Stochastic Assessment of Predictions and Uncertainties for Reflectance Losses Based on Experimental Data for Three Australian Sites

G. Picotti, H. Truong-Ba, C.B. Anderson, M.E. Cholette, T.A. Steinberg, B. Leslie

SolarPACES 2023

11th October 2023, Sydney, NSW, Australia

QUT

HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power

ASTRI
Australian Solar Thermal Research Institute

Content

- Introduction
- Reflectance Loss Model
- Experimental Sites Characterization
- Results
- Conclusions

Introduction

- Soiling is a longtime concern in CSP
- Losses between 0.3%-3% per day reported*,**
- This uncertainty is a key risk factor for financing
- Cleaning may be a significant effort in some locations
- Influential factors not well understood. When does soiling "matter"?

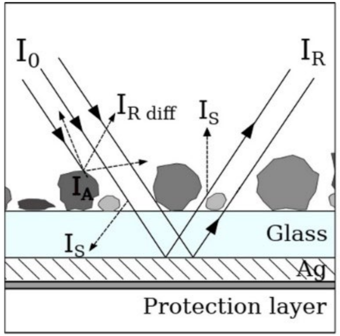
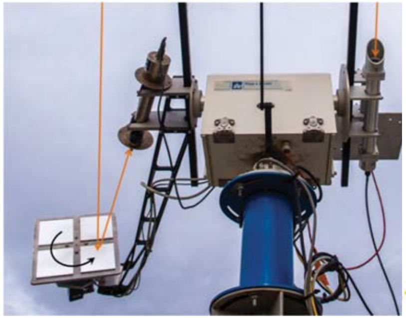


Image from ***


TraCS


D&S 15R-RGB

*A. Alami Merrouni, et al, Renewable Energy, 2020
** K. Ilse, et al., *Joule, 2019*
*** Bellmann et al. (2020), "Comparative Modeling of Optical Soiling Losses for CSP and PV Energy Systems."

Introduction

- Many existing soiling models are available in literature, two main categories:
  - Based on regression or AI (e.g. ANN)
  - Based on physical process modelling
- Regression models are able to provide predictions with “little” effort but may not be easily interpretable, difficult to extrapolate, and tough to diagnose without additional data
- Physical models aid interpretability and increase potential for “portability” to other sites, but require reliable models for each subprocess involved, which are not always accurate
- Statistical tools can be integrated with physically-based soiling models to assess the inherent uncertainty of reflectance losses predictions

(Simplified) Reflectance Loss Model*

- Discretize into intervals $t = t_0 + k\Delta t$, assume deposition velocity is constant in this time
- Sample dust variables at beginning of each interval: $PM_{x,k}\ k = 1,2,\ldots,K$
- Average tilts over each interval, θ_k
- $\tilde{\mu}$ is a property of the site and airborne dust characteristics (size distribution, composition)

$$\hat{A}_{soil,k} \approx \sum_{i=0}^{k-1} \frac{PM_{x,i}}{\overline{PM}_x} \cdot cos(\theta_i) \cdot \tilde{\mu}$$

Cumulative area loss since t_0

$$\hat{\rho}_k = \rho_0 \left(1 - \frac{2\hat{A}_{soil,k}}{cos(\phi_k)\, A_{mirror}}\right)$$

Reflectance at incidence angle ϕ_k

* G. Picotti et al. (2023), Stochastic Soiling Loss Models for Heliostats in Concentrating Solar Power Plants, *Solar Energy 263*

Reflectance Loss Model

Uncertainty is modelled as an error on the deposition velocity

$$\hat{A}_{soil,k} \approx \sum_{i=0}^{k-1} \frac{PM_{x,i}}{\overline{PM_x}} \cdot \cos(\theta_i) \cdot [\tilde{\mu} + \varepsilon_i]$$

where $\varepsilon_i \sim \mathcal{N}\left(0, \sigma_{dep}^2\right)$ are independent non-identical noise terms.

This model has two parameters: $\tilde{\mu}$ and σ_{dep}^2

Reflectance measurements are also considered uncertain:

$$r_{k_i} = \hat{\rho}_{k_i} + \epsilon_{k_i}$$

With $\epsilon_{k_i} \sim \mathcal{N}\left(0, \sigma_{l,k_i}^2\right)$ is the uncertainty for the reflectance measurement (estimated by repeated measurements)

Reflectance Loss Model

Probability distribution

Assuming a fixed incidence and acceptance angle (e.g. a handheld reflectometer)

$$r_l - r_k \sim \mathcal{N}\left(\mu_{l,k}, \sigma_{l,k}^2\right)$$

i.e. a normal distribution. The mean and variance is

$$\mu_{l,k} = -\tilde{\mu} b(\phi_k) \sum_{j=k}^{\ell-1} \alpha_j \cos(\theta_j)$$

$$\sigma_{\ell,k}^2 = \sigma_{dep}^2 b(\phi)^2 \sum_{j=k}^{\ell-1} \alpha_j^2 \cos^2(\theta_j) + \sigma_{r,k}^2 + \sigma_{r,\ell}^2$$

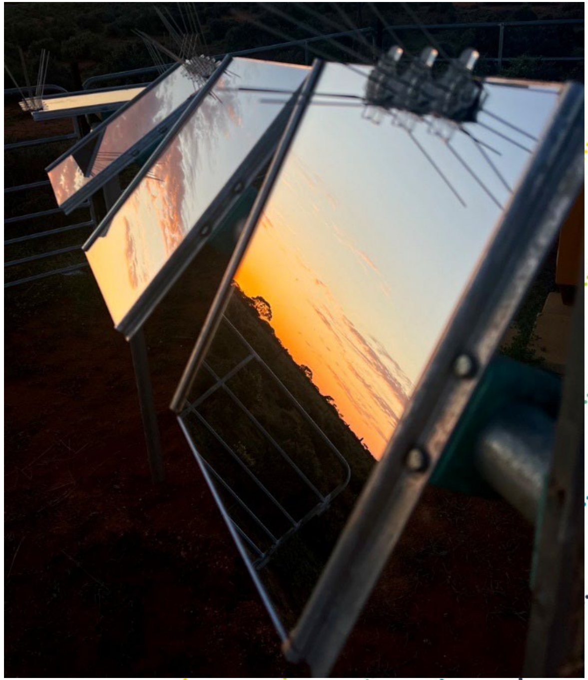
Uncertainty on area loss

Uncertainty on measurements

Reflectance Loss Estimation

Via Monte Carlo Simulation

- The simplified 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



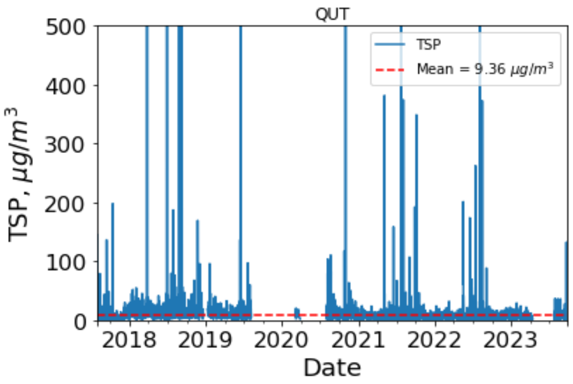
Experimental Sites Characterization

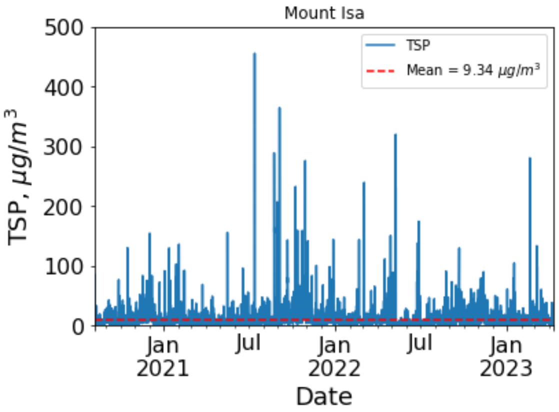
- Purposes: validation, understand data needs, assess orientation impacts, model fitting
- Setup: Dust monitor, weather station, mirror sample rig
- Campaigns lasted ~7 days
- Measurements taken 2x per day
- Rain resets the experiments

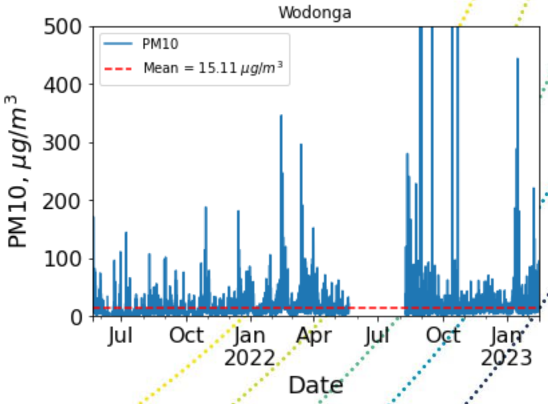
Acceptance Angle: 4.6-46 mrad
Wavelength: 0.4-0.8 µm
Repeatability: ± 0.2%

Experimental Sites Characterization

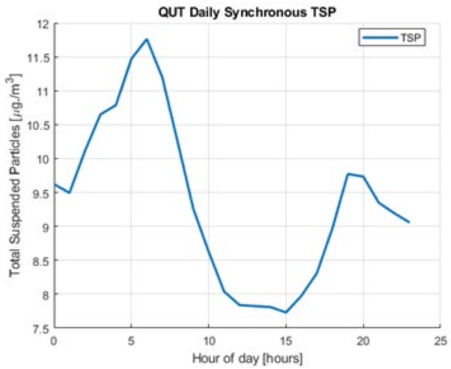
- Airborne dust concentration is measured at each site.
- Different dust samplers provide either TSP or PMx.
- Other weather parameters are also measured but not shown here as the model depends only on TSP/PMx.

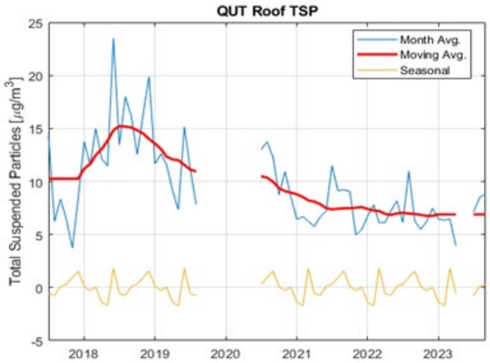






Experimental Sites Characterization

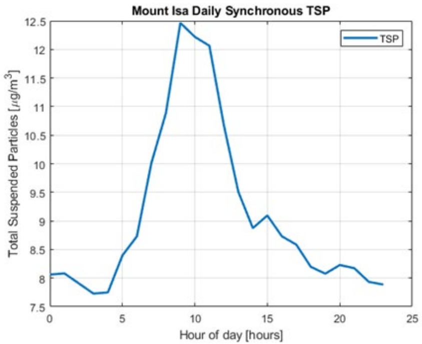


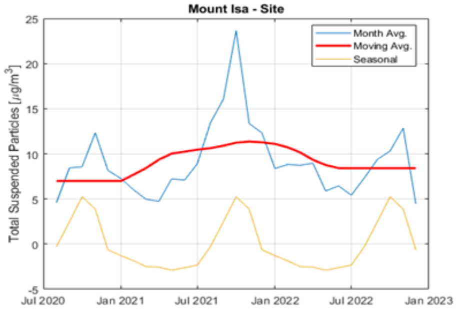


Brisbane

- The collected data are analysed to assess seasonal and daily patterns.
- The data measured at QUT in the Brisbane CBD do not present any clear seasonal pattern.
- A daily pattern is instead clearly identifiable for traffic rush hours in the neighbouring highway.
- The TSP average is around 9.3μg/m^3.

Experimental Sites Characterization

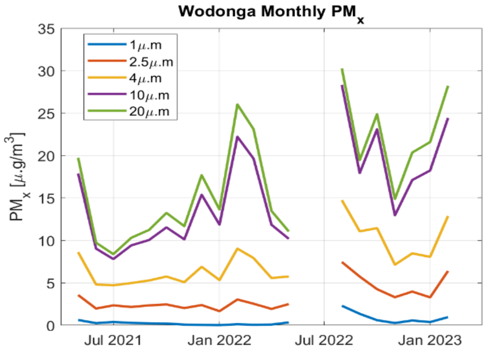


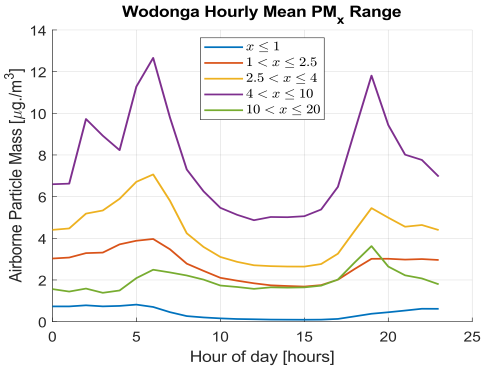


Mount Isa

- The collected data are analysed to assess seasonal and daily patterns.
- The data measured at the outback site in Mount Isa shows a seasonal pattern with higher dust during dry season due to absence of rain scavenging phenomena.
- A daily pattern is observable, likely due increasing wind during daytime carrying more dust.
- The TSP average is around 9.3μg/m^3.

Experimental Sites Characterization



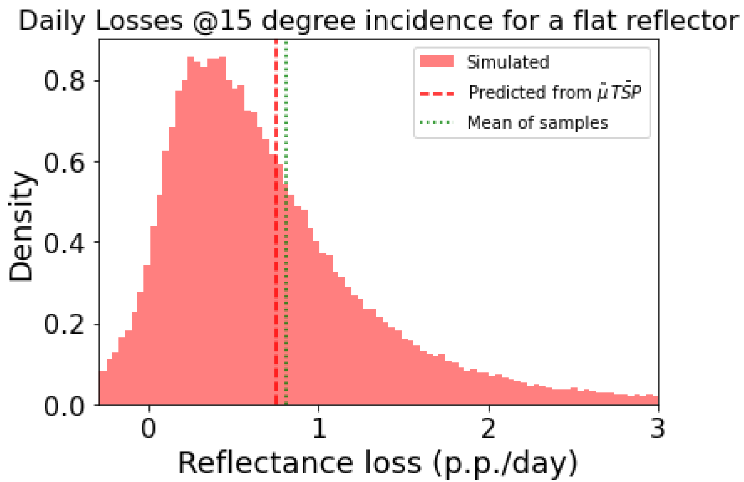


Wodonga

- The collected data are analysed to assess seasonal and daily patterns.
- The sampler in Wodonga also enables assessment of the airborne dust size distribution.
- Roughly 1.5 years of data in Wodonga are not enough for a thorough seasonal assessment.
- A daily pattern is clearly identifiable for traffic rush hours in the neighbouring highway.
- Majority of dust is between 2.5μm and 10μm in size.

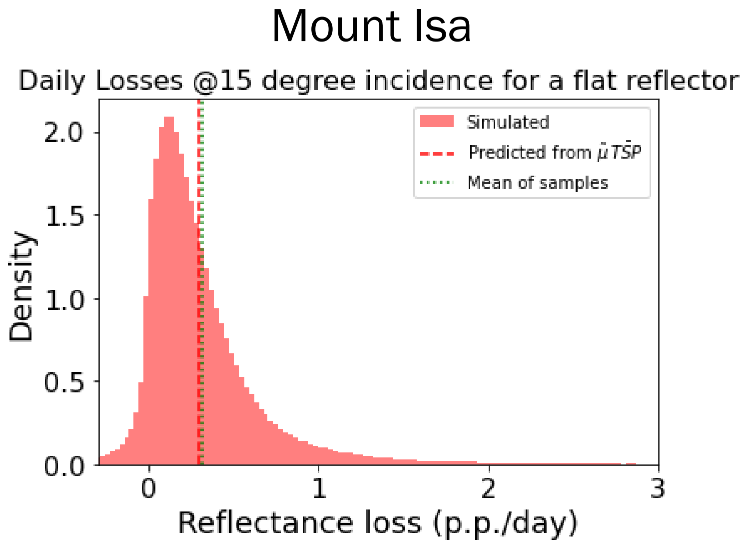
Results

Brisbane



- The mean of the expected reflectance daily losses is 0.77 pp/day
- The median of the expected reflectance daily losses is 0.56 pp/day
- The skewness of the distribution is strongly positive as can be observed by the long right tail
- The width of the distribution suggests that most daily reflectance losses happen in the interval between 0.26 pp/day and 1.00 pp/day
- The 97.5th percentile is 2.88 pp/day, which can be assessed as the most likely "worst case scenario"

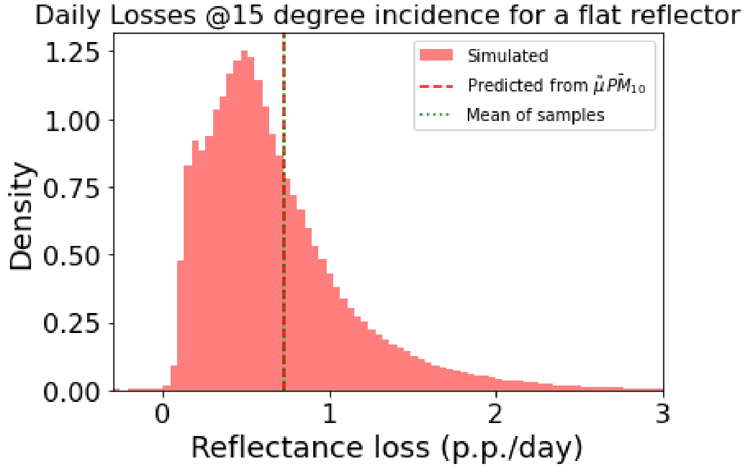
Results



- The mean of the expected reflectance daily losses is 0.31 pp/day
- The median of the expected reflectance daily losses is 0.22 pp/day
- The skewness of the distribution of expected reflectance daily losses is only just positive
- The width of the distribution is limited suggesting that most reflectance daily losses happen between 0.09 pp/day and 0.41 pp/day
- The 97.5th percentile is 1.28 pp/day, which can be assessed as the most likely "worst case scenario"

Results

Wodonga



- The mean of the expected reflectance daily losses is 0.72 pp/day
- The median of the expected reflectance daily losses is 0.58 pp/day
- The skewness of expected reflectance daily losses is strongly positive as can be observed by the long right tail
- The width of the distribution suggests that most reflectance daily losses happen in the interval between 0.37 pp/day and 0.87 pp/day
- The 97.5th percentile is 1.99 pp/day, which can be assessed as the most likely "worst case scenario"

Conclusion

- A stochastic reflectance loss model has been applied on three datasets to provide statistical distributions of daily reflectance losses.
- **Only TSP/PMx data are used for the reflectance losses estimates. This suggest a methodology to obtain expected losses at site selection.**
- Reflectance losses are predicted to be lower in Mount Isa (0.31 pp/day) and higher in Brisbane (0.77 pp/day).
- The developed methodology is paramount for assessment of plant profitability and cleaning resourcing/scheduling at site selection, de-risking prospective CSP plants financing and deployment.
- New experimental sites are being investigated at ABLRF (Adelaide), Port Augusta, NSTTF (Sandia Lab, Albuquerque, USA).
- PLEASE JOIN US FOR THE SOILING DATABASE !

Acknowledgment

ARENA

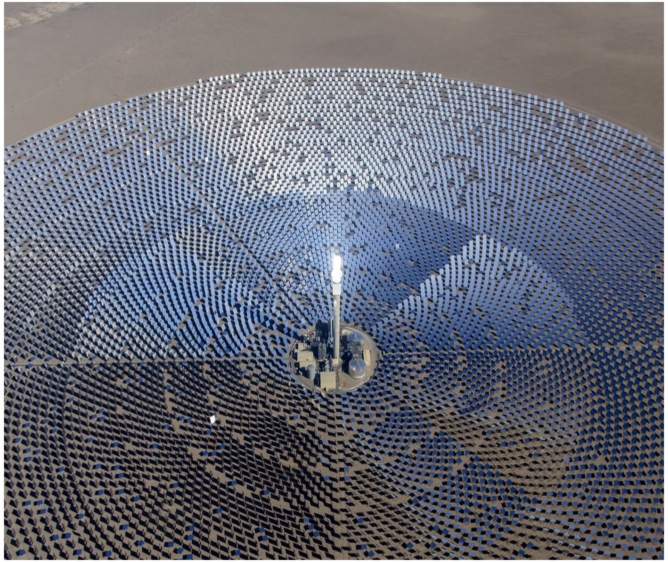
Australian Government

Australian Renewable Energy Agency

The Australian Solar Thermal Research Institute (ASTRI) Program is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA)

QUT

HelioCon
Heliostat Consortium for Concentrating Solar-Thermal Power



Thank you

g.picotti@qut.edu.au