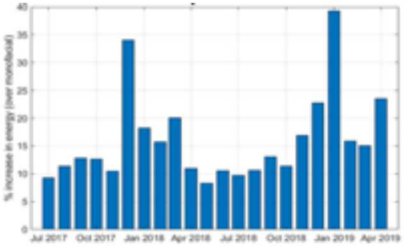


Seasonal and diurnal variation:

- Irradiance
- Angle-of-incidence
- Spectral variation
- Age of snow
- Depth of snow

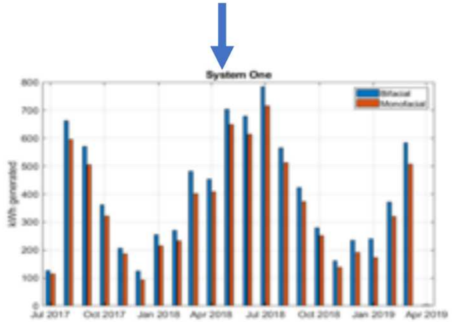
Bifacial Dual-Axis Tracker Systems



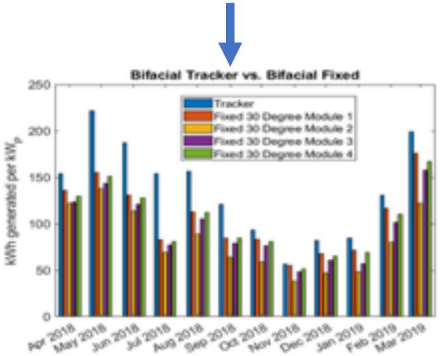


Bifacial Gain

Tracker bifacials outperform tracker monofacials by 14%



Tracker bifacials outperform fixed-tilt bifacials by 41%



Energy Yield