SunShot U.S. Department of Energy

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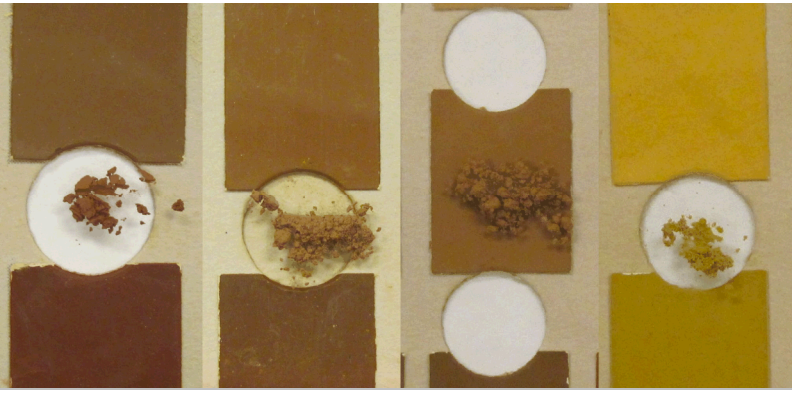

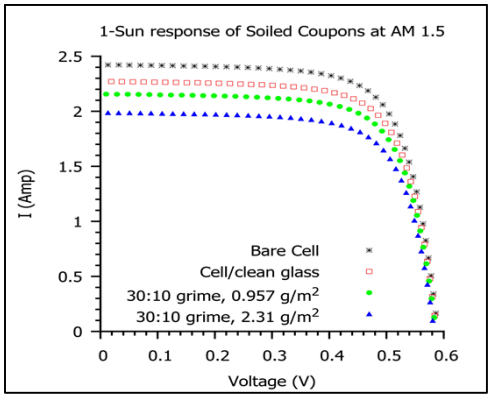

Overview of Sandia's Soiling Program: Experimental Methods and Framework for a Quantitative Soiling Model

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22 October, 2015

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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DOE Regional Test Centers

US Department of Energy Sunshot Initiative

Outline

1. Overview of soiling and effects on PV
2. Laboratory Soiling studies
3. Field work
4. Summary

PV Performance Modeling Steps

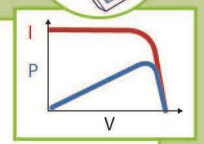
1. **Irradiance and Weather** – Available sunlight, temperature, and wind speed all affect PV performance. Data sources include typical years (TMY), satellite and ground measurements.

2. **Incidence Irradiance** – Translation of irradiance to the plane of array. Includes effects of orientation and tracking, beam and diffuse irradiance, and ground surface reflections.

3. **Shading and Soiling** – Accounts for reductions in the light reaching the PV cell material.

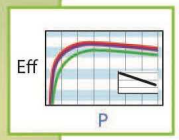
4. **Cell Temperature** – Cell temperature is influenced by module materials, array mounting, incident irradiance, ambient air temperature, and wind speed and direction.

5. **Module Output** – Module output is described by the IV curve, which varies as a function of irradiance, temperature, and cell material.



6. **DC and Mismatch Losses** – DC string and array IV curves are affected by wiring losses and mismatch between series connected modules and parallel strings.

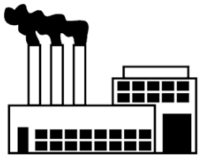
7. **DC to DC Max Power Point Tracking** – A portion of the available DC power from the array is lost due to inexact tracking of the maximum power point.

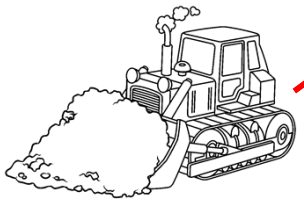


8. **DC to AC Conversion** – The conversion efficiency of the inverter can vary with power level and environmental conditions.

9. **AC Losses** – For large plants, there may be significant losses between the AC side of the inverter and the point of interconnection (e.g., transformer).

10. **System Performance Over Time** – Monitoring of plant output can help to identify system problems (e.g., failures, degradation).





2. Suspended Atmospheric Particulates

5. Precipitation
- Additional suspended soil
- Soil Patterning
- Natural cleaning

6. Solar input

3. Transport (soiling velocity)
- Wind
- Diffusion
- Gravitational Settling

?

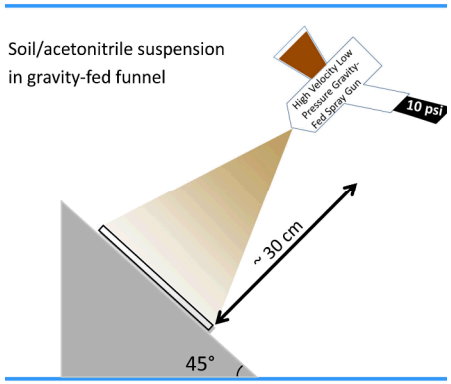
1. Sources
- Wind
- Pollutants
- Construction
- Pollen

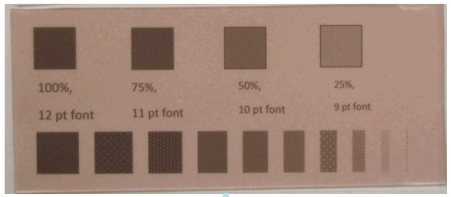
4. Adhesion
- Module surface texture
- Module surface energy
- Tilt angle
- Particle bounce vs stick
- Re-suspension
- Humidity/moisture
- Temperature

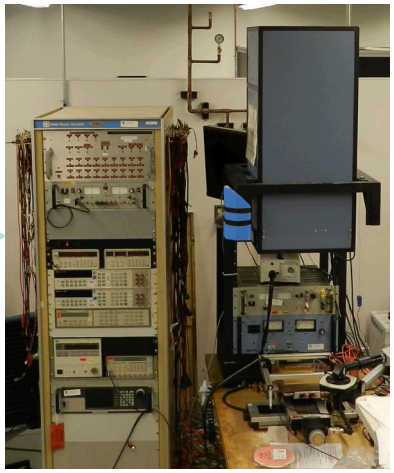
7. Impacts to PV performance
- Normal Incident Attenuation
- Spectral filtering
- Angle of incidence
- Hot spots

Laboratory Soiling – Tools to study fundamental impacts to PV performance

Laboratory Soiling – Methodology and Characterization







- 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
  - UV-Vis spectrophotometer
- **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

Laboratory Results – Measurement Techniques and Attenuation

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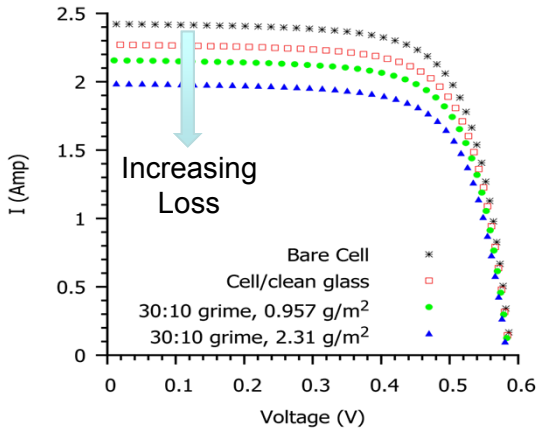
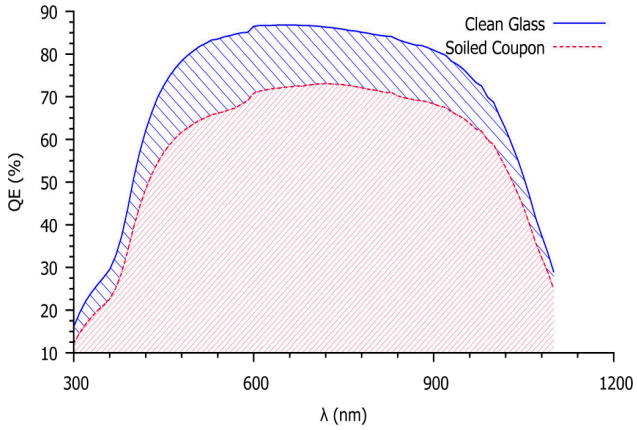
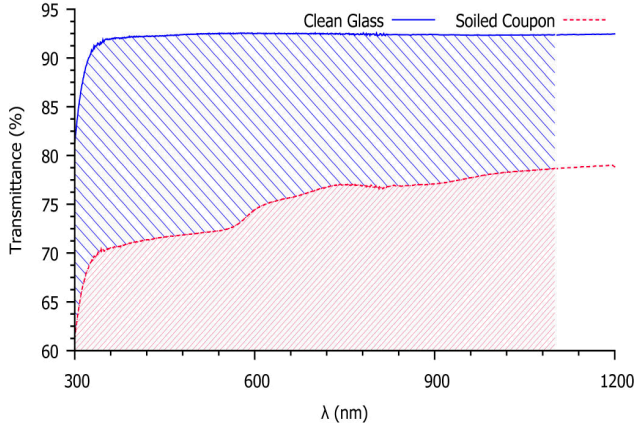
1-Sun Simulator

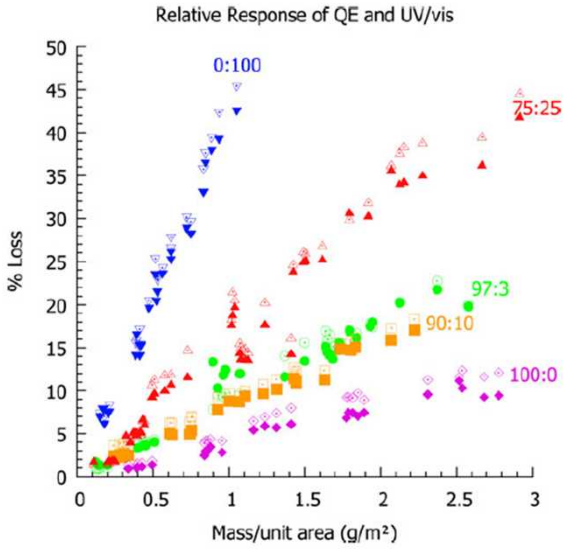


Quantum Efficiency



UV-Vis Spectrometer



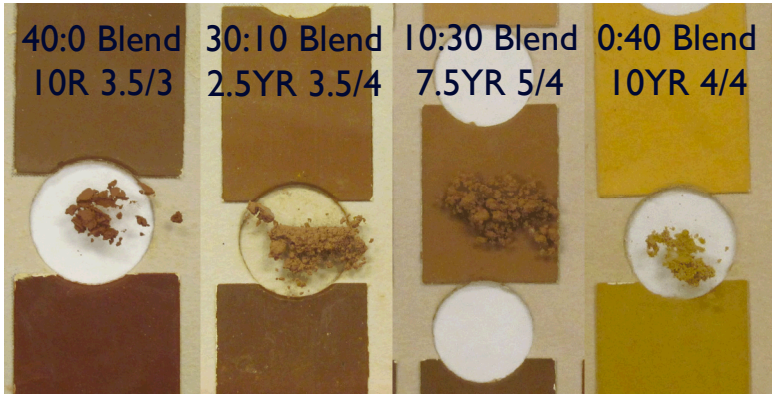


$$Loss = \frac{\int_{300}^{1100} S_{clean}(\lambda)\, d\lambda - \int_{300}^{1100} S_{soiled}(\lambda)\, d\lambda}{\int_{300}^{1100} S_{clean}(\lambda)\, d\lambda}$$

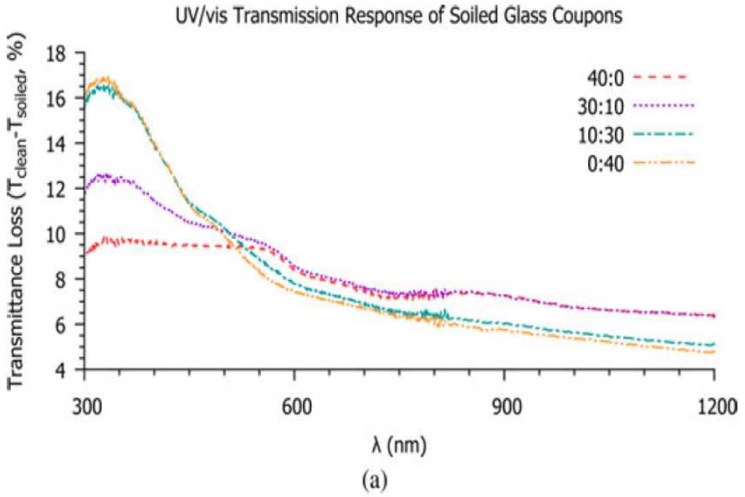
- Demonstrated three complimentary measurement methods
  - Methods based on measuring Transmission Loss correlate very well
  - Reflectance Loss measurements do not correlate well to other methods
- Soils with higher soot content lead to dramatically greater loss

P. D. Burton and B. H. King, "Application and Characterization of an Artificial Grime for Photovoltaic Soiling Studies," *IEEE Journal of Photovoltaics,* 2014

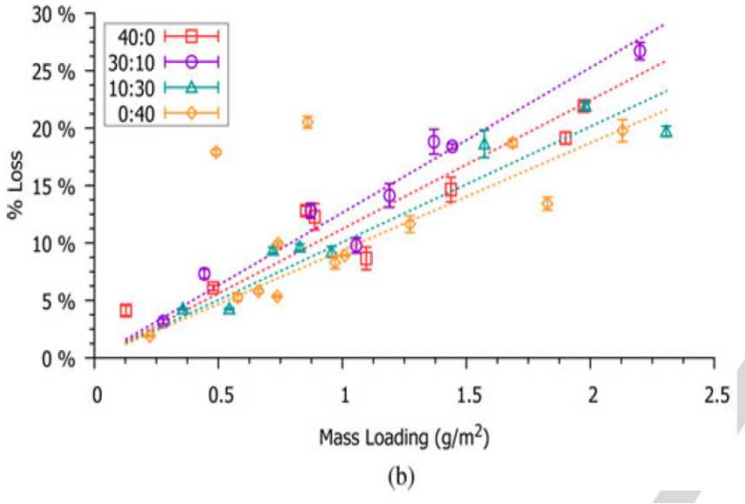
Lab Results – Effect of Soil Composition



Hematite Rich ⟷ Goethite Rich



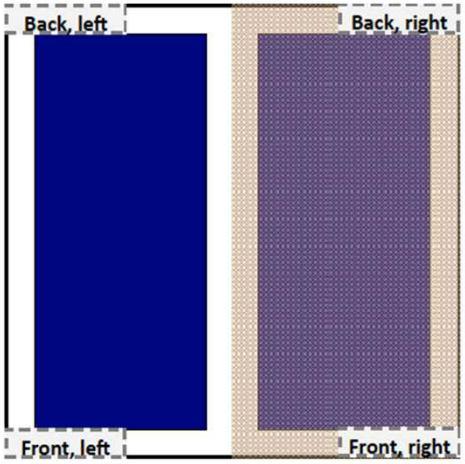
- Developed blends to test compositional effects
  - Four spectrally responsive blends common to the southwest based on iron oxides; hematite (red) and goethite (yellow)
  - Other contents include silica and small levels of carbon
- Soil blends were applied to glass coupons at loading rates up to 2.5 g/m^2, comparable to accumulations seen in nature
- Energy Dispersive Spectroscopy (EDS) indicates that composition is maintained between blending and spraying
- Compositional Effects:
  - Goethite rich soils displayed greater spectral sensitivity, leading to greater attenuation in the blue to UV
  - Hematite rich soils displayed a neutral loss
  - The greatest loss occurred for a blend of the two iron oxides



P. D. Burton and B. H. King, "Spectral Sensitivity of Simulated Photovoltaic Module Soiling for a Variety of Synthesized Soil Types," *IEEE Journal of Photovoltaics,* 2014.

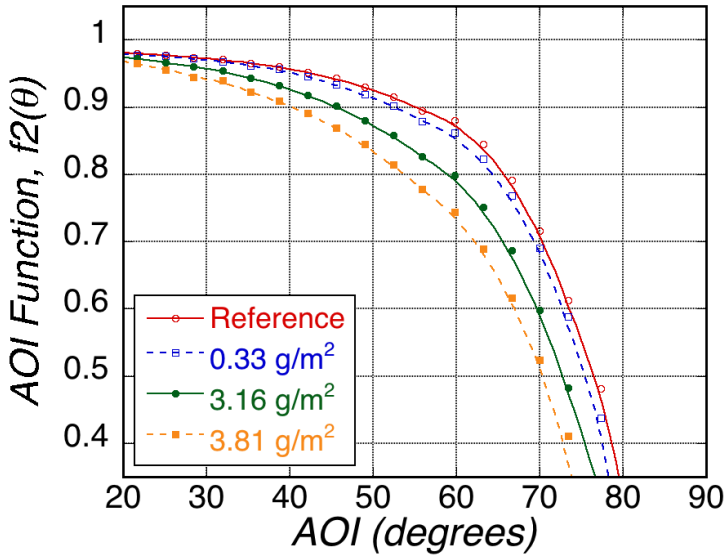
Lab Results – Angle of Incidence

- Synthetic (neutral) soil was applied to one half of custom split reference cell
- Angle of incidence response was measured outdoors on a two-axis tracker
- Low soiling rate (< 0.5 g/m^2) has minimal effect on AOI response compared to a reference curve
- High soiling rate (>3 g/m^2) has a pronounced effect on AOI response
- This effect is **in addition** to attenuation effects and could be a significant consideration for commercial rooftop systems in particular



$$I_{scr} = \frac{I_{sc} E_0}{[E_{DNI} + E_{diff}][1 + \alpha_{Isc}[T_c - T_0]]}$$

$$f_2(\theta) = \frac{\left[\frac{I_{sc}}{I_{scr}}\right]\left[\frac{E_0}{1 + \alpha_{Isc}[T_c - T_0]}\right] - E_{diff}}{E_{DNI} \cos\theta}$$



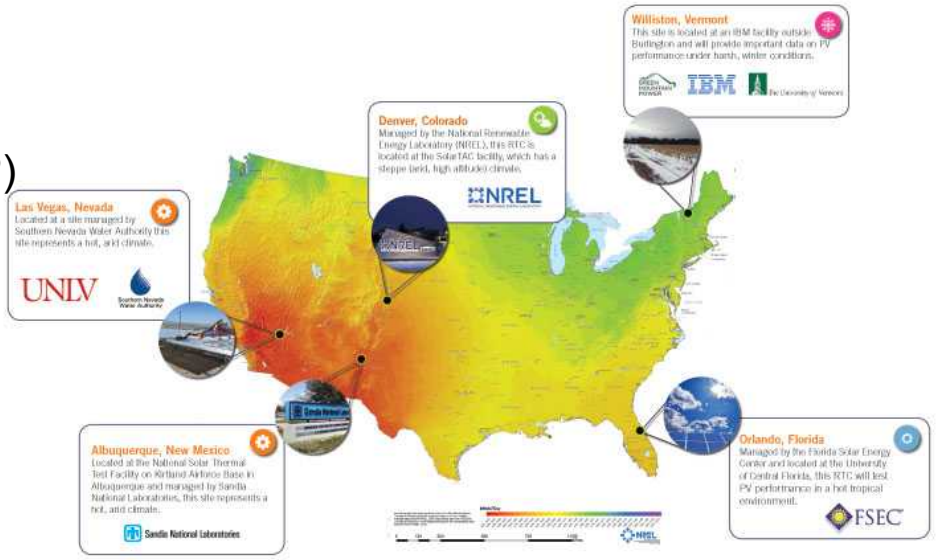
P. D. Burton, A. Hendrickson, S. S. Ulibarri and B. H. King, "Pattern Effects of Soil on Photovoltaic Surfaces", *in preparation*

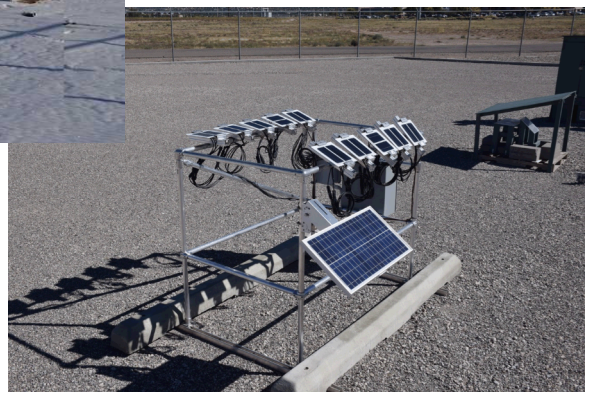
Field Studies – Correlations to real world soiling and impacts on performance

Field Work - Sampling stations deployed at Regional Test Centers

Three types of soiling stations were deployed at the RTCs and 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

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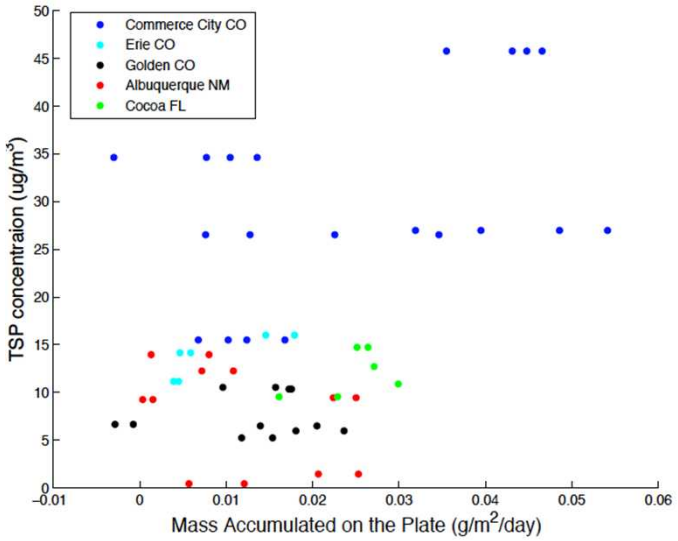
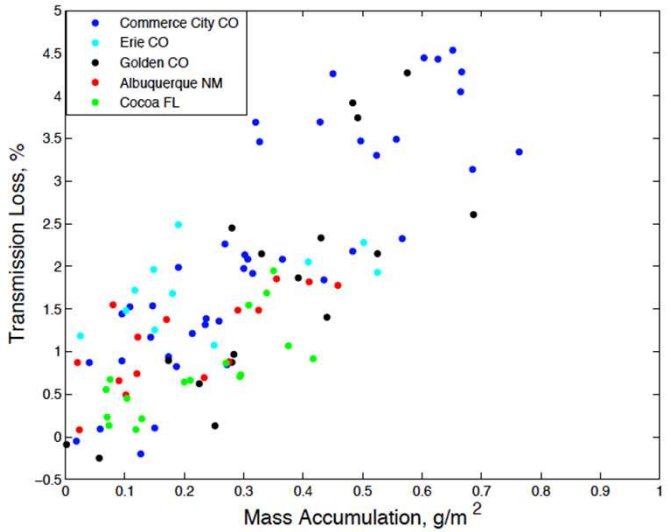
Total Suspended Particulate sampler

- Vacuum and filtration based sampler pulls suspended particulates directly out of the air
- Analysis includes gravimetric and compositional

Naturally accumulated soil

- Replaceable glass collection plates deployed at 0° and 45°
- Analysis includes gravimetric, compositional and transmission loss





L. Boyle, et. al, "Spatial Variability of Soiling of Photovoltaic Cover Plates: Results from Colorado, Florida and New Mexico," *in preparation*, 2015

Performance Loss Station – Arizona State University

Performance Loss Station

- Array of matched reference cells (both sides shunted)
- One side is cleaned regularly and one side is allowed to soil naturally
- Soiling loss is inferred from Isc differential between clean and soiled sides
- Cells are oriented at tilt angles of 0° - 45° in 5° increments
- Preliminary analysis is in process
- Planned multi-year deployment

Summary

- Repeatable laboratory methods have been demonstrated for studying fundamental impacts of soil to PV performance
- Soil composition has been demonstrated to affect PV performance
  - Higher soot content soils attenuate light to a greater extent than low soot content soils
  - Spectrally responsive pigments may alter the spectrum of light reaching the PV cell
- Significant soil accumulation impacts angle of incidence behavior, leading to greater losses than anticipated
- Preliminary analysis of atmospheric samples shows a rough correlation between suspended particulate concentrations and transmission loss
- Performance loss stations are in operation at RTC sites