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Sensitivity of Dust Deposition for Parabolic Trough Collector Mirrors to different Meteorological Drivers

Theory and Results

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Abstract. This abstract presents a soiling forecasting tool (SFT) for assessing the deposition of dust on parabolic trough collector (PTC) mirrors and its cumulative impact on their reflectivity. The SFT was developed by the University of Patras in the frame of the Smart Solar System (S3) project (Horizon 2020 Solar-Era.net). An initial version of the model was presented at the SolarPACES 2022 conference, where the adaptation of the model to dust transport phenomena was demonstrated. The subsequent step in the evolution of the algorithm concerned the calibration of the SFT under different atmospheric conditions. In addition, the model was modified to incorporate meteorological and aerosol forecast data as inputs. The atmospheric predictions of dust and aerosol optical depth are from the global atmospheric forecasts of the Copernicus Atmosphere Monitoring Service. Regarding the meteorological data, three independent sources are used. Those are the Norwegian Meteorological Institute's meteorological forecasts (YR), the METAR meteorological observations from the closest airport, and lastly, the data from the automatic weather station at the location of the PTC system at the KEAN Soft Drinks Ltd factory in Limassol, Cyprus. The aim of this paper is to assess the impact of the three distinct meteorological input sources on the modelled reflectivity and its comparison to measurements taken during the experimental campaign.

Keywords: Soiling Forecast, Dust, Particulate Matter, Parabolic Through Collector, PTC, Weather Forecast

1. Introduction

With the high cost of fuel, the increased possibility of carbon taxation and the pressure to reduce the environmental impact of their business activities, many industrial players are increasingly aware of the need to reduce dependence on fossil fuels. For industry to achieve this goal, appropriate technologies must be available to provide cost-effective and user-friendly alternatives. One of the best renewable options for providing industrial process heat is concentrated solar thermal (CST) technology, as it can use thermal energy storage (TES) to provide heat on demand. To further improve the overall performance of such system, it is necessary to develop a more intelligent control system.

During the EDITOR project (co-funded by SOLAR-ERA.NET), parabolic trough collectors (PTC) and TES were installed at KEAN Soft Drinks Ltd in Limassol, Cyprus, demonstrating full process heat capability. Subsequently, during the S3 project (co-funded by SOLAR-ERA.NET), a smart control system was developed to yield, among others, the optimum timing for cleaning the mirrors of the PTC system.

The first version of the dust deposition algorithm (SFT) was presented in SolarPACES 2022 conference [1] which relied on historical datasets while the new version presented here uses operational datasets (observations and predictions). In this work the important step was to assess the sensitivity of the SFT to different meteorological inputs: (i) forecast data from the Norwegian Meteorological Institute (YR) [2] (main data source for the daily operational estimate of reflectivity), (ii) Meteorological Aerodrome Report (METAR) data from the nearest airport [3] and, (iii) measurement data from a weather station located at the KEAN plant (KEAN, reference calibration).

2. Reflectivity Estimation

The PTC system, which is depicted in Figure 1, is located at the KEAN Soft Drinks Ltd factory, in Limassol, Cyprus. Due to the proximity of the system to the sea (about 250 m) it is affected by local weather systems, such as sea breezes. Its location enhances further dust deposition as it is surrounded by areas of high dust concentration such as coastal sand. In addition, due to the intense Mediterranean climate accompanied by hot and dry summers with frequent dust episodes but also wet, variable winters, the estimation of the deposition rate becomes very demanding.

Figure 1. *Location of the PTC system in Limassol, Cyprus (Google Maps, retrieved 23/06/23).*

The particle deposition on the ground from the atmosphere is represented as particle flux in the atmospheric dust transport models (ADTM), from which the soiling forecasting estimation is derived [1]. Dust accumulation from sedimentation, Brownian motion, and impaction are considered in the estimation of deposition velocity. Moreover, the impact of removal mechanisms such as rainfall and rebound is also considered. The computational procedure was divided into the laminar flow regime and the turbulence flow regime in order to estimate the rate at which dust particles can accumulate on the surface of a PTC mirror. Also, a multitude of modules have been created to replicate the physical mechanisms involved, including the particular PTC geometry and its single-axis rotation, since the PTC system is tracking the sun's position.

The mirror's predicted reflectivity ρ is calculated from the following equation:

$$\rho(t + 1day) = \rho(t) - \rho_{Clean} \cdot SR(t) \tag{1}$$

where ρ_{Clean} is the reflectivity of the clean mirror. The level of dust accumulation on the PTC mirror's surface is estimated from the cleanliness, which is defined as the fraction of soiled mirror's reflectivity at a specific date and time to the mirror's reflectivity in clean state. The soiling rate (*SR*) expresses the decrease in cleanliness with time. In this study, the assumption is made that the *SR* (%) is the daily rate estimation of dust accumulation on the mirror's surface.

3. Results and Discussion

To verify the performance of the SFT utilizing three different meteorological inputs, three distinct series of simulations were done, comparing the reflectivity predictions with the available PTC mirror reflectivity measurements. These reflectivity measurements had been acquired during a campaign that was carried out for the period from October 17th until October 31st, 2022. The three configurations have been optimized separately utilizing all available experimental data on the site; specifically, three bi-weekly campaigns at different seasons of the same year (spring, summer, autumn) were used to calibrate the parameters of each model and estimate its proportionality factor [1].

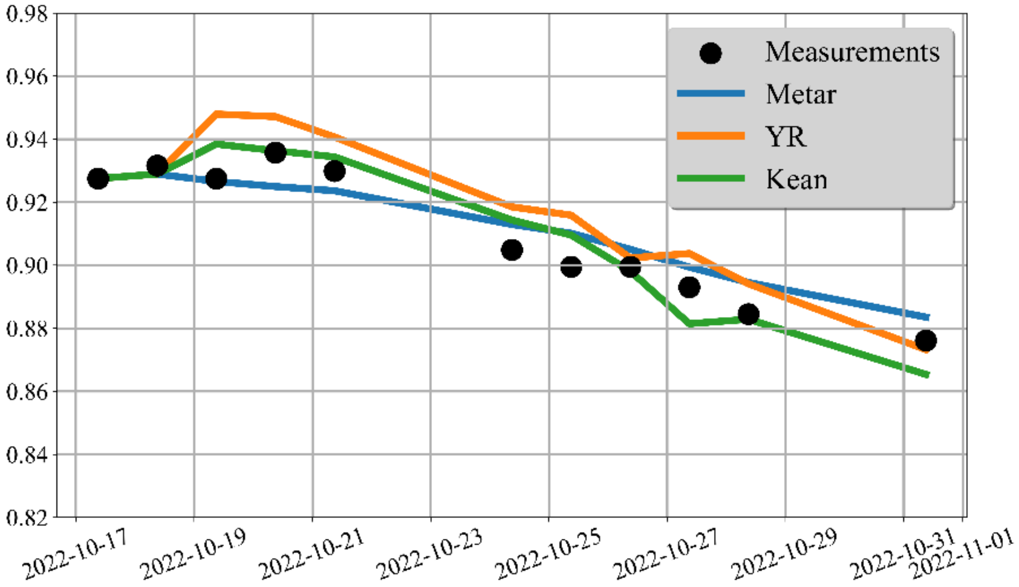

Figure 2. *Reflectivity estimation and comparison with measurements using three different meteorological input data.*

Figure 2 illustrates the predicted mirror reflectivity generated by the three computational experiments against the measured mirror reflectivity (measurements were done with a CONDOR portable reflectometer). In all cases, the SFT model accurately captures the magnitude and variability of reflectivity for the respective time period. The differences between the model configurations arise mostly from the variations in the predicted/estimated/measured rainfall and wind speed.

During the first three days, a rain event affected the system, resulting in its partial cleaning. It is apparent that using YR data, the rain affected the system to a greater extent, while on the contrary, the least effect appeared using METAR data. Unlike YR, METAR data contain precipitation events qualitatively (drizzle, rain, etc); hence, an average rainfall rate for each category in the SFT simulation with METAR data has been adopted. Throughout the calibration period, the highest reduction rate in forecasted reflectivity is observed in the simulation that employed YR data, while the METAR data demonstrates the lowest reduction. YR overestimates the wind speed which affects the impaction and turbulent processes (the soiling rate ratio between laminar and turbulent flow is 1:3 on average) and also overestimates the precipitation amount in the first days, resulting in the highest slope. METAR overestimates the peak wind speed, yielding a small turbulent contribution not seen in KEAN; however, the optimization of the soiling rates across all experimental campaigns under different atmospheric conditions yield a proportionality factor which for this campaign results in the smoothest variability.

Table 1. *Root mean square error of reflectivity for each meteorological input.*

	METAR	YR	KEAN
RMSE	0.7 %	1.1 %	0.6 %

According to Table 1, which displays the root mean square error (RMSE) score for each meteorological input, the simulation that uses KEAN data achieves the best RMSE score, quantifying the findings presented in Figure 2. Overall, the simulation utilizing KEAN weather data has the highest level of accuracy (RMSE=0.6%) compared to the other simulations, closely resembling the observed reflectivity. Unlike the total error across the whole period, it should be noted that in some days the simulation with KEAN data does not capture the observed day-to-day variability. For example, before 27/10 the increased soiling is due to increased impaction arising from an ‘ideal’ wind direction while after 27/10 the small increase in the modelled reflectivity is due to a small rainfall amount recorded. An accurate representation of the variability at those scales would benefit from an optimization across a thorough dataset (going beyond the ~30 days input dataset utilized) covering more atmospheric conditions and allowing the inclusion of more physical processes. Last, it should be emphasized that the KEAN data come from an automatic weather station, and should not be treated as a WMO compliant weather station.

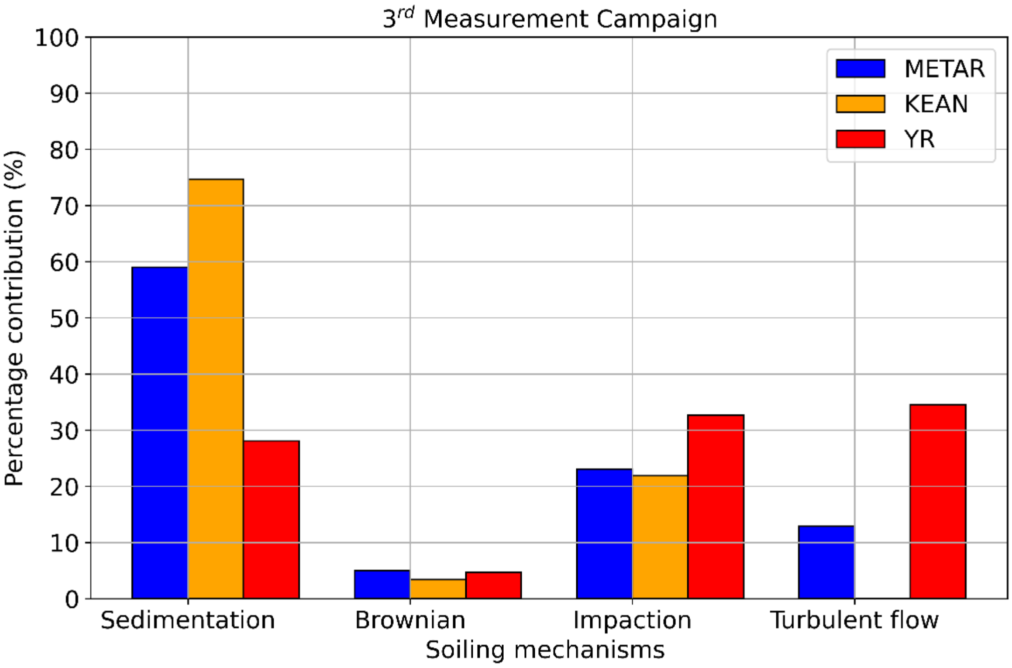

Figure 3. *Effect of deposition mechanisms on the total deposition velocity. Blue bars correspond to the simulation with METAR data, orange bars to KEAN data and red bars to YR data, respectively.*

In general, sedimentation showed the largest effect or contribution in reflectivity prediction (~60%-70% percentage contribution using METAR or KEAN data), impaction the second largest contribution, turbulent flow the third largest contribution, while Brownian motion had the smallest effect as shown in Figure 3. According to the (positive) contribution of each deposition mechanism to the total deposition, it is apparent that the deviations were caused by the overestimation of the wind in the approaches with YR and METAR data. The contribution of impaction and Brownian motion in all three simulations was similar, with the major differences appearing in the effect of turbulent flow which in turn affected the percentage contribution of sedimentation.

The activation of the turbulent flow mechanism occurs only in the METAR and YR simulations. More specifically, in the YR simulation the turbulent flow mechanism was activated more often as the wind data show the largest overestimation compared to the rest of the meteorological data (METAR and KEAN). The combined effect of the positive bias in wind speed coupled with the positive bias in rainfall (Figure 2) leads to a (globally optimized) proportionality factor in the YR simulation that estimates more dust accumulation than the KEAN simulation.

4. Conclusion and Outlook

The results for the specific study period showed that YR meteorological data significantly overestimates wind and precipitation data compared to meteorological data from the weather station at the KEAN Soft Drink Ltd factory, while METAR meteorological data overestimates only wind data. For this reason, the operationalization of the SFT relying only on YR predictions would benefit from an initial data assimilation procedure using observations, thus correcting the errors created by the input of imprecise meteorological forecasts.

To ensure the effectiveness of the SFT using optimal meteorological data, the model should be calibrated with an adequate amount of validation data spanning various atmospheric conditions across several seasons. This is an ongoing procedure.

Data availability statement

The detailed and extensive amount of data supporting the results of this paper is only (and even only in parts) accessible to the consortium members of project S3 within legal restrictions bound by a cooperation agreement. For reasons of maintaining intellectual property, the information and data presented in this paper is limited. Weather forecast data from MET Norway was used for the purpose of exemplarily showing the accuracy of the DNI forecast tool.

Author contributions

A. Voukelatos: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft

J. C. Sattler: Conceptualization, Investigation, Writing – review & editing

S. Dutta: Conceptualization, Investigation, Writing – review & editing

S. Alexopoulos: Conceptualization, Methodology, Writing – review & editing

I. Kioutsioukis: Conceptualization, Data curation, Formal Analysis, Methodology, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Project consortium: Funding acquisition.

Competing interests

The authors declare no competing interests.

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