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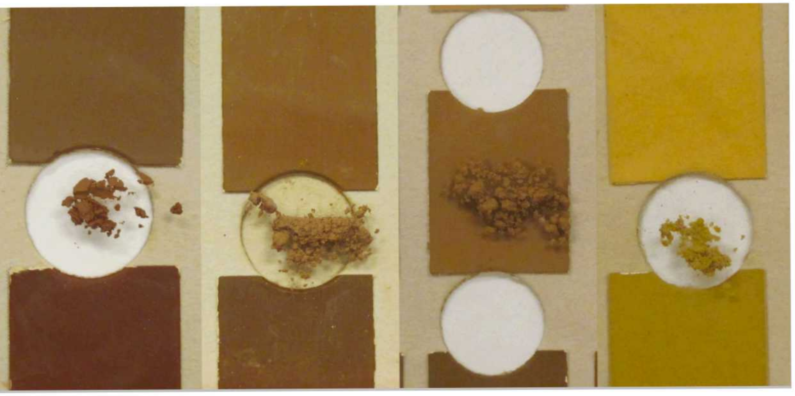

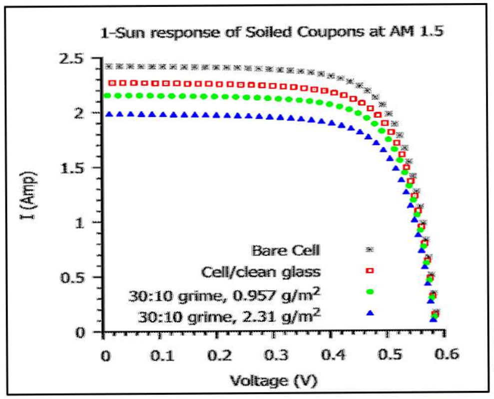

Energy Loss Due to Soiling of Photovoltaic Systems

Bruce King

MRS Spring Meeting

3 April, 2018

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DOE Regional Test Centers

US Department of Energy – Solar Energy Technologies Office

Outline

1. Overview of soiling and effects on PV
2. Field Studies
3. Laboratory Soiling studies
4. Approaches to Mitigation
5. ~~Performance Modeling~~
6. Summary

What is “Soiling”?

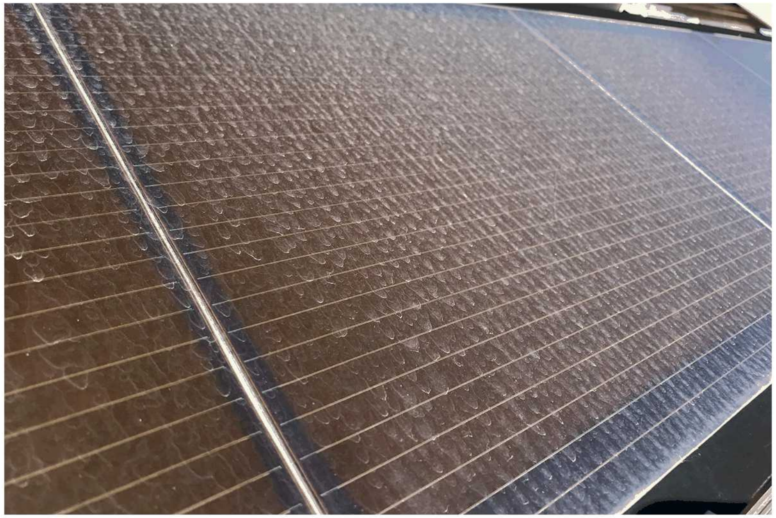
- Conceptually, very simple: accumulation of foreign material on PV panels that causes power loss

- Soiling represents one of the largest sources of uncertainty in energy production of PV systems after solar resource itself
  - Magnitude: annual loss estimates range from 5-25%.

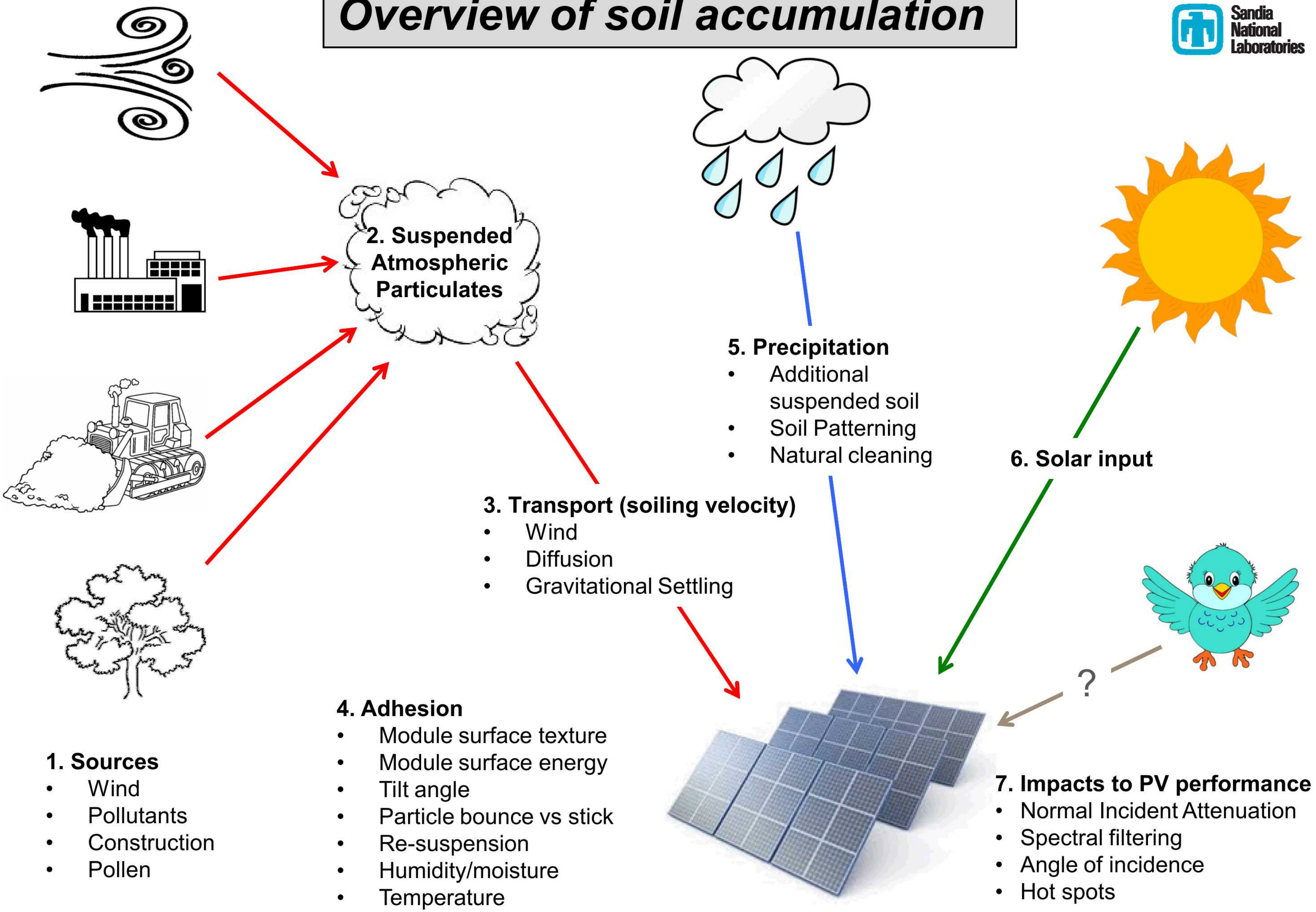
- Impact is direct: 1% soiling = 1% power loss = $

- In an industry plagued by low margins, excessive or unmitigated soiling can be the difference between profit and loss.

- Further, mitigation (e.g. cleaning) can have societal impacts particularly in parts of the world where access to clean water is limited.



Overview of soil accumulation

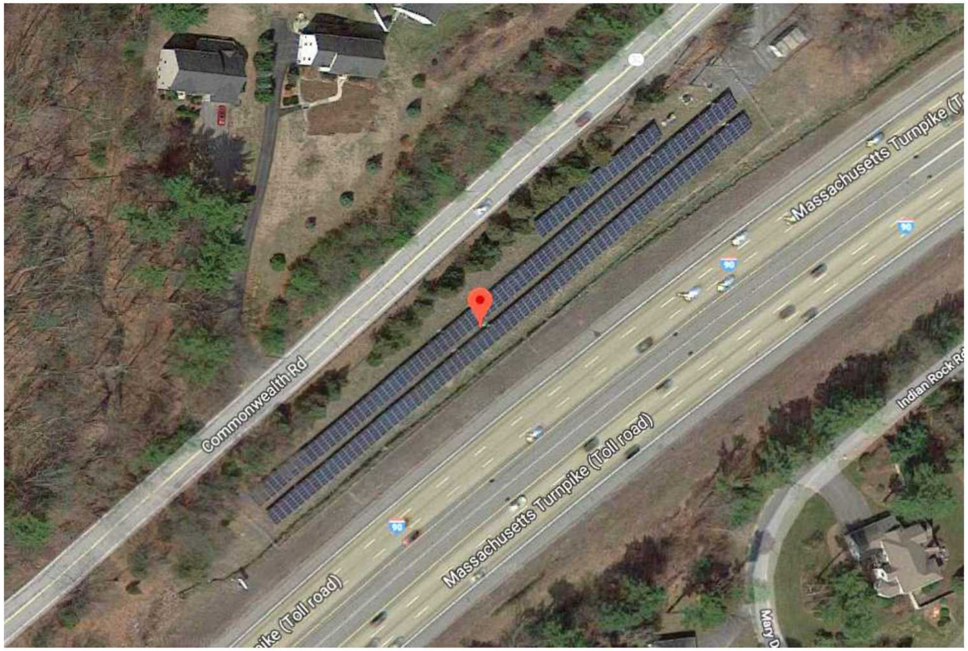


Impact of site selection

- Historically in the US, soiling was thought to be a relatively minor problem (< 7%) compared to other loss/reliability issues
- Many studies focused on MENA where losses can be much greater (> 25%)
- With rapid expansion of PV in the US, large scale plants are being sited on less than optimal land, particularly near dense urban areas

4 MW plant near Lowell, MA

Roadside array west of Boston, MA



Field Studies

Field Studies

Roughly break into three camps:

- Quantifying loss at the system level
  How bad is the problem?

- Science-oriented
  What can we learn about it?

- Operational
  When should I clean?

Quantifying Soiling Loss at the System Level

- Historically, has origins in solar thermal applications
  - Identified as far back as 1942
- Methods
  - “soiling sensor” – clean vs. dirty reference cells
  - Intelligent system analysis
- “Modern era” for photovoltaics – 2006
  - PowerLight (SunPower) study of ~250 operational systems
  - Correlated measured rainfall to power loss and recovery
  - Established one of the most commonly used empirical analysis and modeling paradigms for soiling

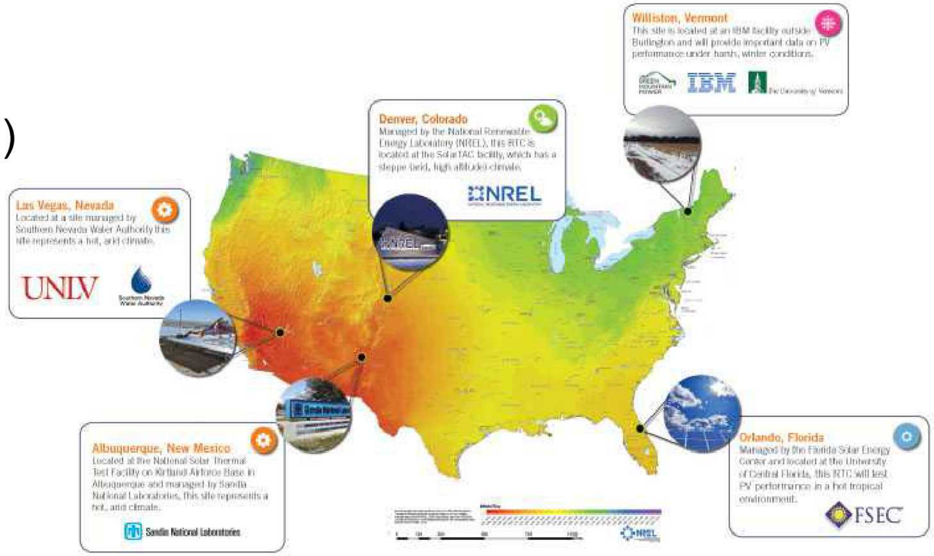
Hottel and Woertz, “The performance of flat plate solar heat collectors,” *ASME Transactions*, 1942

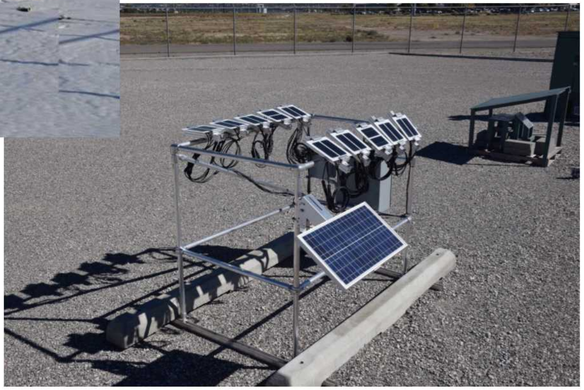
Kimber, et. al., “The effect of soiling on large grid-connected photovoltaic systems in California and the Southwest region of the United States,” *4th World Conference on Photovoltaic Energy Conversion*, Waikoloa, Hawaii, 2006

Regional Field Studies

Three types of soiling stations were deployed at select locations in the US

- Suspended atmospheric particulates (TSP)
- Naturally accumulated particulates
- Electrical performance loss due to accumulated soil





Site	Atmospheric	Electrical
NM RTC (Sandia)	x	x
CO RTC (NREL)	x	x
FL RTC (FSEC)	x	x
VT RTC (IBM)		x
Arizona State University		x
Commerce City, CO	x	
Boulder, CO	x	

Particulate Sampling Stations – University of Colorado, Boulder

Total Suspended Particulate (TSP) sampler

- Vacuum and filtration based sampler pulls suspended particulates directly out of the air (PM10/PM2.5)
- Gravimetric and compositional analysis

Naturally accumulated soil

- Replaceable glass collection plates deployed at 0° and 45°
- Gravimetric, compositional and transmission loss analysis

Key findings

- Demonstrated correlation between TSP concentration and transmission loss
- Validated simulated (laboratory) soiling as a method to study soiling in a controlled environment

Boyle, et. al, “Regional and National Scale Spatial Variability of Photovoltaic Cover Plate Soiling and Subsequent Solar Transmission Losses,” *Journal of Photovoltaics*, 2017

Burton, et. al., “Quantification of a Minimum Detectable Soiling Level to Affect Photovoltaic Devices by Natural and Simulated Soils,” *Journal of Photovoltaics,* 2015

Operational - Measurement Devices

- Primary purpose is to inform system operators when to clean
- Limited commercial availability, no standardization. Many home-built solutions
- Home-built solutions can be labor intensive - or worse, generate misleading data if not maintained

Direct power loss measurement

- Monitor electrical performance of PV module matched to the array
- Integrated cleaning system
- Integrated reference device

Indirect measurement

- Uses internal light source to detect dust....infer loss
- No widespread adoption yet, jury is still out

Laboratory Soiling – Tools to study fundamental impacts to PV performance

Motivation

Sandia National Laboratories

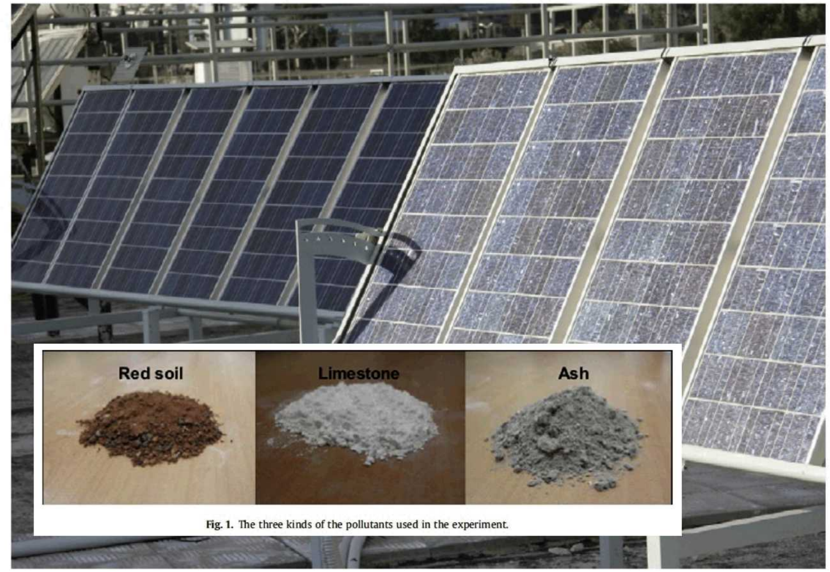
Economics of soiling loss provides strong motivation to develop a deeper scientific understanding of the environmental processes that lead to soil accumulation, the detailed effects on PV performance and effective mitigation strategies

Goals:

- Control soil composition, mass loading on panel/coupon, remove measurement uncertainty in device performance
- Accelerate the number of tests that can be performed and reduce the costs associated with such testing.
- Enable experiments to be performed at a central location using regionally-specific soil samples rather than requiring lengthy outdoor tests in each region.

Early Laboratory Studies

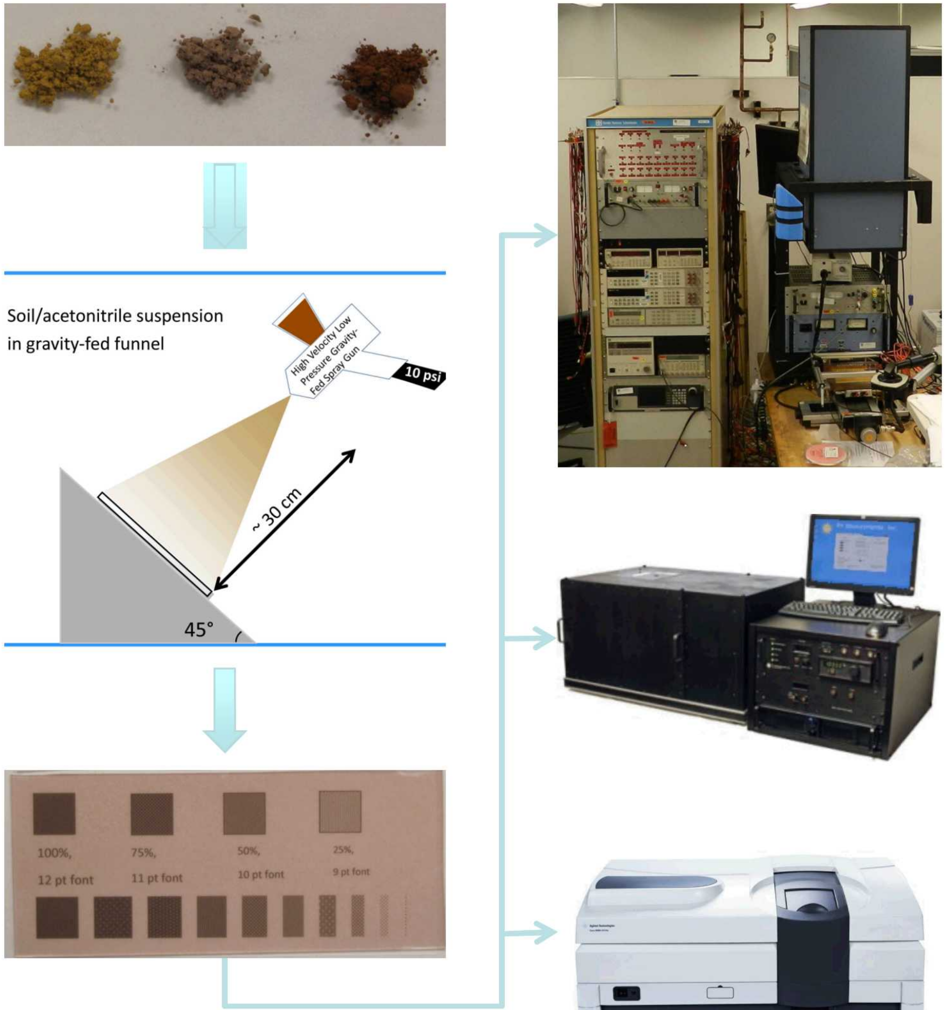
Brown, et. al., "Soiling Test Methods and their Use in Predicting Performance of Photovoltaic Modules in Soiling Environments," *38th IEEE-PVSC*, 2012.



Kaldellis, et. al., “Systematic experimental study of the pollution deposition impact on the energy yield of photovoltaic installations,” Renewable Energy 36, 2011.

- Early studies to simulate soiling attempted to control composition, but did not control deposition rate or level of soiling
- Dry application, ”shaker studies”, results mainly qualitative/comparative
- Brown demonstrated the potential impact of anti-soiling coatings
- Kaldellis demonstrated the impact of soil composition

Deterministic Method (Sandia)



- Traceable soil components are blended to match known natural soil types/compositions.
- Blends are sprayed onto glass coupons at varying loading rates.
- Transmission loss is measured using three different instruments
  - One-sun cell simulator
  - Quantum efficiency (PV Measurements QEX-10)
  - UV-Vis spectrophotometer with integrating sphere (Cary 5000)
- **Goals:**
  - Correlate composition to loss; determine the degree to which soil type influences loss
  - Provide a tool to industry to study soiling and soil mitigation

P. D. Burton and B. H. King, "Artificial Soiling of Photovoltaic Module Surfaces using Traceable Soil Components," in *39th Photovoltaic Specialists' Conference*, 2013

Key findings: details of loss mechanisms

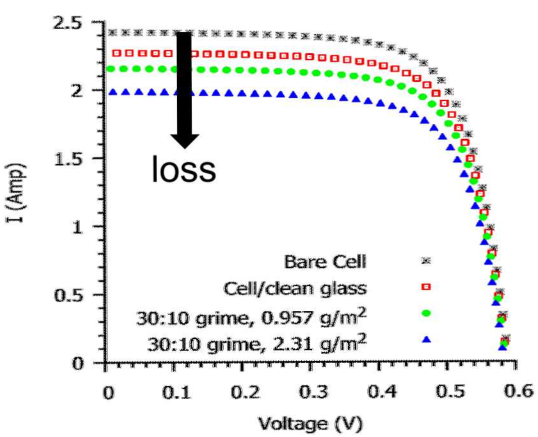
- Loss is primarily seen as a reduction in photo-generated current

- Soiled modules may also run hotter, resulting in voltage loss

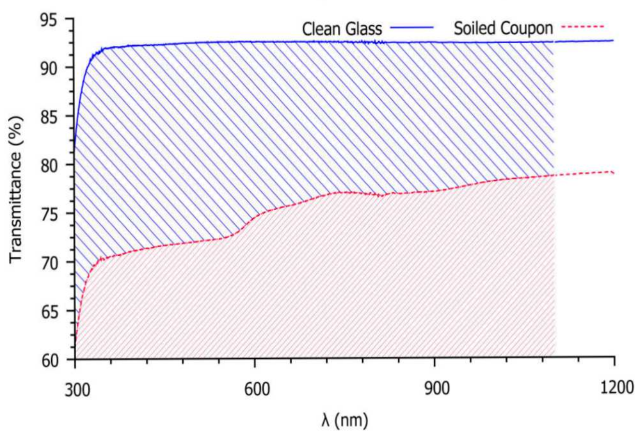
Loss Mechanisms

- Shading loss: direct sunlight is blocked by particles
- Spectral loss: particles alter the spectrum of light reaching the cell due to absorption and scattering
- Reflection losses: particles alter reflective properties of module surface

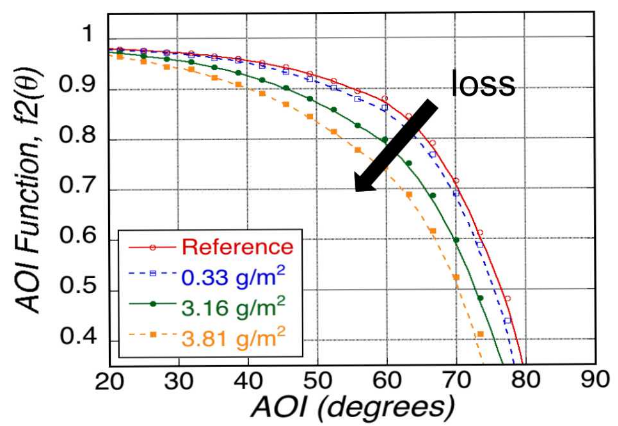
Solar Simulator



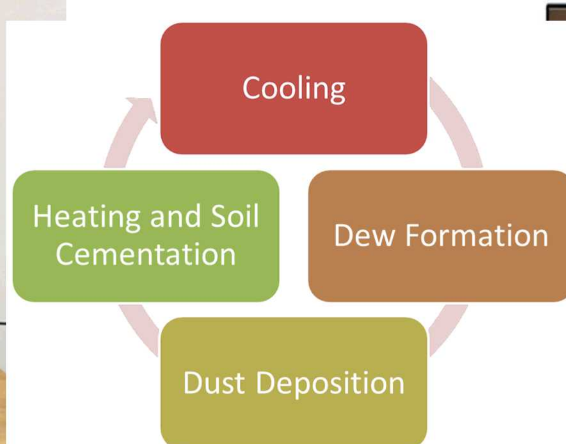
UV/Vis

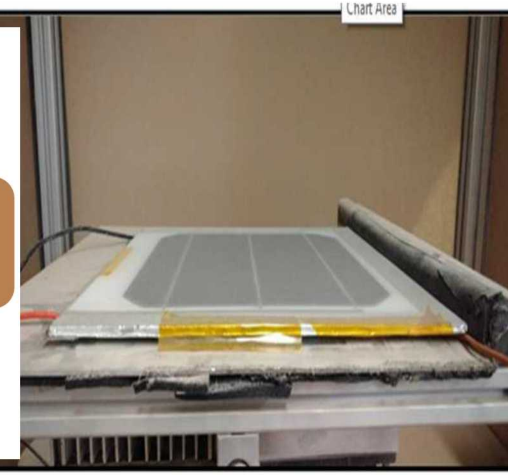


Reflection Losses



New Approaches:
Simulating Diurnal Cycles (ASU-PRL)





- Fluidized-bed aerosol generator for suspending soil
- Temperature controlled sample holder
- Controlled humidity

- Optimize dust, thermal and humidity cycles
- Correlate with field measurements to determine equivalent deposition rate

Mani G. TamizhMani, "Indoor In-Situ Soil Deposition Chamber Representing Natural Dew Cycles," 2017 International PV Soiling Workshop, Dubai

Mitigation Methods

Mitigation Methods

Two approaches are in use today

- Periodic cleaning
- Application of anti-soiling coatings (ASC) to PV module cover glass

In development

- Electrodynamic screens (EDS)
    - Transparent film containing parallel rows of electrodes
    - Pulsed high-voltage to repel particles electrostatically

Mazumder, et. al, "Mitigation of Dust Impact on Solar Collectors by Water-Free Cleaning With Transparent Electrodynamic Films: Progress and Challenges," *Journal of Photovoltaics*, 2017

Cleaning

SunPower Oasis
www.sunpower.com

Hand/Truck Washing

- Low-tech solution to a "simple" problem
- Scalable from small to large systems
- Key drawbacks
    - Labor intensive = $
    - Water intensive
    - Economics can be improved with better field sensors

Robots!

- Many examples, few established
- Best applied at large scale
- Water-free solutions are emerging
- Key drawbacks
    - Difficult to retrofit to older systems
    - Abrasion of glass & coatings (e.g. Antireflective, Antisoiling)
    - Additional O&M costs associated with mechanical systems

Mitigation: Anti-soiling coatings

Two primary functions:
- Resist soil accumulation
- Enhance soil release

Approaches
- Hydrophobic vs Hydrophilic
- Which is best may depend on site-specific soiling
- Typically sol-gels (but not always)

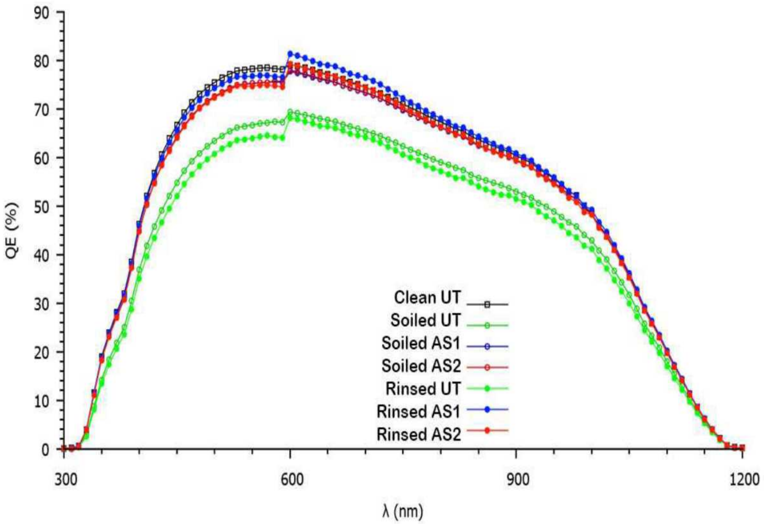
Considerations
- Pre-applied vs. retro or field applied
- Durability
- Effectiveness can be difficult to prove
- Some coatings are also advertised as being Antireflective (ARC), which have greater market acceptance

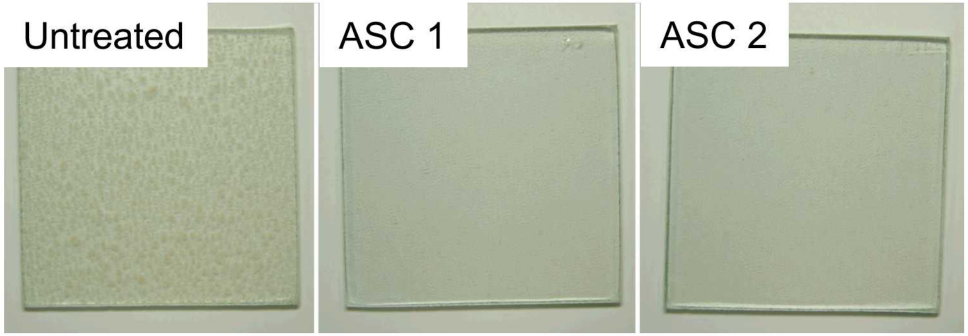
Hydrophobic – relies on water droplet formation, droplets carry particles

Hydrophilic – enhances water sheeting

Proof of concept: Demonstration of ASC effectiveness

- Simulated soil was applied to three samples using Sandia's spray deposition method
- Soil release efficiency was characterized by simple rinsing and physical wiping
- Transmission loss was characterized before and after cleaning
- Rinse test
  - Untreated - displayed greater loss after rinsing.
  - AS1 - recovered fully
  - AS2 - did not recover significantly





	Untreated	ASC 1	ASC 2
Soiled	-13.3%	-2.6%	-2.3%
Rinsed	-16.2%	0.2%	-2.2%
Wiped	0%	0%	0%

Opportunities (through Materials Science-colored glasses)

- Development and characterization of durable antisoiling coatings (most obvious)
- Development of better soil sensors through a fundamental understanding of particulate properties and behavior.
- Fundamental characterization of dust/mineral adhesion to PV surfaces (informs development of mitigation methods)