Soiling Forecast and Measurements for large PV Power Generation Projects in Dessert Environments.

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Abstract **Levels of atmospheric dust in dessert geographical regions are amongst the highest across diverse climatological systems. In these types of climates atmospheric dust content strongly depends on the target location and often presents specific seasonal patterns.**

The performance of photovoltaic power plants operating in such dessert conditions will deteriorate by the accumulation of dust particles upon the glass front plate of PV Modules (Soiling).

Successful Engineering, Finance, Operation & Maintenance of utility scale power plants therefore require a sound estimation of a one-year, time-dependent soiling profile for each particular project site. This can be achieved, time allowed, during the course of preliminary on-site studies based on outdoor measurements. In other circumstances soiling estimations will be required.

This work is focused on the determination of soiling loss profiles using qualified outdoor measurements from a reference site extended with the application of time series of satellite based solar irradiation and aerosol optical depth data and a combination of four-months ground measurements of comparative (clean/soiled) module performance for a site located in a region of the Nubian Dessert (Egypt).

Index Terms **— soiling, field studies, ground- and satellite based estimation of soiling rates, dessert climates, utility scale PV power plants**

I. Introduction

Soiling modifies the spectral characteristics and reduces the amount of solar irradiance incident on the cells of photovoltaic modules[1]. In dessert climates soiling effects can be significantly higher than in regions with mild climates[2].

Energy production forecasts used to support engineering and financial performance expectations of utility scale PV power plants in dessert regions will therefore require a sound estimation of soiling losses.

The cross utilization of soiling loss results from various locations is not always meaningful because industry standards do not exist and different experimental methodologies and time length of measurements are applied. Reference values from one location could only be applied to another site if qualitative and quantitative analysis of a large set of site characterization parameters reveal valid similitudes amongst climatologies and methodologies.

In the present work we propose a mix approach based on the application of satellite based irradiation and aerosol data combined with ground-based, outdoor measurements of soiling losses measured at the target and a reference site.

Time-schedule limits the measurements conducted in this study to 6 months.

II. Meteorological Data

A. *Solar resource*

This study uses a 20-year time series of solar irradiation components, wind speed and temperature for the target site in the area of Benban, Egypt. A summary of long-term average yearly values calculated from complete calendar years (1994-2014) shows:

Global Horizontal Irradiation	2341.1 kWh/m²
Diffuse Horizontal Irradiation	801.5 kWh/m²
Air Temperature at 2 m	23.4 °C

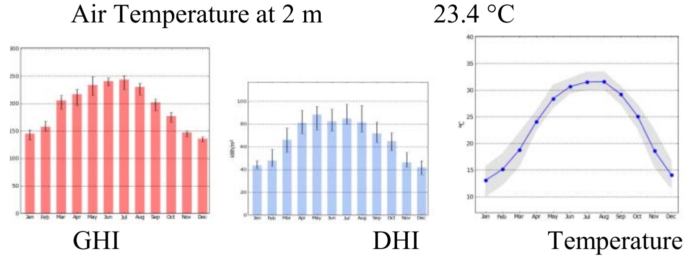

Fig.1. Monthly sums: long-term average, min/max for Global (GHI) and Diffuse (DHI) Horizontal Irradiation and Temperature

B. *Aerosols*

We consider *primary aerosols* i.e. particles, in particular dust, suspended in the atmosphere.

Aerosol Optical Depth (AOD) is a dimensionless number which represents the extinction, by absorption or by scattering, of the solar beam irradiation and measures the amount of aerosols in the vertical column of air between the top of the atmosphere and the Earth's surface.

A time series of AOD [3] data based on satellite images was sourced for this study from the European Center for Medium Weather Forecast (ECMWF) available from the year 2003 onwards with daily time-steps. Figure 2 presents monthly averages for the time period [01.Jan–31.Dec]-2015 and [01.Jan-30Apr]-2016.

AOD levels in January and February 2016 remained nearly constant followed by a strong growth in February. For the 2003-2015 the AOD profile presents a maximum during May and June and a decrease towards the winter months.

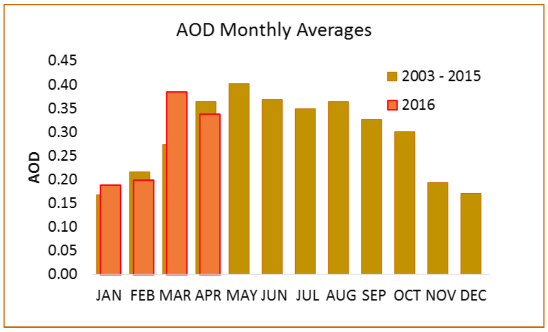

Fig. 2. AOD Time Series (2003-2014) and 2016 values

III. REFERENCE STUDIES

Soiling studies have been performed for diverse geographical locations under application of different experimental and theoretical approaches [4]. The different aspects and parameters that influence any determination of soiling values need to be considered along one of the following three characteristics dimensions

1. Measurement Methodology & Time-Length of Study
2. Site and soiling material
3. System Design (cells, modules, strings)

The length of time that a particular study was carried upon is also relevant if seasonal effects can be expected in the project site of consideration.

In the following sections only those studies will be considered that have been completed outdoor, under "natural" environmental conditions, have extended over a length of time of at least 6 months and have applied the same measurement methodology (temperature corrected, short circuit current measurements) for the characterization of soiling.

C. Reference site characterization

In order to establish correspondence between two different sites the following aspects will be considered:

- Solar Resource (Global Horizontal Irradiation)
- Temperature (Average Day Ambient)
- Wind Speed
- Humidity
- Precipitation (Rainfall)
- Aerosol Optical Depth (AOD)
- Average Particle Size
- Dust Deposition Rate and Surface Distribution

The above mentioned environmental variables influence the characteristics and seasonal patterns of soiling effects. Unfortunately, the interrelationship between AOD, deposition rates and surface distribution on soiling rates has been seldom reported.

The selected studies apply a methodology of tandem measurements of short circuit current on pairs of PV modules with the reference unit subject to periodical cleaning.

	GHI	Air Temp	Humidity	Wind Speed	Rainfall	Maximum % Loss (Period)
Benban, Egypt	1.00	1.00	1.00	1.00	1.00	
Helwan, Egypt	0.85	0.84	2.08	0.90	16.00	15
Tuwald, S. Arabia (*)	0.96	1.06	2.23	0.64	18.50	0.5/Day
Riyadh, S. Arabia	0.96	1.01	0.96	0.87	48.50	25
Dhahran, S. Arabia	0.87	1.01	1.77	1.10	57.50	35
Mesa, AZ, USA	0.91	0.89	1.12	0.72	80.50	3.7
Tempe, AZ, USA (*)	0.91	0.89	1.08	0.72	81.00	3.7
Kuwait, Kuwait	0.88	1.00	1.27	1.05	91.00	50
Gran Canaria, Spain	0.91	0.58	2.69	1.44	129.00	20
South. Centr. Valley, CA, USA	0.80	0.61	2.23	0.72	132.50	8.6
Jodhpur, India	0.86	1.01	1.54	0.28	142.00	5, 6
Davis, CA, USA	0.78	0.58	2.42	0.46	217.00	20
Malaga, Spain	0.79	0.68	2.46	0.69	263.50	20
Navarra, Spain	0.65	0.50	2.58	17.18	319.50	6, 15
Berkeley Springs, WV, USA	0.62	0.46	2.46	0.74	457.00	10,12,17
Chenai, India (*)	0.84	1.05	2.69	0.64	723.00	2.2

Table. 1. Reference sites and relevant meteorological variables

For sites referenced in Table 1 a database of solar resource and other meteorological variables has been generated with support of appropriate software [1]. The following Figure 3 shows different degrees of correlation amongst meteorological variables across locations

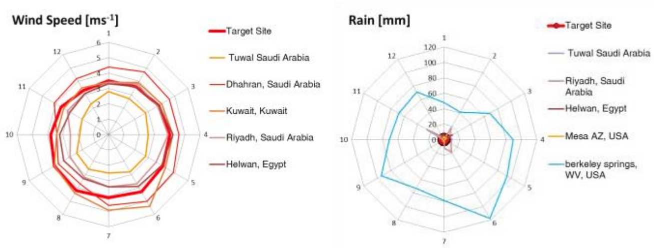

Fig. 3. Rainfall and wind speed envelopes for the target site.

Many of the climatological variables for the Hewan (Egypt) site present a good match with those on the target site. The applied soiling assessment also used short circuit current measurements but it failed to provide control values from a clean module. All other sites in Table 1 ranked further away from the target site with much higher rainfall levels. Because rainfall has a direct impact in reducing soiling we conclude that only the Tuwald site in Saudi Arabia [5] presents a reasonable level of agreement with the target site. For the rest of this study the soiling rates of (0.5%/day) reported for the Tuwald site were used, as references values, for the initial estimation of a soiling profile for the target site.

IV. SOILING FORECAST

We use a complete statistical year of AOD data [3] to correlate, at the time of this publication, with four months of outdoor soiling measurements from the reference location of the target site.

[1] Meteonorm V-7.2

The 2003-2015 data time series shows increasing AOD levels from January through May. Later on, June through August present a nearly constant, AOD level. Finally from September through December a decrease is suggested. The yearly averaged AOD = 0.292 will be used as normalization factor to compute the percentile rate of change in AOD. An estimate of AOD daily rates is presented in the Table 2 below:

AOD	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Month average	0.168	0.217	0.274	0.364	0.402	0.369	0.349	0.365	0.326	0.300	0.193	0.172
Av_daily	0.0041	0.0214	0.0146	0.0109	0.0016	-0.0017	0.0026	0.0019	-0.0030	-0.0121	-0.0021	0.0067
change rate	0.41%	2.14%	1.46%	1.09%	0.16%	0.17%	0.26%	0.19%	0.30%	1.21%	0.21%	0.67%

Table 2. AOD monthly averages and daily rates of change

V. Soiling Measurements

Soiling has often been experimentally determined through performance measurements of cells, modules or string outputs. Frequently used methods are based either on short circuit current or maximum power point measurements. The generally accepted methodology [6] for measuring PV module soiling is to measure the ratio of the electrical outputs, usually current or power, of a clean and a soiled PV module. For data collected continuously over long periods of time, side-by-side measurements of a clean and dirty device should be made simultaneously.

The impact of soiling can be quantified through a Soiling Loss Factor (SLF) which has been defined [7] as the ratio of effective energy of a cell (module) subject to soiling effects and a clean cell (module)

$$SLF = \frac{G_{eff\ Soiled}}{G_{eff Clean}} \tag{1}$$

In the previous equation G_{eff} represents the effective incident irradiation.

Meteorological performance data has been collected for a period of four months: Global and Diffuse Horizontal Irradiation, Direct Normal Irradiation, Temperature ambient, Wind Speed & Direction, Humidity and Rainfall. Solar irradiation is measured with two different sensors:

Fig. 4. Rotating-Shadow-Band-Irradiometer

One Rotating-Shadow-Band-Irradiometer (RSI)[2] as illustrated in Figure 4 before and ISO 9060 "Secondary Standard" pyranometer[3] .

The meteorological station[4] handles data acquisition with an eight analog channels data logger that performs current and voltage measurements for up to four pairs of PV-modules with different cell technologies.

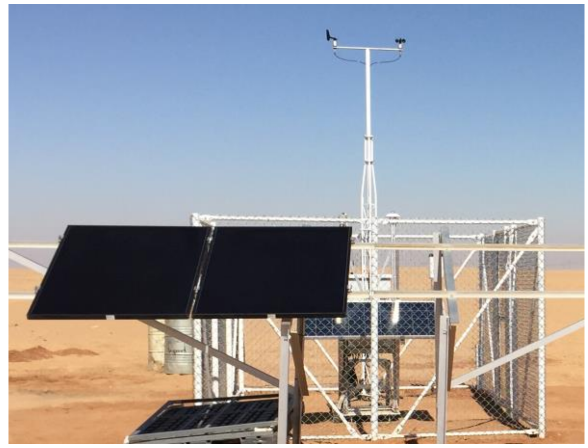

Fig. 5. Test modules and Station Enclosure

High data acquisition sampling rates (10 secs) were applied to deliver 10 minutes averages for all relevant climatological and performance variables. The measurement campaign has started in January-2016 and will extend until June-2016.

This study considers short circuit current measurements as the metric for soiling losses based on the following equation to define the Soiling Loss Factor (SLF) as:

$$SLF_{I_{SC}} = \frac{C^{I_{SC}}_{Soil}}{C^{I_{SC}}_{Clean}} \cdot \frac{[1 - \alpha\ (\mathrm{TMOD} - 25^\circ\ \mathrm{C})]_{Soil}}{[1 - \alpha\ (\mathrm{TMOD} - 25^\circ\ \mathrm{C})]_{Clean}} \cdot \frac{I_{SC\ Soil}}{I_{SC\ Clean}} \tag{2}$$

The temperature correction in (2) refers to α which is the temperature coefficient of the module-specific short circuit current. The calibration constants C_{Soil} and C_{Clean} were determined based on measured Isc at the beginning of the measurement period when both PV modules were clean.

The results presented in the following sections correspond to SLF measurements for a 60-Cells, poly-crystalline 250W_p PV-Module. A significant degree of correlation can be observed between increasing AOD and SLF (soiling) levels. The single correlation between AOD levels with a magnitude $\Delta(AOD) \geq 0.3$ originated a 2% higher soiling losses as it can be observed for example on January 19th. In February the observed changes in SLF are smaller. Most of the large gradients in AOD levels have been related to reported sand storms.

[2] CSP Services
3 EKO MS-802,
[4] Ammonnit Meteo- 40

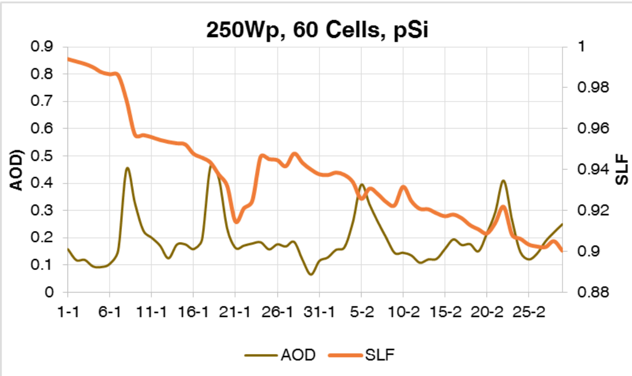

Fig.6a. AOD (Satellite) & SLF (Measurements), [Jan-Feb]-2016

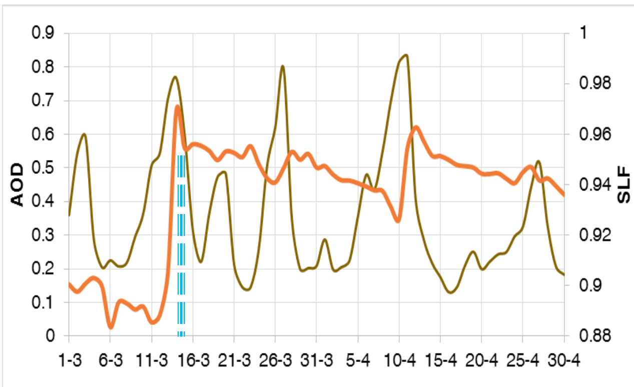

Fig.6b. AOD (Satellite) & SLF (Measurements), [Apr-Mar]-2016

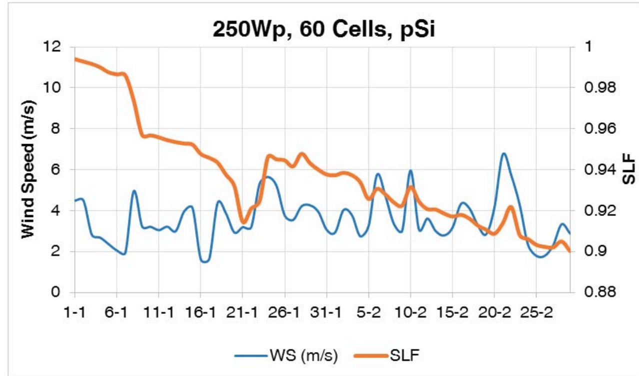

Fig.6c. Wind Speed & SLF (Measurements), [Jan-Feb]-2016

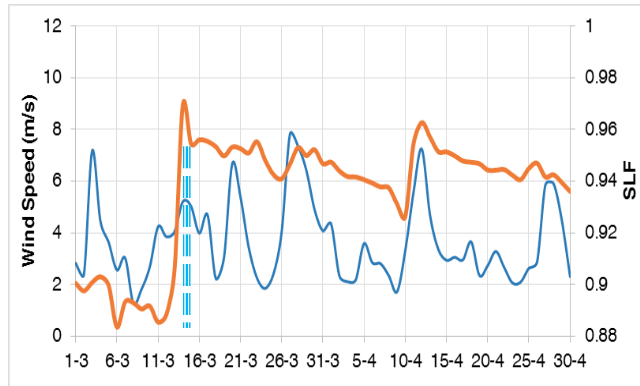

Fig.6d. Wind Speed & SLF (Measurements), [Mar-Apr]-2016

The Table 4 below presents a summary of meteorological observations registered by service personal on site.

	Sand Storm	Rainfall
January		
February	1, 10 , 21	
March	2, 3, 12, 16, 20, 21, 28, 29	13, 14
April	11, 12	

Table.4. On-Site observed meteorological events

Another important influence on soiling is wind speed (gradient). Beyond a certain threshold value, possibly 5 m/s, wind positively counteracts soiling most likely by removing a significant portion of dust particles on the module glass surface. Figures 6.c, 6.d illustrate the correlation between wind speed and soiling gradients.

Further consideration of the correlation between soiling, aerosols and wind speed suggest that for wind speeds below a threshold of 5 m/s aerosol gradients > 0.2 produce increased soiling losses. This type of behavior can be observed on Jan 7th and 17th.

High gradients in aerosols do not have a major impact on soiling for days with wind speed gradients > 5m/s, as it can be observed for February 22nd, March 26th and April 13th.

These observations suggest that a proper estimation of soiling loss profiles requires consideration of both AOD and wind speed (WS) data at a daily time scale. Further analysis of wind profiles shows that wind speeds derived from satellite data are considerably lower than values measured on the ground. Daily wind speed gradients for a typical meteorological have been estimated with a scaling factor (WS_G = 2.5*WS_S) derived with the satellite to ground measurements ratio obtained during the measurement period.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
JAN	8	7	6	6	6	8	7	8	7	6	6	10	6	6	6	5	8	9	5	6	8	8	6	6	8	7	6	8	7	7	7
FEB	7	6	10	7	7	8	9	8	7	7	7	7	5	8	7	6	9	7	8	7	8	9	6	10	10	7	10	7	5		
MAR	7	7	8	7	9	12	8	10	11	10	15	15	8	7	11	9	8	9	7	7	7	8	9	11	9	11	8	9	7	8	7
APR	13	9	9	8	8	10	9	9	8	8	8	9	10	8	9	9	8	9	13	9	10	8	9	9	9	9	8	10	10	12	
MAY	10	10	7	10	11	12	10	11	13	11	8	9	7	11	11	9	6	9	9	9	10	8	8	8	8	10	13	12	12	11	8
JUN	9	9	8	7	8	8	9	13	13	9	8	10	8	6	8	7	9	8	8	8	11	10	11	9	8	8	8	7	9	7	
JUL	6	7	8	8	9	6	7	7	8	8	8	8	9	9	8	8	8	7	8	9	8	7	9	8	8	6	8	9	9	9	8
AUG	8	7	11	9	10	11	9	7	9	8	13	7	6	8	7	7	7	7	7	7	7	5	6	9	8	8	6	6	7	7	6
SEP	8	7	11	9	10	11	9	7	9	8	13	7	6	8	7	7	7	7	7	7	7	5	6	9	8	8	6	6	7	7	6
OCT	7	7	7	5	7	9	7	6	6	8	10	8	6	7	7	8	6	6	7	6	5	6	6	5	5	5	5	6	7	6	7
NOV	5	6	5	5	6	6	7	7	6	5	5	5	6	5	5	5	6	7	6	6	4	6	6	5	6	6	7	6	5	5	
DEC	4	6	5	5	6	4	5	5	6	5	6	8	6	6	5	5	5	7	5	5	5	7	6	5	5	6	6	6	6	8	6

Fig.7. Wind Speed Gradient above threshold [2003-2016]

The Figure 7 above presents a wind speed gradient map for a statistical year based on satellite data for the time period [1.1.2003-31.12.2015]. Wind speed gradients are shown numerically for each day of the year and highlighted by a color scale with 5 m/s in white represents the threshold related to measurable changes in soiling.

The statistics suggests than for this particular project site March, April, May, June, August & September are months of especially high wind activity. Ambient temperature and relative humidity do not present profiles that would suggest an influence on changes in SLF.

VI. Analysis

Soiling losses profiles (SLF) correlate with changes of three climatological variables: AOD, Wind-Speed and rainfall. During the initial phase of the measurement campaign there was no cleaning of the target modules. Therefore the natural development of a layer of soiling particles has only been altered by rainfall. This fact determines a particular external singularity in connection with estimations of soiling rates. Most likely the mechanical characteristics (size, shape, and mass) of soiling particles will generate a soiling layer with a time dependent thickness which will change under the influence of external factors.

One of such factors is the main airflow direction on the glass module surface. In this case the modules were mounted at 25° facing south while the wind direction during the period of measurements was mostly north. Therefore the airflow patterns around the modules must have been similar to a backward facing ramp with flow separation over the upper edge and low velocity bubbles on the module front glass.

A single axis horizontal tracking system, in contrast, will be more favorably aligned with nearly the same prevalent wind speed direction. Under these circumstances a single axis tracking system would exhibit lower soiling losses than a fix mounted.

Monthly values of soiling (SLF), measured on different time scales from begin-to-end of the period, exhibit different rates of change such as indicated in Table 5.

Month	Δ(SLF /Day)	Event
January	-0.20 %	
February	-0.13 %	
March 01-12	-0.13 %	
March 13-14	+8.00%	Rainfall
March 15-31	-0.07 %	
April	~0.00%	
01January-12March	-0.13 %	

Table.5. SLF Rate of change for different time periods

VII. Summary

An approach for the generation of time dependent soiling profile has been attempted by systematic analysis of the correlation between soiling loss factors, aerosol (AOD) and wind speed gradients.

Monthly measured soiling losses are at 6%, 4% levels for January and February. In March, two days of rainfall provided more than 8% recovery on SLF while the SLF rates for the period before and after the rainfall were approximately 1%. Simultaneous consideration of the AOD and Wind-Speed Gradient profiles as well as potential rainfall in June or July would result in a "U" shaped SLF to be expected mainly because of the relative decay in wind activity in the last months of the year.

Our results suggest that rainfall, daily AOD and wind speed gradients of certain magnitude are the major meteorological factors that impact soiling losses. A conclusive projection of soiling, extended for a full year, in connection with these variables is at this point in time not possible.

We expect that after the completion of a full year of continued measurements many of the most important factors impacting soiling for these type of climatic conditions will become evident to support the application of the methodology with lower requirements for on-site measurements.

Finally, a more in-depth understanding of the mechanical and chemical characteristics of the soiling materials would certainly contribute to fine tune decisions related to the more appropriate cleaning methodologies to apply during O&M activities.

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