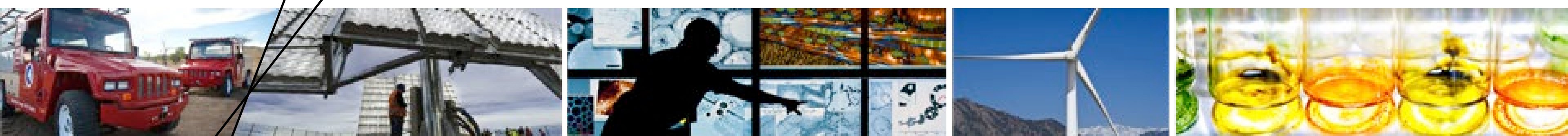
The Modeling of the Effects of Soiling, Its Mechanisms, and the Corresponding Abrasion



PV Module Reliability Workshop

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

- **Background**
- **Project Description and Objectives**
- **Focus Areas**
  – Soiling Rate Model
  – Mechanisms
  – Standards
- **Summary**
- **Acknowledgements**

Background

- **Problem:**
  - Natural soiling has reduced the energy output of PV systems since the inception of the technology.
  - Soiling is a complex problem that increases uncertainty and drives up LCOE through lost energy production, increased O&M costs, and higher finance rates.
    - Overall, soiling may be adding ¢1/kWh to LCOE in the United States (may be worse in some other parts of the world) depending on the site.
  - In NREL's comprehensive review of solar energy soiling,[1] the issues have been discussed in the literature for more than 70 years, and yet "the fundamental properties of dust and its effect on energy transfer are still not fully understood, nor is there a clear solution to the problem."
- **Goal:**
  - NREL's team will work with the PV community to go beyond the past work to try and understand the processes involved so that the effects of soiling can be predicted for different environmental conditions.
  - Provide the PV industry with the tools and knowledge necessary to devise cost effective mitigation.

[1]Sarver et. al., Renewable and Sustainable Energy Reviews, 2013, vol. 22, issue C, pages 698-733

Project Description and Overview

- **3 year long competitively selected SuNLaMP project:**
  - Addressing Soiling: From Interface Chemistry to Practicality
- **Soiling reduces PV energy output & increases LCOE two ways:**
  - Indirectly through increased performance uncertainty → higher finance rates
  - Directly through reduced power output
- **Working with stakeholders and PV community from the outset**
  - Focus on addressing 3 main problems to decrease LCOE
    - **Predictive soiling loss models:** predict annualized (perhaps seasonal) losses at new PV plant sites. (reduce performance uncertainty)
    - **Quantify the different soiling mechanisms:** develop guidelines of the appropriate properties PV module surfaces and coatings might need to reduce soiling. (increased power output)
    - **Standards:** develop durability standards for PV module coatings.
      - Perhaps artificial soiling standard

- **Slide on previous attempts to predict soiling rates**

Site Specific Soiling Loss Rates

- **Past efforts are narrowly applicable physics based models.**
- **This effort focuses on empirical modeling that attempts to include all possible predictive variables and predicts *annualized* and *seasonal* losses.**
- **Annual empirical metric more achievable and provides significant value in 30 year performance predictions, seasonal metric provides guidance in O&M planning.**
- **Industry driven: PV manufactures and power plant owners are sharing high quality data from over 200 sites to enable this effort to be successful.**

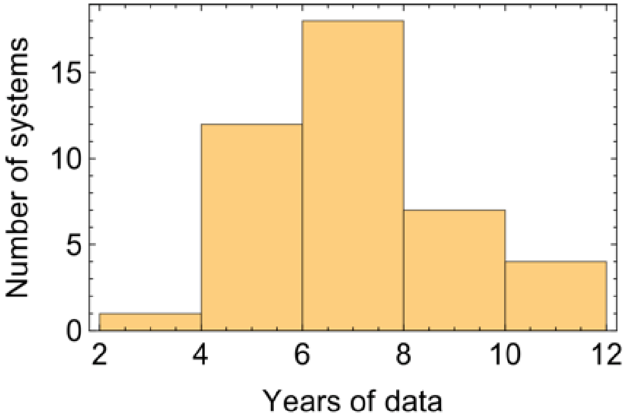
Picture of initial data sites used for identifying the key model parameters. The sites are representative of the different climatic zones within the US and should provide the requisite information needed for robust models.

Soiling Rate Model Parameters

- Examples of production data information
  - Location
  - Module model
  - Mounting info
  - System layout
  - Calculated soiling loss
  - Met/Soiling data
  - Detailed site description
  - Maintenance/cleaning logs
  - Inverter power
  - Wind speed
  - Ambient temperature
  - Irradiance (GHI)
- Other data and possible sources:
  - NSRDB[1]: irradiance
  - PRISM[2]: precipitation, temperature
  - NASA MERRA[3]: wind, temperature, humidity, pwv
  - In-house: highways, airports, railways, industrial sites, urban environments
  - NLCDB[4]: land cover, agriculture

[1]http://nsrdb.nrel.gov/
[2]http://www.prism.oregonstate.edu/
[3]http://gmao.gsfc.nasa.gov/research/merra/
[4]http://www.mrlc.gov/

- Lessons learned so far?



Creating automated means to process the data, provide further quality checks, and determine daily/monthly/annualized soiling rates. The processed data from the 64 sites will be used for model development. The data processing will be as automated as possible so information from additional sites can be added with minimal amounts of effort.

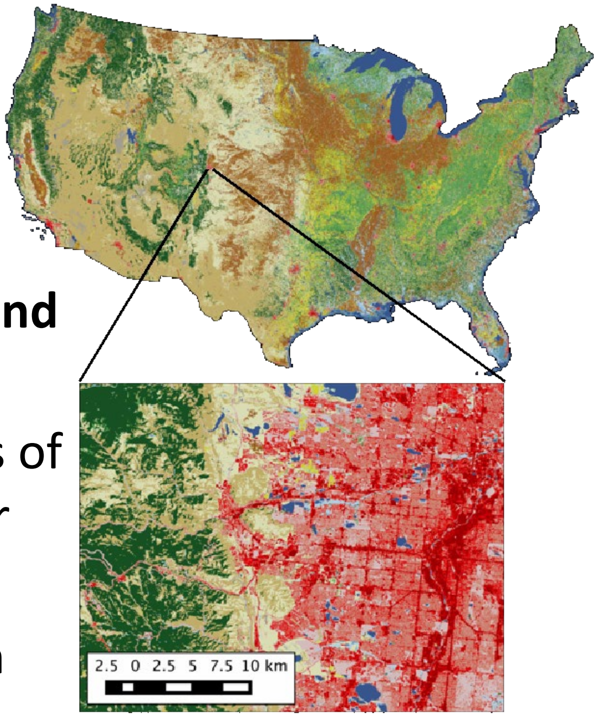
Modeling Methods

- Focus on small but high quality data sets. Supplement the data with potential predictive variables quantified from EPA particulate maps, rainfall maps, NOAA, and USGS (guided by PVQAT 12). Once supplementation is complete, multi–variate analysis techniques will be used to determine which predictive variables are relevant ($p<0.05$).
- Based on Pareto chart of the predictive variables expand data sets to over 100 sites.
- Apply neural network analysis, cluster algorithms and other data mining techniques to determine possible nonlinearities/complex relationships.
- Empirical coefficients will be derived for all models using a learning data set and then the "best" model(s) will be determined by the root mean square error (RMSE) statistics based on application against a validation data set.

www.mrlc.gov

e.g.,: National Land cover database:

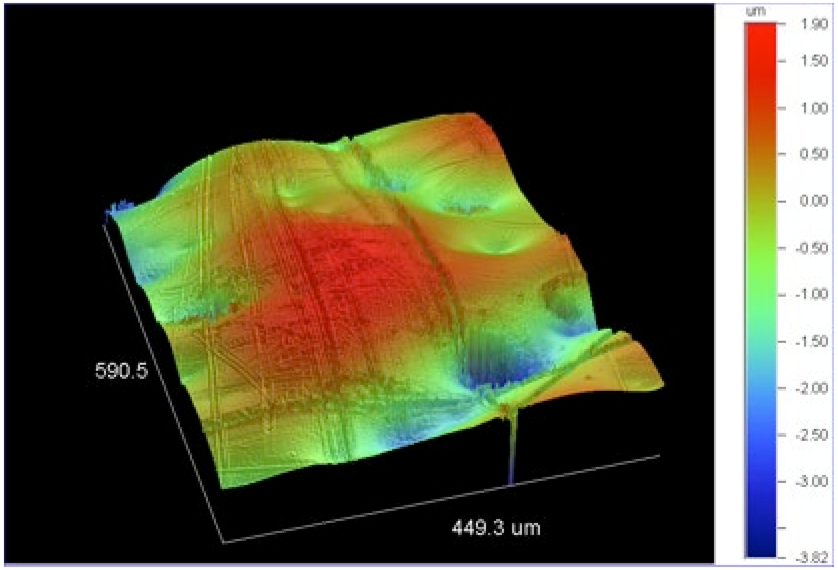
- 16-classes of land cover
- 30m resolution



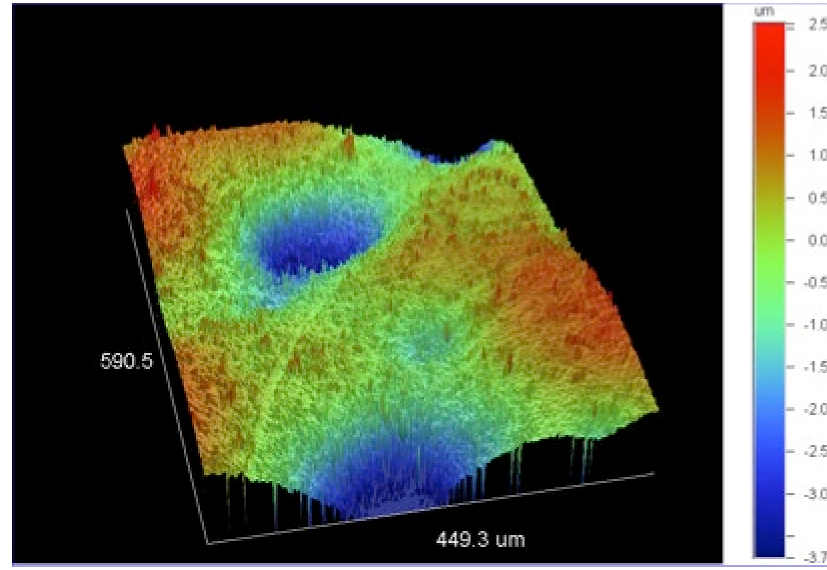
Weathered PV Module Glass Analysis

Siemens M55 module

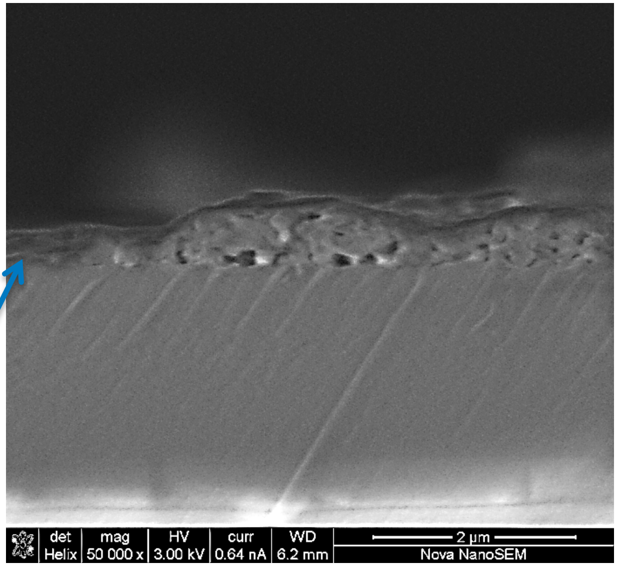
control



28 years in field



- **White light optical profilometry of module glass**
  - Provides information over large lateral length scales on module glass and AR coatings
  - Scratches and large scale (~mm) hillocks were observed on control sample.
  - The small-scale roughness of control and aged modules appears qualitatively different.
  - SEM and EDS show thin salt layer may be present on glass surface



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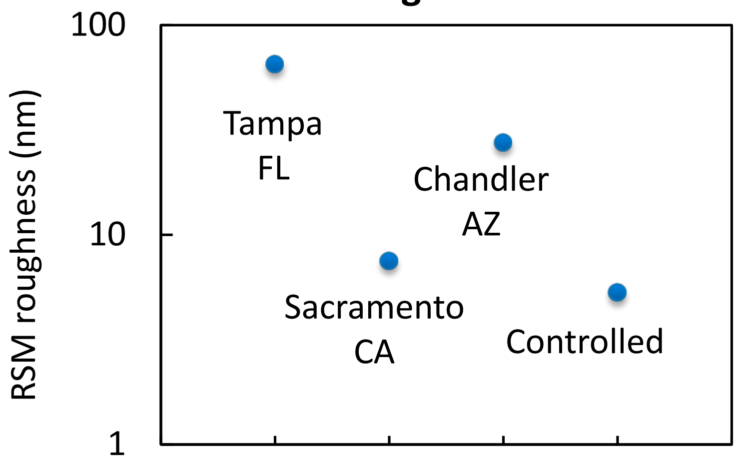
AFM-Based Characterization

AFM Roughness

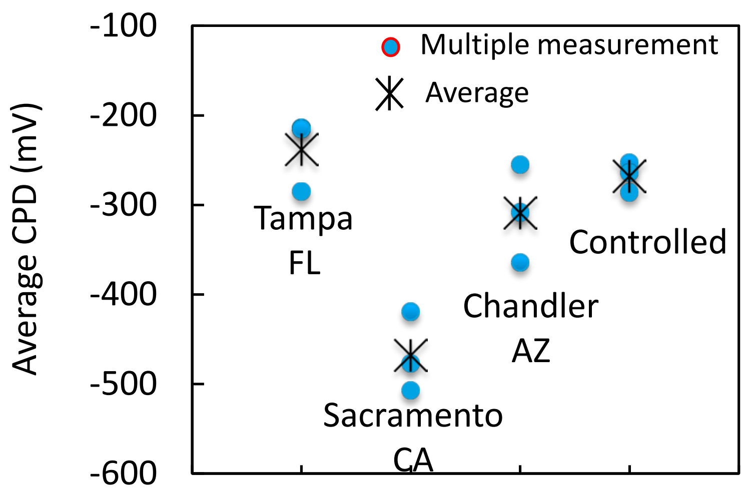


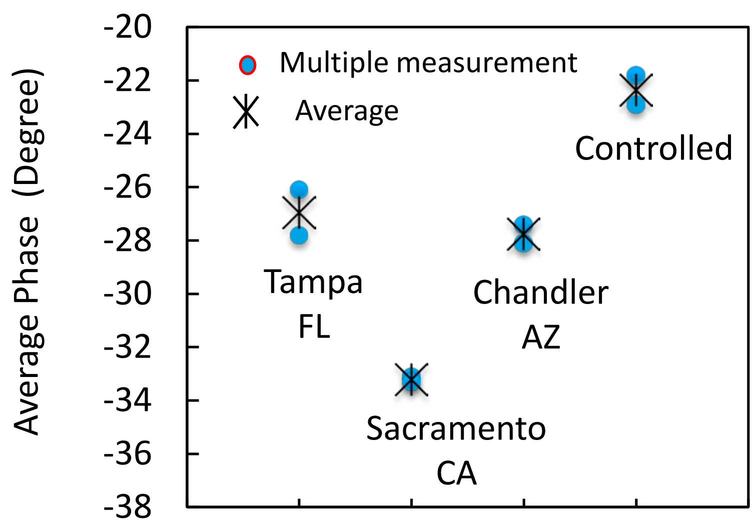
- Roughness: Tempe>Chandler>Sacramento
- Phase lag and viscosity/softness: Sacramento>Chandler ≈ Tempe
- Contact Potential Difference: Sacramento>Chandler>Tempe

AFM-based techniques:

- 2D and real 3D data and roughness.
- Phase imaging/lag: elasticity, adhesion &friction.
- Lateral force: inhomogeneity not from topography.
- Force-distance curves: adhesion (e.g. capillary).
- EFM/KPFM: electrostatic interaction.
  - Electrostatic/Kelvin Probe Force Microscopy

KPFM Electrostatic Potential



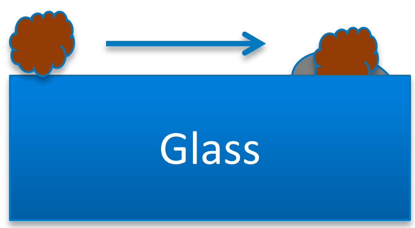


Mechanism Investigations

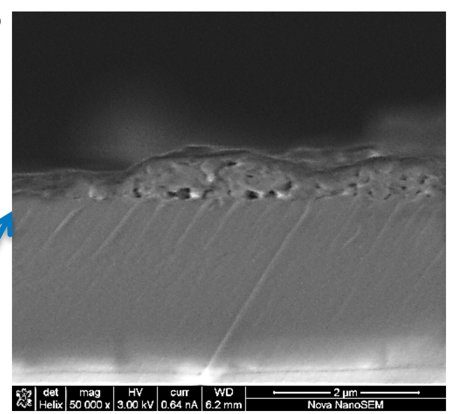
- **Conclusions from initial literature survey**
  - Early work attempted to address mechanism issues more
    - E.g.,
  - A lot of work identifies soiling issues, but do not evaluate/identify exact adhesion mechanism
    - E.g.,
- **To go beyond just "observing" soiling we must systematically evaluate each adhesion mechanism involved at each step.**

- If gravity or wind brings dust to the surface, what makes it stick?
  - Kaz's recent paper binding energy
- What role does humidity play?
  - Reduces electrostatics?
  - Enables capillary?
  - What is relative strength?
- What is the effect of surface properties and dust composition?
  - Surface roughness?
  - Surface Energy?
  - Conductivity?
- Is the roughness due to weathering from chemical etching of the glass or surface deposits?

Physisorption goes to chemisorption



After outside weathering



Sample Observations

- Dust that has been on the surface for a while tends to be harder to remove.
- Humidity and dew cycle seem to increase soiling.
- Soiling is often not uniform on module.

Mechanism Investigations

- **To address these mechanism questions, quantify impact of individual mechanisms, e.g.,:**
  - Study effects of substrate roughness, relative humidity (RH), probe/substrate conductivity, surface energy, and surface contamination on:
    - Van der Waals forces
    - Electrostatic adhesion
    - Capillary forces
    - Hydrogen bonding

e.g., use Atomic Force Microscopy Based Measurements and Analysis

force-distance (f-z) curves, lateral force microscopy (LFM), phase imaging (PI), electrostatic force microscopy (EFM).

  - Identify potential sources of salt; leaching from the module glass, airborne salt, and leaching from deposited soiling materials like alumina-silicate or clay particles.
    - Accelerated testing of glass and dust
- **With individual mechanisms quantified, then evaluate complex or multiple step soiling mechanisms**
  - e.g., cementation

Soiling Mechanisms

- **Working through literature to develop an investigation plan for each combination of mechanisms and surface properties**
  - Physics/chemistry based interactions or bonding
    - Atoms and Electrons
    - Probably most interested in psuedo-covalent bonding
- **Quantify at both the atomic and macroscopic scales**
- **Evaluate both "model" and field samples to ensure all appropriate mechanisms are characterized**
  - Leverage "standards" work
- **Summary of what we believe/know now**
- **Identify the specific mechanisms associated with soiling to find appropriate mitigation processes for a given region**
  - e.g., develop optimized cleaning schedules and techniques for a given region based on the type of environmental factors that may cause **irreversible soiling.**
- **Techno-economic based preventative approaches**
  - e.g., efficacy of anti-reflection/anti-soiling coatings.
- **Bridge the gap between the surface science and actual field operation**
  - Provide the community with an understanding of how to select between different surface properties
    - e.g., hydrophobic, hydrophilic and photocatalytic, for different locations and to optimize optical, self-cleaning, anti-soiling, and durability characteristics.

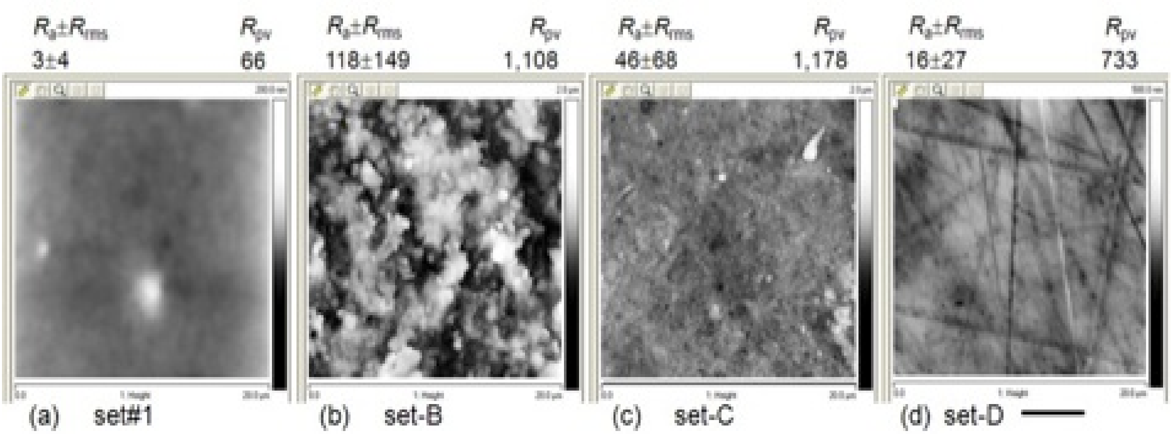
Adhesion Mechanisms/ Surface Properties	Gravity	Surface Energy	Vander Waals	Capillary	Charge Double Layer	Electrostatic/ coulombic	Complex/ cementation	Chemical Bond
Polymeric	VW	W	TBD	TBD	VS	VS	VS	VS
Textured glass	VW	W	TBD	TBD	TBD	TBD	VS	VS
Nanostrutured	VW	W	TBD	TBD	TBD	TBD	TBD	VS
Smooth glass	VW	W	W	TBD	TBD	TBD	TBD	VS
Photocatalytic	VW	TBD	TBD	VS	TBD	TBD	VS	VS
Hydrophilic	VW	TBD	TBD	VS	TBD	TBD	VS	VS
Electrically conducting	VW	TBD	TBD	TBD	VW	VW	TBD	VS
Hydrophobic / low surface energy	VW	VW	VW	TBD	TBD	TBD	TBD	TBD

VW - Very Weak, <10 kJ/mol
W - Weak, < 25 kJ/mol
M - Moderate, ~50 kJ/mol
S - Stong, >75 kJ/mol
VS - Very Strong, >100 kJ/mol

Coatings Standards: Overview

- **Determine repeatable indoor abrasion test procedures suitable for PV surfaces**
- **Deploy coating samples at various test sites, acquire aged PV modules with standard solar glass.**
- **Correlate degradation of veteran PV modules with indoor abrasion test procedures,**
  - Test variations in accelerated protocols to improve correlation.
  - Incorporate best accelerated test protocols into draft IEC standards. (Validation efforts will need to be ongoing as samples are maintained in the field more than 3 years)
- **Submitted draft standard to IEC.**

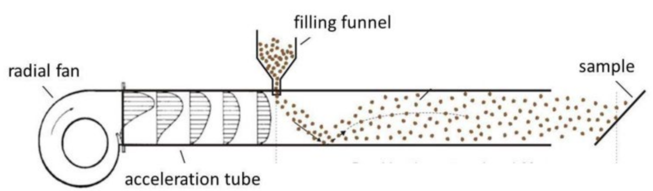
Images of (a) pristine PV module surface, relative to degradation (b)-(d) due to weathering and cleaning. Proc. SPIE, 2010, 7773-02



Indoor Abrasion Test:

Summary and Approach Based on the Literature

- **Relevant existing methods (popular use & literature):**
  - Falling sand test, e.g., ASTM D968 & DIN 52348
  - Forced sand impingement , e.g., MIL-STD-810G or ASTM G76.
  - Machine abrasion (linear or rotary), e.g., BS EN1096-2, ASTM D4060, or ASTM D2486
  - Abrasive media in tumbler or shaker, e.g., DUR-5.2.9 and DUR-5.2.5



Schematic of forced sand impingement test. From Klimm et. al., *Proc. Euro. Weathering Symp*. 2015.

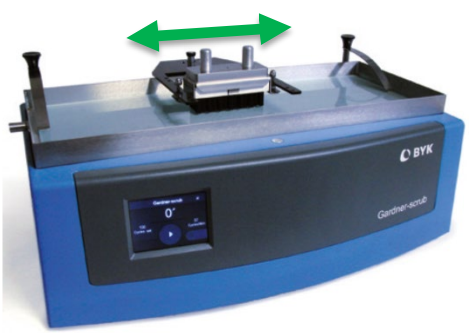
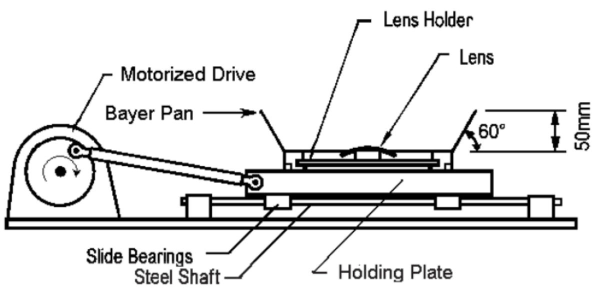


Photo of BYK Abrasion Tester PB-8100. www.byk.com



Schematic of abrasive media "Bayer" shaker from DUR-5.2.5

- **Limitations:**
  - Existing methods (samples & procedure) are not tailored to PV industry
  - Existing methods typically too severe for coated glass, e.g., result in frosted glass.
- **Recommend develop: falling sand, forced sand impingent, linear machine abrasion methods.**

Adapt/Define Accelerated Abrasion Test(s)

Potential Candidates

- **Falling sand tests**
  - ASTM D968 & DIN 52348 used in industry
  - Moderate impact velocity, e.g., ~5.7 m/s for 1.65 m fall distance
  - 3 kg of sand overly damaging to coatings even substrate (frosted glass)
  - Modify orifice diameter, sample angle, fall distance, abrasive medium… to PV industry
- **Forced sand impingement tests:**
  - MIL-STD-810G or ASTM G76.
  - High impact velocity (18-29 m/s) to account for most severe storms and locations.
  - Test equipment, labs commercially available.
- **Machine abrasion:**
  - BS EN1096-2 (for window glass), ASTM D4060 (Taber Abraser), ASTM D2486 (for wall paints)
  - Use rubberized pad, bristle, or felt tip in conjunction with water and/or grit.
  - Rotary or linear actuation of abrasive.
  - EN1096 most often referenced/used, even though known as not industry relevant .

Specimens for Field and Indoor Study

- **Presently acquiring a set of commercial specimens, to be used for the abrasion test standard development and soiling mechanisms study.**
- **3” square coupons in most cases…12” if necessary for manufacturer processing**
- Field results will be compared to indoor results to validate modes and magnitude of abrasion damage
- Field samples will also be examined to quantify accumulated soil facilitating modeling of soiling mechanisms and validating indoor soiling tests.
- Also ASU is developing “artificial soiling” techniques that may be the start of a standard

VENDOR	SUBSTRATE	AR FUNCTIONLIZATION	AS FUNCTIONLIZATION	STATUS
1	PMMA	N/A	N/A	at NREL
2	glass	graded index	N/A	in fabrication
2	glass	graded index	new	in fabrication
2	glass (reference)	N/A	N/A	at vendor
3	glass	1/4λ,dielectric	N/A	fabricated
4	glass	1/4λ,polymer	hydrophillic in hydrophobic	in fabrication
5	glass	graded index	hydrophobic	in fabrication
5	glass	graded index	olephobic	in fabrication
5	glass	graded index	hydrophillic in hydrophobic	in fabrication
4, 5, 7	glass (reference)	N/A	N/A	at NREL
6	glass	graded index	N/A	in fabrication
6	glass	graded index	N/A	in fabrication
6	glass (reference)	N/A	N/A	at vendor
7	glass (tempered)	N/A	N/A	at NREL

Table of specimens to be examined in the study.

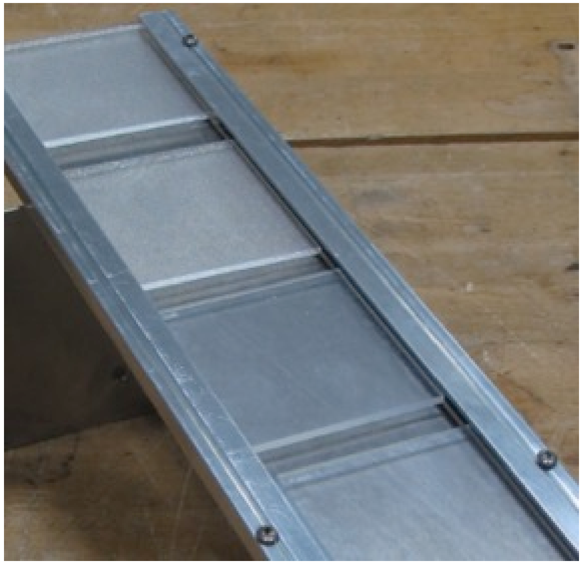
Coupon Deployment

- Sacramento, high soiling agricultural location
- ASU, Tempe Arizona, U.S. dry desert
- Mumbai India, IIT, urban with high soiling rate and monsoon season
- K.A.CARE Northeast Saudi Arabia dry and high frequency sandstorm location
- DEWA in Dubai, both represent desert climate with dew cycles and sandstorms

Easily deployable rack if partner cant provide rack

Coupon identification

Coupon holder



For this task, the deployment sites are being selected based on having very harsh weathering conditions, including high amounts of dust/sandstorms, humidity level, and high temperatures. This should help identify coating abrasion/durability issues quickly to help guide the development of the standards.

Summary

- **Overall, soiling may be impacting PV installations by 4% to 10% or more (LCOE ¢0.3/kWh to ¢1/kWh, respectively) depending on the site from lost energy production, which could be eliminated with an "ideal" solution.**
- **The need to address soiling to remove roadblocks in U.S. PV markets has created intense interest that is best addressed by pooling knowledge from around the world.**

Predict Soiling Rates
- PV performance data, >200 sites
- Data mine important soiling parameters
- Develop robust predictive models
- Validate models

Evaluate Durability with Soiling
- Deploy samples in field
- Analyze field specimens
- Develop accelerated tests
- Correlate results
- Develop IEC standards with international community

Characterize Soiling Mechanisms
- Deploy specimens at sites
- Collect representative samples
- Characterize soiling materials
- Isolate individual mechanisms
- Characterize surfaces
- Identify complex mechanisms

Outcomes

Reduce Performance Uncertainty
- Predict seasonal, annual and 30 year soiling loss rates for new sites
- Help establish cleaning schedules and O&M costs

Module Coating Standards
- Accelerated tests for validating durability and performance of PV coatings in different soiling conditions

Coating Deployment Guidelines
- Critical requirements for coating performance in different environments
- Help establish cleaning schedules
- Enables techno-economic analysis

Lower LCOE

- Financial institutions reduce rates for borrowing
- Integrators reduce cleaning costs
- Coatings companies have standards to meet
- Companies can focus on developing coatings with the right properties for the environments that make economic sense

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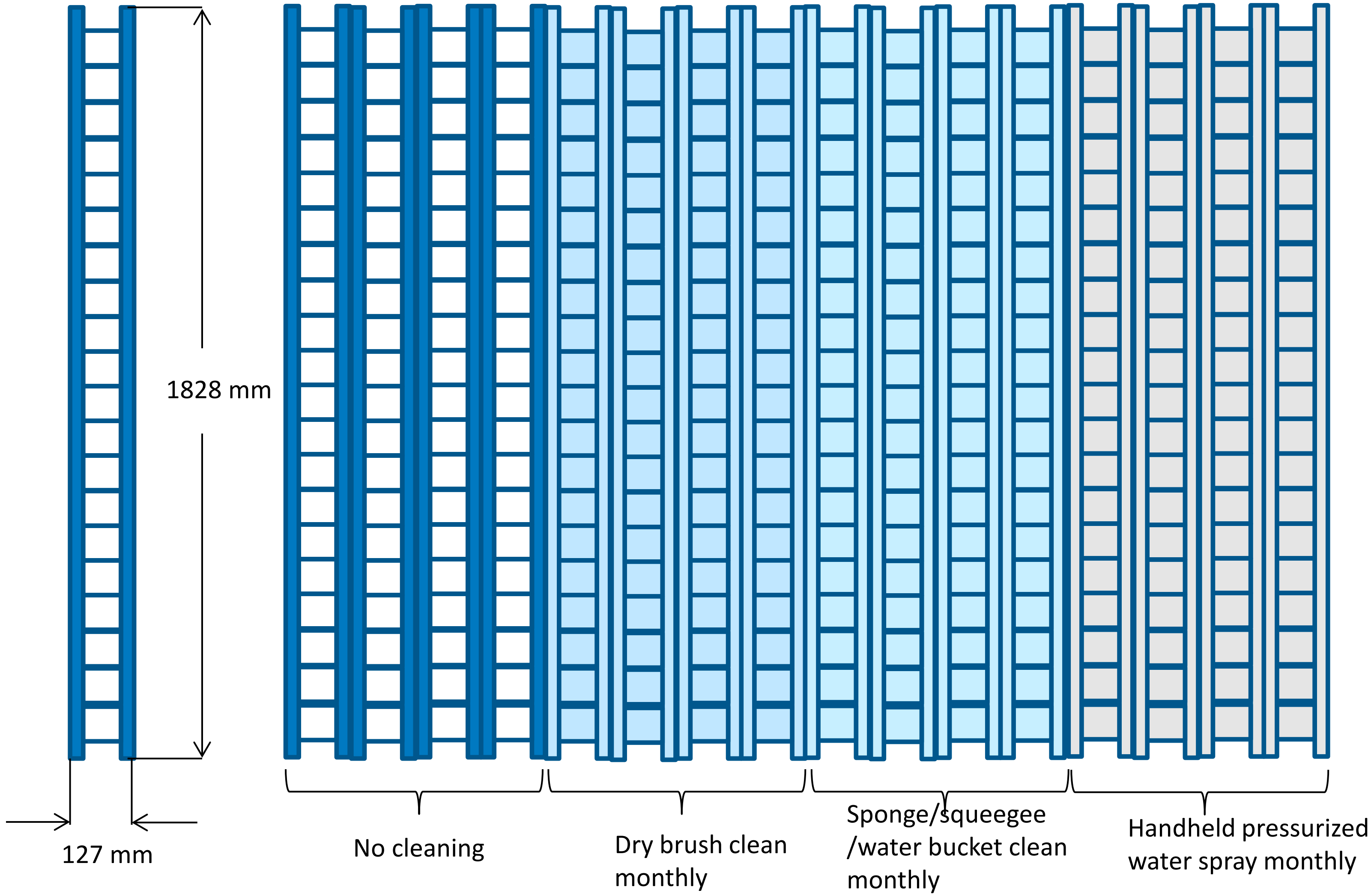
Backup Slides

(QPI) FY16Q2 Field test description

Individual unit holds 20 coupon replicates, Ready to attach to rack

Example demonstrates testing 4 different coating types and 4 different cleaning/treatment methods (20 coating replicates allows returning coupons to NREL in various years and for potential breakage). Possibility of testing 20 unique coatings results in 1828 mm by 5072 mm rack



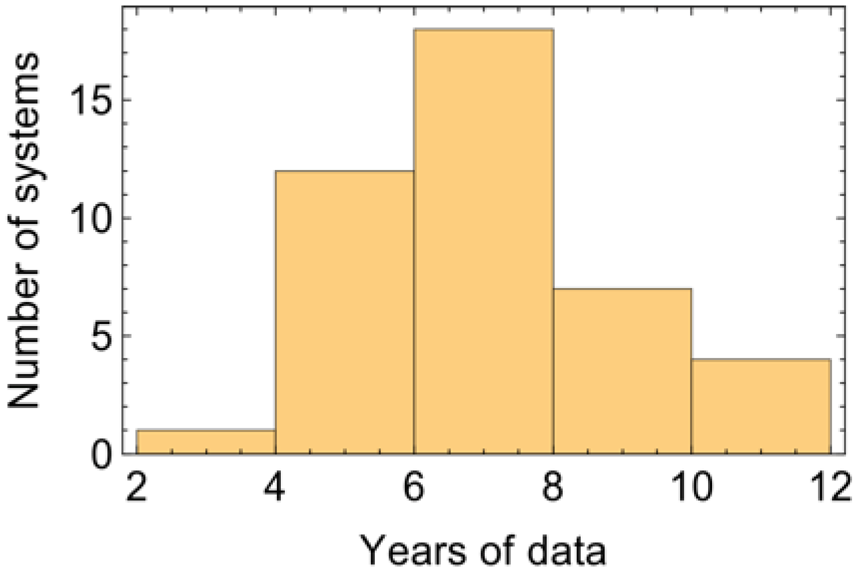
(QPI) FY16Q1 Geographic distribution of 64 sites

Site locations: SunPower Sun Edison

Initial data are from sites that are representative of the different climatic zones within the US and should provide the requisite information needed for robust models.

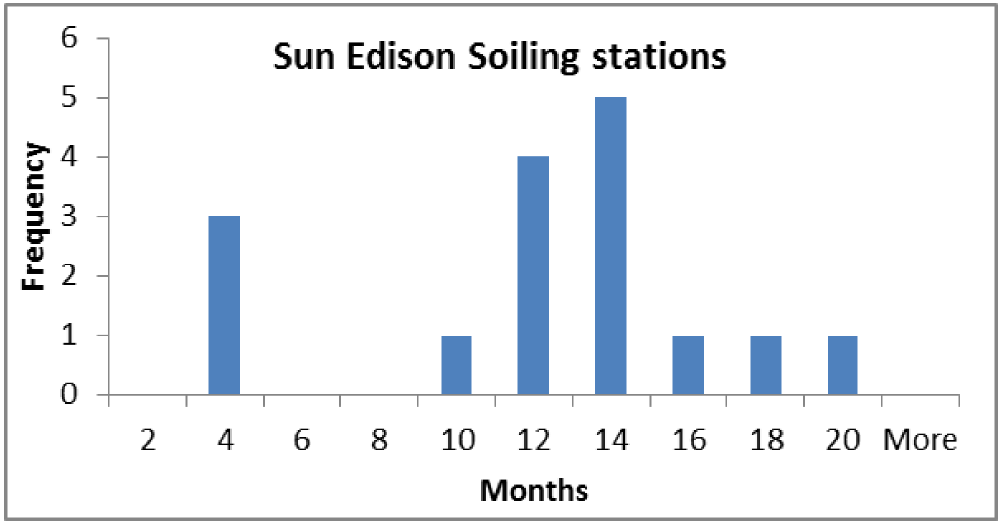
(QPI) FY16Q1 SunPower data

- **15 minute production data from 44 unique sites**
  - Inverter power
  - Wind speed
  - Ambient temperature
  - Irradiance (GHI)
- **Pre-screened by SunPower for quality**
  - Assessing internally also
- **Data spans 3–12 years**
  - (ending in fall 2014)
- **SunPower calculated daily soiling on 16 sites**



(QPI) FY16Q1 SunEdison soiling station data

- **Hourly data from 20 unique sites**
  - DHI, DNI, DHI
  - Humidity
  - Pressure
  - Wind speed/direction
  - Precipitation
  - Clean/dirty reference cell V_{oc} and I_{isc}



Need different pictures

Images from Sun Edison commissioning reports

Initial Studies of Soiling

- **Obtained an initial set of PV modules that had been in the field for 17-18 years and compared with controls that had not been deployed.**
  - Using to evaluate what soiling/degradation mechanisms are present and what characterization needs to be done.

Sample ID	Sample Description	Location	Model	Module Type	Years Exposed	Mounting
#1	Tempered glass	Tempe, AZ	Siemens, M55	Aged	18	Open rack
#2		Tempe, AZ	Siemens, M55	Control	0	N/A
#3		Sacramento, CA	Siemens, M55	Aged	18	Open rack
#4		Sacramento, CA	Siemens, M55	Control	0	N/A
#5		Chandler, AZ	ASE Americas, ASE-300-DGF/50	Aged	17	Rooftop

XPS analysis of module glass: initial results

Q: Why perform chemical analyses of module front surfaces?

A: Mechanical, optical, and other properties such as propensity for water adsorption all depend on glass composition.[1]

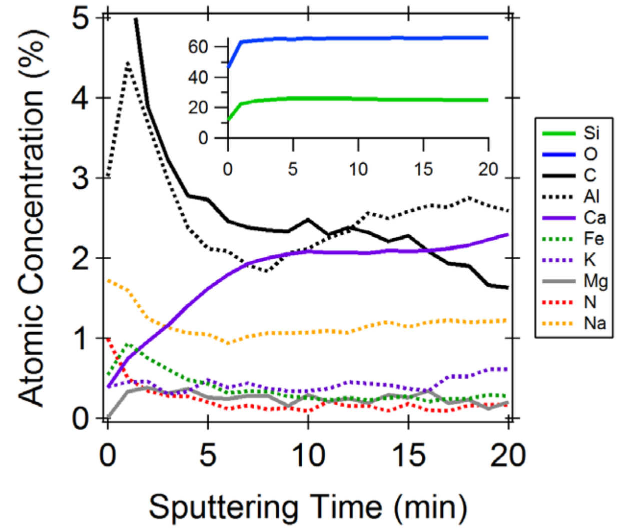
XPS concentrations, DI/UV/O_3-cleaned samples

sample	Atomic Concentration (%)									
	N	O	F	Na	Mg	Al	Si	K	Ca	Fe
Siemens control	1.0	67.9	0.3	1.4	0.8	2.7	23.4	1.1	0.8	0.6
Siemens 18 yr AZ	1.2	68.1	0.5	0.7	1.9	4.5	20.0	0.6	1.1	1.4
Siemens 18 yr CA	1.4	68.5	0.4	0.7	1.0	3.9	21.1	0.3	0.7	2.0
ASE 17yr AZ	1.1	67.9	0.2	0.3	2.8	5.7	18.3	0.6	1.3	1.9
ASE, in fracture	0.1	68.3	0.2	3.7	---	0.5	25.1	---	1.9	0.2

Controls and aged samples show different compositions.

Surface and bulk also have different compositions.

Depth profile, Siemens control



Sputter depth profiling of these insulating samples appears possible and should provide additional information about subsurface in select cases.

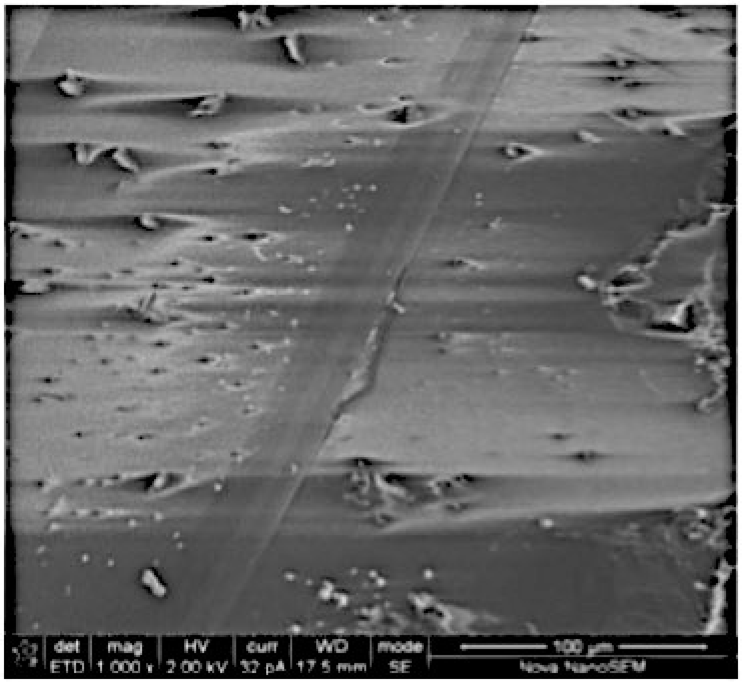
Note high amounts of carbon at surface of soiled glass.

1. Hayashi et al., *Surface Science* **507-510** (2002) 872; Cleaver et al., *KONA Particle and Powder Journal* **22** (2004) 9

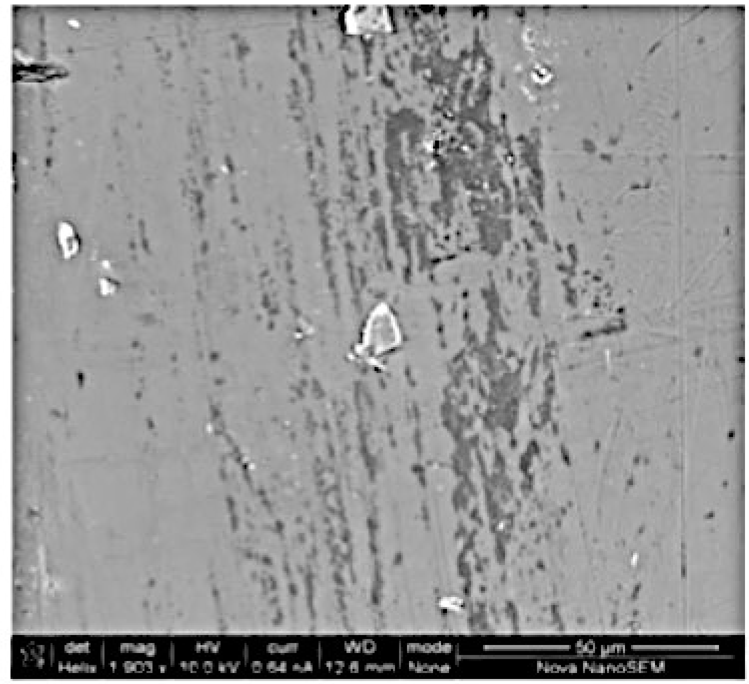
SEM with No Conductive Coatings Applied for Analysis

SEM - Development of procedure to analyze high-resistivity glass samples in low-vacuum mode with no secondary conductive coatings applied.

High-Vacuum



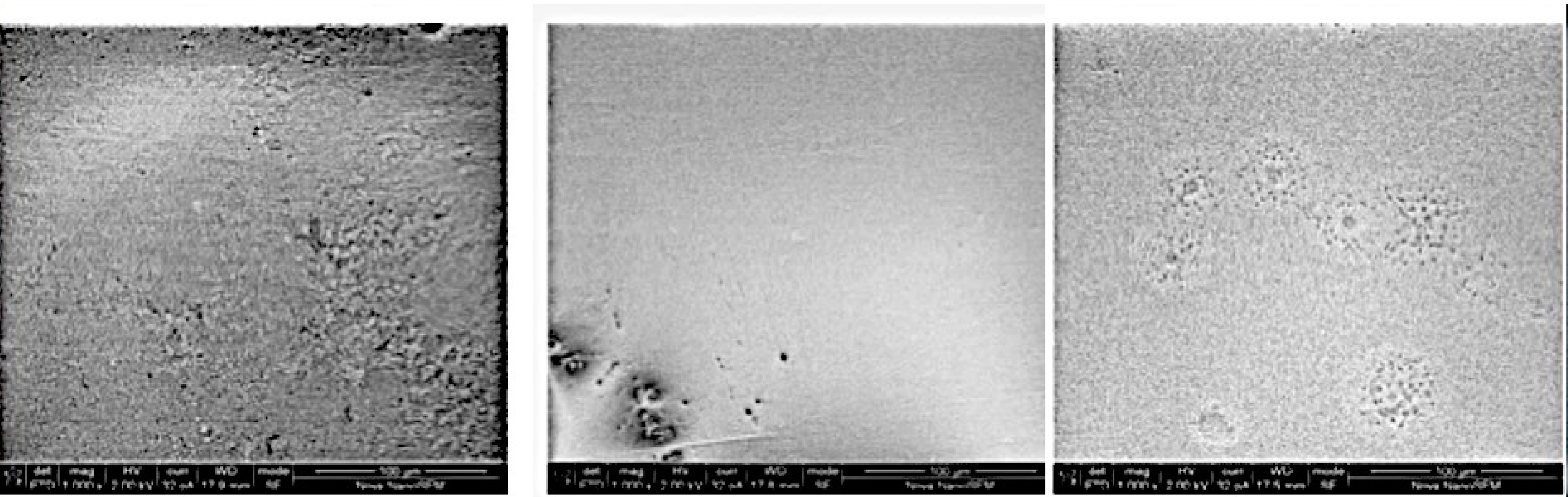
Low-Vacuum



For most semiconductor samples charging is not a problem for SEM analysis. However, for the glass samples in the Soiling project significant charging in high-vacuum analysis is observed (left). Using low vacuum decreases the charging without the need to contaminate the surface with a conductive thin film.

SEM (uncoated) of Weathered Glass

SEM has a large field of view and is suitable to study distribution and size of soiling particles on glass, as well as to study small features of the glass surface.

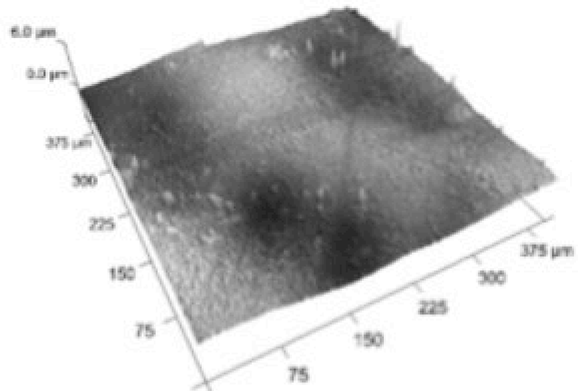


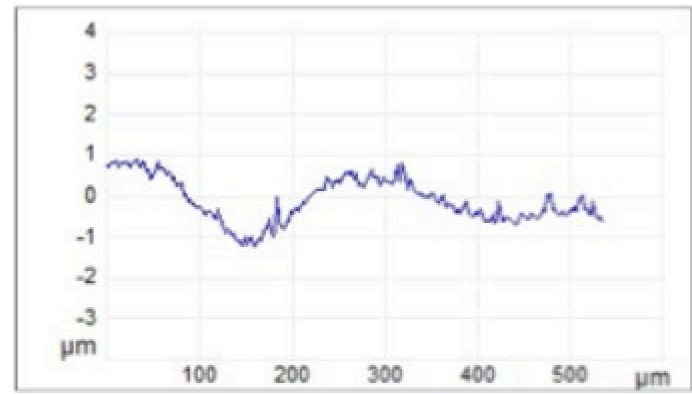
SEM images from samples of three solar panels operated outdoors for about 18 years in three different locations (Tempe, AZ, Sacramento, CA, and Chandler, AZ, respectively) showing different topographies and some apparent damage due to weather exposure. It is also clear that the type of damage is location dependent.

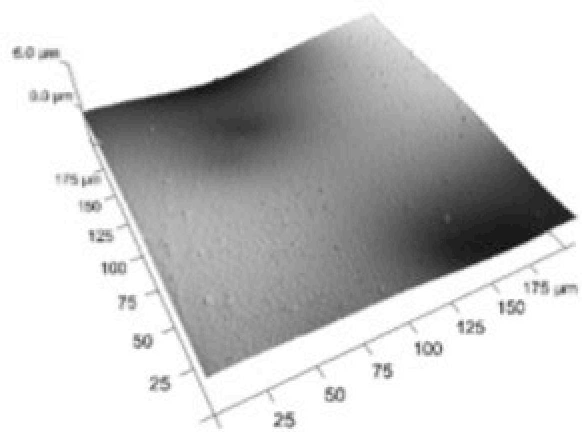
AFM Comparison of Weathered Glass

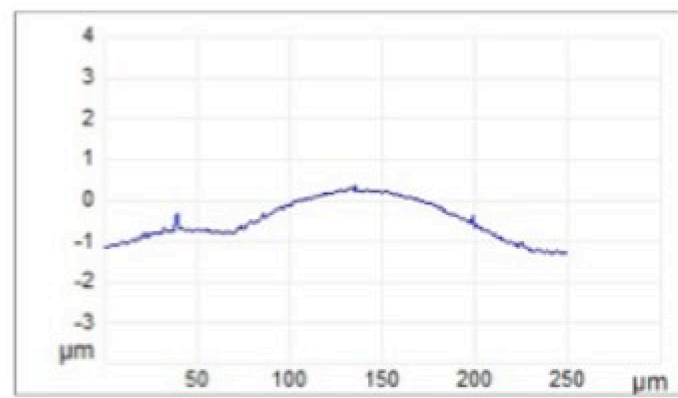
The 3D (x,y,z) data collection and high-magnification capabilities of the AFM allows for acquisition of 2D and real 3D images as well as measurements such as quantification of surface roughness. This allows for the study of changes on the surface topography of glass and AR and soiling layers before and after soiling.

AFM 3D images (left) and linescan on the panel from Tempe (top) and the control sample. While larger scale roughness is similar, the AFM is clearly able to quantify the increase in small scale roughness of the Tempe sample due to weathering.









Different Approaches

- **Physics/chemistry based interactions or bonding**
  - Atoms and Electrons
  - Probably most interested in psuedo-covalent bonding
- **Quantify at both the atomic and macroscopic scales**
- **Evaluate both “model” and field samples to ensure all appropriate mechanisms are characterized**
  - Leverage “standards” work

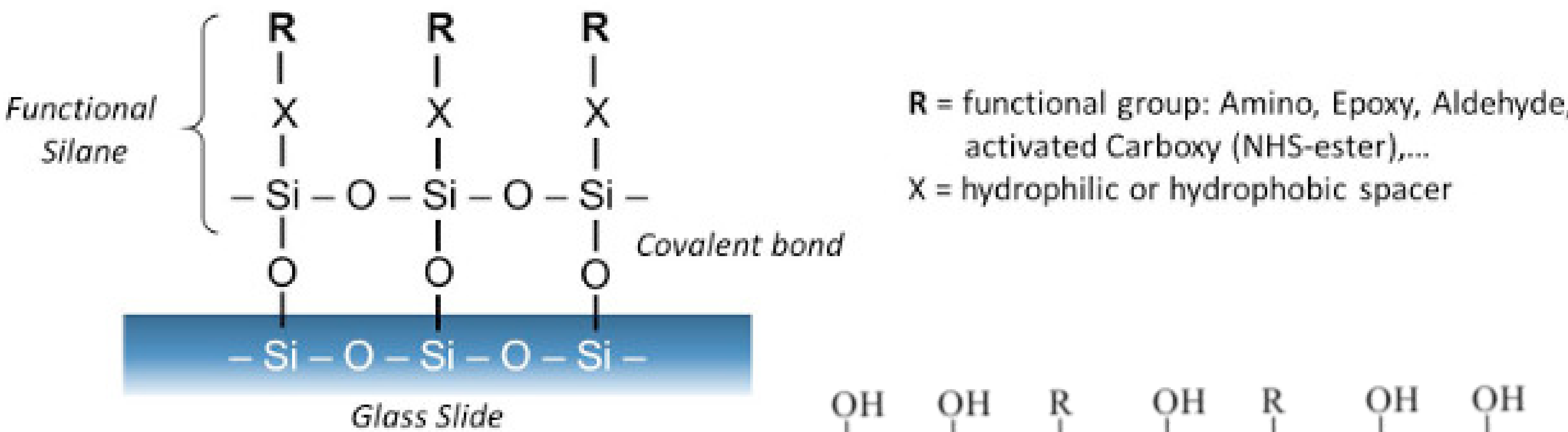
1. Terminology: Strength of interaction forces - physisorption and chemisorption

Interaction forces responsible for adsorptive bonds

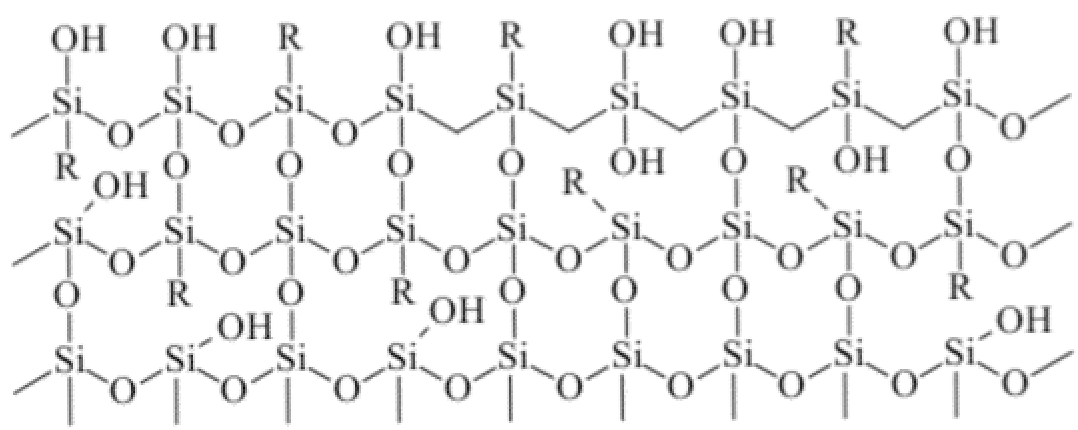
Kind of interaction	Strength of interaction
van-der-Waals	Very weak (usually less than 50 kJ/mole)
ionic	Strong (Coulombic origin) > 100 kJ/mole
covalent	Strong (quantum-chemical origin) > 50 kJ/mole
metallic	Strong (quantum-chemical origin), E > 50 kJ/mole

e.g., Model Surfaces to Evaluate Mechanisms

- **Create and evaluate different surfaces and quantify interactions**
- **Quantify different adhesion with different tools**
  - e.g., EFM/KPFM to measure electrostatic and Vandeer Waals with silica tips



Starts with glass.
Can have many different layers and interactions.
Evaluate range (e.g., superhydrophilic to superhydrophobic) of surfaces properties.

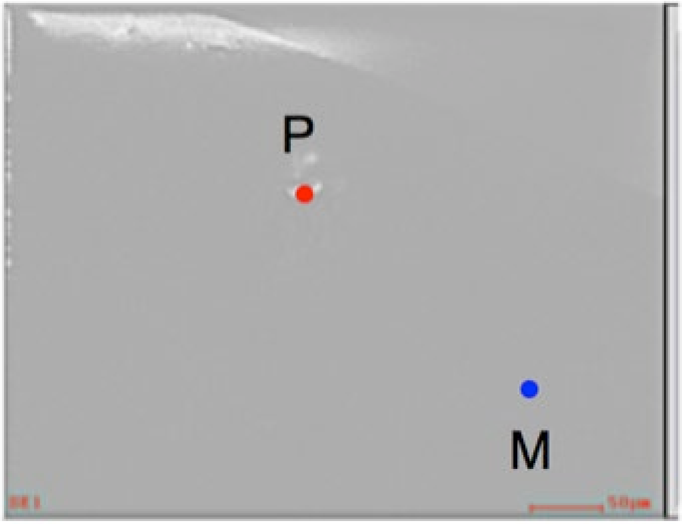


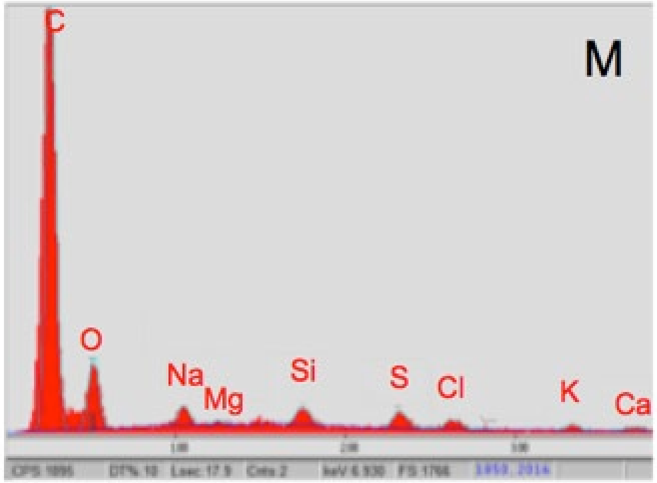
EDS Identifies Soiling Contaminants

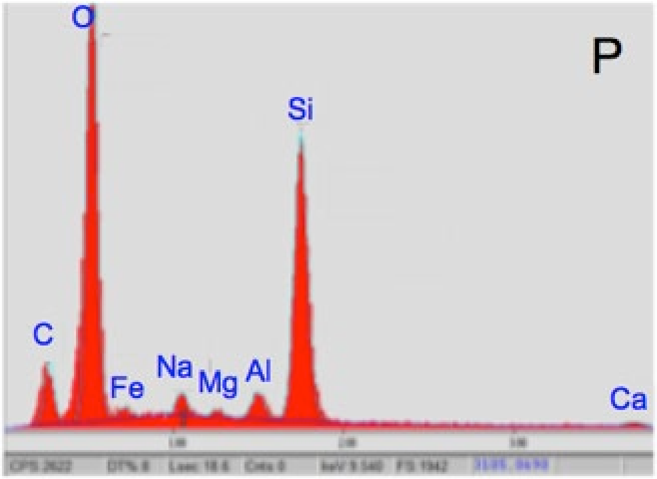
Complimentary to XPS, EDS allows for the analysis of the composition with high spatial resolution. This makes it possible to analyze the glass substrate and individual soiling particles.

C	O	Fe	Na	Mg	Al	Si	S	Cl	K	Ca
81.4	11.7	-	1.3	0.2	-	1.3	1.5	1.0	0.8	0.7
21.0	50.5	2.2	1.7	0.5	1.9	21.2	-	-	-	0.9

Large difference in composition between the matrix (SiO_2) and analyzed particle.







Concentration of the sample from Tempe at two different spots (P – particle, M – Matrix).