Optical Characterization of PV Glass Coupons and PV Modules Related to Soiling Losses

Greg P. Smestad, Ph.D.
Sol Ideas Technology Development

Leonardo Micheli, Ph.D.,
National Renewable Energy Laboratory (NREL)

Thomas A. Germer, Ph.D.,
National Institute of Standards and Technology (NIST)

Eduardo F. Fernández, Ph.D.
University of Jáen, Spain

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Outline

• Soiling Overview
• Ångström formula
• Experimental Procedure
• Transmission Results
• Angle of Incidence effects
  – Model vs. Experiments
• Coupon vs. PV Module
• Conclusions
• Q&A

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http://pubs.acs.org/doi/pdf/10.1021/acs.estlett.7b00197
or www.solideas.com/projects/pvquality/
Fig. 1.5 A PV module using individual solar cells. For example, the two solar cells shown can be individually (series) connected silicon cells.
Soiling: Definition

Accumulation of dust, dirt and particles on the surface of PV modules.

Drop in power output: can be > 50%.
Drop in energy yield: 0 to 6% in the U.S.
The map contains data from over 83 sites in the USA:
- 41 soiling stations (square markers);
- 42 full-scale PV systems (triangular makers).

Map available at: www.nrel.gov/pv/soiling.html
c-Si PV plus LA air

Soiled Residential PV System of David Bernal in Los Angeles (Photo by Greg Smestad)
CdTe PV array plus birds equals PV soiling

First Solar array of Markus Beck in coastal mountains of N. California. Photo by Greg Smestad
Soiling economical perspective

**Motivation**
- 15 MW plant
- Average day
  - 12h daylight, max 10% clouds, Sept/March
- Location
  - Northern Italy or comparable
- Feedin Tariff 0,20€/kWh
- Soiling 10% park average

**Loss in € per day ?**

1. < € 1,000.—
2. € 1,000.—< € 5,000.—
3. € 5,000.—< € 10,000.—
4. € 10,000.—< € 50,000.—
5. > € 50,000.—

Soiling losses are **€ 1,500.—**

€ 100.—/MWP/day

€ 550,000.— for a 15 MWP PV Plant a year
But only € 365,— for a 10 kWp private Rooftop!
Cost of cleaning a PV array

IR Hot Spots: A Reliability Issue

PID in PV: A Degradation issue


Fig. 4. Subtractive electroluminescence images taken at 4.1-A forward-bias current on module type A with salt; (a), 73.3% power remaining; (b) without salt, 84.7% power remaining. Degraded areas appear dark.
Fig. 10. AOI curve of cleaned and moderately soiled PV module.
Incidence Angle & Alignment Effects

Gostein¹, Caron², Littmann², IEEE PVSC, 2014
¹Atonometrics. ²First Solar
What will scatter light?

- Film residue
- Roughness
- Spherical particles
- Not-so-spherical particle

Source: Predicting, Modeling, and Interpreting Light Scattered by Surfaces
SPIE Short Course SC492
Thomas A. Germer, Ph.D., Sensor Science Division National Institute of Standards and Technology
Definition of Particulate Matter

Particulate matter (PM): concentration (\(\mu g/m^3\)) of solid particles and liquid droplets suspended in 1 m\(^3\) of air.

**PM\(_{10}\) Sources:**
- Crushing or grinding operations
- Dust stirred up by vehicles on roads

**PM\(_{2.5}\) Sources:**
- Motor vehicles, power plants, residential wood burning, forest fires, agricultural burning, industrial processes.

Source: https://www.airnow.gov/index.cfm?action=aqibasics.particle

13 March 2018
Spectral Effects of Soiling

- Ångström turbidity formula
- **Experimental procedure**
- After 8 weeks (San José, CA)
- Fitting San José Transmission Data
- Fitting San José and Chennai Data
- Visible and NIR Hemispherical transmittance for all the sites
Atmospheric Scattering

For mathematical treatment, a convenient parameter to express the size of a scattering particle $\pi \omega / \lambda$, where $D_i$ is the particle diameter. Let the index of refraction and $\lambda$ the wavelength in micrometers. It is considered that

\[
\pi \omega / \lambda < 0.6 / \pi,
\]

when $\pi \omega / \lambda < 0.6 / \pi$, scattering is governed by Rayleigh's theory, and in a cloudless atmosphere applies to molecules, most of which have a size $\sim 1$ (note that radio waves scattering by clouds also Rayleigh scattering); when $\pi \omega / \lambda > 5$, scattering is chiefly diffuse reflection processes seldom occurring in the earth's atmosphere; and particle sizes smaller than one-tenth the wavelength of light can be approximated 1/4 the wavelength of light. (a) Rayleigh scattering, (b) Mie scattering.

Ångström turbidity formula

$$\tau_{a\lambda} = \exp(-\beta \lambda^{-\alpha} m_a)$$

$\beta \to 0.0$ to $0.5$ or even higher

- An index representing the amount of aerosols (particles) present

$\alpha = 4$ for small non-absorbing particles
$\alpha = 1$ for small absorbing particles
$\alpha = 0$ for large particles

- Wavelength ($\lambda$) exponent
- Generally $0.5$ to $2.5$ (Ångström suggested $1.3$)

$m_a$ is the optical path length
Spectral impact of soiling: Experiments

<table>
<thead>
<tr>
<th>City, Country</th>
<th>Coordinates</th>
<th>Climate classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chennai, India</td>
<td>13.08, 80.27</td>
<td>Equatorial savannah with dry winter (Aw)</td>
</tr>
<tr>
<td>El Shorouk City, Egypt</td>
<td>30.12, 31.61</td>
<td>Desert climate (Bwh)</td>
</tr>
<tr>
<td>Golden (CO), USA</td>
<td>39.74, -105.18</td>
<td>Snow climate, fully humid (Dfb)</td>
</tr>
<tr>
<td>Jaén, Spain</td>
<td>37.79, -3.78</td>
<td>Warm temperate climate with dry summer (Csa)</td>
</tr>
<tr>
<td>Penryn, UK</td>
<td>50.17, -5.13</td>
<td>Warm temperate climate, fully humid (Cfb)</td>
</tr>
<tr>
<td>San José (CA), USA</td>
<td>37.29, -121.91</td>
<td>Warm temperate climate with dry summer (Csb)</td>
</tr>
<tr>
<td>Tezpur, India</td>
<td>26.70, 92.83</td>
<td>Warm temperate climate with dry winter (Cwa)</td>
</tr>
</tbody>
</table>
Experimental procedure

- Seven 4 cm x 4 cm x 3 mm-thick low iron glass coupons shipped to each location.
- Coupon 1 to 6 installed outdoors at zero tilt angle for eight weeks.
- Coupon 0 kept in a dust free container and used to calibrate each spectrophotometer.
- Weekly transmission measurements for coupons 1, 2, 3.
- Daily weather and particulate matter (PM) concentration recorded.
- A dry cleaning is performed by using a microfiber cleaning cloth.
  • Coupon 1 cleaned every week, Coupon 2 every four weeks.
After 8 weeks (San José, CA)
Fitting San José Transmission Data

\[ \tau_{a\lambda} = \exp(-0.00178\lambda^{-0.592}16.5) \]

C1
C2
C3

Hemispherical Transmission

Wavelength (microns)

C7 vs C0  C2 vs C0  C3 vs C0  Modelled C3

13 March 2018
Ångström equation returns in both cases high $R^2$ ($\geq 90\%$), and low RMSE ($<0.3\%$).
Ångström equation returns in both cases high $R^2$ ($\geq 90\%$), and low RMSE (<0.3%).

...but fitting at low wavelengths can still be improved.
Hemispherical transmittance (8 weeks)

Hemispherical transmittance in the visible and NIR range of coupon 5 for all the sites (above) and for the low soiling sites (below), referenced to the transmittance of coupon 0.
Quantum Efficiency of PV

![Graph showing quantum efficiency of PV materials]

- m-Si
- p-Si
- a-Si
- CdTe
- CIGS
Predicted affect of soiling on PV technologies

Light Obscuration by Particles

- Optical microscopy
- SEM (San José, CA)
- Particle Area and Hemispherical Transmittance
  - Fractional Loss versus Particle Coverage
SanJose_a_500x.jpg, Keyence microscope
SEM (San José, CA)

Source: 2017 NIST talk, Greg P. Smestad et al., Images by Helio Moutinho, Ph.D. National Renewable Energy Laboratory
Particle Area and Hemispherical Transmittance

- Average particle area was determined by high resolution optical microscopy.
- Percentage of the surface covered by particles was estimated.

Broadband hemispherical transmittance (300-2500 nm)

- A linear correlation, with $R^2$ higher than 0.99, is found by comparing the percentage area covered by particles to the hemispherical transmission.
- The broadband hemispherical transmission could be directly obtained from the coverage area, independently of location, dust type and composition.
Fractional Loss versus Particle Coverage

Fractional Particle Coverage

Fraction Loss

slope = 0.80±0.02

$R^2 = 0.99$
Angular Characteristics of Scattered Light

• Reflection
• Bidirectional Scattering Distribution Function (BSDF)
• Model
  o Cleanliness Standard
  o Particle size (D) and number, N
  o Experiment vs. Model (theory)
Types of reflection

Specular, diffuse, and spread reflection from a surface.
Fig. 2.10 Geometry for calculation of the absorptivity from a polished (left side) and textured (right side) light absorber. In each case, a summation of multiple reflections must be made in order to calculate the absorptivity. The angle $\theta_1$ is measured from the surface normal.

These equations can be used to predict the reflectivity, otherwise known as the reflection coefficient, of a solar cell absorber material. The index of refraction value for Si, for example, is approximately 4 at a wavelength of 600 nm (see Fig. 2.3). For a wafer in air ($n_0 = 1$), this yields a value for the reflectivity value between 30 and 40%. In other words, only about 70% of the light enters a bare Si wafer. If nothing were done about this loss, a solar cell would be impractical and inefficient.

Instead, if a thin ARC is deposited on the Si wafer, for example, reflection can be minimized at certain wavelengths. This is understood by recalling that a beam of light undergoes a phase change of $(180 \, \text{deg})$ when passing from a medium with lower index of refraction to one with a higher index of refraction. No phase change occurs from a medium of higher $n$ value to a lower $n$ value medium. A portion of the incident beam is not reflected; it is transmitted at the back surface at the ARC-Si interface and reflected from there (see the left side of Fig. 2.10). If the thickness of the ARC, $t_{ARC}$, allows an optical path $2t_{ARC} = \frac{1}{2} n_{ARC}$, then destructive interference occurs between the two beams, and the light enters the Si wafer across the ARC with little reflection loss. This condition is expressed as

$$r_0 = 1 - \frac{4n_{ARC}}{n_{ARC} + n_{glass}}$$

where $n_{ARC}$ is the index of refraction of the ARC (e.g., $n_{SiO_2} = 1.4$–1.5, $n_{TiO_2} = 2.3$, and $n_{Si} = 1.8$–1.9). For example, a reflection minimum at a wavelength of 600 nm requires a 100-nm thickness of $SiO_2$, while only 65–70 nm is required for an ARC if $TiO_2$ is used. This so-called quarter-wave coating allows for a minimum in the reflection coefficient described by

$$r_0 = 1 - \frac{4n_{ARC}}{n_{ARC} + n_{glass}}$$
The double interaction model (Nahm and Wolfe) is basically a Mie scattering theory with four paths coherently added, accounting for the reflectance of the substrate as a function of the incident and scattering angles.
Describing the scatter from a delocalized scatterer

The **Bidirectional Scattering Distribution Function** (BSDF) is the fraction of power scattered per unit projected solid angle.

\[ f_r = \lim_{\Omega \to 0} \frac{P_r}{\Omega P_i \cos \theta_r} \quad [\text{sr}^{-1}] \]

- **Scattered power [W]**
- **Solid angle [sr]**
- **Incident power [W]**
- **Polar scattering angle**
The cumulative distribution = N(D)
Distribution density, dN(D)/dD

The distribution of particles is given by IEST-STD-CC 1246E, with cleanliness level \( L =1000 \). N(D) is cumulative number of particles per unit area having a diameter between \( D \) (in \( \mu m \)) and \( L \) (in \( \mu m \)).

\[
N(D) = 10^{0.926[(\log_{10} L)^2 - (\log_{10} D)^2]/(0.1 \text{ m}^2)}
\]

\[
= 10^{-0.926[(\log_{10} L)^2 - (\log_{10} D)^2] - 11} \text{ } \mu m^{-2}
\]
IEST-STD-CC1246D Cleanliness Standard

\[ \log N = 0.926(\log^2 L - \log^2 D) \]
Angular Characteristics of Scattered Light

Experiments
Plotting N and D using the Cleanliness Standard

\[
-3 - 0.926 \times (\log_{10} D)^2
\]

\[
\log_{10} \frac{N}{\mu m^2}
\]

\[
(log_{10} D/\mu m)^2
\]
Some conclusions

We found the particle size distribution for soiling on glass coupons fits IEST-STD-CC 1246E, with a cleanliness level $L = 800-1000$. 
Goniometric Optical Scatter Instrument

- Laser based
- Dynamic range: up to 16 decades (in sr$^{-1}$)
- Wavelengths: UV, Vis, NIR (here, 532 nm)
- Full polarimetric capabilities

- Samples up to 300 mm in diameter
- Rayleigh-scatter-limited instrument signature
- Nearly any incident/scattering directions
The Transmission Data (San José)
Reflectivity vs incidence angle

\[ \rho(\theta_i, 2\pi) \]

specular reflectance of glass

IEST-STD-CC 1246E
Cleanliness 1000

Thomas A. Germer, NIST

13 March 2018
Calculated Hemispherical Reflectance of Soot Particles

Using IEST-STD-CC 1246E Distribution Cleanliness 1000
What’s next?

• Passage of light through a small glass coupon does not necessarily equal the pathway through the PV Module.
  • EQE measurements for PV mini-modules
• Refinements and testing of the models
• Analysis of data from the other sites
• Mitigation of PV soiling
  • Anti-soiling coatings
  • Cleaning techniques (abrasion standard)
Optical Characterization of PV Glass Coupons and PV Modules Related to Soiling Losses

Greg P. Smestad, Ph.D.
Sol Ideas Technology Development

- Atmosphere
- Transport
- Deposition
- Cementation

- Dust

- Transmission
- Reflection
- EQE
- Module Power Loss

- Optics

- Monitoring
- Economics
- Cleaning
- Abrasion
- Coatings

- Performance

- Time dependence
- PID (EL after soiling)
- IR Hot Spots
- Solar Plant O&M

- Reliability

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Graphic: G. Smestad / NREL
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$$n_{ARC}t_{ARC} = \frac{\lambda}{4},$$

where $n_{ARC}$ is the index of refraction of the ARC (e.g., $n_{SiO_2}$ or $n_{SiO_2} = 1.4-1.5$, $n_{TiO_2} = 2.3$, and $n_{SiN_4} = 1.8-1.9$). For example, a reflection minimum at a wavelength of 600 nm requires a 100-nm thickness of $SiO_2$, while only 65-70 nm is required for an ARC if $TiO_2$ is used. This so-called quarter-wave coating allows for a minimum in the reflection coefficient described by

$$\rho_{ARC} = \frac{\lambda}{4},$$
Reflection across an interface

The value depends on the angle (vs. the surface normal) and it also depends on the index of refraction (and the direction of the beam).
Fig. 2.10 Geometry for calculation of the absorptivity from a polished (left side) and textured (right side) light absorber. In each case, a summation of multiple reflections must be made in order to calculate the absorptivity. The angle $\theta$ is measured from the surface normal.

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$$\frac{2t_{ARC}}{\lambda} = \frac{1}{2}\frac{n_{ARC}}{n_{Si}}$$

where $n_{ARC}$ is the index of refraction of the ARC (e.g., $n_{SiO_2}$ or $n_{SiO} = 1.4-1.5$, $n_{TiO_2} = 2.3$, and $n_{Si} = 1.8-1.9$). For example, a reflection minimum at a wavelength of 600 nm requires a 100-nm thickness of $SiO_2$, while only 65-70 nm is required for an ARC if $TiO_2$ is used. This so-called quarter-wave coating allows for a minimum in the reflection coefficient described by

$$n_{ARC}t_{ARC} = \frac{\lambda}{4}$$

The Passage of light through coupon is not equivalent to PV Module

- Polished or clean
- Textured or soiled

- Ref
- T

Solar cell

Glass

Air
Light Trapping in a PV Module

Extracted from Fig. 6.3. A flat plate PV module. The backsheet (typically Tedlar) results in a white surface between cells. Light is shown undergoing total internal reflection at the top of the plate and reflection at the bottom. The light is collected by solar cells, but can escape the system if it’s at the right angle (< the critical angle for the transparent dielectric plate or PV glass).

Smestad, Greg P.
Optoelectronics of solar cells / by Greg P. Smestad.
p. cm.-- (SPIE Press monograph ; PM115)
Includes bibliographical references and index.
ISBN 0-8194-4440-5 (softcover)
1. Solar cells. 2. Optics. I. Title. II. Series.
Conclusions (Optics of PV soiling)

• Estimating soiling losses using the transmission from glass coupons may not easily translate to knowledge about power losses from PV modules.

• We have measured themispherica transmission of soiled PV glass coupons.

• There is a linear correlation between the area covered by particles and the broadband hemispherical transmittance.

• Soiling produces a higher attenuation at shorter wavelengths (Ångström turbidity formula) compared to longer wavelengths.

• The impact of soiling is likely higher on PV materials with larger bandgap (a-Si, CdTe).

• Soiling Losses are certainly a function of input angle.
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- EPSRC SUPERGEN SuperSolar Hub’s “International and industrial engagement fund” for the project “Global investigation on the spectral effects of soiling losses”

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  Greg P. Smestad, Sol Ideas Technology Development  
  smestad@solideas.com — www.solideas.com
The International PV Quality Assurance Task Force (PVQAT, "PV cat") leads global efforts to craft quality and reliability standards. Website: http://www.pvqat.org

Greg P. Smestad, Sol Ideas Technology Development
smestad@solideas.com — www.solideas.com
Prior talk

• Greg has given a talk before at the IEEE SCVPVS.

• He was invited to speak to the Santa Clara Valley Chapter of the IEEE PhotoVoltaic Society on January 15, 2015.

• His talk surveyed solar energy-related engineering and entrepreneurship in emerging market countries,
  – emphasis on strategies for coping with the absence of a grid.

• http://www.solideas.com/outreach/solar-emerging-markets.html