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

Heliostat Consortium: Heliostat Soiling

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SolarPACES 2022
September 29th 2022

conceptual design • components • integration • mass production • heliostat field

Outline

- Motivation, Scope, and Team
- Roadmapping activity: where can HelioCon make an impact?
  - State of the art in measurements, modelling, and mitigation
  - Analysis of Research Gaps
- Recommended Pathway & Ongoing work
- Conclusions

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NREL Transforming ENERGY

Sandia National Laboratories

ASTRI

Roadmap to Advance Heliostat Technologies for Concentrating Solar-Thermal Power

Guangdong Zhu,[1] Chad Augustine,[1] Rebecca Mitchell,[1] Matthew Muller,[1] Parthiv Kurup,[1] Alexander Zolan,[1] Shashank Yellapantula,[1] Randy Brost,[2] Kenneth Armijo,[2] Jeremy Sment,[2] Rebecca Schaller,[2] Margaret Gordon,[2] Mike Collins,[3a] Joe Coventry,[3b] John Pye,[3b] Michael Cholette,[3c] Giovanni Picotti,[3c] Maziar Arjomandi,[3d] Matthew Emes,[3d] Daniel Potter,[3a] and Michael Rae[3a]

1 National Renewable Energy Laboratory
2 Sandia National Laboratories
3 Australia Solar Thermal Research Institute (ASTRI)
3a The Commonwealth Scientific and Industrial Research Organization
3b Australian National University
3c Queensland University of Technology
3d University of Adelaide

Heliostat Consortium (HelioCon)

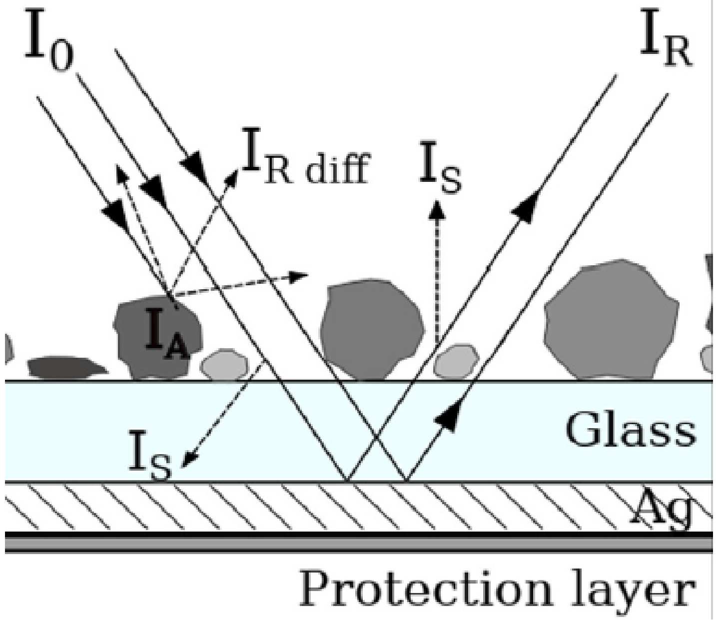
US Energy Department has funded 5-year heliostat consortium:

- To advance U.S. heliostat technologies, capabilities and national workforce
- $25M + cost share: 30% of funds allocated to RFPs for engagement of US industries and other stake holders

conceptual design • components • integration • mass production • heliostat field

Soiling losses for CSP plants

- Loss of reflectance can be an important detrimental factor in solar tower plant productivity
- Losses between 0.3%-3% per day reported*,**
- Cleaning costs and productivity losses due to soiling have both a significant and comparable costs (in some locations?)
- Influential factors are not well understood. When does soiling “matter"



Bellmann et al., *Solar Energy*, 2020

*A. Alami Merrouni, et al, Renewable Energy, 2020
** K. Ilse, et al., *Joule, 2019*

Soiling subtask

Motivation, Scope, and Team

- Started in February 2022
- Goal: characterize soiling losses and plan mitigation measures for existing and planned CSP plants
- Key areas:
  - Soiling measurements
  - Modelling and characterizing soiling processes
  - Mitigation (including cleaning and coatings)

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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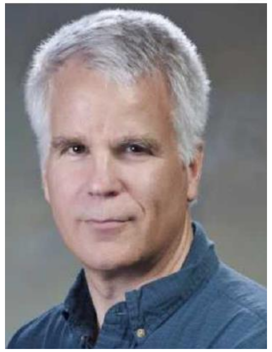
Rebecca Schaller



Randy Brost

QUT

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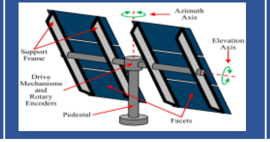
Michael Cholette

Giovanni Picotti

Year 1: Roadmapping Study

Heliostat Development Cycle	Conceptual Design:	Heliostats Components:	An Integrated Heliostat:	Mass Production of Heliostats:	A Heliostat Field:
					

- Roadmapping study for each topic
  - State of the art
  - Gaps & Gap analysis
  - Recommended pathway
- Roadmapping study report released[1]
- Soiling sections: Section 11 & Appendix A

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1. https://www.osti.gov/biblio/1888029

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Roadmap: State of the Art Review

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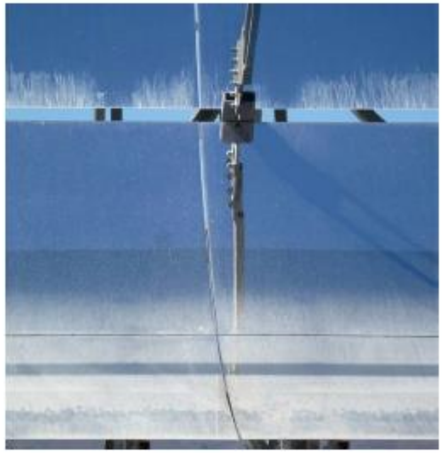
Reflectance measurements

*A. Heimsath, INSHIP Deliverable 3.4, 2(

(A) TraCS (TraCS4 variant shown)

Guidelines

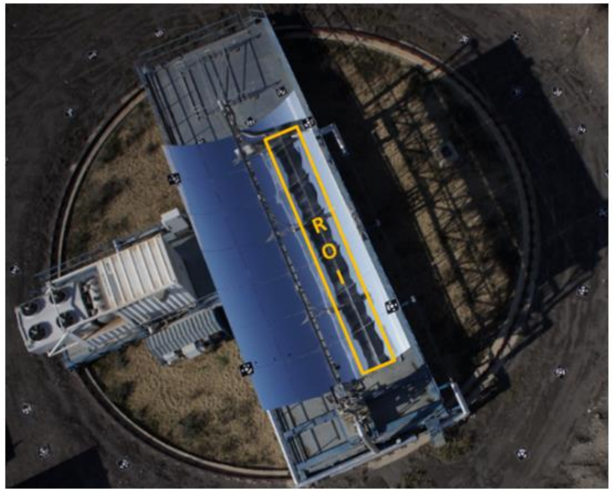
Recommendations for reflectance measurements on soiled solar mirrors



Version 0.1

July 2022

Authors: F. Wolfertstetter (DLR), F. Sutter (DLR), E. Lüpfert (DLR), M. Montecchi (ENEA), C. Pelayo (UNIZAR), C. Heras (UNIZAR), G. Bern (Fraunhofer ISE), M. Bitterling (Fraunhofer ISE), A. Heimsath (Fraunhofer ISE), A. Fernández-García (CIEMAT), J. Wette (CIEMAT), C.-A. Asselineau (IMDEA Energy, ANU), Guangdong Zhu (NREL)



A picture from Qfly*

*F. Wolfertstetter et al., *SolarPACES* 2019

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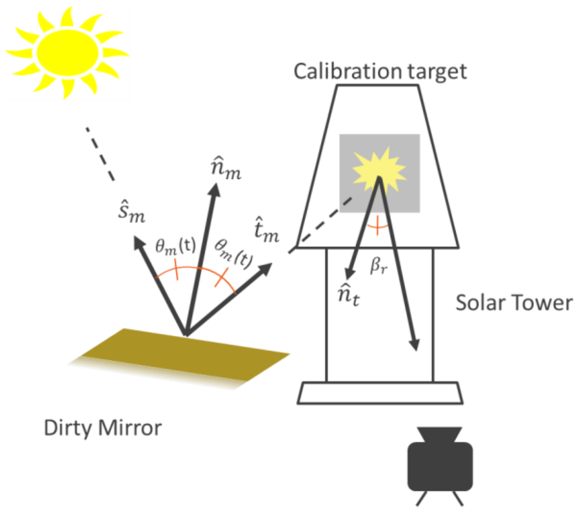
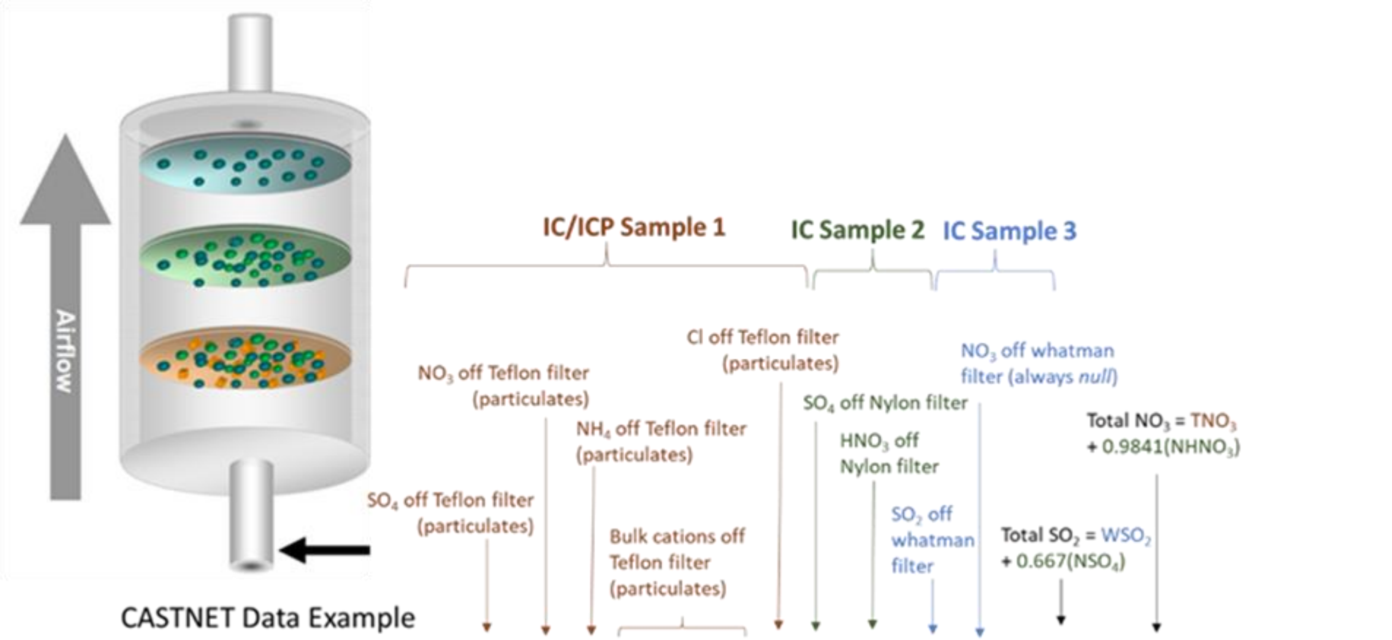


**Wang, et al., *SolarPACES* 2019

Airborne dust measurements

PM_X, TSP measured with samplers like this:

Composition measurements available (e.g. CASTNET below), but not typically exploited in modelling:



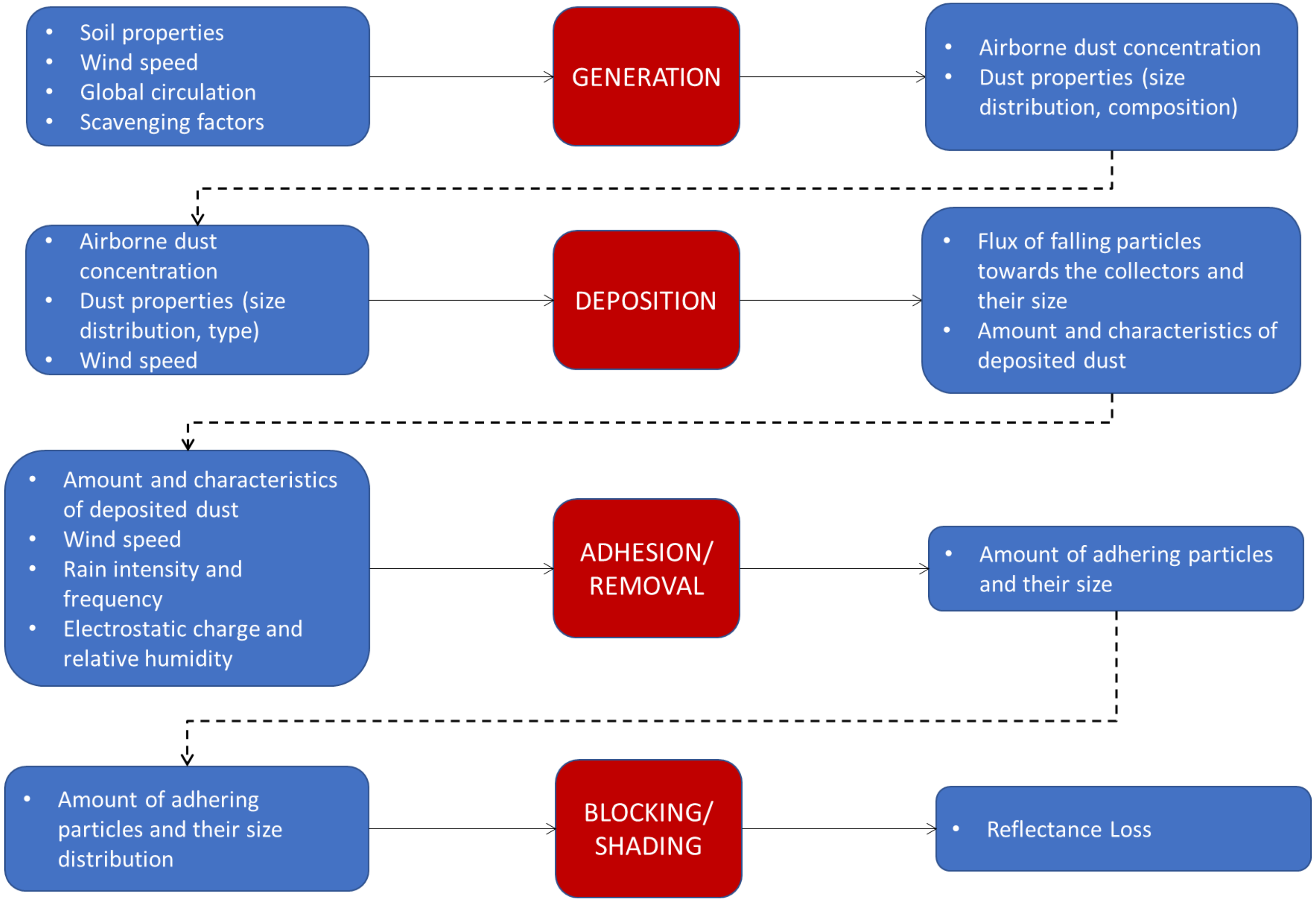
CASTNET Data Example

SITE_ID	TYPE	DATEON	DATEOFF	TSO4	TNO3	TNH4	CA	MG	NA	K	CL	NSO4	NHNO3	WSO2	WNO3	TOTAL_SO2	TOTAL_NO3	
VOY413	C	01/28/2020 11:50:00	02/05/2020 10:47:00	0.598	1.455	0.584	0.036	0.012	0.061	0.023	0.041	0.066	0.298	0.119	null	0.163	1.749	More data...

Do Not Distribute Beyond the Team

Modelling & Characterizing Soiling

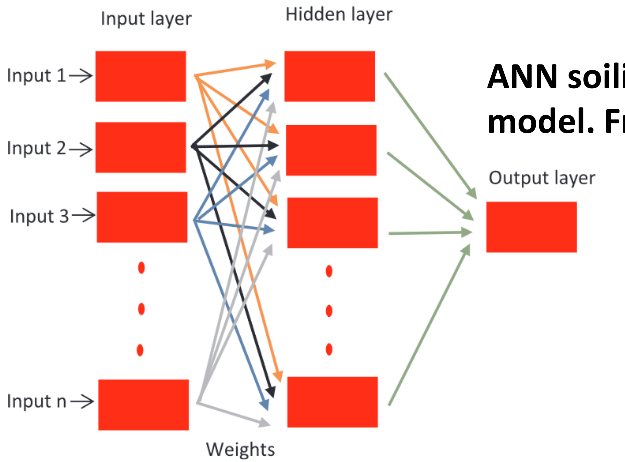
Overview of soiling processes



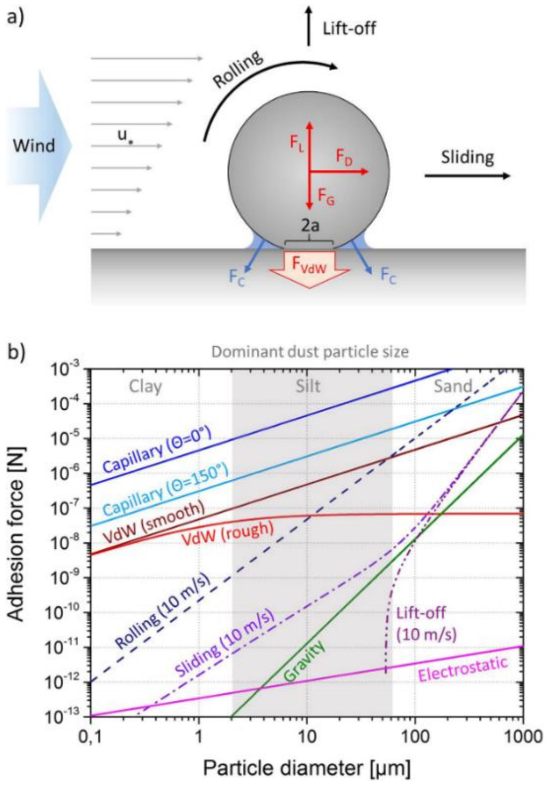
From: G. Picotti et al., *Renewable and Sustainable Energy Reviews*, 2018.

Soiling loss modelling for CSP plants

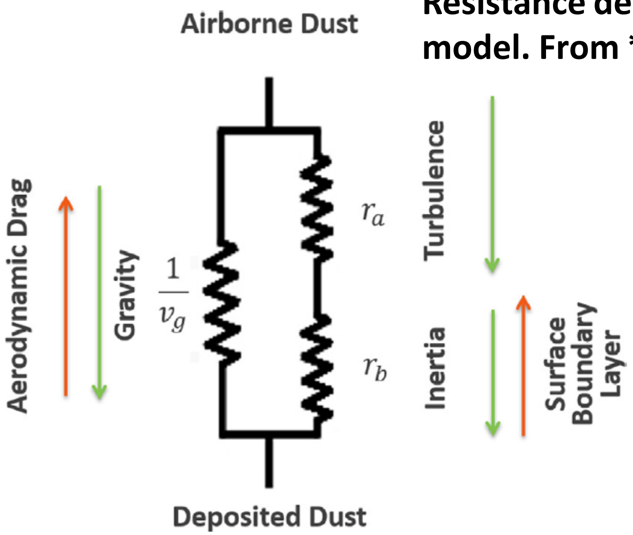
- Basic division: physical vs. regression/ AI (e.g. ANN) approaches*,**
- Nice feature of AI: reasonable predictions for a site without too much "effort"
- Challenges with this approach:
  - Physical meaning lost
  - (likely) poor extrapolation to other sites
  - Bad predictions hard to diagnose — only remedy is "more data"
- Bottom line: AI great for existing plants, portability is not clear



ANN soiling model. From **



Removal/Adhesion modes. From ***

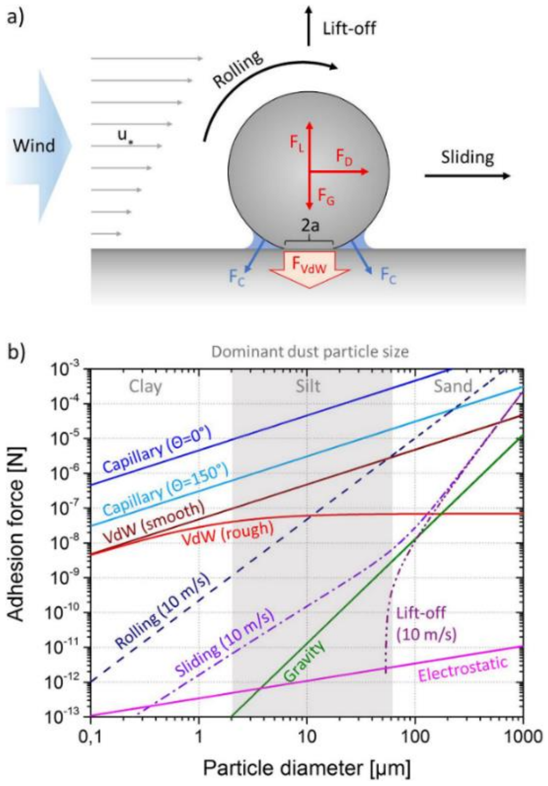


Resistance deposition model. From ****

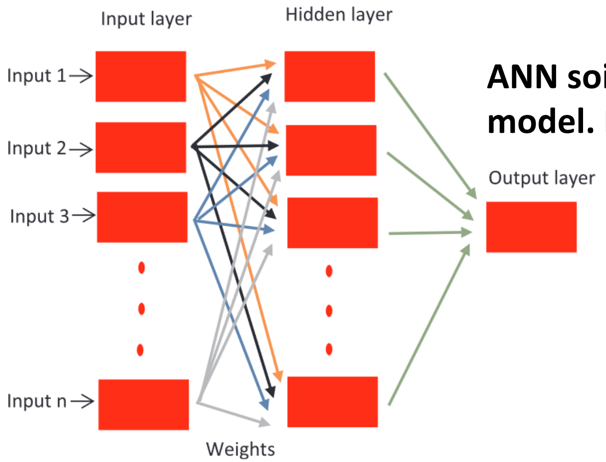
* Bonanos, et al., *SolarPACES 2019*
** Conceição, and Collares-Pereira, *Solar Energy Materials and Solar Cells*, 2018
*** Ilse et al., *Renewable and Sustainable Energy Reviews*, 2018
**** *G. Picotti et al., Solar Energy, 2018*

Soiling loss modelling for CSP plants

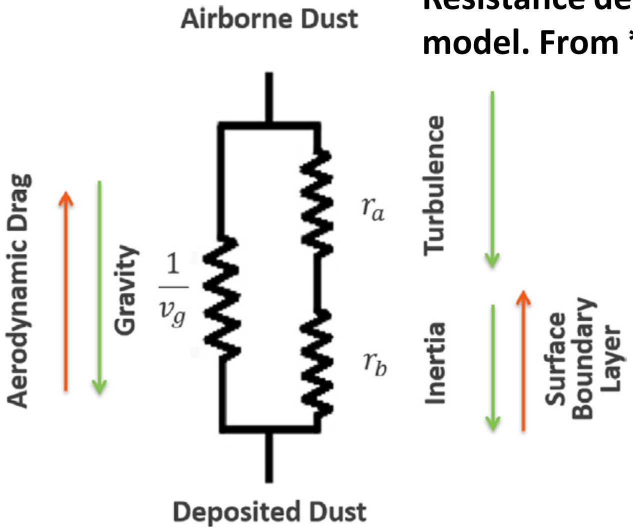
- Soiling losses during site selection are highly uncertain
- Among the few physical, most are resistance-like models
- Many unvalidated simplifying assumptions (moisture ignored, spherical particles, site “roughness”)



Removal/Adhesion modes. From ***



ANN soiling model. From **



Resistance deposition model. From ****

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** Conceição, and Collares-Pereira, *Solar Energy Materials and Solar Cells*, 2018
*** Ilse et al., *Renewable and Sustainable Energy Reviews*, 2018
***** G. Picotti et al., Solar Energy, 2018*

Mitigation

- Basic challenges: cleaning system selection, how many cleaning devices to buy (if any), and when to clean.
- Cleaning systems vary widely, but trucks (either contactless or brushed) are common for CST heliostats
- Significant automation activity in Fresnel, PV, Parabolic Trough, some newer systems for tower systems (Cosin, Heliogen)
- Anti-soiling coatings seem effective in some cases, but durability remains a question

FRENELL Robot

Hector Robot

*A. Heimsath, INSHIP Delivererable 3.4

Cosin Solar Automated System

http://www.supconsolar.com.cn/en/news/detail/id/10099.html, Accessed 2-September

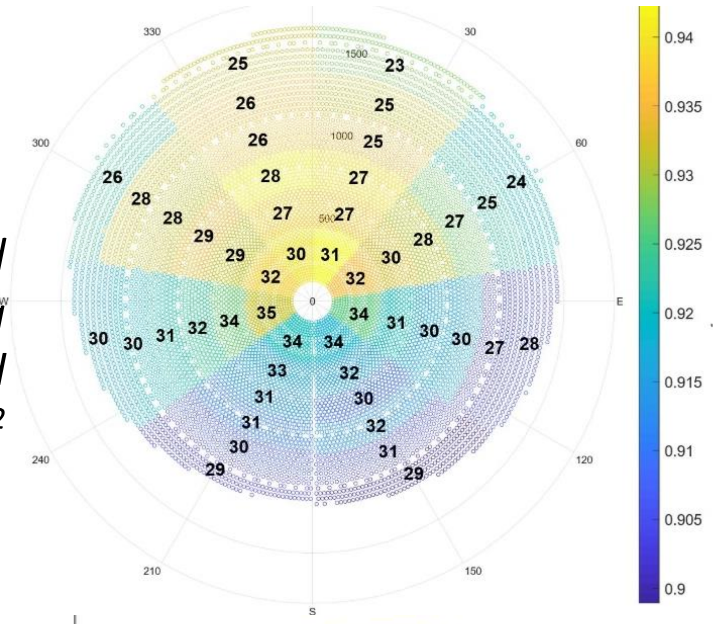
PSA manual washing

**.Bouaddi et al., *Sustainability*, 2018,

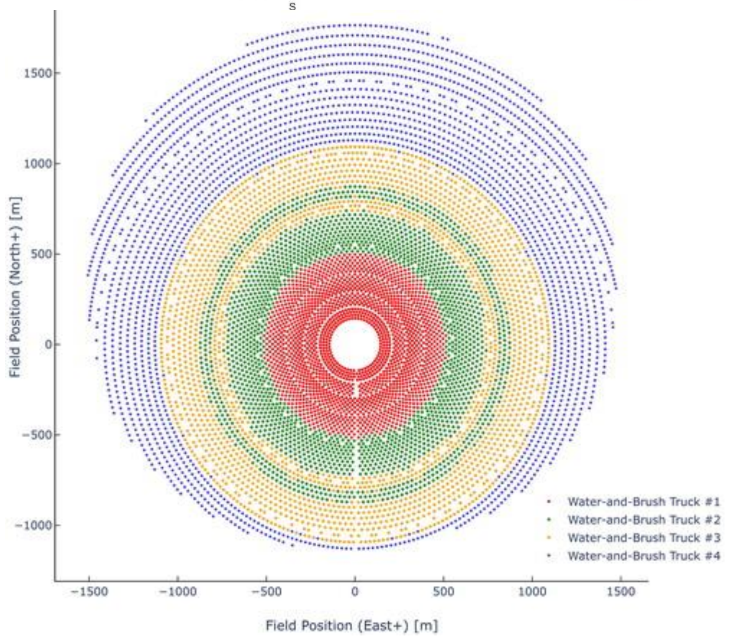
Mitigation

- Optimisation of cleaning resources and policies/schedules sought to minimise cleaning-related costs or profit
- Results show resourcing is the most important decision, schedule/order of cleaning secondary *if you own the equipment*
- If equipment is *not* owned (i.e. "on call"), then timing is more important and condition-based cleaning can offer significant savings[1,2,4]
- Existing studies are for fixed plant designs.

Optimised cleaning schedule and soiling factor[2]



Optimised truck/tech/crew assignments[3]



1. H. Truong Ba, et al., *Solar Energy,* 2017
2. G. Picotti et al., *Solar Energy*, 2020
3. Wales et al., *IIE Transactions*, 2021
4. H. Truong-Ba et al., *Renewable Energy*, 2020

Roadmap: Research Gaps & Ranking

Gaps & Ranking

What's missing and what's important?

- Based on literature review, research gaps were identified
- Ranking according to a three tier system:
  - **Tier 1**:
    - Gaps identified as "must address" gaps. If not addressed, would fundamentally prevent heliostat technology from being improved **or**
    - Gaps with a high potential to result into a high techno-economic impact (LCOH)
  - **Tier 2:**
    - Gaps with a potentially high or medium techno-economic impact (LCOH) to any pre-identified heliostat baseline system(s) **or**
    - Gaps that can be addressed with relatively small effort but with low techno-economic impact to all heliostat baseline systems
  - **Tier 3:**
    - Gaps with a potential low techno-economic impact to all heliostat baseline systems

Further analysis of Tier 1 gaps to prioritize activities for coming years

Soiling Gaps

Tier 1

Develop methods to assess if soiling may be a problem at a site early in design

Conceptual Design	Components	Integrated Heliostat	Mass Production	Deployed Field
So1: Soiling evaluation at site selection So4: Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood	So3: No standard or data to assess anti-soiling coating durability/performance in CSP applications			So2: Design and automation of new cleaning systems is underexplored

Soiling Gaps

Tier 1

Can we alter the design/cleaning regime to balance CAPEX + OPEX + Soiling Losses?

Conceptual Design	Components	Integrated Heliostat	Mass Production	Deployed Field
So1: Soiling evaluation at site selection So4: Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood	So3: No standard or data to assess anti-soiling coating durability/performance in CSP applications			So2: Design and automation of new cleaning systems is underexplored

Soiling Gaps

Tier 1

Coatings often noted as promising, but durability & performance (e.g. specularity) are not well understood

Conceptual Design	Components	Integrated Heliostat	Mass Production	Deployed Field
So1: Soiling evaluation at site selection So4: Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood	So3: No standard or data to assess anti-soiling coating durability/performance in CSP applications			So2: Design and automation of new cleaning systems is underexplored

Soiling Gaps

Tier 1

New cleaning system designs looks promising, but they are often one-off, and commercial uptake is uneven. Why?

Conceptual Design	Components	Integrated Heliostat	Mass Production	Deployed Field
So1: Soiling evaluation at site selection So4: Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood	So3: No standard or data to assess anti-soiling coating durability/performance in CSP applications			So2: Design and automation of new cleaning systems is underexplored

Recommended pathway and ongoing work

Recommended Pathways

*And likely **next activities** in HelioCon*

Tier I Gaps	Recommended Pathway
So1: Soiling evaluation at site selection	• Develop and refine physical models for soiling predictions • Develop tools to assess expected plant performance that include soiling and optimal design of cleaning systems • Development of standard site characterization measurements/ experiments • Field validation of models using targeted experiments • **Create a "soiling database" that includes soiling data available for different areas of the world.**
So2: Design and automation of new cleaning systems is underexplored	• **In close collaboration with industry partners, review existing technology and characterize their performance** • Develop functional requirements and cost models for cleaning systems • Develop new cleaning designs that address these functionalities • Include collaboration with CSP plant operators through initial design, prototype • Develop a best practices manual about suggested methodologies and techniques for optimal heliostats washing

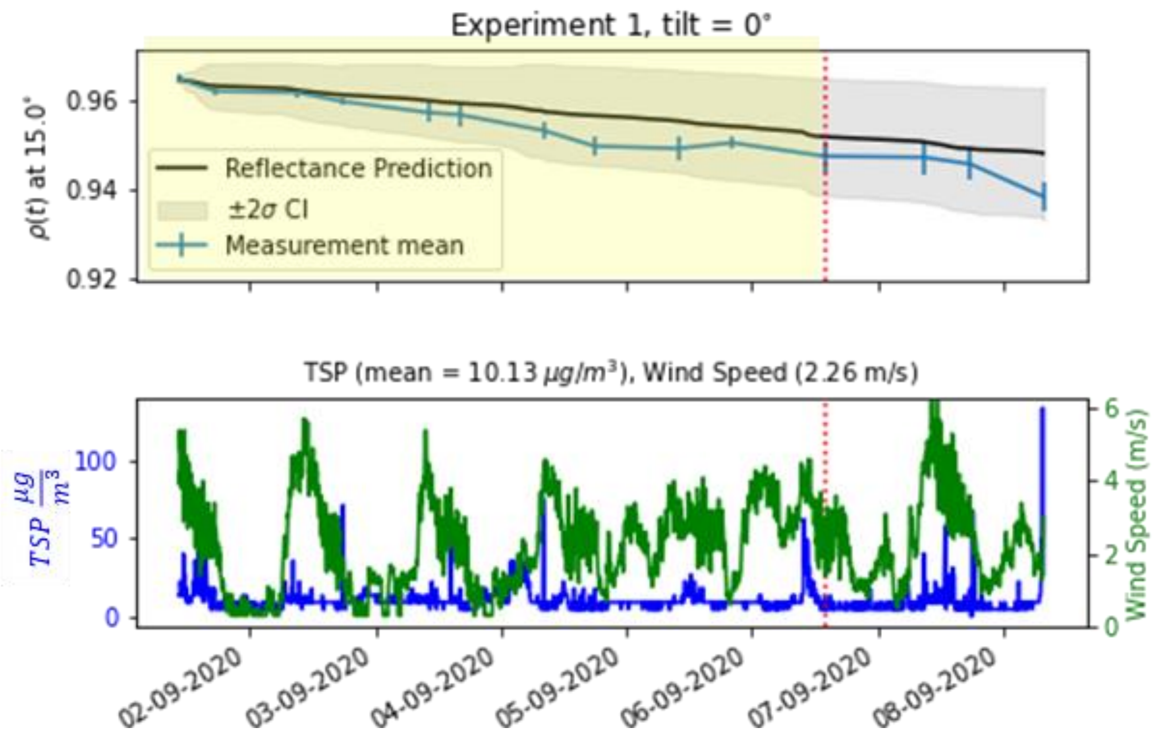
Recommended Pathways

*And likely **next activities** in HelioCon*

Tier I Gaps	Recommended Pathway
So3: No standard or data to assess anti-soiling coating durability/performance	• Coordinate with similar efforts in PV to characterize durability of coatings • Develop standards and tests for optical performance of coatings in CSP applications
So4: Trade-offs between soiling losses, cleaning regime, design choices (e.g., site selection, solar multiple), and heliostat reliability are poorly understood	• **Develop and verify heliostats reliability models (preliminary model available from prior work)** • **Identify key design parameters that interact with optimal cleaning regime** • **Continue to develop cleaning optimization methods/tools to include revenue and costs associated with key design choices and heliostat reliability** • Collaborate with industry partners to refine and deploy above tools on existing plants to understand accuracy and ease of use • Conduct studies on using tools for new sites

Year 1 & Ongoing work

- Soiling prediction model extended to provide prediction uncertainty
- Experimental campaigns in Australia
- Python library for soiling modelling and (so far simple) cleaning optimization on GitHub[1]
- Presentation on HelioSoil by G. Picotti this afternoon in Mesilla (235) at 16:20.



Year 1 & Ongoing work

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

Year 1 & Ongoing work

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HelioSoil

A library for soiling analysis and mirror washing for Concentrating Solar Power (CSP) heliostats.

Summary

This library provides tools developed for predicting soling reflectance losses for Solar Tower CSP plants using weather and plant design data. The deposition model has one free parameter (hrz0>1) which is the ratio of a reference height to the roughness length of the site. The value can either be assumed (e.g. expertise, literature) or (better) may estimated via some experimental procedure via the `fitting_experiment` class. In order to account for the effects of tracking on soiling, the solar field is divided up into a number of sectors and a single "representative" heliostat is used to represent the soiling status of the entire sector.

The details of the soiling model (including the sectorization and fitting procedure) can be found in [1-3] and a demo of soiling loss predictions can be found in `demo.ipynb`. The fitting of hrz0 using experimental data is demonstrated in `hrz0_fitting_demo.ipynb` using experimental data collected at the Queensland University of Technology (QUT), which are discussed in [1]. The data from these experiments are provided in the `data/qut_experiments`.

In addition to a soiling model, this library provides a basic economic and cleaning schedule modules to 1) understand the economic losses due to soiling given a certain number of cleaning crews, and 2) enable optimization of the cleaning trucks and washing frequency. A demonsration of this capability is available in `heuristic_optimization.ipynb` [1] and discussion on the economic and cleaning models can be found in [3,4].

Contributors 2

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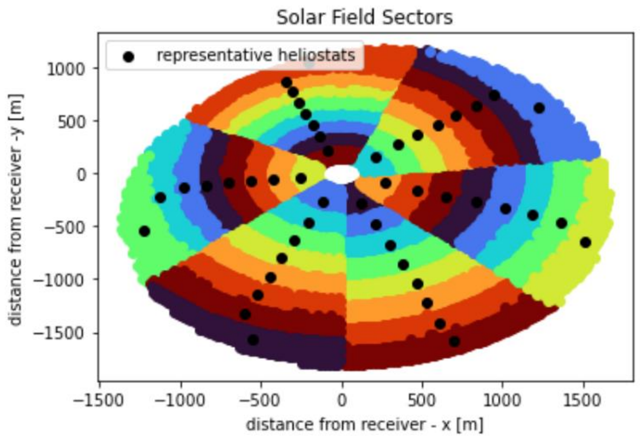
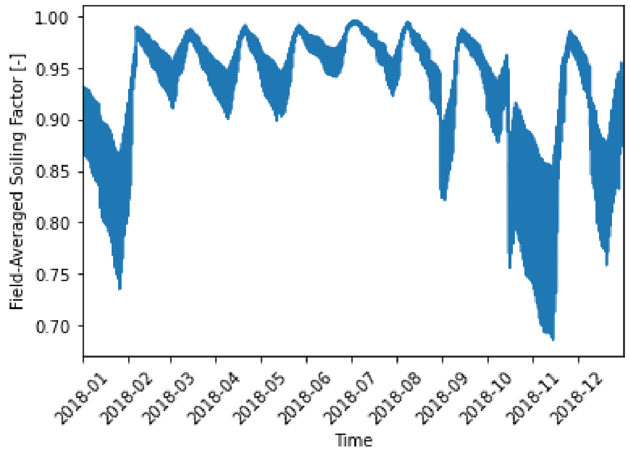
Languages

Jupyter Notebook 90.4% Python 9.6%





1. https://github.com/cholette/HelioSoil

Conclusions

- Roadmap report published
- Main gap themes:
  - Developing tools to assess soiling and plan mitigation early in design
  - Promising areas are underexplored (or underreported) in literature: coatings, cleaning technology design
- Ongoing work in modelling, soiling campaigns, ***building soiling database,*** co-optimisation of cleaning regime and design
- ***If you are interested in working together, please reach out***

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