Improved PV Cleaning Schedule Optimization Using a Markov Decision Process Approach

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Soiling of PV panel surfaces is estimated to create 4% annual losses in global PV energy production, for some sites even surpassing 45%.[1]
These losses can be mitigated by manual cleanings of the panels, but the tradeoff between soiling losses and the cleaning costs has to be considered.
A high variability in environmental factors (e.g. single strong natural soiling or cleaning events) makes it challenging to predict future soiling losses.
This new method increases the profitability of PV cleaning schedules by utilizing probabilistic weather forecasts to optimize the future cleaning dates and it can assess the general economic potential of PV cleaning only based on widely available data.

Methods

Forecasting the soiling process

Soiling by particulate matter (PM):

One of the main sources of soiling is the deposition of airborne particles. There is a high correlation between PM_{10} and $PM_{2.5}$ concentrations and PV soiling.

HSU soiling model:

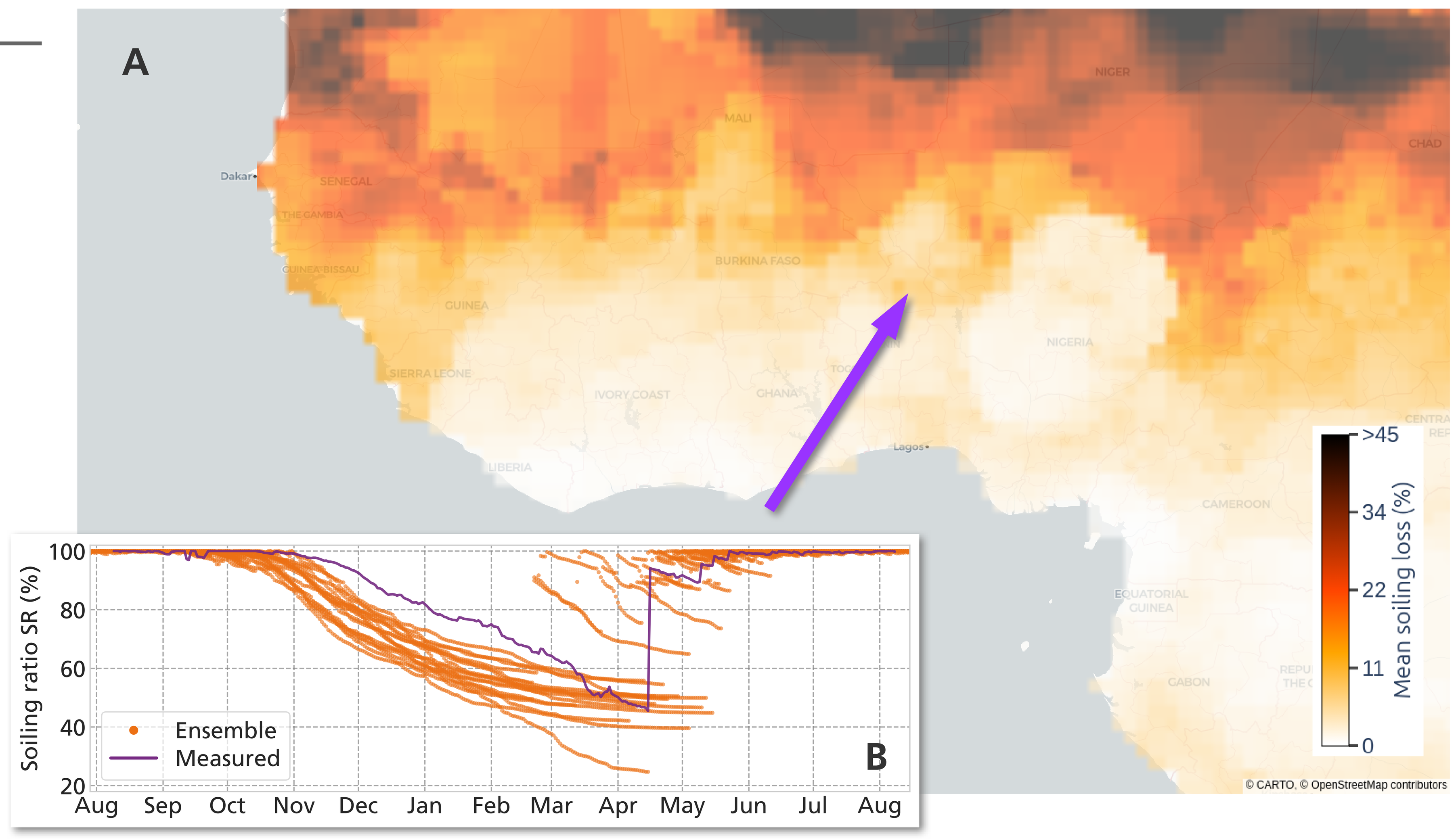
It is used to estimate future soiling based on PM. It assumes soiling to be a function of PM concentrations and effective settling velocities.[2] Natural cleaning is considered by 80% partial cleaning when the daily rain sum surpasses 1mm.

Input data:

2003-2019 of CAMS PM reanalysis data[3] and MERRA-2 precipitation reanalysis data[4] are used as input for the HSU model.

The final soiling ensemble forecast:

1 year forecasting horizon, with 16 members (each historical year used as one member), encoding past climatological conditions.



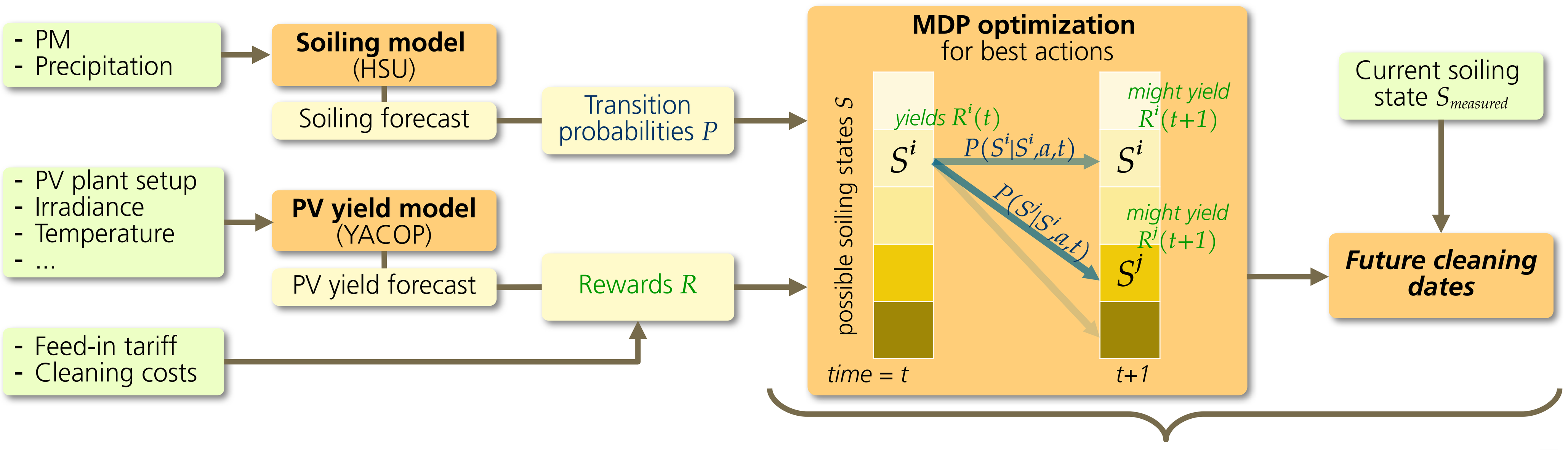
A: Mean soiling ratio between 01.08.2021 and 01.08.2022 in west Africa calculated with the HSU soiling model based on CAMS PM and MERRA-2 precip. reanalysis data. B: Soiling ensemble forecast (orange) and measured soiling ratio (WAPP data[5]) for the dry period at the location Malanville, Benin (2021/2022).

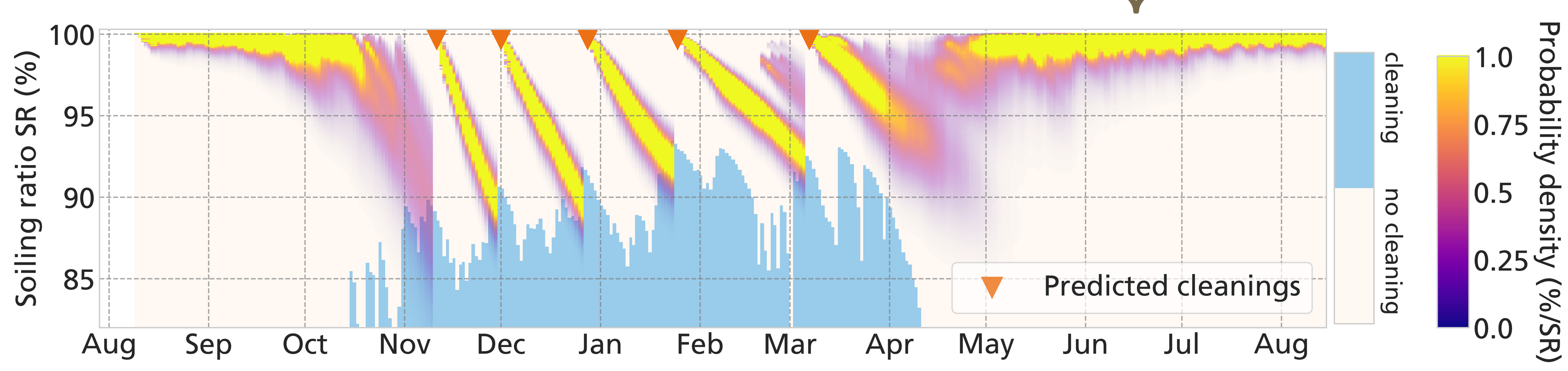
Forecasting the energy generation

YACOP (Yield Assessment Calculation and Optimization Program[6]) is used for a 1 year horizon forecast of the daily PV energy yield based on the mean of 2012-2019 MERRA-2 meteorological reanalysis data.

Markov decision process (MDP) optimizer

- The whole time dependent probability distribution of future soiling is used.
- The system is described by its state (soiling ratio), changing in discrete time steps (days) according to certain transition probabilities (natural processes). Each day an action is taken (clean or do not clean) and a reward (net income) is collected.[7]
- Maximizes the expected future reward by finding the best actions with a backwards propagation algorithm

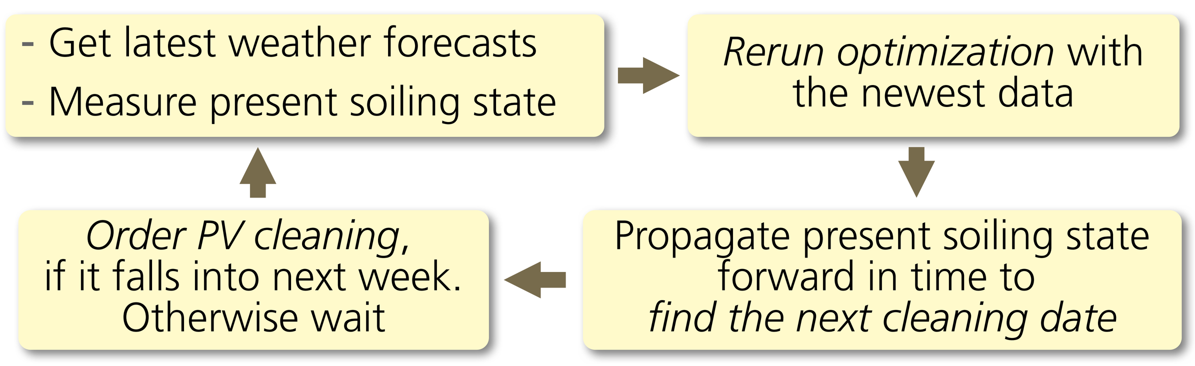




Optimization result for Malanville, Benin (2021/2022). Blue area: cleaning has the higher expected future reward at these state and time points. Yellow-purple: SR probability distribution propagated by the Markov transition probabilities from initial state SR_0=100%, forecast cleaning when 50% of the distribution enter ‚do cleaning' states

Extension to an online-algorithm

PV cleanings usually only require a few days of preparation
→ optimization is updated daily until preparations have to be made



Results

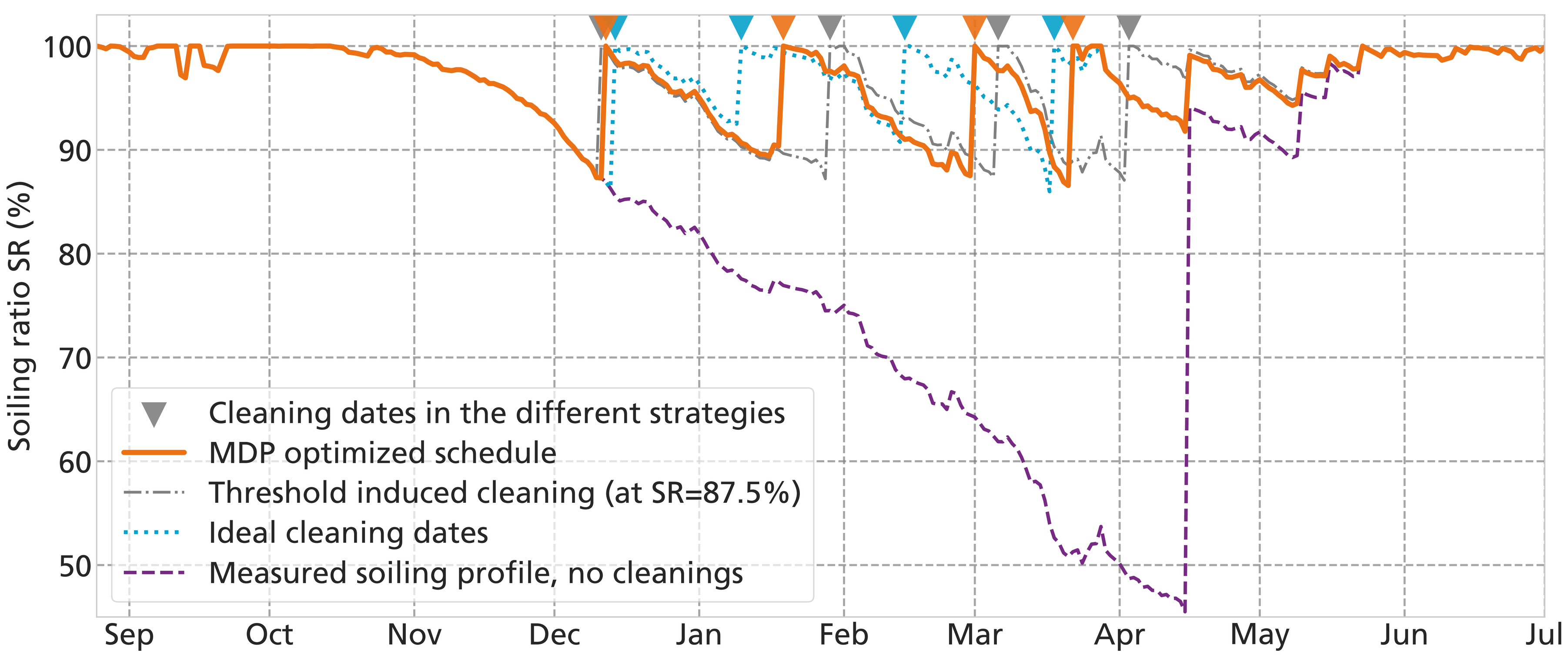
Case study Malanville, Benin

Long dry periods and high PM concentrations yield strong soiling losses, making cleaning particularly relevant in this region.
The soiling ratio was measured in-situ for a 1 year cycle in 2021/2022.[5] A 50MW$_p$ PV plant is simulated in this period to compare different cleaning schedules:

Imrovement compared to	Net income (%)	Generated energy (%)
No cleanings	9.7	12.1
Threshold induced cleanings	0.4	0.4
Ideal cleaning dates	-0.7	-0.6

Ideal cleaning schedule derived from the real observations in hindsight, Threshold optimized on the PV plant simulation for the years 2003-2019 (same input data as MDP optimizer) Thresh: SR=87.5%

- The MDP optimizer performs better than threshold based cleaning.
- It reaches 99.3% of the maximal net income that can be earned with ideal cleaning dates, in this case study.



Cleaning strategies simulated for the measured soiling scenario at Malanville, Benin (2021/2022)

Conclusions

- PV plant cleaning schedules can be improved, based only on open-access meteorological data and current soiling measurements.
- The new method outperforms conventional cleaning schedule optimization, especially in the scenario of strongly varying soiling rates.
- Other information sources (e.g. real time weather forecasts for the next days) can be integrated into the optimization to increase the accuracy further.
- Cleaning strategies can now be benchmarked on historical scenarios against the best possible cleaning schedule.
- Other potential applications of the MDP optimization framework in the PV industry can be explored (e.g. charging/discharging of BESS).

References

1. Ilse, Klemens et al. (2019). "Techno-Economic Assessment of Soiling Losses and Mitigation Strategies for Solar Power Generation". In: Joule 3.10, pp. 2303–2321. doi: 10.1016/j.joule.2019.08.019.
2. Coello, Merissa and Liza Boyle (2019). "Simple Model for Predicting Time Series Soiling of Photovoltaic Panels". In: IEEE Journal of Photovoltaics 9.5, pp. 1382–1387. doi: 10.1109/JPHOTOV.2019.2919628.
3. ECMWF (2024). Copernicus Atmospheric Monitoring Service. url: atmosphere.copernicus.eu (Last accessed: 11/24/2024).
4. NASA (2024). MERRA-2. url: gmao.gsfc.nasa.gov/reanalysis/MERRA-2/ (Last accessed: 11/24/2024).
5. West African Power Pool (2023). url: ecowapp.org/en/news/measurement-summary-solar-development-sub-saharan-africa (Last accessed (11/24/2024).
6. Loevenich, Matthias et al. (2024). "YACOP - A Fully Flexible Modeling Environment for the Techno-Economic Assessment of Energy Systems". In: Poster presentations. url: https://elib.dlr.de/206463/ (Last accessed: 12/16/2024).
7. Truong Ba, H. et al. (2017). "Optimal condition-based cleaning of solar power collectors". In: Solar Energy 157, pp. 762–777. issn: 0038092X. doi: 10.1016/j.solener.2017.08.076.
8. Abu-Naser, M. (2017) "Solar Panels Cleaning Frequency for Maximum Financial Profit". In: Open Journal of Energy Efficiency 6, 80-86.

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