U.S. Department of Energy
HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

Forecasting Soiling-Related O&M Costs for Concentrating Solar Power Tower Plants

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Agenda

Heliostat Consortium (HelioCon) Objectives

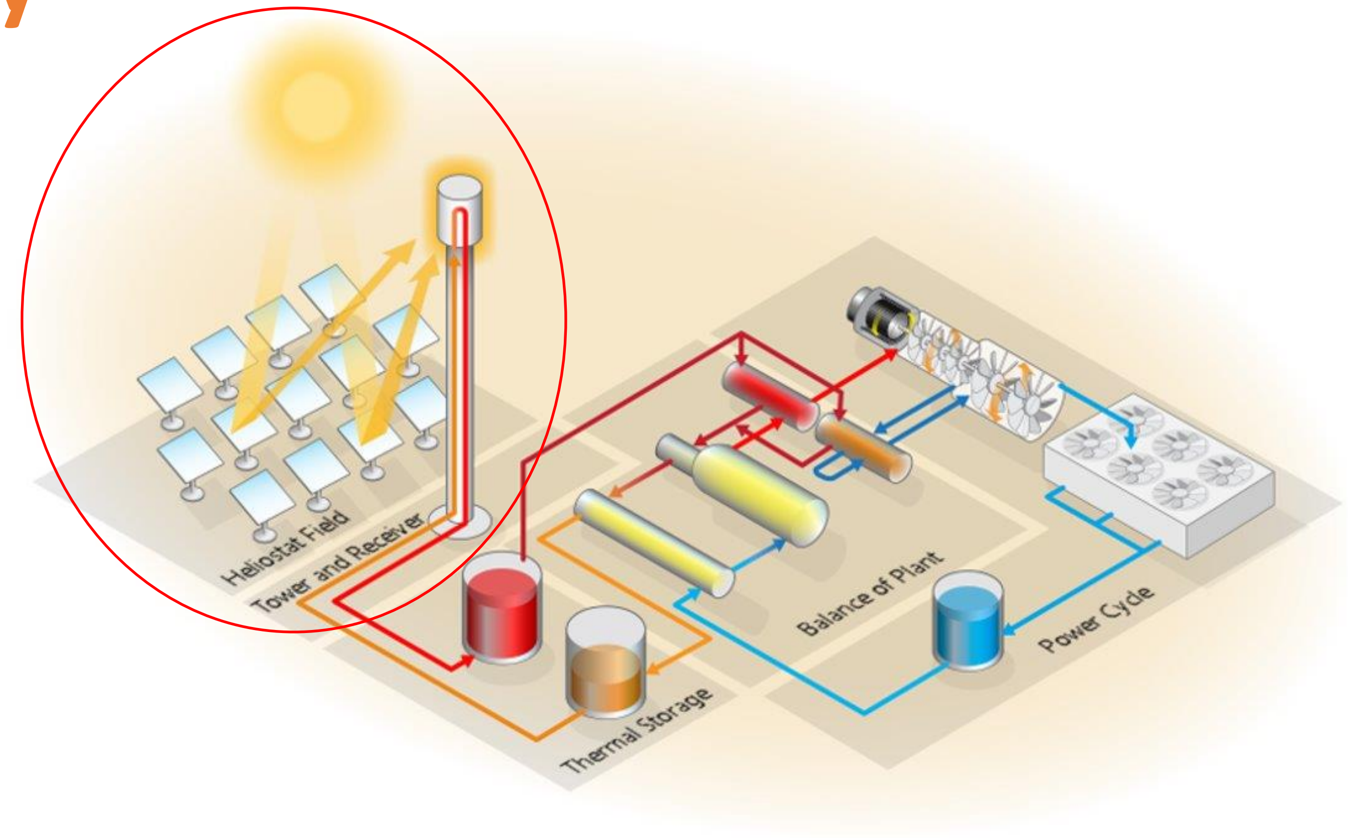
- Form U.S. centers of excellence focused on heliostat technologies to restore U.S. leadership
- Develop strategic core validation and modeling capabilities and infrastructure at DOE's national labs (NREL and Sandia)
- Promote workforce development by integrating academia, industry, and all stakeholders

This talk focuses on work supporting the Technoeonomic Analysis (TEA) task within HelioCon

Image source: https://heliocon.org/about/about_heliocon.html

We attempt to address a TEA gap addressed in the HelioCon Roadmap Study

- Identified TEA gaps:
  - Lack of a validated model for:
    - **solar field O&M costs**
    - high-temperature IPH applications
- Path forward:
  - **Develop a heliostat field O&M model that accounts for the cost of mirror washing and heliostat repairs and replacements, and their impact on heliostat field performance.**
  - Develop a CSP model that creates and incorporates correlations for tower and receiver costs for IPH applications.
  - Coordinate work with other HelioCon topics, perform sensitivity analysis in models, and engage industry to improve knowledge gaps.



Schematic of a CSP plant; our analysis is restricted to the solar field, tower and receiver encircled above.
Image source: Cox et al. (2023)

Agenda

Literature Review

- <u>Soiling</u>
  - Sarver et al. (2013): Arid and windy locations are subject to efficiency losses as high as 10% per day for a horizontal surface
- <u>Improving operations</u>
  - Wolferstetter et al. (2018): Methodologies for PV and parabolic trough plants
    - Clean the solar field with optimal frequency
    - Clean the solar field when reflectance falls below a threshold
    - Assign temporary crews when needed
  - Alon et al. (2014): Wash rate is maximized by optimizing routing
  - Ashley et al. (2018): Optimize short-term routing for two vehicles, which is consistent over the year
  - Zolan and Mehos (2022): Determine economics of extra vehicles on call for dust storms
  - Cholette et al. (2023): Determine staffing levels using stochastic soiling model

<u>Our goal</u>: Optimize, for the life of the plant, the number and type of wash vehicles to use, and the assignment of those vehicles to heliostats.

Mixed-integer nonlinear program: Objective

$(\mathcal{W})$ **Formulation**

$$\min_{P,W,X,E} \sum_{t \in \mathcal{T}} \left(r_t \cdot \sum_{f \in \mathcal{F}} \left(d_{ft} \sum_{v \in \hat{\mathcal{V}}_f} (s_{vt} + \bar{s}_{ft} E_{vt}) X_{vft} \right) + \sum_{v \in \mathcal{V}} c^W_{vt} W_{vt} \right) + \sum_{v \in \mathcal{V}} c^P_v P_v$$

- Revenue losses due to soiling
- Costs of crews, including labor and wash materials
- Costs of vehicles over operating horizon

Mixed-integer nonlinear program: Constraints

$$
\begin{aligned}
\text{subject to} \quad & \sum_{v \in \hat{\mathcal{V}}_f} X_{vft} = 1 && \forall f \in \mathcal{F},\ t \in \mathcal{T} \quad (1a) \\
& E_{vt} = \sum_{f \in \hat{\mathcal{F}}_v} \tau_{vf} \cdot X_{vft} && \forall v \in \mathcal{V},\ t \in \mathcal{T} \quad (1b) \\
& X_{vft} \leq W_{vt} && \forall v \in \hat{\mathcal{V}}_f,\ f \in \mathcal{F},\ t \in \mathcal{T} \quad (1c) \\
& W_{vt} \leq P_v && \forall v \in \mathcal{V},\ t \in \mathcal{T} \quad (1d) \\
& E_{vt} \geq 0 && \forall v \in \mathcal{V},\ t \in \mathcal{T} \quad (1e) \\
& P_v \in \{0,1\} && \forall v \in \mathcal{V} \quad (1f) \\
& W_{vt} \in \{0,1\} && \forall v \in \mathcal{V},\ t \in \mathcal{T} \quad (1g) \\
& X_{vft} \in \{0,1\} && \forall v \in \hat{\mathcal{V}}_f,\ f \in \mathcal{F},\ t \in \mathcal{T}. \quad (1h)
\end{aligned}
$$

Each solar field section must be assigned to one truck in each period

Mixed-integer nonlinear program: Constraints

$$\text{subject to} \quad \sum_{v \in \hat{\mathcal{V}}_f} X_{vft} = 1 \qquad \forall f \in \mathcal{F},\ t \in \mathcal{T} \quad \text{(1a)}$$

$$E_{vt} = \sum_{f \in \hat{\mathcal{F}}_v} \tau_{vf} \cdot X_{vft} \qquad \forall v \in \mathcal{V},\ t \in \mathcal{T} \quad \text{(1b)}$$

$$X_{vft} \leq W_{vt} \qquad \forall v \in \hat{\mathcal{V}}_f,\ f \in \mathcal{F},\ t \in \mathcal{T} \quad \text{(1c)}$$

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$$X_{vft} \in \{0, 1\} \qquad \forall v \in \hat{\mathcal{V}}_f,\ f \in \mathcal{F},\ t \in \mathcal{T}. \quad \text{(1h)}$$

A vehicle's wash period is equal to the sum of the wash times of assigned mirrors

Mixed-integer nonlinear program: Constraints

$$
\begin{aligned}
\text{subject to} \quad & \sum_{v \in \hat{\mathcal{V}}_f} X_{vft} = 1 && \forall f \in \mathcal{F},\ t \in \mathcal{T} && \text{(1a)} \\
& E_{vt} = \sum_{f \in \hat{\mathcal{F}}_v} \tau_{vf} \cdot X_{vft} && \forall v \in \mathcal{V},\ t \in \mathcal{T} && \text{(1b)} \\
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\end{aligned}
$$

Assignment requires hiring, and hiring requires a vehicle purchase

Mixed-integer nonlinear program: Constraints

$$
\begin{aligned}
\text{subject to} \quad & \sum_{v \in \hat{\mathcal{V}}_f} X_{vft} = 1 && \forall f \in \mathcal{F},\ t \in \mathcal{T} \quad \text{(1a)} \\
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\end{aligned}
$$

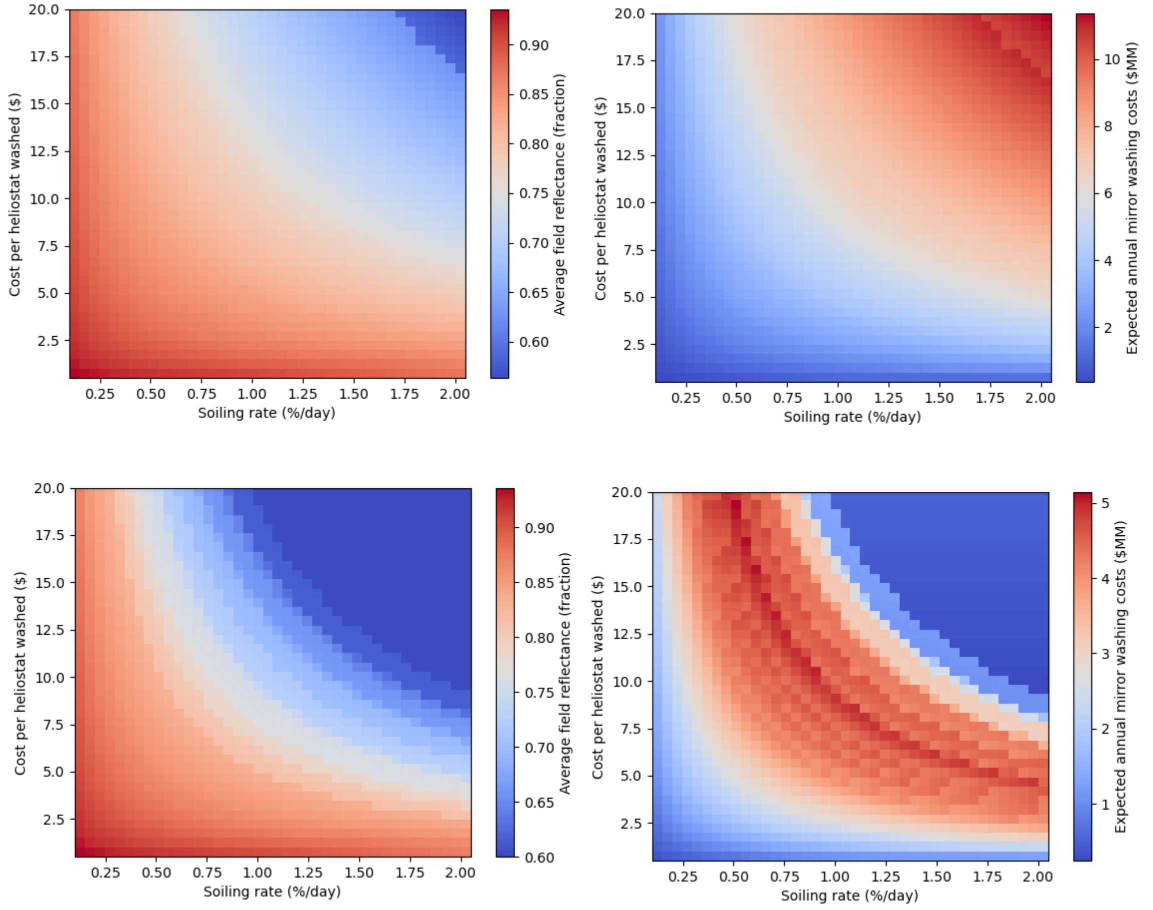
Purchases, hiring, assignments are all binary decisions

Preliminary Results

- We can optimize wash crew planning and obtain expected performance and cost
- If we incorporate uncertainty in cost or soiling rate, estimates with confidence intervals are straightforward
  - However, we want to avoid the assumption of constant soiling loss over time, which is the next step in our exploration

0% minimum reflectance

60% minimum reflectance



Average Reflectance

Annual Costs

Ongoing work

- Introduce stochastic soiling model
- Simulate infrequent events (precipitation, dust storms) and determine impact on costs

Agenda

1. Motivation
2. O&M Cost Forecasting Progress
3. Soiling Studies and Database

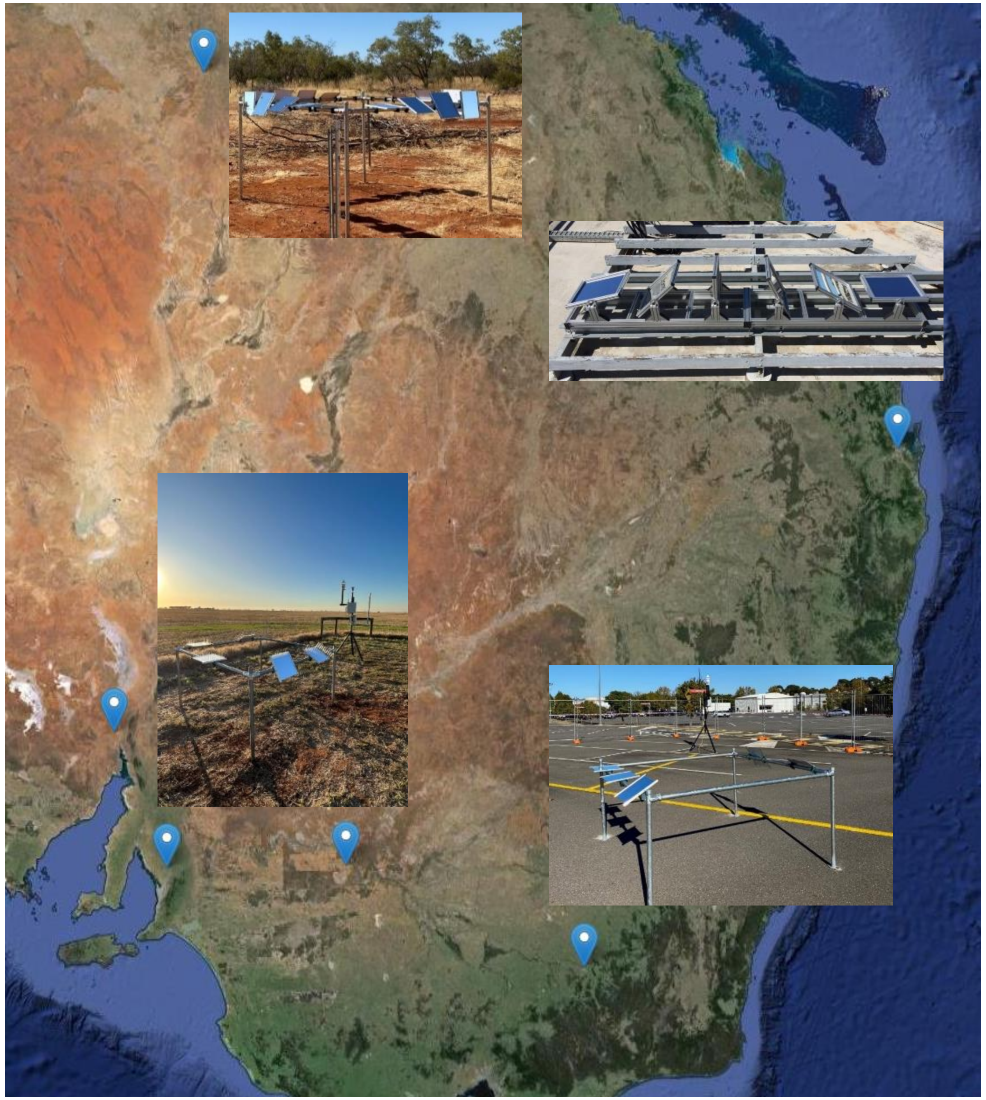
Soiling Experiments

Reflectometers

(Half) Acceptance Angle: 4.6-46 mrad
Wavelength: 0.4-0.8 µm
Repeatability: ± 0.2%

(Half) Acceptance Angle: 145 mrad
Wavelength: 435-1050 µm
Accuracy: <0.4%

Dust samplers



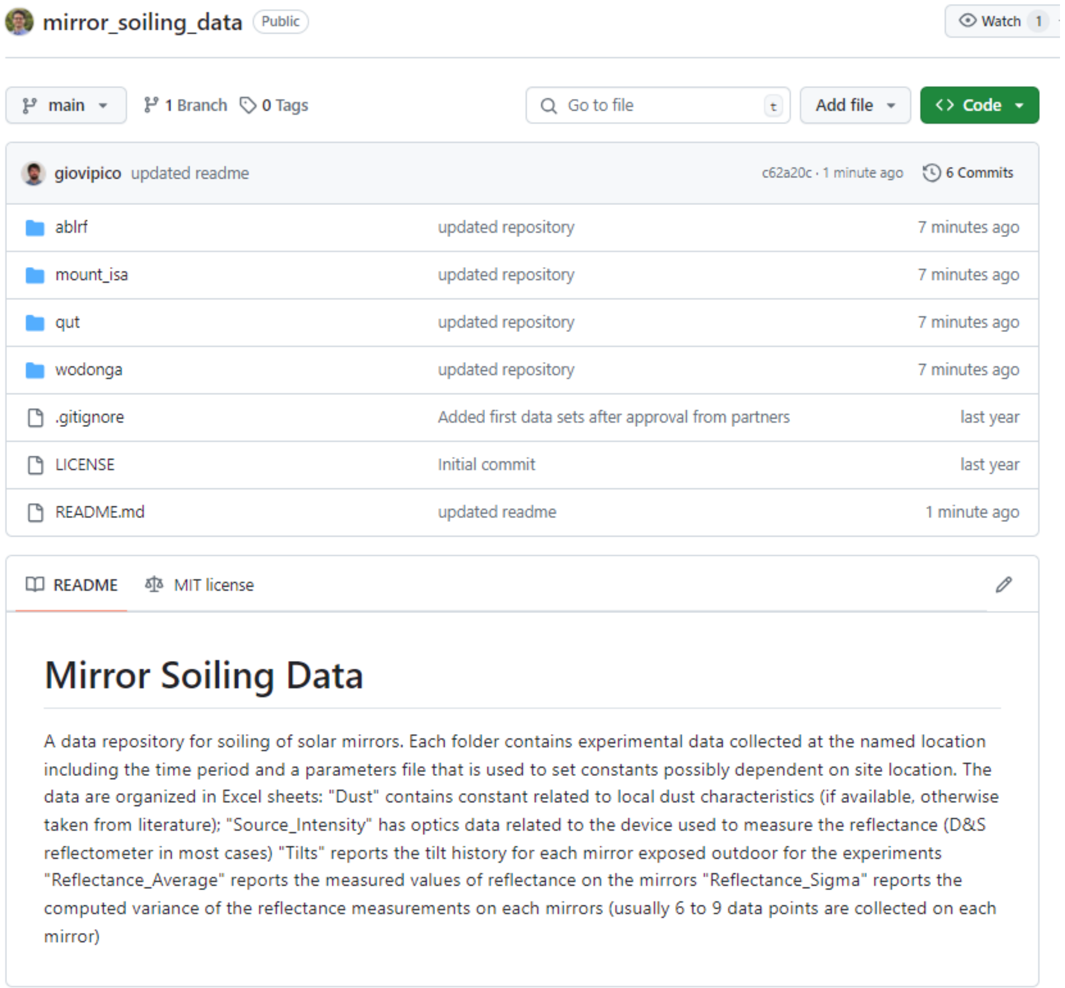
Data collected so far at 6 sites in Australia:

- Brisbane, QLD (QUT)
- Mount Isa, QLD (Vast)
- Wodonga, VIC (Mars Petcare)
- Roseworthy, SA (Uni Adelaide)
- Port Augusta, SA (Vast)
- Carwarp, VIC (RayGen)

Data collection planned at one perspective site in Australia, one research centre in USA, and one research centre in Spain:

- Yadnarie, SA (RayGen)
- Albuquerque, NM (SANDIA)
- Madrid (IMDEA Energy)

Soiling Database


mirror_soiling_data Public
Watch 1
main 1 Branch 0 Tags Go to file Add file Code
giovipico updated readme c62a20c · 1 minute ago 6 Commits

ablrf	updated repository	7 minutes ago
mount_isa	updated repository	7 minutes ago
qut	updated repository	7 minutes ago
wodonga	updated repository	7 minutes ago
.gitignore	Added first data sets after approval from partners	last year
LICENSE	Initial commit	last year
README.md	updated readme	1 minute ago

README MIT license

Mirror Soiling Data

A data repository for soiling of solar mirrors. Each folder contains experimental data collected at the named location including the time period and a parameters file that is used to set constants possibly dependent on site location. The data are organized in Excel sheets: "Dust" contains constant related to local dust characteristics (if available, otherwise taken from literature); "Source_Intensity" has optics data related to the device used to measure the reflectance (D&S reflectometer in most cases) "Tilts" reports the tilt history for each mirror exposed outdoor for the experiments "Reflectance_Average" reports the measured values of reflectance on the mirrors "Reflectance_Sigma" reports the computed variance of the reflectance measurements on each mirrors (usually 6 to 9 data points are collected on each mirror)

Reflectance data collected in the aforementioned sites are being made publicly available in a "soiling database" currently hosted in GitHub

Discussion is ongoing regarding improved solutions for host website and data usage availability

Industrial partner data are subjected to NDAs and sharing approval

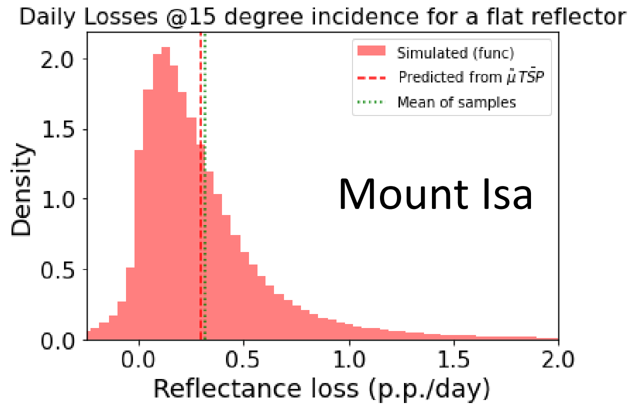
https://github.com/cholette/mirror_soiling_data

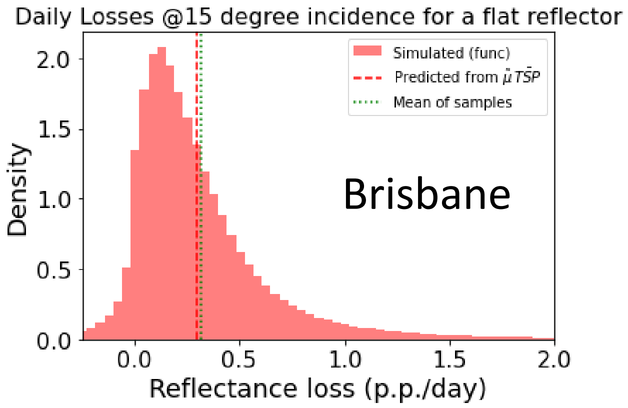
Daily Soiling Losses Assessment

The developed soiling model admits a straightforward procedure for estimating soiling rate distributions:

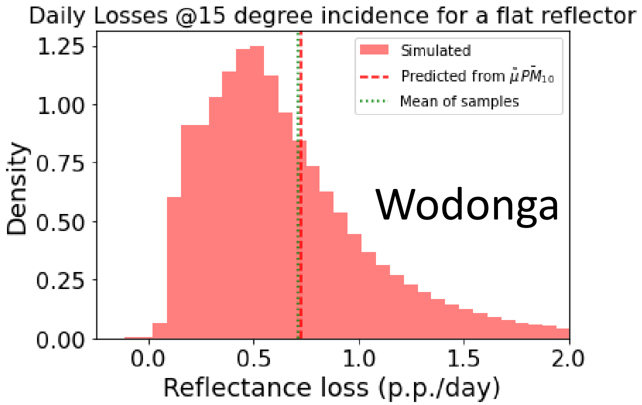
- Sample parameters (from estimated distribution)
- Sample dust loadings
- Sample from resulting reflectance change distribution
- Repeat M times

Results are presented for some of the surveyed sites

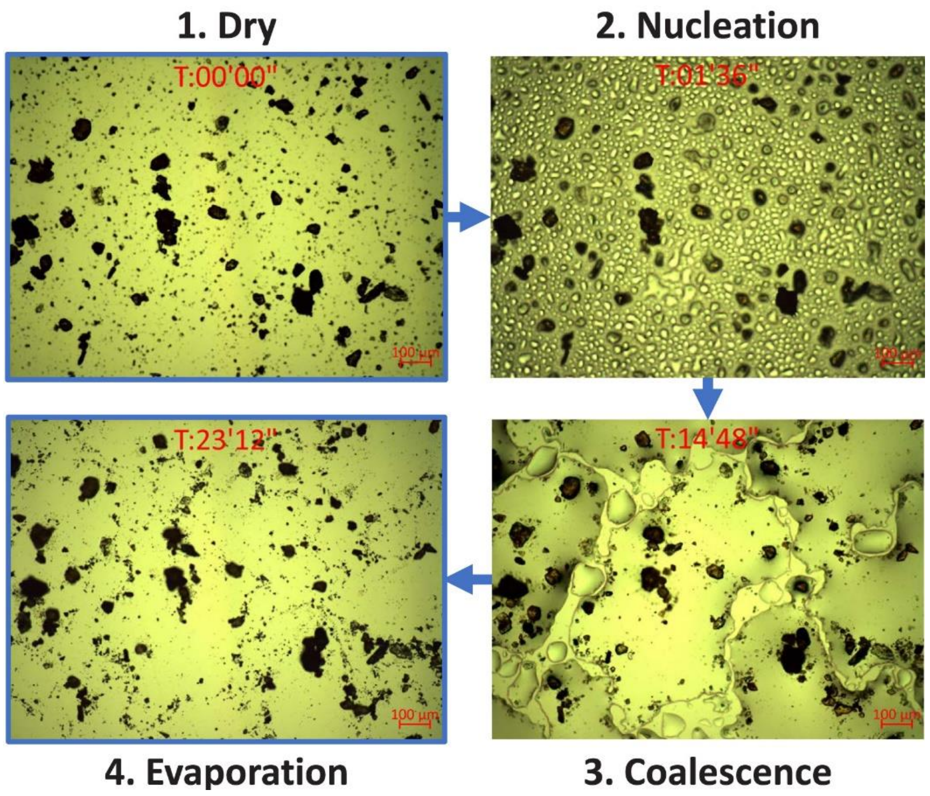




Carwarp



Condensation Impact on Soiling

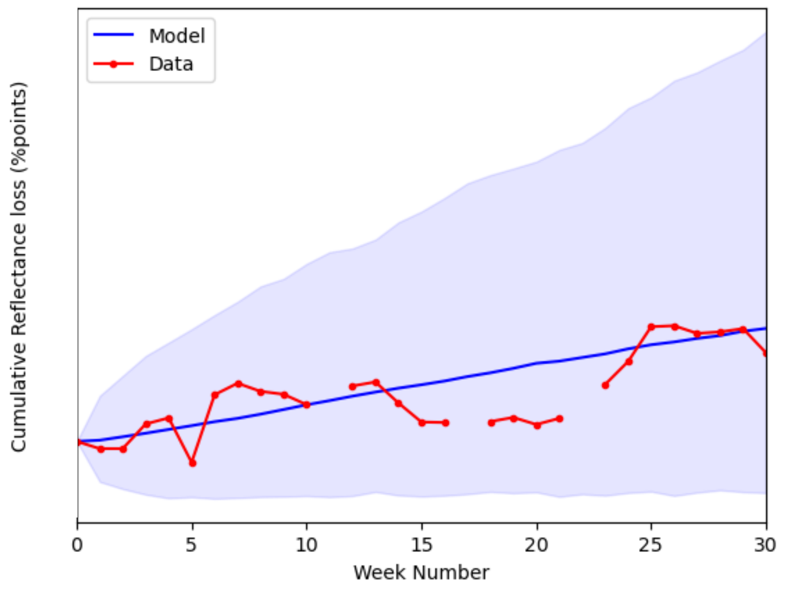


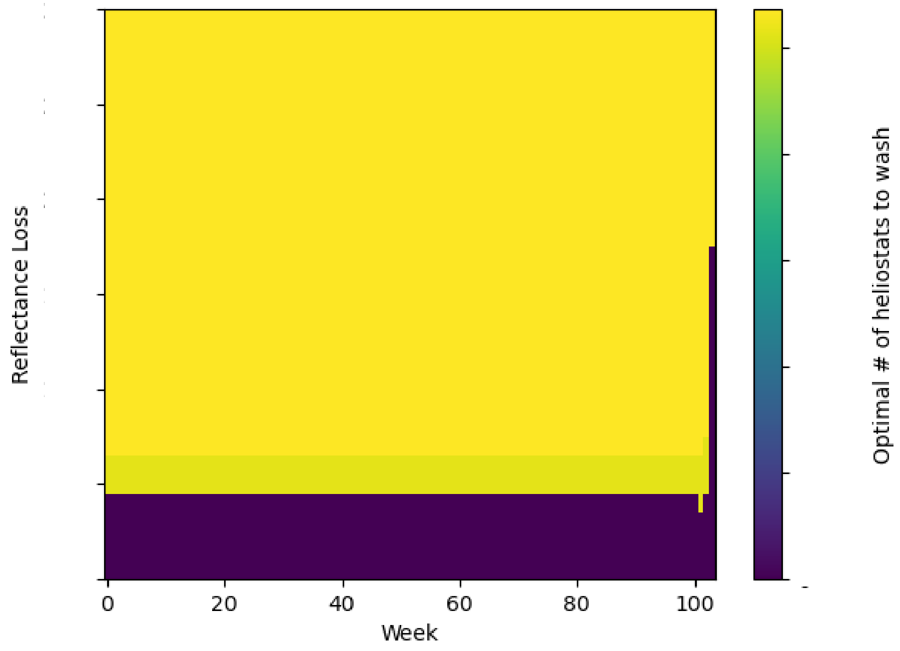
Key findings:

- Heavy dew tests showed higher cleanliness values compared to lower condensation loads and dry conditions
- Larger mean particle diameters were linked to higher condensation loads due to agglomeration of smaller particles, while increasing tilt angles decreased mean diameters.
- Increasing tilt angle from horizontal to 70 degrees reduced dust deposition by 80% and 50% for dry and evaporated samples, respectively.
- An inter-comparison of devices revealed a strong correlation, particularly between the pFLEX and D&S specular reflectometers, with a Pearson correlation of 97%.

Mirror washing at Ivanpah

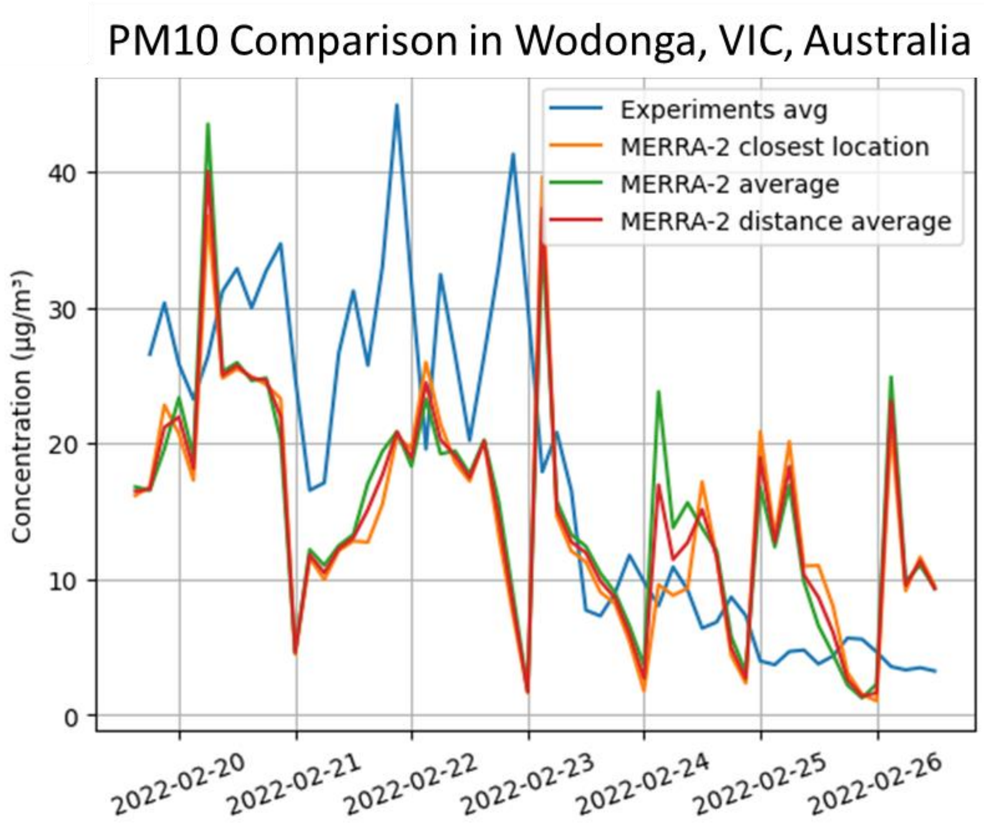
- Analyzed sectorial losses
- Fit field-average model (right, top)
- Optimized reflectance-based cleaning
- Can often be simplified to clean/don't clean (right, bottom)
- Can offer significant savings compared to fixed-schedule cleaning (bottom)

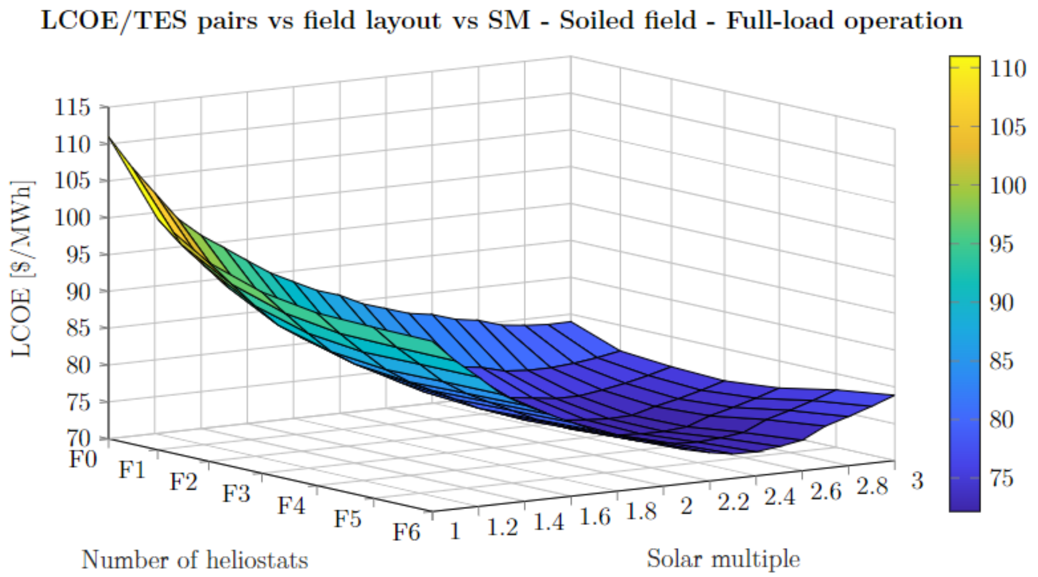




Soiling Subtask ongoing activities

- Building the soiling database — permissions and new campaigns
- Design considering soiling (bottom)
- Benchmarking activities
  - Satellite reanalysis vs. ground measurements (right)
  - Deposition + loss models from literature





- Engagement with international researchers working on soiling (e.g. IMDEA, PSA, Fraunhofer ISE)
- Modelling refinements on horizon

Questions?

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