Water saving in solar power plants with the help of soiling forecasts

Natalie Hanrieder, Fabian Wolfertstetter, Stefan Wilbert
German Aerospace Center (DLR)
Institute of Solar Research

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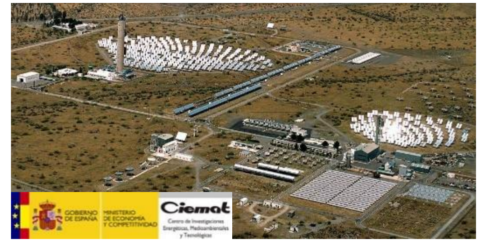
Natalie.Hanrieder@dlr.de

DLR

Meteorological R&D @ DLR Institute of Solar Research



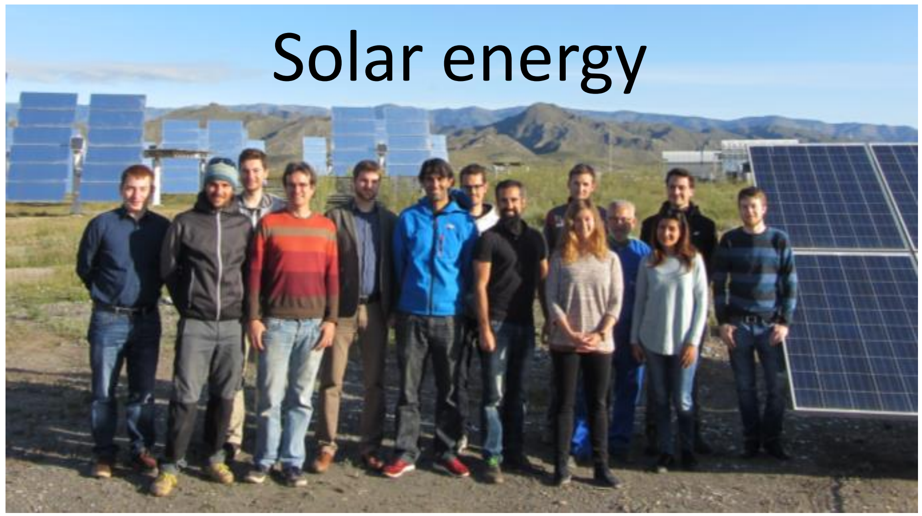
METAS
DLR + CIEMAT
PSA

Meteorological station for solar technologies

Solar energy related meteorological measurements, modeled data and validation

Standardization

Nowcasting



Evaluation of meteorological effects on power plants

Soiling / Ageing

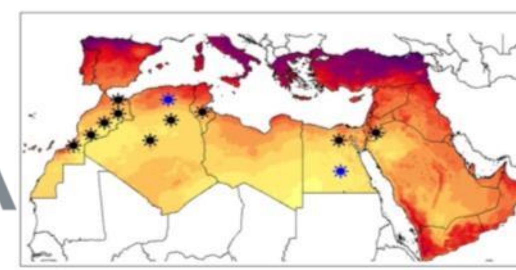
Radiation extinction in solar power plants

Solar spectra

Evaluation of long term radiation data

Instrument calibration / characterization

enerMENA



Why do we need to save water in solar plants?

Concentrated Solar Power plants (CSP)

CSP demand high direct normal irradiances (DNI) and are therefore usually located in rather drier regions, e.g. the MENA (Middle-Eastern and northern-African) region.

→ Water is a scarce resource at many potential CSP locations.

CSP plants consume water for cooling, within the steam cycle, **mirror cleaning**

The purpose of the **EU SOLWARIS project** is to upscale, implement and demonstrate cost-effective technologies and strategies

→ significant reduction of water consumption in CSP plants while maintaining high energetic performance of electrical power production

SOLWARIS

Solving Water Issues for CSP plants

grant agreement No 792103

Photovoltaic (PV)

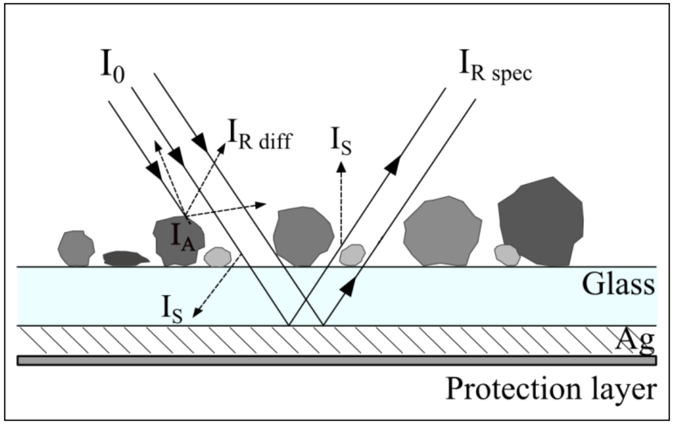
- Same accounts for PV
- Support e.g. cheaper and more cost efficient operation and yield of large, or hard accessible PV plants

Soiling for CSP and PV collectors

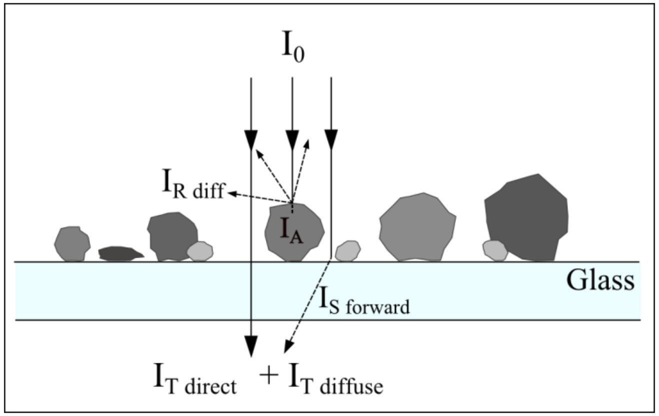
In **both technologies** optical losses occur due to:

- Diffuse reflection
- Scattering
- Absorption

CSP: Glass-silver mirror



PV: Glass transparent cover



CSP:

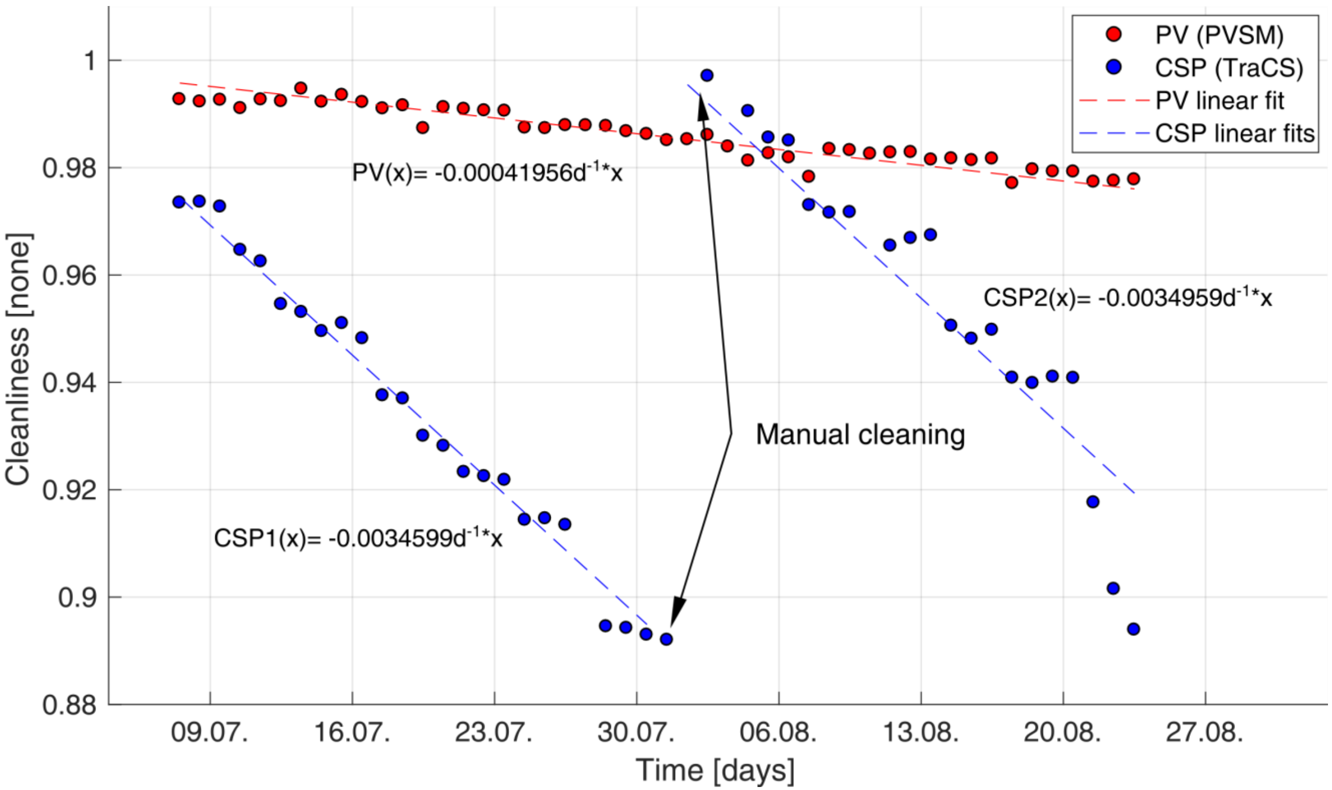
- 2 passages through the soiling layer
- 1 passage through the (soiled) absorber tubes glass cover
- Most forward scattered light is lost

PV:

- 1 passage through the (soiled) glass cover
- Most forward scattered light is NOT lost

Soiling for CSP and PV collectors

Parallel measurements of PV and CSP soiling



Source: Bellmann et al. (2020). 2020. Comparative modeling of optical soiling losses for CSP and PV energy systems. Solar Energy 197, 229–237

→ CSP soiling rate approx. **8-9 times higher** than PV (0.35%/d and 0.04%/d in Evora, Portugal)

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How can we save water in solar plants?

<u>Strategies tackled in the SOLWARIS project (CSP)</u>

- Coatings for the mirrors and receivers → reduction of soiling rate of the components
- Fences → protection of solar field from dust
- Ultrasonic cleaning technology → cleaning of mirrors with a fraction of the water consumption of state of the art cleaning technologies
- **Soiling forecasting product**

  → assistance for the optimization of the cleaning schedule for the next three days in advance

  → cleaning activity can be ceased before an upcoming heavy soiling or rain event in order to save water and cleaning costs.

Soiling forecasts also for PV interesting (e.g. in Germany considering rain, pollen, pollution, etc.)

How can we save water in solar plants with the help of soiling forecasts?

- Cleaning operators have to find the best trade-off between reduced **cleaning costs** and increased optical **solar field efficiency**
- Cleaning performance has to be quantified **financially**
- **Time resolved** analysis and **realistic soiling** rate dataset is crucial

Soiled PV panel

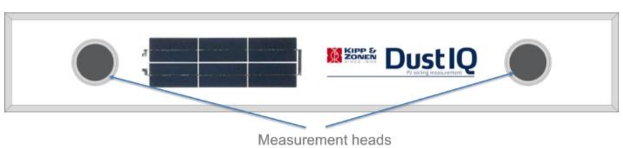
Soiled trough at CIEMATs Plataforma Solar de Almería, Spain

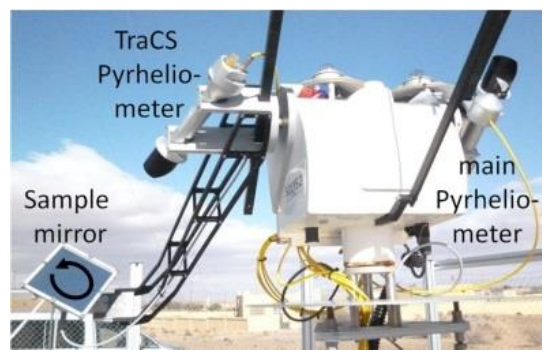
How can we save water in solar plants with the help of soiling forecasts?

<u>Motivation:</u>

- There are several instruments for soiling measurement available
- Long term measurement of the soiling rate is time consuming, costly and only **for singular points** (within solar field or in resource assessment)
- Project developers require more global data for site selection
- A soiling model could predict the soiling rate from other weather parameters that are more broadly available
- Design model such that it can be integrated into a global dust and weather forecasting model

  => **soiling forecast, soiling map**





Devices & Services R15

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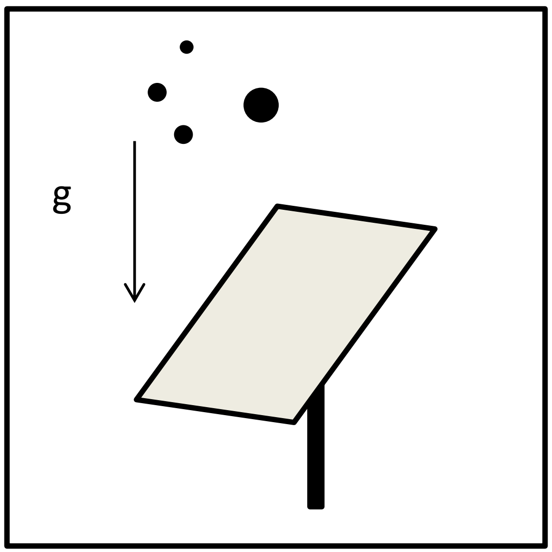
DLR's Soiling model: main deposition mechanisms

Model is based on atmospheric aerosol transport literature

Particle deposition there is characterized by the **deposition velocity** towards the ground – not the collector!

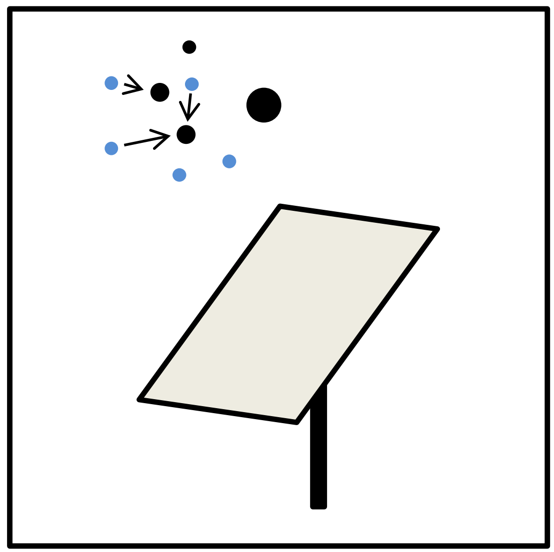
Sedimentation



- Gravitation

$$v_S = \sin(mirr_{el})\left(\frac{d_p^2 \cdot g \cdot (\rho_{aerosol} - \rho_{air})}{18 \cdot \eta_{air}}\right)$$

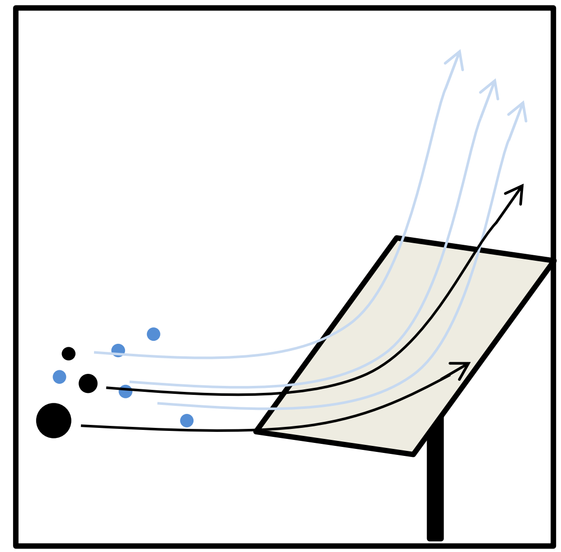
Brownian motion



- Thermal motion

$$v_B = \alpha_{Brown} \cdot u_{wind}\left(\frac{\frac{\nu_{air}}{k_B \cdot T}}{3 \cdot \pi \cdot \eta_{air} d_p}\right)^{-\gamma}$$

Impaction



- Air stream/wind

$$v_{Im} = \alpha_{Im}\left(\frac{\sigma_{orientation} u_{wind}}{1 + \exp(-f_{Im}(St - 1))}\right)$$

$$v_D = v_S + v_B + v_{Im}$$

Also considered: Rebound, resuspension, rain washing, cementation, mirror/panel orientation

Wolfertstetter F, S. Wilbert, F. Terhag, N. Hanrieder, A. Fernandez-García, C. Sansom, P. King, L. Zarzalejo, A. Ghennioui, Modelling the soiling rate: Dependencies on meteorological parameters, AIP Conference Proceedings 2126, 190018 (2019)

DLR's Soiling model

modeling of covered area:

Depends on collector orientation (variable for CSP)

Solar collector surface

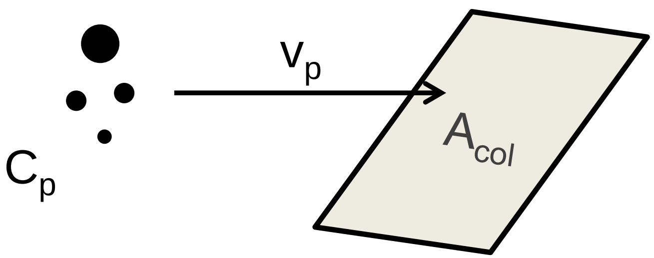
Particle concentration in P/m³

$$A_{cov} = A_{col} \cdot \sum_{d_p=0.25\mu m}^{32\mu m} \left(C_p \cdot v_p \cdot D_p{}^2 \cdot \frac{\pi}{4} \right)$$

deposition flux

disk area assuming spherical particles

Dependent on wind speed and direction, RH, aerosol particle number size distribution (0.25 – 32 µm), ambient temperature



Modeled covered area is fitted by parametrization to measured soiling rate → soiling model is optimized to fit best measured soiling rate

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enerMENA network **Operational since 2010 -2013**

12 meteorological measurement stations (solar irradiance, temperature, pressure, relative humidity, wind, etc…)

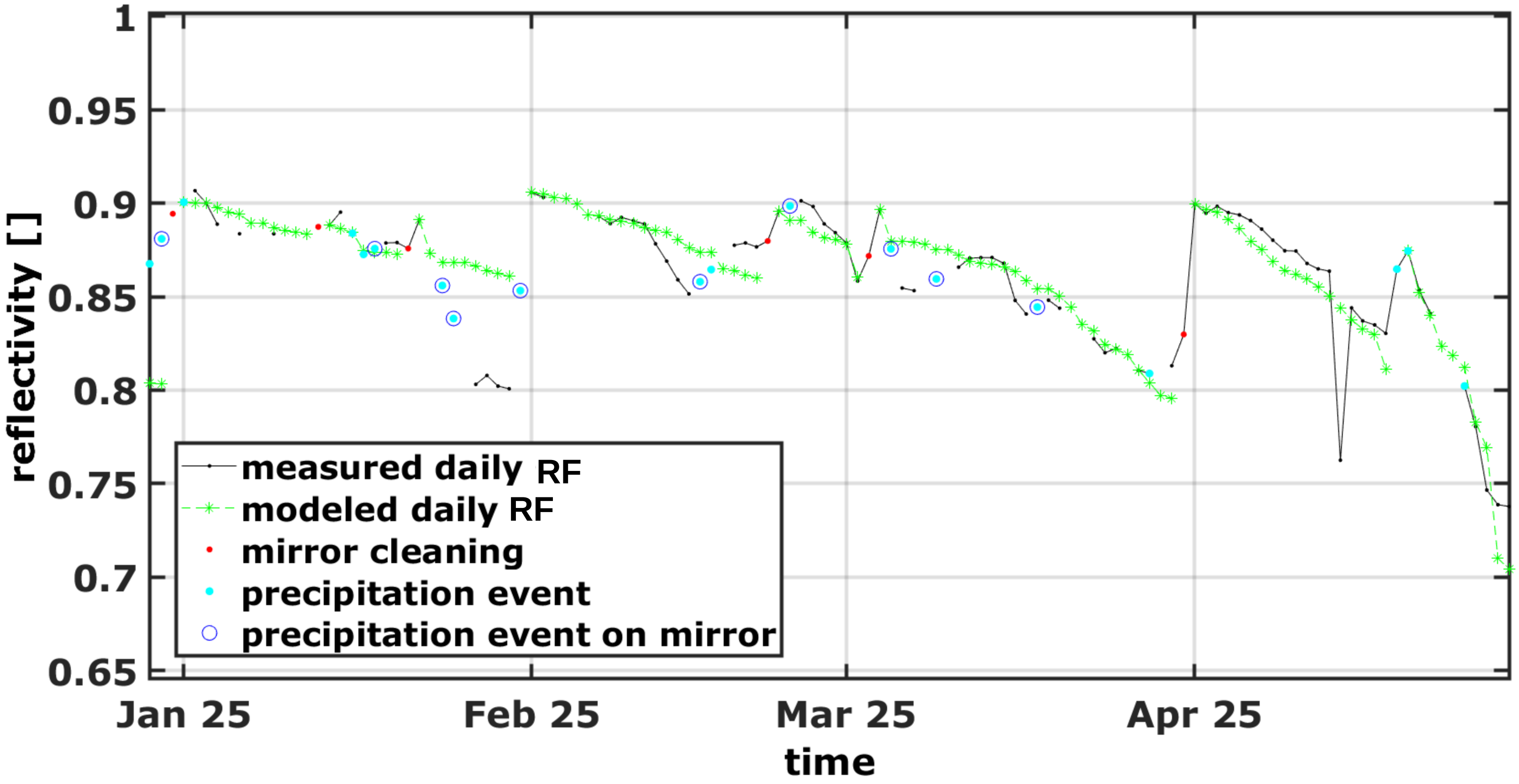
Soiling model evaluation for CIEMATs PSA (Spain) and Missour (Morocco)

Grimm EDM164 Particle counter

TraCS for mirrror soiling

https://www.dlr.de/sf/en/desktopdefault.aspx/tabid-8680/12865_read-32404/

Soiling model: Testing Example time series PSA (2014)

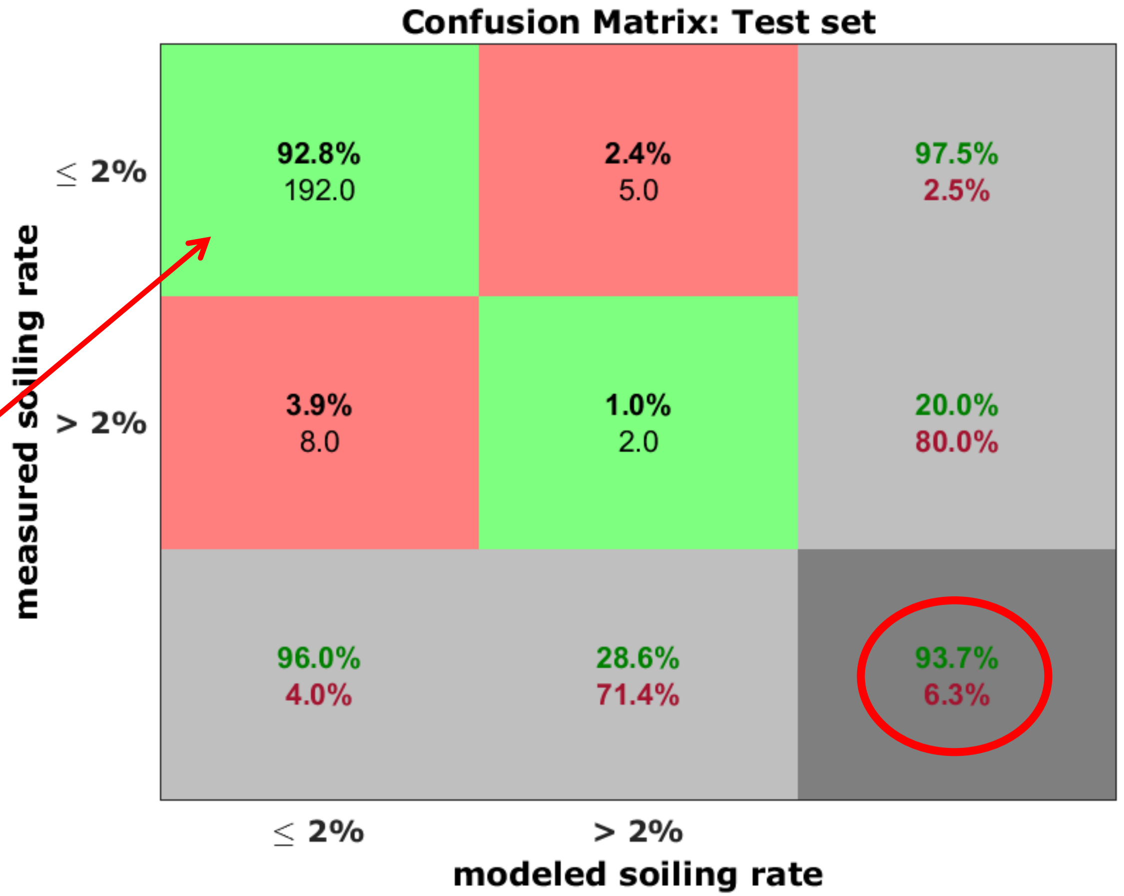


Soiling model performance with measurement data

Approximate soiling information is often sufficient for cleaning scheduling

Binning of soiling rate into
- low soiling rate (≤ 2% per day)
- high soiling rate (> 2% per day)

Result:
- low soiling days are predicted correctly with about 93% probability for test set at PSA
- In more than 93% model predicts binning correctly

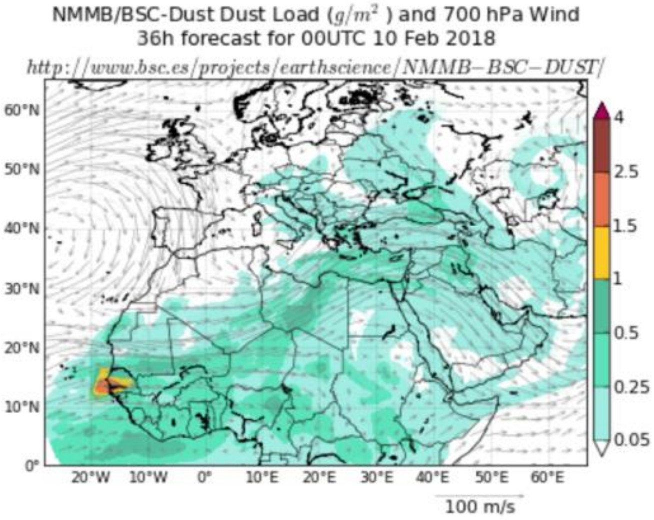


Soiling rate map and forecast

- Atmospheric **dust transport model** NMMB MONARCH by BSC:
  - Based on weather forecasting models
  - 36h (regional) – 72h (global) forecast of atmospheric dust load and „deposition“ in 10 x 10 km^2 resolution
  - The model includes the weather parameters used in our soiling model

⇒It is possible to integrate the soiling model into dust transport models

- Expected outcomes:
  - soiling rate forecast for the next 72 hours
  - soiling rate map from reanalysis of historical dust model data



https://dust.aemet.es/forecast

Cleaning optimization: Example CSP

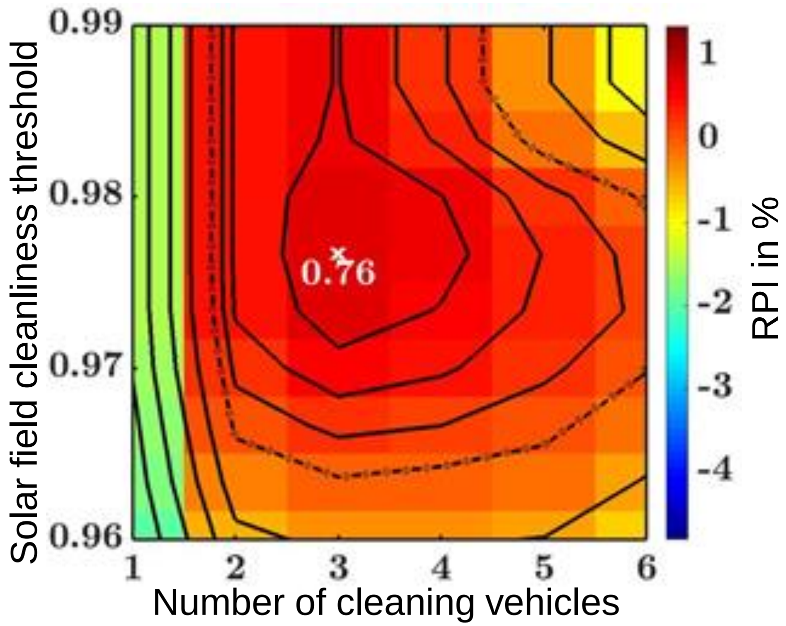
- 50 MW plant with 7.5 h storage
- Water and brush based cleaning vehicles
- Cleaning related technical and financial parameters (see table)
- Cleaning costs:
    - Labor, water, fuel, depreciation of cleaning vehicles
- **5 years** of soiling rate measurement data at PSA
- >**28 years** of irradiance and weather data

Parameter	Value
Nominal turbine power	$49,9\,MW$
Number of loops in Solar Field	156
Aperture area of solar field	510.000 m^2
Thermal storage	7.5 h
Cooling	water
Planned lifetime	25 years
DNI-yearly sum at PSA	2388 $kWh/m^2/a$
Equity ratio	30 %
Specific operating costs	1.8 $EUR/m^2/a$
Feed-in tariff	0.27 EUR/kWh
Cleaning velocity for one unit	9 loops / shift
Number of personnel per vehicle	1
Cleaning vehicle fuel consumption	6 – 8 l/loop
Cleanliness after cleaning	0.986
Demin. water consumption of cleaning unit	1 m^3/loop
Estimated lifetime of cleaning unit	15 years

Wolfertstetter, F., Wilbert, S., Dersch, J., Dieckmann, S., Pitz-Paal, R., & Ghennioui, A. (2018). Integration of Soiling-Rate Measurements and Cleaning Strategies in Yield Analysis of Parabolic Trough Plants. *Journal of Solar Energy Engineering*, *140*(4), 041008.

Cleaning optimization: Example CSP

- A **reference cleaning strategy** is chosen as a reference point: constant, daily cleaning in one shift with 1 vehicle
- Cleaning policies are compared to reference by **relative profit increase (RPI)**
- **Study**: condition based cleaning policies: Vary number of vehicles and cleanliness threshold

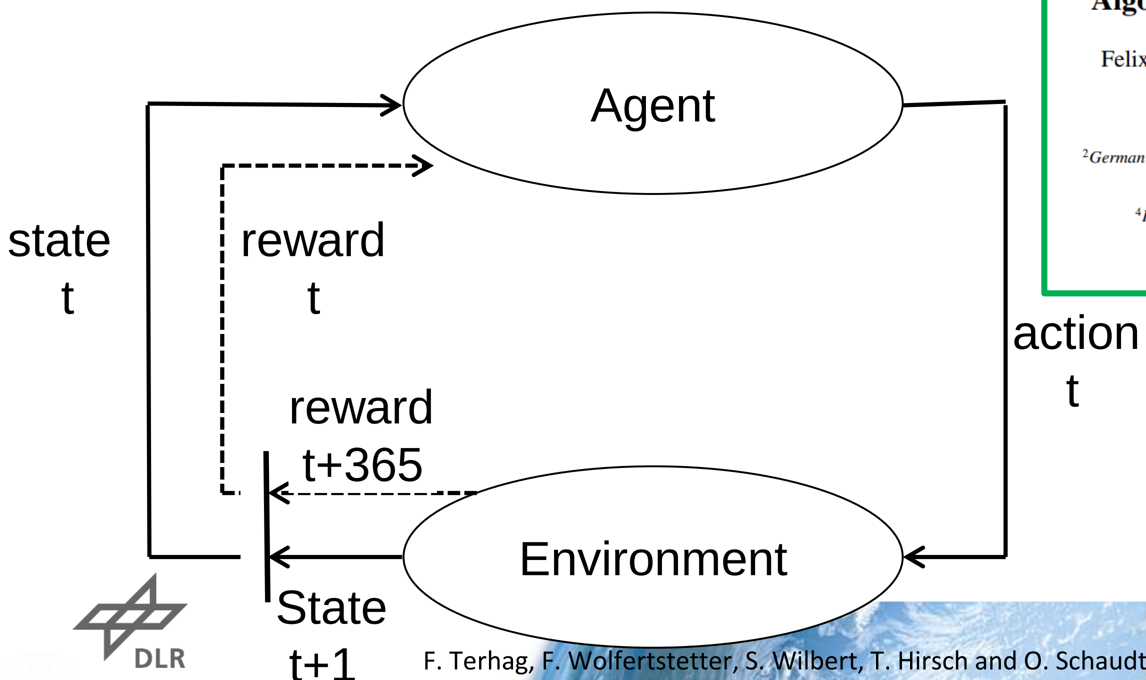


Can cleaning strategy be improved by reinforced Learning and forecast?

Wolfertstetter, F., Wilbert, S., Dersch, J., Dieckmann, S., Pitz-Paal, R., & Ghennioui, A. (2018). Integration of Soiling-Rate Measurements and Cleaning Strategies in Yield Analysis of Parabolic Trough Plants. *Journal of Solar Energy Engineering*, *140*(4), 041008.

Optimization of Cleaning Strategies based on Artificial Neural Networks -- Assessing the Benefit of Soiling Rate Forecasts

- agent = cleaning policy
- action = daily cleaning decision (cleaning with 0 – 2 vehicles in 1 or 2 shifts each)
- state = solar field cleanliness, weather data, optional: **forecast** for irradiance class and high/low soiling rate
- Reward = **relative profit increase (**RPI)



Optimization of Cleaning Strategies Based on ANN Algorithms Assessing the Benefit of Soiling Rate Forecasts

Felix Terhag[1], Fabian Wolfertstetter[2,a),b)], Stefan Wilbert[2], Tobias Hirsch[3] and Oliver Schaudt[4]

[1] *University of Cologne, Mathematical Institute, Weyertal 86-90, 50931 Cologne, Germany*
[2] *German Aerospace Center (DLR), Institute of Solar Research at Plataforma Solar de Almería, Crtra Senés km 4, 04200 Tabernas, SPAIN*
[3] *DLR, Institute of Solar Research, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany*
[4] *RWTH Aachen University, Department of Mathematics, Pontdriesch 10, 52062 Aachen, Germany*

a) Corresponding author: fabian.wolfertstetter@dlr.de
b) URL: http://www.dlr.de

F. Terhag, F. Wolfertstetter, S. Wilbert, T. Hirsch and O. Schaudt, Optimization of Cleaning Strategies Based on ANN Algorithms Assessing the Benefit of Soiling Rate Forecasts, AIP Conference Proceedings 2126, 220005 (2019);

Optimization of Cleaning Strategies based on Artificial Neural Networks -- Assessing the Benefit of Soiling Rate Forecasts

- Each training run involves full simulation year, i.e. 365 states and cleaning decisions
- Option to provide agent with soiling rate and weather forecast information
- Drawback: Training of reinforced learning agent requires a **large amount of data**

→ 5 years of soiling data and 28 years of weather data is **not enough** for reinforced learning

→need to increase database by **synthetic data extension**

→For details please check the publication or write me a mail

F. Terhag, F. Wolfertstetter, S. Wilbert, T. Hirsch and O. Schaudt, Optimization of Cleaning Strategies Based on ANN Algorithms Assessing the Benefit of Soiling Rate Forecasts, AIP Conference Proceedings 2126, 220005 (2019);

Optimization of Cleaning Strategies based on Artificial Neural Networks -- Assessing the Benefit of Soiling Rate Forecasts

- Reinforcement learning strategy nearly doubles the **relative profit increase** (to 1.3%) of the condition based strategy if no forecast is provided
- RPI is even more increased to 1.4% with forecast information

- Note: PSA is not a heavy soiling location
- Much higher results are expected for regions with higher dust loads

Forecast Horizon in days	RPI in [%]
ø	1.28
1	1.33
2	1.36
3	1.37
6	1.36

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Thank you for your attention.
Questions?

→ Natalie.Hanrieder@dlr.de

References

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- Felix Terhag, Fabian Wolfertstetter, Stefan Wilbert, Tobias Hirsch and Oliver Schaudt, Optimization of Cleaning Strategies Based on ANN Algorithms Assessing the Benefit of Soiling Rate Forecasts, AIP Conference Proceedings 2126, 220005 (2019); https://doi.org/10.1063/1.5117764