Energy yield of PV power plants – Approaches for the determination of yield losses due to dust soiling in desert climates

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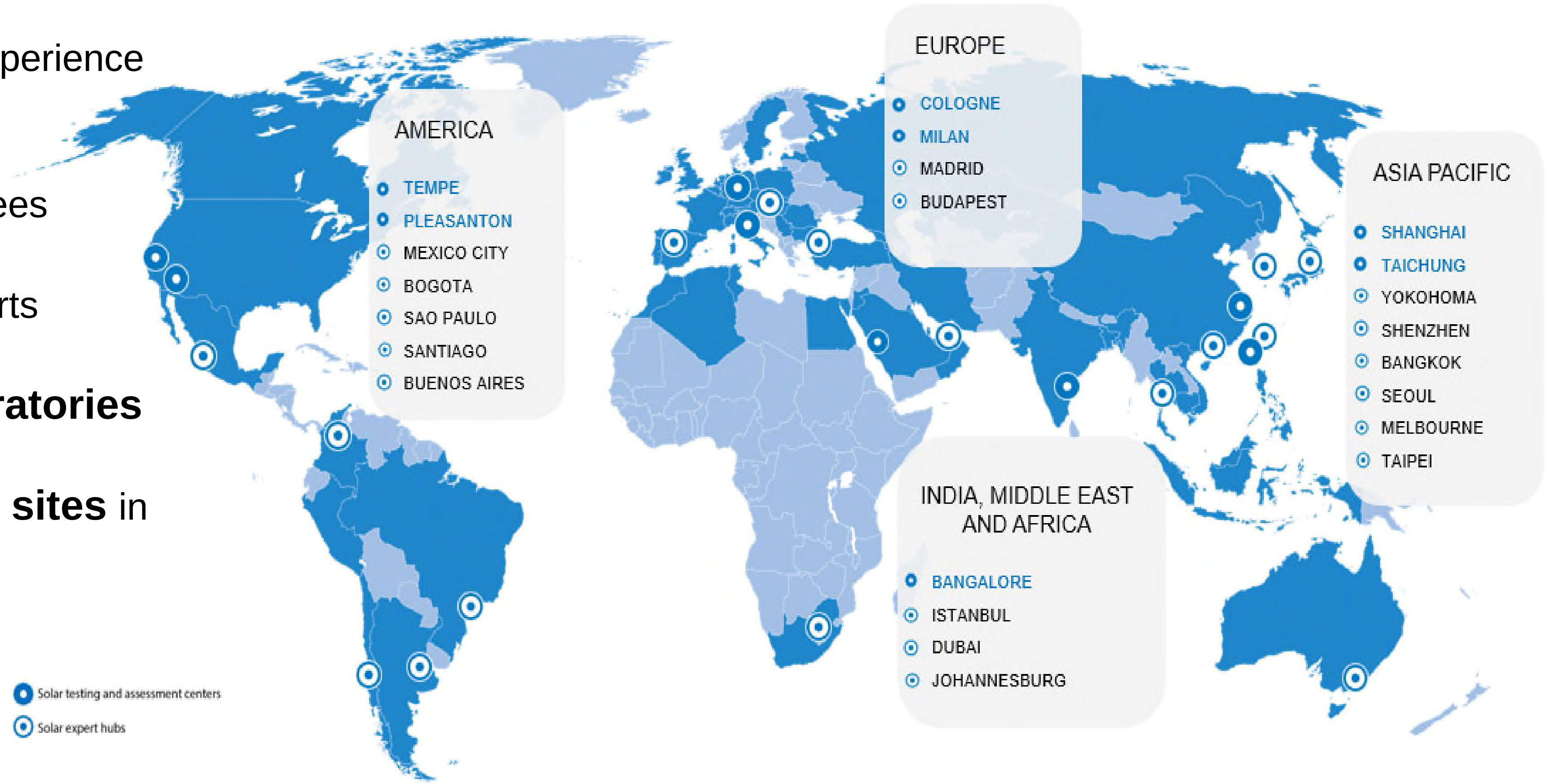
4 Outdoor test sites in different climates



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- Time-series analysis of soiling data measured in Saudi-Arabia
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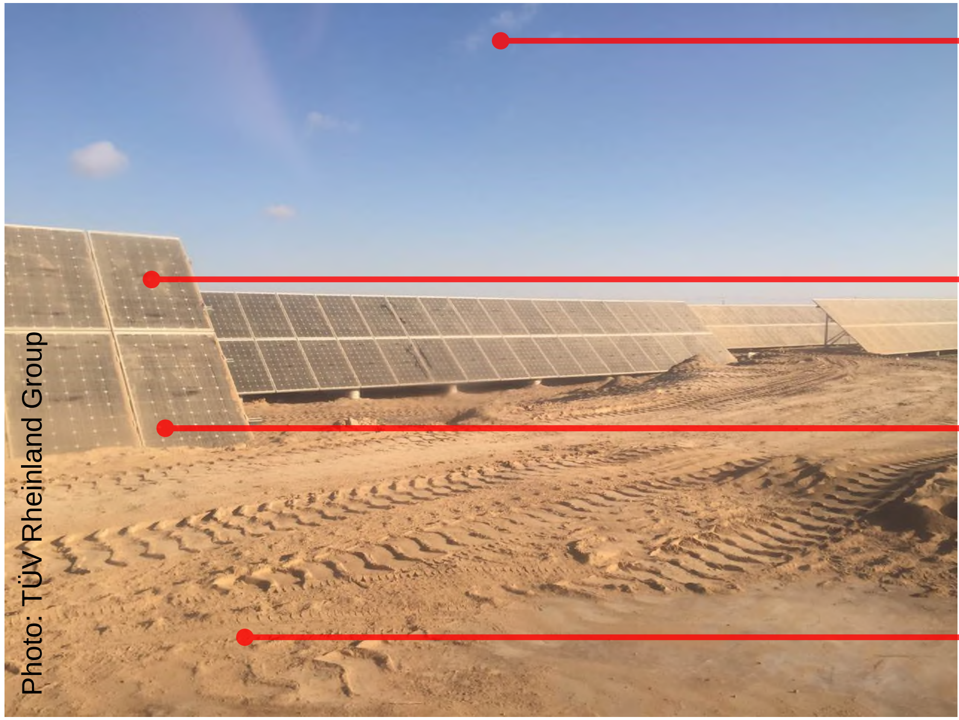
- Summary

Introduction

- Dust deposition on the PV module surface is a complex phenomenon, which is mainly influenced by the environmental/weather conditions, mounting principle and glazing characteristics.
- PV soiling loss in desert climates are site-specific and highly depend on periodical cleaning.



Climatic impacts:
- Airborne dust concentration
- Air humidity/dew events
- Wind conditions
- Rain events

Glazing characteristics:
- Adhesion characteristics
- Surface structure

Installation conditions:
- Tilt angle (gravity effects)
- Height above ground

Surrounding environment:
- Dust mineral composition

TÜV Rheinland test sites for PV energy yield measurement (PV-Climate project)

Cologne, Germany

Tempe, Arizona, USA

Thuwal, Saudi-Arabia

Chennai, India

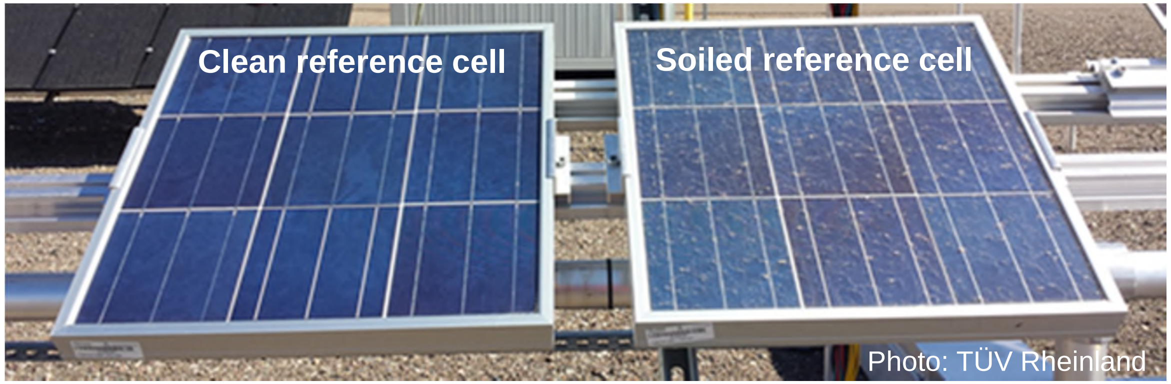
Location	Köppen-Geiger climatic classification	Tilt angle / Ground surface	Yearly sum of in-plane solar radiation	Fraction of low irradiance (GPOA < 200 W/m²)	Average ambient temperature (GPOA> 15 W/m²)	Annual precipitation*)	Average relative humidity
Cologne (Germany)	Cfb (temperate)	35° / Gravel	1257 kWh/m²	19 %	13,0 °C	774 mm	74.3%
Tempe (Arizona, USA)	Bwh (desert)	33.5° / Gravel	2396 kWh/m²	5 %	25,6 °C	219 mm	33.4%
Chennai (India)	Aw (sub-tropical)	15° / Concrete	2102 kWh/m²	9 %	30,5 °C	1197 mm	74.7%
Thuwal (Saudi-Arabia)	Bwh (desert)	25° / Gravel	2329 kWh/m²	4 %	30,2 °C	70 mm	66.8%

*) http://de.climate-data.org

TÜV Rheinland “PV-Climate” test site in Thuwal (Saudi-Arabia)

Location	King Abdullah University of Science and Technology (KAUST) New Energy Oasis (NEO) Thuwal, Saudi-Arabia
Geographical position:	22.3°N / 39.1°O 3 m above sea level
Inclination angle of test rack	25°
Surroundings	University ground (gravel covered) coastal environment (Red Sea)
Operation of test site	Since March 2015

TÜV Rheinland test sites – Soiling Monitoring



Side-by-side irradiance measurement with two reference cells (RC):

a) RC_{CLEAN}: Daily manually clean

b) RC_{SOILED}: Naturally soiled and weekly manually cleaned

- **Mini-modules:** 3x3 cell layout, center cell short circuited and surrounded by dummy cells, encapsulated Pt100 temperature sensor (T_{CELL})
- **PV based soiling measurement:** Effective irradiance at a solar cells is referenced ⇨ Spectral and angular effects are comparable to fielded PV modules
- **Effective irradiance** at cells:

$$\frac{I_{SC,MEASURED}/\{1+\alpha \cdot (T_{CELL}-25°C)\}}{I_{SC,STC}} \times 1000\,\frac{W}{m^2}$$

$\alpha - I_{SC}$ temperature coefficient

$I_{SC,STC} -$ Calibtrated I_{SC}@STC

- **Data recording interval:** 30 s, synchronously with meteorological parameters (solar irradiance, spectral irradiance, wind, ambient temperature, rel. humidity)

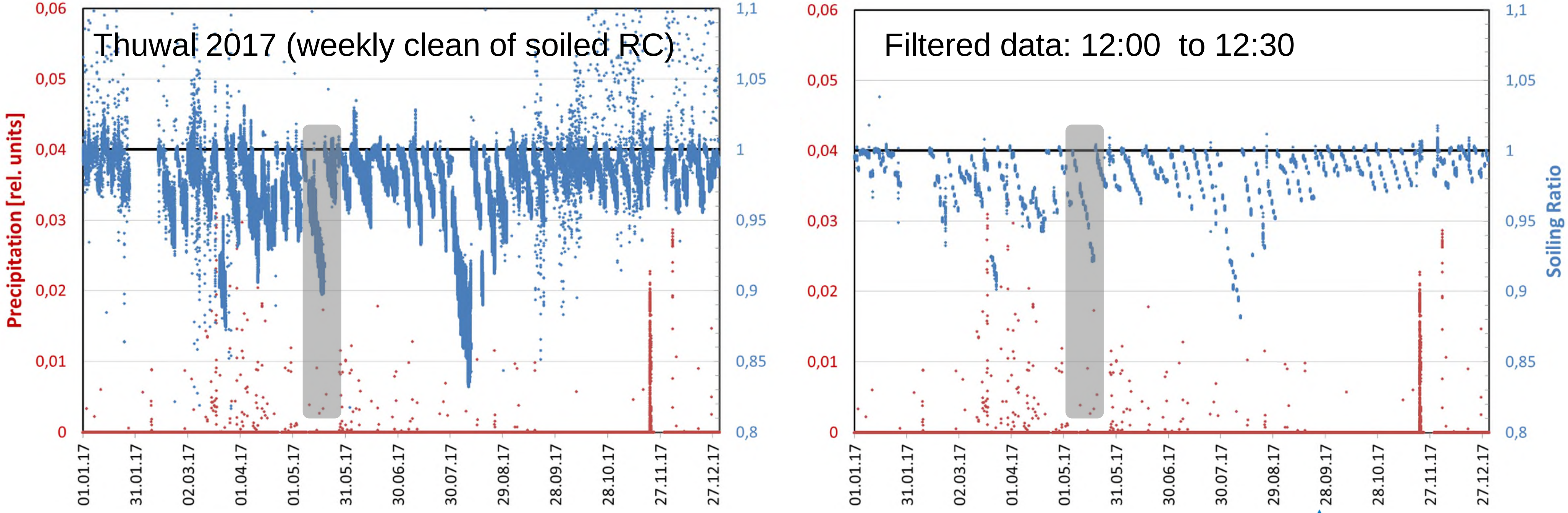
Time series analysis of soiling data

Soiling Ratio at a certain time:

$$SR = \frac{Solar\ irradiance\ measured\ with\ \mathbf{soiled}\ reference\ cell}{Solar\ irradiance\ measured\ with\ \mathbf{clean}\ reference\ cell}$$

$$SR = 1\ if\ both\ cells\ are\ clean$$

- High resolution SR data are subject to considerable daily scatter, which disappears for noon data



Time series analysis of soiling data

The soiling ratio is not constant during the day but is a function of the angle of incidence (AoI): Higher AoI values will cause lower SR values, except in the early morning and evening times.

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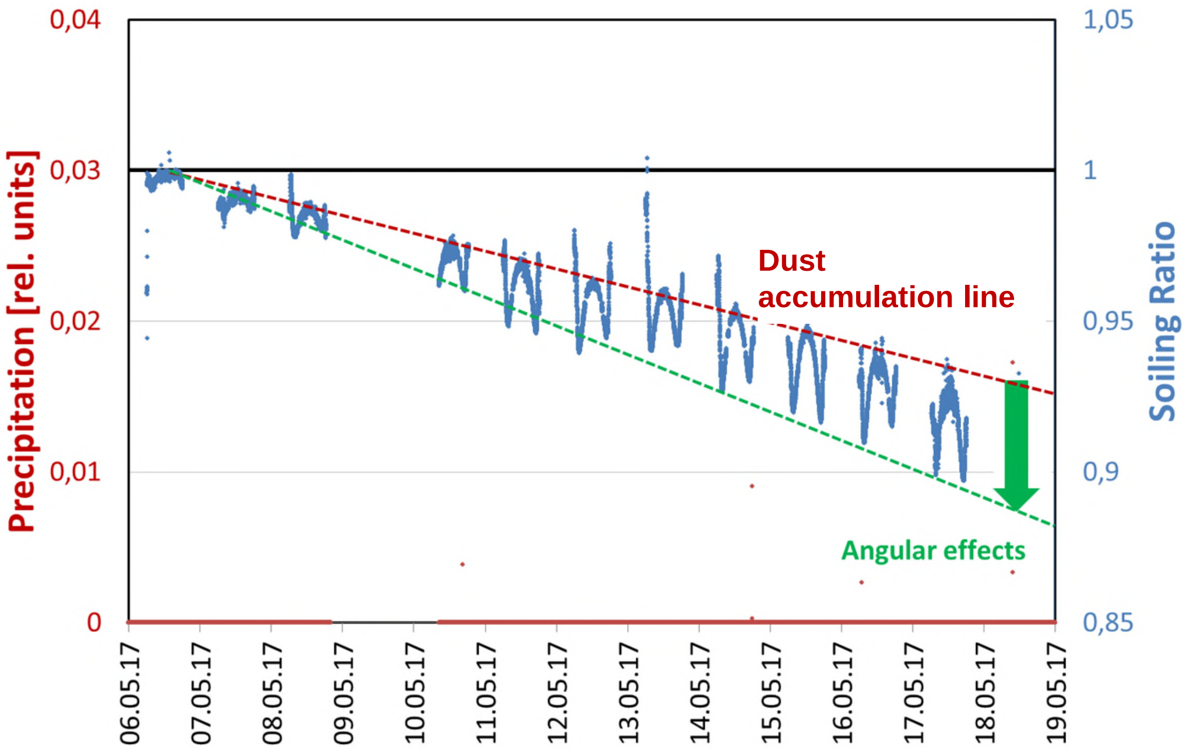

- Daily SR curve is W-shaped ⇨ Scattering effect for non-normal incidence
- The dust deposition rate in a certain period of time can be concluded from the SR value around noon
- Impacts of angular effects gain weight with increasing dust deposition
- Rises in early morning and afternoon are unimportant due to low irradiances

Daily average soiling ratio is relevant for PV soiling loss analysis as angular effects are considered.

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Time series analysis of soiling data

Annual Average Soiling Ratio:

$$\overline{SR}_{YEAR} = \frac{Annual\ insolated\ solar\ radiation\ measured\ with\ \mathbf{soiled}\ reference\ cell}{Annual\ insolated\ solar\ radiation\ measured\ with\ \mathbf{clean}\ reference\ cell}$$

- The angle-dependent part of PV soiling loss ($\overline{SR}_{YEAR}$ -1) can be derived from the "Annual Average Soiling Ratio" for two conditions:

a) Calculation of $\overline{SR}_{YEAR}$ without any data filtering

b) Calculation of $\overline{SR}_{YEAR,Noon}$ where only data around noon are taken into account

$$\overline{SL}_{YEAR,AoI} = \overline{SR}_{YEAR} - \overline{SR}_{YEAR,Noon}$$

PV soiling loss Thuwal 2017 (weekly clean)	
$\overline{SR}_{YEAR}$ -1	-2.24%
$\overline{SR}_{YEAR,Noon}$ - 1	-1.86%
$\overline{SL}_{YEAR,AoI}$	-0.38%

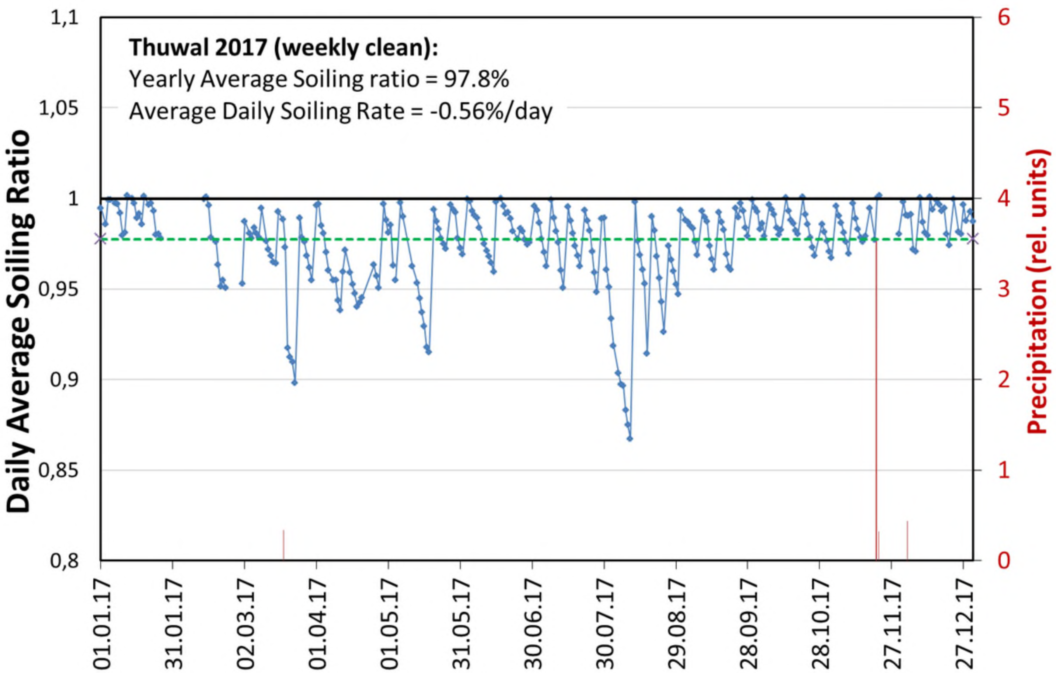
Angle of incidence (AoI) dependent part of annual PV soiling loss is significant (20% in 2017 for weekly clean) !

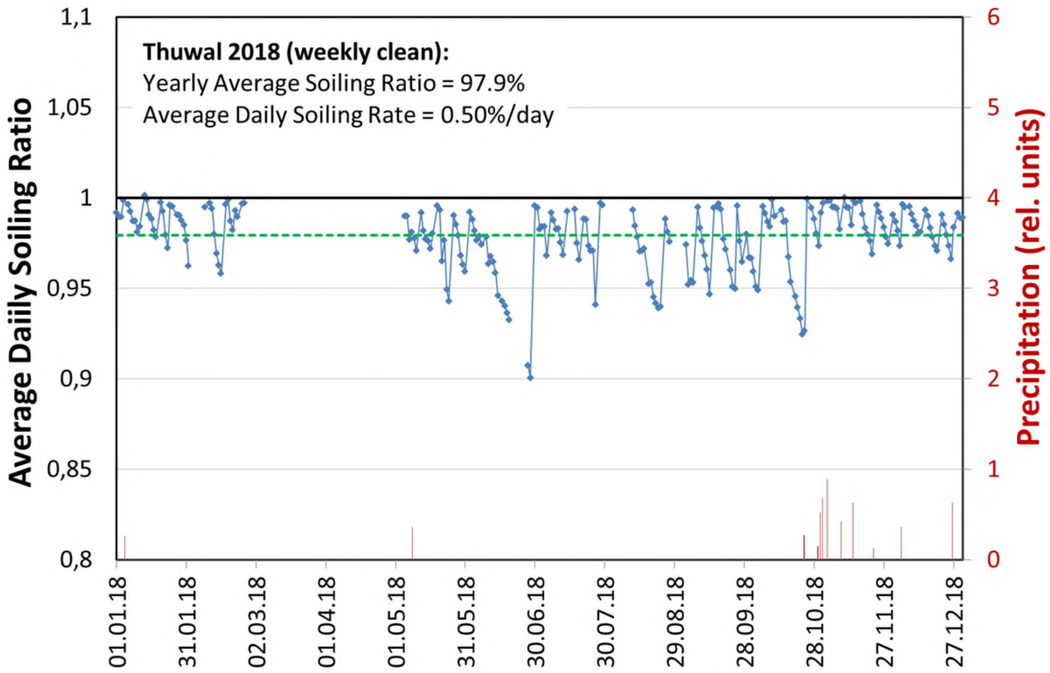
Data set Thuwal 2017:

Time series analysis of soiling data

Daily Average Soiling Ratio:

$$\overline{SR}_{DAY} = \frac{Daily\ insolated\ solar\ radiation\ measured\ with\ \mathbf{soiled}\ reference\ cell}{Daily\ insolated\ solar\ radiation\ measured\ with\ \mathbf{clean}\ reference\ cell}$$





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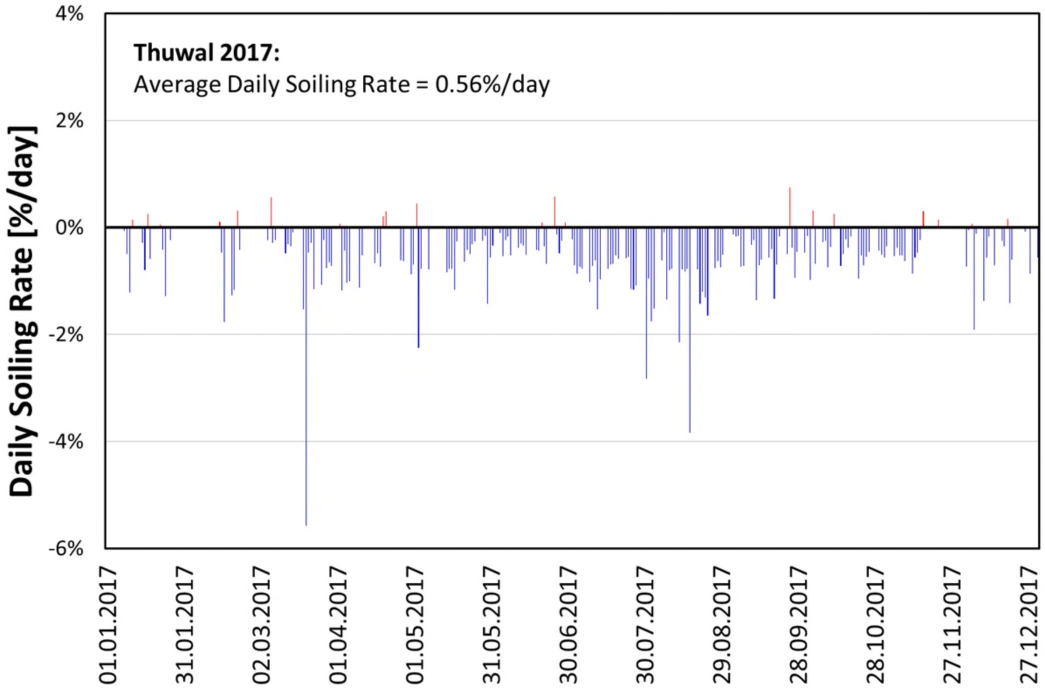
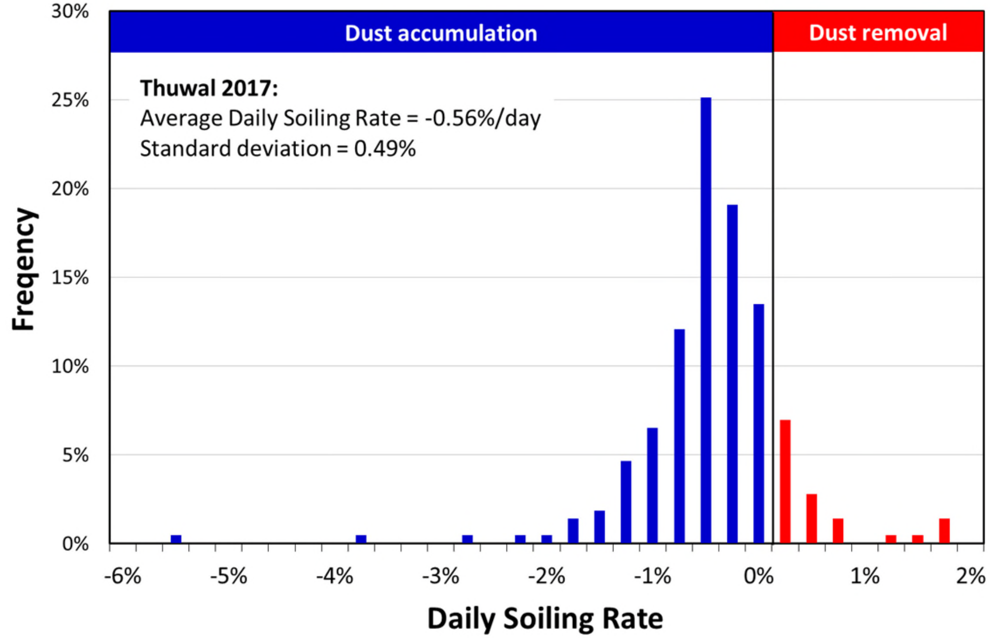
Time series analysis of soiling data

- Soiling conditions at a desert location can be described by the daily soiling rate (DSR), expressed in % per day (day-to-day change of daily average soiling ratio $\overline{SR}_{DAY}$)

$$\mathrm{DSR_N} = \overline{SR}_{DAY,N} - \overline{SR}_{DAY,N-1}$$

N: actual day
N-1: previous day





Variability of Annual PV Soiling Loss

Location: Thuwal, Saudi-Arabia (weekly clean)
Cleaning schedule: Weekly

Year	No. data days	No. rain days	Annual soiling loss [%]		Daily soling rate [% per day]		
			Total [1]	AoI dependent part	Average	Std.dev.	Maximum [3]
2017	342	4	-2,24	20%	-0,56	0,49	-5,6
2018	290	12	-2,08	17%	-0,50	0,51	-3,0
2019 [2]	104	2	-1,84	14%	-0,45	0,47	-1,6

[1] Calculated from 5am to 7pm
[2] until 30 April 2019
[3] Sandstorm impact

- Referencing the frequency distribution of daily soiling rate is a suitable approach for characterizing location specific soiling.
- The annual mean value of daily soiling rate and its standard deviation are suitable parameters for describing the year-to-year variation of soiling impacts on PV energy yield.

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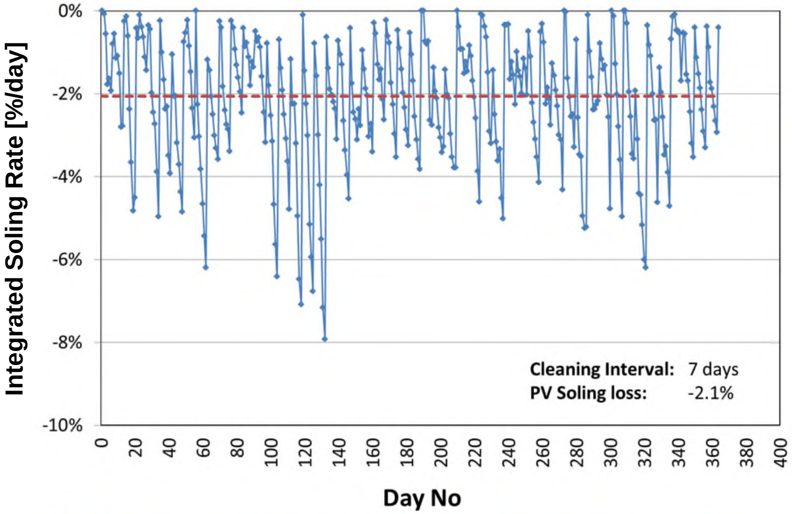
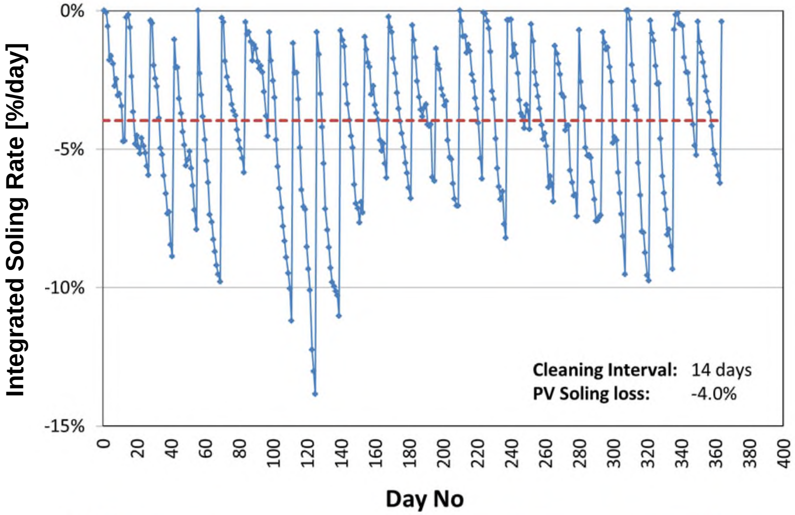
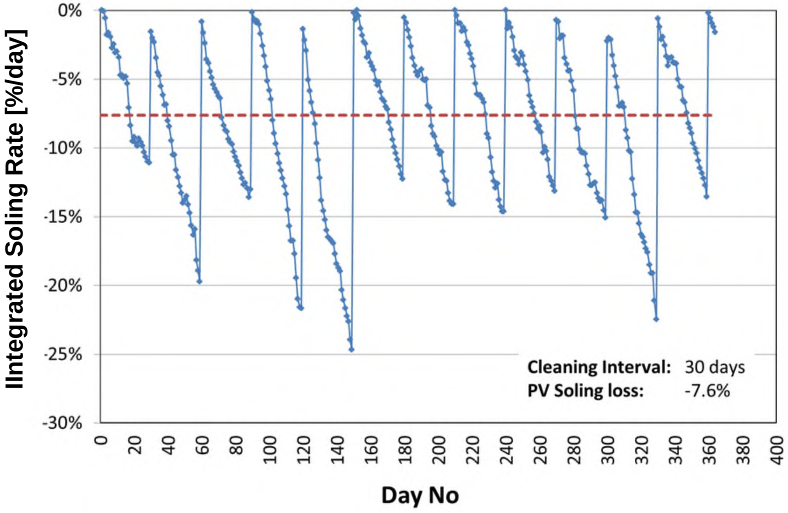
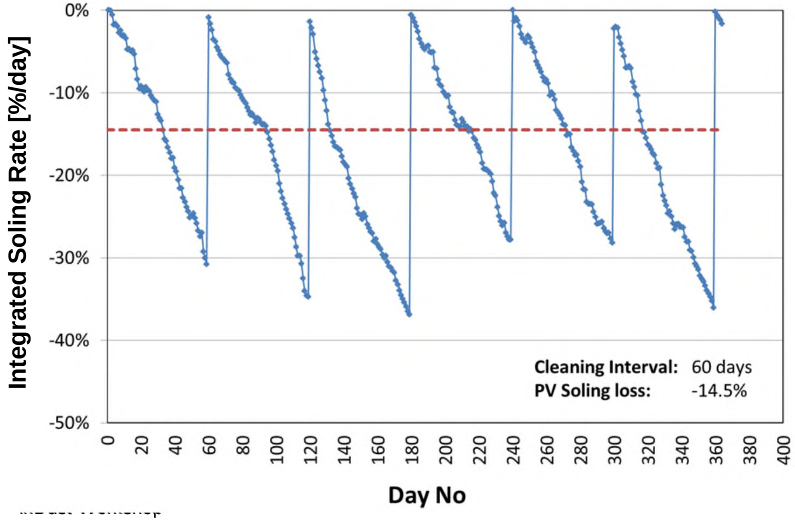
Impact of cleaning schedule





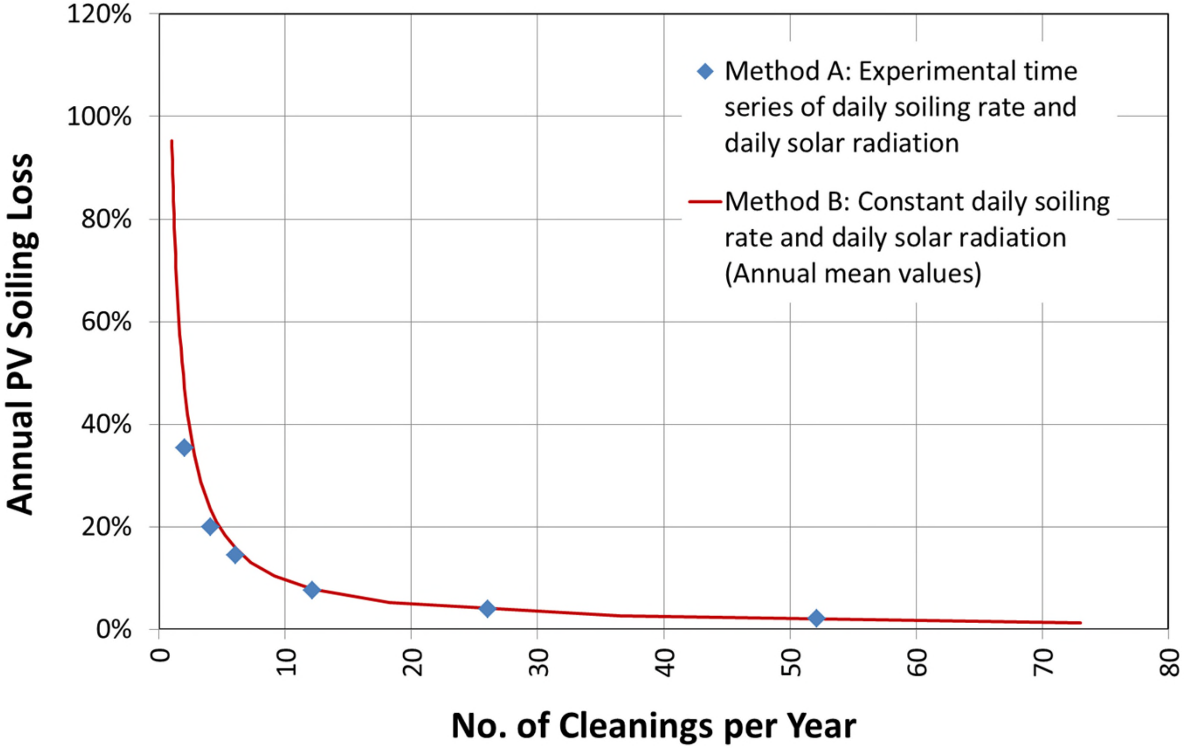




Simulation of annual PV soiling loss for variable cleaning interval based on time-series of:

- Daily soiling rate
- Daily solar insolation, measured with "clean" irradiance sensor

Impact of cleaning schedule on PV soiling loss



Soiling loss calculation:
(rain events not considered)

Method A:
Time-evolution of daily soiling rate and the variation of daily insulated solar radiation are considered.

Method B:
Annual mean value of daily soiling rate (-0.52%/day) and annual mean value of daily insulated solar radiation (4.8 kWh/m²) are assumed for all days.

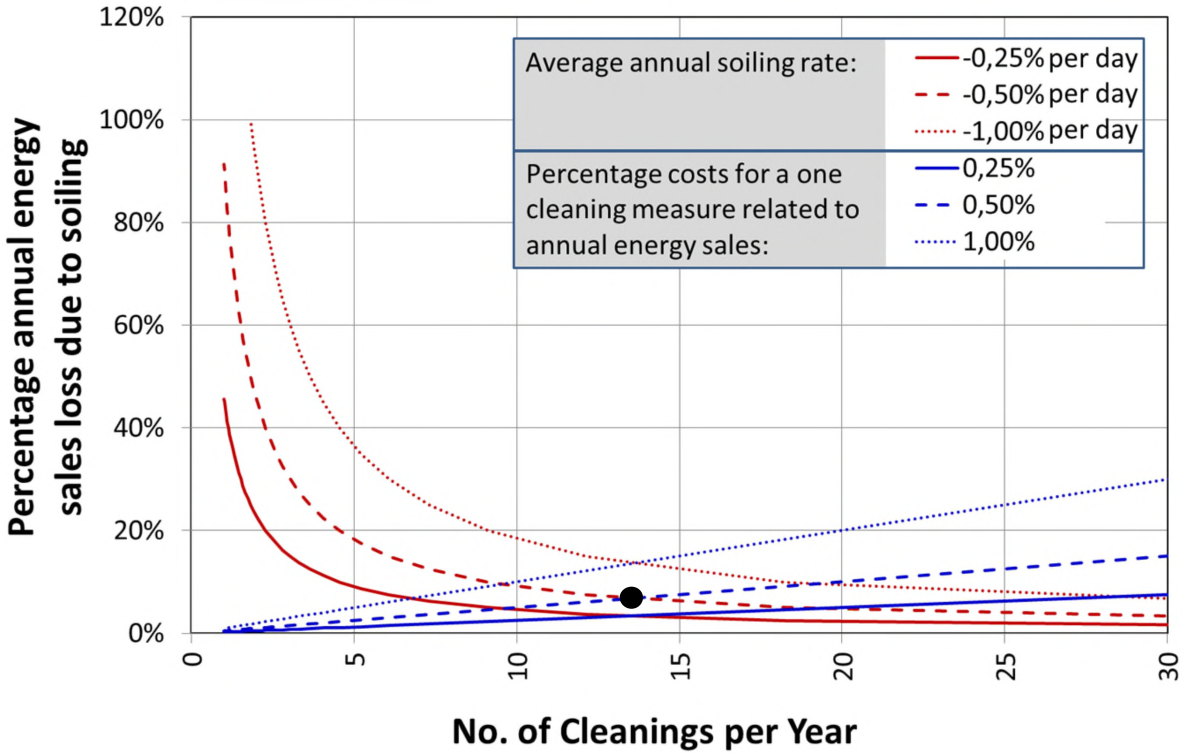
- Results of both methods are in good agreement if more than 10 cleaning measures per year are applied.

Optimum cleaning interval

- The Optimum cleaning interval results from various parameters, which are highly location dependent.

Parameter	
Energy Sales Revenue lost from Soiling	Depends on ▪ dynamic soiling rate ▪ size of PV power plant, ▪ sum of insolated annual solar radiation ▪ feed in tariff or PPA agreement ▪ Degradation rates
Cleaning Cost	▪ No. of cleanings per year ▪ Rain frequency ▪ <u>Robotic dry clean:</u> Investment, maintenance, electricity ▪ <u>Manual wet clean:</u> Use of water, transport, labor
Cleaning efficacy	Dust may not be 100% removed, in particular if cementation is observed
Cleaning damage	Cleaning procedure may cause abrasion effects on glass surface

Optimum cleaning interval



Optimal number of cleaning measures per year results from the intersection of two curves:

a) Annual energy sales loss due to soiling ⇨ red curves

b) Percentage-based cleaning costs (related to projected annual energy sales) ⇨ blue curves

Example:

Average soiling rate -0.5%/day and 0.5% unit costs for cleaning lead to 14 cleanings per year, resulting in 6% PV soiling loss.

- **-0.5%/day average soiling rate:** Optimal cleaning interval is expected in the range 10 to 20 annual cleanings, resulting in annual energy sales losses in the range 5% to 10%.

Summary

- Soiling monitoring at four TÜV Rheinland “PV-Climate” test sites
- Four years data base available for desert climate in Thuwal (Saudi-Arabia)
- Daily soiling rate is suitable parameter for site characterization
- Distribution of daily soling rate is bell-shaped
- Daily soiling rate: Average = -0.5%/day, maximum = -5.6%/day
- Angular part of PV soiling loss lies in the range 14% to 20% (weekly clean)
- Minimum 10 cleanings per year needed to keep PV soiling loss below 10%
- Optimal cleaning schedule can be derived from average daily soiling rate and average daily solar insolation