Contents

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REDUCING PHOTOVOLTAIC PERFORMANCE UNCERTAINTY THROUGH DEVELOPMENT OF ENHANCED SOILING MEASUREMENT AND MODELING TECHNIQUES

1. ABSTRACT

In efforts to displace fossil fuels with a clean and sustainable alternative, Photovoltaic (PV) energy generation facilities have been scaled up from the megawatt (MW) to the gigawatt (GW) scale over the last 10-15 years. This scale up has taken PV from a negligible part of the world's energy supply to a critical component. As a critical component within a stable and reliable world energy infrastructure, PV performance and the associated uncertainties must be well understood. Decades of research efforts have focused on modelling PV performance as a function of the key factors of irradiance and temperature, but only minimal focus has been given to understanding variation in PV performance due to the settling of pollution, dust, pollen, or other airborne particulate matter (PM) on the surface of PV panels (PV soiling). The installation of GWs of PV in dusty desert environments has brought PV soiling to the forefront in PV modelling research and this Doctoral Thesis seeks to contribute to improve PV soiling measurements, the ability to extract relevant soiling metrics from PV production data, and enhanced soiling modelling techniques.

Similar to efforts over the past 30 years to thoroughly characterize the solar resource across the globe, it is now recognized that detailed PV soiling measurements are needed in dusty regions of the world. Soiling has been measured at a small number of locations using side-by-side PV devices (a soiling station) where one device is regularly cleaned (manually or by automated water spray) while the second device is allowed to soil; the ratio of these two signals is called the soiling ratio. These so-called soiling stations provide valuable data but have not been deployed on a wide scale due to both cost and maintenance challenges. In the last five years, a new class of low-cost, low-maintenance optical soiling detectors have been introduced to facilitate a broader set of PV soiling measurements.

As part of this thesis, a U.S. patent was published for an optical PV soiling measurement device titled, "Methods and Systems for Determining Soiling on Photovoltaic Devices." While

this patent covers a wide ranges of possibilities for potential commercialization, key claims in relation to this thesis are as follows: 1) A controllable artificial light source (monochromatic or of a range of wavelengths) projects light onto a soiling detector (typically a glass encapsulated PV cell), 2) The detector output is baselined under clean conditions with the light source turned on, 3) The detector surface is allowed to soil and measurements are taken at night with the light source turned on, 4) the ratio of the soiled measurements to the baseline measurements provide the ability to infer soiling losses on nearby PV devices and, 5) by establishing detectors under specific monochromatic light sources, soiling losses can be inferred on PV devices built from varying semi-conductor devices. While the full patent contains much of the information attached to the various publications, in this thesis, these findings are maintained in association with each publication.

For commercialization purposes, the physical device associated with patent application was named Detector Unit for Soiling Spectral Transmittance (DUSST) and prototype testing was initiated. Some of the first DUSST units were tested with cyan, green, and amber monochromatic LEDs as the light source and silicon cells as the detector. First indoor testing was conducted via artificial soiling of glass coupons with kaolinite, polygorskite, and Arizona test dust. The results showed, regardless of LED or test dust, there was higher than a 0.98 R^2 between transmission losses measured by DUSST and that by a spectrophotometer. A unit with a green LED (530 nm) was further calibrated, thermally characterized, and validated per testing with coupons soiled outdoors in Jaen, Spain. The results showed that a piecewise linear model provided the best calibration coefficients, and that thermal correction of 0.052 mA/°C could be applied to the detector output to correct for self-heating of the LED. Transmittance measurements of the outdoor soiled coupons correlated well with transmittance predicted by DUSST measurements, with a R^2 of 0.94 and a root mean square error (RMSE) of 1.4%.

Additional variations of DUSST were built and tested in response to lessons learned from first prototypes. A new version was tested with seven white LEDs, which resulted in a single calibration coefficient even under high soiling rates. A tubular shroud was tested for protecting the LED lens from soiling and a photodiode and reference dust sensor were evaluated for correcting noise in the output signal. A full chamber study (-25 °C to 40 °C) was conducted on DUSST sensors including heated enclosures for power and control electronics. Variations of the

DUSST sensor were tested outdoors in three U.S. states and Riyadh, Saudi Arabia. In some locations, the DUSST sensor measured long term soiling rates that were nearly identical to soiling rates from standard PV soiling stations. In other locations substantial LED lens soiling was recorded and therefore the soiling rates from DUSST over reported the soiling rates from the standard soiling stations. Chamber and outdoor test results pointed to key design improvements like a higher aspect ratio collimating tube to protect the LED lens, selecting optics that minimize temperature dependency, and a pulsed operation of the LED to minimize power consumption for battery operated systems.

To further demonstrate patent claims and future capabilities of DUSST, an experimental investigation was conducted over 46 weeks in Jaen, Spain. The solar spectrum was regularly measured while glass coupons naturally soiled outdoors. The transmittance losses of the coupons were used to evaluate spectrally resolved transmittance soiling losses for six PV semiconductors. The data were then used to evaluate the accuracy of estimating soiling losses per three soiling spectral transmittance models: 1) transmittance is assumed to be flat an equal to the transmittance at a single wavelength, 2) empirically fitting of a single exponential model based on transmittance at two measured wavelengths, and 3) empirically fitting of a single exponential model based on transmittance at three measured wavelengths. Considering all hemispherical transmittance loss measurements recorded from the outdoor samples (ranging from 0.0% -7.4%), the three variable model had a maximum mean absolute error (MAE) below 0.5% while the two variable model achieved a maximum MAE of 0.7%. The results also demonstrate, that when predicting soiling losses, the MAE for each model is dependent on the degree of soiling loss, the incoming irradiance, and the semiconductor material. Specifically, transmittance losses increase in the short wavelengths (blue region) compared to the longer wavelengths as soiling levels increase. Increasing soiling levels resulted in increases in MAE of each model while the two and three wavelength models generally outperformed the flat transmittance model. Considering silicon PV, all three models performed similar to each other with average MAE from 0.1% to 0.2% for all but red-rich irradiance conditions. In the case of silicon soiling under a red-rich spectrum, adding incremental measurement of single wavelengths (from one to three) reduced the MAE of the respective models. The findings directly relate to the accuracy of measuring soiling losses per DUSST using one, two, or three monochromatic light sources while also providing design guidance on selecting DUSST LEDs.

In parallel to the efforts to develop and validate DUSST, this thesis also focused on several PV soiling modelling efforts. Data from nine soiling stations were examined for extracting a monthly soiling rate metric compared to several other existing annual soiling rate metrics. These various measures of the soiling rate were used as inputs into a previously published sawtooth soiling model and then compared against the soiling profile directly extracted for each of the nine sites per RMSE. For seven of the nine sites RMSE was lowest using the monthly metric, while for the other two sites the monthly metric was tied for lowest or had the second lowest RMSE. This work also examined optimization of PV cleaning periods (washing PV panels to remove soiling and recover performance). While it is simple to retroactively examine data and determine a cleaning was justified, in practice it is difficult to determine when a cleaning should occur because this requires forecasting the next significant rain event. Historic 30-year rainfall data was coupled with two stochastic weather-generation algorithms (Markov model and Spell-Length model) to forecast a rainfall pattern and resulting soiling profile for five of the nine sites. These profiles were then compared against to the existing soiling station data in terms of best cleaning dates. The results showed that regardless of weather-generation algorithm or soiling rate metric, the forecasted cleaning date was within 5-6 weeks of the date per the soiling station. While this accuracy is too low to plan cleaning dates, the results show that additional value could come from future work tying weather-generation algorithms with PV soiling forecasting.

The current accepted PV soiling model assumption is that temporal soiling follows a sawtooth pattern (cleaning events like rainfall result in a step performance improvements or vertical shifts that separate linear declines in performance due to incremental soiling each day). The assumption of a single linear decline between cleanings can be violated for various reasons like a short-term change in airborne dust levels from items such as changing wind patterns or an agriculture harvesting season. Data from the nine soiling stations were used as a test case to determine if soiling modelling could be improved by detecting additional segmentation beyond the baseline cleaning events. Piecewise-linear regression and three changepoint algorithms were applied to capture changes in the soiling rate between cleaning events and then a soiling rate was fit to each new subperiod. The additional segmentation provided a 40% reduction in RMSE in the best-case scenario but there was no obvious best-case model as the results varied by site. Piecewise regression and the Facebook Prophet algorithm showed the highest improvement on average across the nine sites (RMSE reduction of 20%) but there is room for tuning each of the models and therefore future work should still consider a range of models on broader set of soiling data sets.

The final work of this thesis investigated improved methods to fully automate cleaning detection within PV time series data. A validation data set was established consisting of the daily performance index (PI) for 22 PV systems where cleaning dates were prelabeled. The state-of-the-art algorithm for detecting cleaning events was evaluated against several adaptations of the existing method as well as additional filtering criteria to reduce noise in the daily PI prior to cleaning detection. A 43% absolute improvement was achieved in the mean F1 score (0.36 to 0.79) when adjusting the state-of-the-art approach to include irradiance prefiltering and detecting cleanings as related to the 40-day rolling median of the absolute day-to-day deviation in the PI. While these results suggest a path to full automation of cleaning detection, future work should determine if the results can be repeated on additional data sets.

2. INTRODUCTION

PV soiling losses (energy generation losses due soil blocking incoming irradiance from reaching the PV cells) can vary between 1% in climates where rainfall is frequent to 80% in deserts such as the Middle East [1]. PV soiling directly and indirectly results in a higher levelized cost of PV electricity (LCOE); directly through lost revenue and indirectly as higher system performance uncertainty is propagated through the financing of PV facilities. Soiling losses are complex and can vary seasonally and from year-to-year at given location. Losses can also vary dramatically over distances as short as a few kilometers due to localized pollution sources or climatic variation [1, 2, 3]. The most common approach to mitigation of soiling losses is through washing of solar panels but both labor costs and water availability can make this impractical. As a result, alternative solutions such as robotic wet and dry cleaning or so-called anti-soiling coatings have been considered [4]. Currently no soiling mitigation strategy has proven to be techno-economically applicable across the wide range of environments where PV is installed. In some cases, the most economic choice is an upfront modelling of expected soiling losses which are then allowed to vary naturally with no mitigation [4]. Due to the complexity of soiling, there has been in increased effort in recent years to both academically study soiling and to measure and collect soiling data in a similar way that the PV community has achieved for solar irradiance.

The effort has been three pronged: focusing on 1) improved soiling measurement equipment and data collection [5-14], 2) algorithms to extract soiling losses directly from PV time series power data [15-22], and 3) developing soiling loss models based on environmental parameters [2, 3, 23-31]. These efforts are closely connected. It is most important to a PV system owner to quantify soiling losses at the system level, as this is the most accurate accounting for lost energy and directly drives project operations and maintenance (O&M) and financial decisions. Unfortunately, soiling losses are complicated by other loss factors that are related to variables such as irradiance, shading, and temperature; hence why direct soiling measurement are also important. State-of-the-art soiling measurement equipment typically have a measurement area less than 1 m^2 while PV plants can cover km^2 of area. As soiling can vary over such large areas there is a need for methods to translate soiling measurements to PV system level losses. Collecting soiling measurements in parallel with the extraction of soiling losses per PV inverter data enables the development of appropriate translation equations. Finally, any academic effort to develop soiling loss models based on environmental parameters requires validation against soiling loss measurements or losses extracted from PV data.

Building a network of soiling data has been limited due to fact that soiling measurement equipment can be on the order $5,000 to $10,000 to deploy and then requires ongoing O&M costs to enable achieving a long-term dataset. A typical soiling station consists of two PV devices, one that is regularly cleaned (the reference device) and another that soils naturally over time (the test device); where soiling is quantified as the ratio of the electrical output of the dirty to the clean device. In some cases, the reference device is cleaned manually by O&M teams while in other cases cleaning is automated using brushes, pressurized water or other solutions [10, 11]. Figure 1 displays a manually cleaned soiling station where each detector is a silicon reference cell.

Figure 1. A typically manually cleaned soiling station with small silicon reference cells.

Due to cost and challenges with these solutions, there has been a recent introduction to the market of a class of optical sensors that seeks to reduce cost and complexity by eliminating the need for regular cleaning. The ‘MARS” and “DustIQ” are both examples of this new class of sensor [12, 13]. While both MARS and DustIQ are intended to offer solutions to some of the soiling measurement challenges, neither device has yet proven to be a widespread solution.

The first work of this thesis is focused on the introduction, prototyping, and validation of an optical sensor that is low-cost and low-maintenance while having potential functional benefits over the MARS and DustIQ sensors. For example, the MARS sensor relies on the pixelated sensor of a camera and an algorithm to determine soiling losses on the glass above the sensor [12]. Comparatively, the proposed device included in this thesis requires no complex algorithm and the detector can be as simple as a PV cell. The DustIQ uses a LED, similar to the device that will be developed in this work, but the detector measures internal reflection [13], resulting in a higher noise to signal ratio as compared to the transmission measurement used herein. Work by professors and post-doctoral researchers at the University of Jaen [14], (Dr. Almonacid. Dr. Fernandez, and Dr. Micheli), have also demonstrated that while measuring soiling losses per transmission of single wavelength LED, it is possible to calculate the losses for PV cells constructed of various semi-conductor materials.

Kimber et al [15] provided some of the earliest work in extracting soiling loss information from PV time series data and developed what it generally referred to as a sawtooth model for modeling soiling losses. The basic premise is that a PV PI time series can be segmented by rainfall cleaning events, where soiling losses will linearly increase (PI declines) within each of the segmented periods. Each cleaning event results in performance improvement (a vertical shift in the PI) and the resulting graph of the PI overtime looks like a sawtooth. Mejia [16] tested several variations of the Kimber model on PV systems in southern California and corroborated the assumption of linear soiling between rainfall events. Both Kimber and Mejia segmented the PI time series using rain data but did not reach a clear recommendation of the rain threshold that was necessary to be deemed a cleaning event. Deceglie [18] introduced the stochastic rate and recovery algorithm (SRR) to improve the Kimber model and automate soiling loss extraction. Open-source code of the SRR algorithm is available per the National Renewable Energy Laboratory's (NREL) github repository, Rdtools [32]. SRR per [18] does not rely on rainfall to segment the PI time series but segments the data by automatically detecting statistically significant positive shifts in the rolling median of the PI. Deceglie also introduced the Theil Sen estimator for fitting soiling periods and a Monte Carlo approach to report soiling loss uncertainty. Figure 2 provides an example of a sawtooth fit to PV PI data where the data has been segmented by cleaning events detected by the SRR algorithm as well as rainfall events (green dashed vertical lines). Dry periods less two weeks (common from late 2018 through February of 2019) were assumed to have no soiling losses (the soiling fit per the red line is set equal to 1).

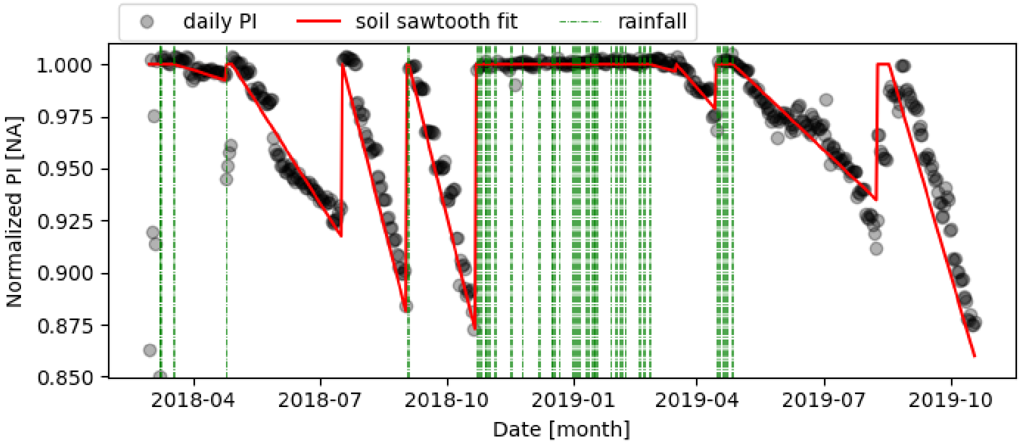

Figure 2. An example of a soiling sawtooth (red lines) pattern being fit to normalized PV PI data. The soiling fit was set to 1 (no soiling) for rainy periods (less than two weeks between rainfalls)

Skomedal [21] tested a version of SSR on field data from the Middle East and reported that while valuable: 1) the statistical threshold for cleaning detection needed to be adjusted based on site specific data, 2) the SRR's accuracy varied by site, and 3) additional noise filtering could improve SRR results. In a later article, Skomedal [22] presented the Combined Degradation and Soiling (CODS) algorithm, focused on both simultaneously extracting degradation rates and soiling profiles. Similarly to SRR, CODS relies on segmenting the PI signal per detected cleaning events but a Kalman filter was used to derive the soiling signal between cleanings, which allows for nonlinear or slowly changing soiling rates over each period (significantly different than linear assumption within the sawtooth approach). Currently the SRR algorithm is still the most broadly used algorithm but improvements are needed due to several limitations: 1) A full validation has only been run on a synthetic data series, 2) the uncertainties reported are only associated with the fitting procedure and do not provide uncertainties in association with the true soiling rates and soiling losses, and 3) the algorithm has no means to handle nonlinear soiling periods or transitions from negligible soiling periods to measurable soiling rates.

The second focus of this thesis is to develop improved soiling models and methods for extracting soiling trends from PV data. A data set of PV systems will be manually labelled for upward shifts that meet criteria to be cleanings due to rain or other factors. This curated data set will serve as benchmark to test the SRR method [18] to determine if improvements can be made in automated algorithms for cleaning detection (soiling interval separation). The curated data set will be shared via an open-source platform so that other researchers will have the opportunity to benchmark other methods. Additionally: 1) soiling station data will be examined to develop metrics for capturing seasonal variation in soiling and for forecasting optimal cleaning periods, and 2) change point algorithms will be evaluated as a method to capture shifts in linear soiling rates. All the above will focus on demonstrating an automated algorithm for determining soiling trends and metrics with reduced uncertainty and improved applicability.

The present thesis directly addresses one of the biggest causes of loss in PV performance in Europe and worldwide. The regions with the highest irradiance, the most favorable conditions for PV and the highest investments, including Spain, southern Europe, and northern Africa, are also those that are at higher risk of soiling because of the dry and sandy soil, the long seasons without rainfalls, the high concentrations of particulate matter and/or a combination of these and other factors. A correct monitoring of soiling is required to plan the most convenient cleaning schedule, which allows for maximizing energy revenues while minimizing O&M costs.

3. JUSTIFICATION

There has exponential growth of PV installations in the last 10 years that is expected to continue in the coming decades as the world addresses climate change through a reduction in CO_2 emissions. This exponential growth of PV has pushed PV installations to high insolation and dust prone regions of the word. Such installations result in a higher LCOE for PV due to substantial losses of energy production due to soiling of the PV panels, increased O&M cost, and higher finance rates due to the uncertainty associated with modelling and predicting soiling losses. The overall justification of this PV soiling research is to reduce PV LCOE which enables broader adoption PV and hence supports worldwide goals to reduce CO_2 emissions and combat climate change. This work specifically focuses on providing lower cost soiling measurements which in turn enable more broadly measuring and mapping soiling risk around the world. Independent engineers and finance institutions can then use this data to de-risk PV projects and provide lower finance rates for new installations. Furthermore, the soiling model development in this effort is geared at both helping O&M teams make better techno-economic decisions for existing PV plants as well as extracting soiling loss data from existing facilities. Improved O&M directly reduces LCOE while extracting soiling loss data feeds directly to the previous goal of enhanced mapping of soiling risks that are applied to reduce uncertainty when designing and funding new PV facilities.

4. OBJECTIVES

The primary objective of the research is to reduce the uncertainty of PV performance models through development of enhanced soiling measurement and modelling techniques. Beyond the baseline electrical characteristics of the PV module and system under consideration, PV performance is primarily impacted by the location specific solar resource (irradiance), soiling levels, and ambient temperature and other meteorological characteristics. While performance as a function of irradiance and temperature are well characterized, soiling and the expected impact on PV is not well understood. This is both because soiling has not been historically measured in contrast to irradiance and temperature data, and because soiling varies across small distance scales due to location specific pollution sources [1-3]. This research seeks to generally reduce the uncertainty, risk, and associated cost of PV soiling through the following specific objectives:

Objective number 1**. Develop a low-cost and low-maintenance PV soiling sensor.**

Objective number 2. **Develop enhanced modelling techniques for the extraction of PV soiling data and soiling metrics from both PV systems and soiling station data while targeting guidance for optimized cleaning of PV plants**.

These objectives can be further broken down into sub-objectives that align with target publications of this thesis.

Objective number 1.1. *Register a patent application which describes and protects unique claims of a novel transmission-based optical soiling sensor*

In order to broadly collect time series soiling data, low-cost and low-maintenance soiling sensors must be readily available. The proposed path is to apply for a patent for an optics-based sensor where a fixed light-emitting diode (LED) light source is projected onto a PV cell or other electrical sensor that is covered with PV glass. As the glass soils the output of the sensor is expected to drop linearly with the level of the soiling deposit. As previously described, there are existing optics-based sensors and therefore a patent application must capture novel claims and benefits compared to existing devices.

Objective number 1.2. *Conduct critical research to validate performance of the proposed novel optical soiling sensor and to support success of patent application and possible commercialization of the device.*

In parallel to a patent application the objective is also to build various prototypes of the novel soiling sensor and characterize and validate performance both in the laboratory and in field settings. Design improvements will be made along the way in response to lessons learned from initial prototypes and testing. Similarly, we will collect field data on soiling of glass coupons to better understand the spectral variability of soiling transmittance losses; where this data will also be directly applied to evaluate measurement errors associated with the above optics-based soiling sensor as well as suggest design considerations to reduce the associated measurement errors.

Objective 2.1: *Evaluate metrics for seasonal variation in PV soiling and the forecasting of optimal cleaning periods.*

There is sufficient evidence in the literature that soiling rates vary in different seasons due to weather patterns, pollution sources, and other factors but there are no validated metrics for capturing this variation and forecasting optimal cleaning periods [1-3]. Various monthly soiling metrics will be extracted from soiling station data and these metrics will be evaluated per existing soiling models to determine if monthly metrics are beneficial over existing annualized metrics. Additionally, the models which include monthly data will be incorporated with weather data to forecast optimal cleaning periods to minimize soiling losses.

Objective 2.2: *Evaluate models for detecting changes in soiling rates across periods that have been segmented by detectable cleaning events.*

Currently available soiling models generally assume a sawtooth pattern of linearly declining performance that are segmented by detectable cleaning events. While there are locations that very distinctly demonstrate such a sawtooth pattern there are other locations that show violations of this pattern. For example, a cleaning event occurs at the start of a rainy season, but a substantial soiling trend does not begin until the rainy season ends (see the long rainy period in Figure 2). In order enhance the existing soiling models, several techniques will be evaluated to detect changes in the soiling rate across a cleaning segmented data period. Models that incorporate soiling rate change detection will be evaluated against the existing baseline sawtooth models.

Objective 2.3: *Evaluate modelling improvements for automated detection of PV system cleaning events.*

The existing algorithms for extraction of soiling trends from PV system data rely of some form of determination of cleaning events for segmenting the data. While there have been efforts to automate the cleaning detections, the variability in data noise from PV system to PV system often means that the data analyst must subjectively tune the extraction algorithm for a given system. Here the objective is to introduce improvements to cleaning detection model that allow for full automation as well as to provide a data set to the PV community for validation of these and future improvements to soiling extraction algorithms.

5. PUBLICATIONS OF THE THESIS

5.1 List of Publications

Article No 1	"Design, Characterization and Indoor Validation of the Optical Soiling Detector DUSST"
Authors	A. Fernandez-Solas, L. Micheli, M. Muller, F. Almonacid, E. Fernandez
Journal	Solar Energy
Volume etc.	Volume 211, 11/2020
Classification JCR	Energy and Fuels 38/114 (Q1)
Impact Factor	5.742 (2020)
DOI	10.1016/j.solener.2020.10.028

Article No 2	"An In-depth Field Validation of "DUSST": A Novel Low-maintenance Soiling Measurement Device"
Authors	M. Muller, L. Micheli, A. Solas, M. Gostein, J. Robinson, K. Morely, M. Dooraghi, Y. Alghamdi, Z. Almutairi, F. Almonacid, E. Fernandez,
Journal	Progress in Photovoltaics
Volume etc.	03/2021
Classification JCR	Energy and Fuels 17/114 (Q1)
Impact Factor	7.953 (2020)
DOI	https://doi.org/10.1002/pip.3415

Article No 3	"Selection of the Optimal Wavelengths for Optical Soiling Modelling and Detection in Photovoltaic Modules"
Authors	L. Micheli, E. F. Fernandez, M. Muller, G. Smestad, F. Almonacid,
Journal	Solar Energy Materials and Solar Cells
Volume etc.	Volume 212 04/2020
Classification JCR	Material Science Multi-Disciplinary 69/333 (Q1)
Impact Factor	7.267 (2020)
DOI	10.1016/j.solmat.2020.110539

Article No 4	"Extracting and Generating PV Soiling Profiles for Analysis, Forecasting and Cleaning Optimization"
Authors	L. Micheli, E. F. Fernandez, M. Muller, F. Almonacid
Journal	IEEE Journal of Photovoltaics
Volume etc.	Volume: 10, Issue: 1, Jan. 2020
Classification JCR	
Impact Factor	3.887 (2020)
DOI	10.1109/JPHOTOV.2019.2943706

Article No 5	"Improved PV Soiling Extraction through the Detection of Cleanings and Change Points"
Authors	L. Micheli, M. Theristis, A. Livera, J.l Bessa, A. Solas, J. Stein, G. Georghiou, M. Muller, F. Almonacid
Journal	IEEE Journal of Photovoltaics
Volume etc.	Volume: 11, Issue: 2, March 2021
Classification JCR	
Impact Factor	3.887 (2020)
DOI	10.1109/JPHOTOV.2020.3043104

Article No 6	"Automated Detection of PV Cleaning Events: a Performance Comparison of Techniques as Applied to a Broad Set of Labeled PV Data Sets"
Authors	M. Muller, K. Perry, L. Micheli, F. Almonacid, E. Fernandez
Journal	Progress in Photovoltaics
Volume etc.	Under review
Classification JCR	Energy and Fuels 17/114 (Q1)
Impact Factor	7.953 (2020)
DOI	

Patent Documents	"Methods and Systems for Determining Soiling on Photovoltaic Devices"
Inventors	E. Fernandez, M. Muller, L. Micheli, F. Almonacid,
Record of Invention	ROI-17-85 registered July 6th, 2017
U.S. Patent Application	Pub. No. US 2019/0312548 A1, October 10th, 2019
U.S. Published Patent	Patent No.US 10,734,946 B2, August 4th, 2020

5.2 Connection of the publications with the thesis objectives

5.2.1 Objective 1.1. Register a patent application which describes and protects unique claims of a novel transmission-based optical soiling sensor

This objective has been achieved by the three patent associated documents provided in section 5.1 (record of invention ROI-17-85, patent application US 2019/0312548 A1, and published patent US 10,734,946 B2). The record of invention documented the basic features of the intended soiling sensor with first conception of the device documented via emails between the inventors on April 19, 2017. This was followed by a draft paper of conceptual ideas on June 23rd, 2017 and reduction to practice and testing on July 5th, 2017. The published patent application titled, "Methods and Systems for Determining Soiling on Photovoltaic Devices", was achieved on October 10th, 2019 and includes an extensive legal description of the claims as well as supporting evidence that the claims can be achieved. The published patent was achieved on August 4th 2020. The legal claims and evidence are based on the published papers documented in section 5.2.2 and hence are not repeated here. The optical soiling sensor, for further publication and commercialization, was named "Detector Unit for Soiling Spectral Transmittance" (DUSST) and a basic schematic of DUSST as described by the patent is provided in Figure 3.

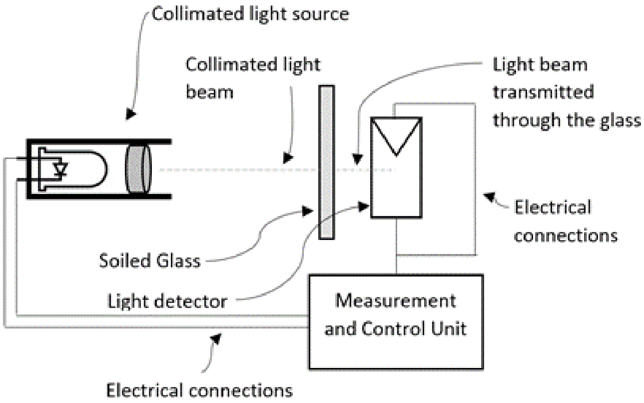

Figure 3. Schematic of the DUSST sensor.

While patent language allows for significant variation of the DUSST unit, the embodiment in Figure 3 shows:

1) A collimated light source projecting onto a piece of soiled glass with a detector behind the glass.
2) The light is transmitted through the soiled glass and soiling losses are measured by comparing the detector measurement with soiled glass to the same measurement with clean glass.
3) For practical purposes the detector is an encapsulated solar cell where short circuit current is measured.
4) The light source and detector together are assumed to produce a stable measurement such that the practical change between measurements is the level of soiling on the glass surface.

Additional key provisions of the patent are:

1) Computational methods for calculating spectral components of soiling losses.
2) Computational methods for calculating soiling losses on various semiconductor materials.
3) Methods to correct for degradation of the device over time.
4) Soiling loss estimates rely on transmittance measurements.
5) Measurements can be conducted at night (do not rely on solar irradiance).

The first prototype DUSST sensors were constructed to support the patent application and laboratory testing was conducted as shown in Figure 4.

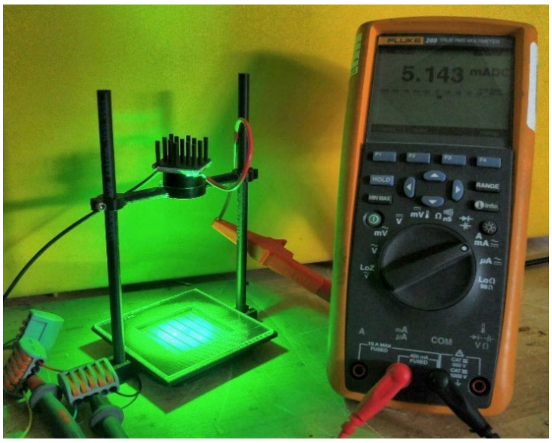

Figure 4. Picture of the first prototype built for the indoor validation process. DUSST is shown with a green LED (530nm) projected onto an encapsulated silicon solar cell.

Initial indoor and outdoor prototyping and testing of DUSST was published and presented per the 35th annual E.U. PV Solar Energy Conference (2018) and the 46th annual PV Specialist Conference (2019) (see section 5.3 O.1 and O.2) These publications supported the successful patent publication and demonstrated the following:

1) DUSST measures the transmittance of artificially soiled glass with a high accuracy (R^2=97.6%) and that it can calculate the soiling loss of a silicon cell with a mean absolute percentage error of 0.6%.
2) High accuracy measurements of artificially achieved soiling losses were demonstrated using LEDs with three distinct wavelengths.
3) High accuracy measurements were achieved with three artificial dust sources: kaolinite, polygorskite, and Arizona road dust.
4) Multiple months of outdoor soiling trends were measured at NREL that were consistent with dry periods separated by rain and snow events.

5.2.2 Objective 1.2: Conduct critical research to validate performance of the proposed novel optical soiling sensor and to support success of patent application and possible commercialization of the device.

Article No 1: “Design, Characterization and Indoor Validation of the Optical Soiling Detector DUSST”
Article No 2: “An In-depth Field Validation of “DUSST”: A Novel Low-maintenance Soiling Measurement Device”

Article No 3: "Selection of the Optimal Wavelengths for Optical Soiling Modelling and Detection in Photovoltaic Modules"

Objective number 1.2 was achieved by the three articles cited above.

In article No 1, *"Design, Characterization and Indoor Validation of the Optical Soiling Detector DUSST"* a version of DUSST similar to what is shown if Figure 4 was subjected to thermal characterization and calibration for estimation of soiling loss measurements. Specifically, the light source consisted of off-the-shelf components from Luxeon Star LEDS. A monochromatic green (530 nm) LED was prepackaged with a 9° Fraen collimating lens and a heat sink from Luxeon. The LED was also powered by the Luxeon Buckpuck 3021, which was designed to provide constant current to the LED. The detector was an encapsulated polycrystalline solar cell with a glass front surface, where the output measurement was short circuit current (I_{sc}). Thermal characterization consisted of turning the LED on for greater than 20 minutes at laboratory conditions of 24 °C ambient temperature and 40% relative humidity. Current, voltage, and temperature were measured every 2 s for each of the components in the DUSST setup. It was found that each of the component's temperatures increased per a logarithmic trend which leveled off after approximately 10 minutes (LED heating 20 °C, Buckpuck heating 10 °C, and the detector only heating 2 °C). The LED voltage linearly decreased with LED temperature and this linear rate was consistent with the manufacturer reported temperature coefficient. The decrease in LED voltage with increasing temperature resulted in decreasing light output but it was found that that a single linear correction factor (-0.052 mA/°C) could be applied to PV detector to account for changing LED temperatures.

Twelve screening masks of differing levels of grey (measured transmission losses ranging from 19%- 97%) were printed via a laser printer to develop a calibration model for the DUSST version under test. DUSST measurements under the screening masks were compared to transmittance measurements of the masks at 530 nm and both exponential and a piecewise-linear calibration models were considered. The piecewise-linear calibration (one calibration coefficient for losses less than or equal to 33%, and one coefficient for losses greater than 33%) resulted in the lowest RMSE and therefore was adopted for calibration and evaluation of DUSST per testing with coupons soiled outdoors. It is worth noting that the need for two calibration coefficients was determined to be due such low light levels reaching the solar cell (due to both the low intensity green LED and the increasing transmission losses) and the known nonlinear behavior of solar cells under low light levels. Twelve PMMA Plexiglass coupons were naturally soiled outdoors for varying lengths of time at the University of Jaen. Transmission losses were measured for all the coupons (losses ranging from 6.8% to 21.4% at 530 nm) and then losses were calculated per DUSST measurements with the established calibration model. The DUSST calculations in comparison to the measured transmittance resulted in an RMSE of 1.38% and R^2 of 0.94.

The overall results of Article No 1 demonstrated that the prototype of DUSST could be a viable method for estimating transmittance and soiling losses, hence aligning with objective 1.2 in validating device performance as was needed to support some of the basic claims of the associated patent application. The thermal characterization results suggested that future work should investigate a wider range of temperatures as necessary for outdoor use and that LED turn on times should be short to avoid self-heating. Similarly, the resulting piecewise-linear calibration for soiling losses suggested that design changes should consider a higher intensity LED to avoid nonlinear performance of the solar cell detector under low-light conditions.

Article No 2, “An In-depth Field Validation of “DUSST”: A Novel Low-maintenance Soiling Measurement Device” expands on Article No 1 by considering multiple designs of DUSST, expanding thermal characterization from -25 °C to 40 °C, and conducting outdoor testing against standard soiling stations at multiple locations. Article No 2 again supports objective 1.2 per validation of the DUSST device to support the patent application but also demonstrates more advanced work to consider design iterations that facilitate commercialization of the device. While the baseline device associated with Article No 1 is included in this work, various testing also includes a tubular shroud to protect the LED lens from soiling, a photodiode to provide a feedback measurement of LED intensity, a higher light intensity design which consists of 7 white LEDs packaged together, and a nine-unit package that is intended to measure soiling non-uniformity and evaluate glass coating efficacy. Based on the self-heating found in Article No 1, all testing in Article No 2 is associated with a turn of time of the LED of less than 5 seconds so self-heating is negligible. In this operational state all components of DUSST are expected to operate at the associated ambient conditions. Lessons were learned from each of tests conducted in this work.

The 7-LED design presented in this work demonstrated a fivefold increase in light intensity and as result a single linear calibration coefficient was sufficient for all grayscale transparency masks tested (up to a 75% transmission reduction). The DUSST control electronics were housed in an insulated, outdoor-rated enclosure that included a heater to protect the electronics from being exposed to condensation under subfreezing temperatures. The DUSST sensor and the enclosure were placed in a thermal chamber where ambient temperatures were varied from -25 °C to 40 °C. The sensor was tested both with and without the enclosure heater activated and, in both cases, the DUSST detector produced and output that was quadratically related to chamber ambient temperature. Testing with a photodiode mounted at the edge of LED lens demonstrated that light intensity linearly increased with ambient temperature. Alternatively, the detector output still showed a quadratic relationship with photodiode output. This result, coupled with lens test data from the literature, suggested that quadratic relationship could be explained by a temperature dependence of the optical focal length. While the chamber testing provided temperature calibration curves for applying to outdoor data at a wide range of temperatures, the results also pointed to considering future optical designs with reduced temperature dependence. Chamber testing also demonstrated that control electronics and therefore the DUSST LED output could be impacted by temperature driven variation in the power supply circuit. As a result, one of the deployed field units included a duplicate DUSST sensor that was protected from soiling and was tested as a method for removing noise from the daily DUSST soiling measurements.

DUSST units of various designs from those mentioned above were deployed in Utah, California, Riyadh, Saudi Arabia, and Colorado. The deployment in Utah included a reference DUSST sensor that was protected from soiling and applied to reduce signal noise. These devices were subjected to ambient temperatures ranging from -12 °C to 17 °C and the data was compared to soiling measurements taken on two sets full size PV panels. A multi-week soiling trend was recorded by both DUSST and the PV panels where soiling progressed from 0% to approximately 3%. The daily soiling ratios showed a maximum difference of 0.5% although most days resulted in a different of less than 0.25%. It was also demonstrated that reference DUSST device reduced the standard deviation of measurement error from 0.24% to 0.04%. In California the DUSST sensor was similar to that described in Article No 1 although a photodiode was attached to LED lens surface to provide light intensity feedback. A three-month soiling trend was recorded by both the DUSST device and a soiling station consisting of PV reference cell pairs. The raw DUSST signal over-reported the soiling trend but correction with the photodiode resulted in a slope or soiling rate for the three months of -0.19%/day while the soiling station reported -0.20%/day. Two strong soiling trends were measured in Riyadh (ambient temperatures as high as 40 °C) by both the DUSST sensor (as described in Article No 1) and a soiling station consisting of PV reference cell pairs. In both trends the DUSST sensor significantly over reported the soiling rate as compared to the soiling station. At one point in the data collection period the DUSST LED lens was cleaned and a recovery of 3.7% was achieved. Although more detailed lens soiling data was not collected, the one data point suggests that lens soiling is a possible reason why the DUSST sensor was over-reporting soiling losses compared to the soiling station. Three deployment sites were achieved in Colorado and nine side-by-side DUSST units were deployed at each site for measuring coating efficacy as well as evaluating non-uniform soiling over an area of 0.5 by 0.5 m. While significant soiling trends and non-uniform soiling were tracked at each Colorado site no PV stations existed at these sites for a cross comparison of soiling rates. Each of the DUSST sensors at the Colorado sites included a tubular shroud protect the DUSST lenses from soiling but lens soiling still occurred at dirtiest sites and was measured ranging from 1.2% to 8.6%.

The overall results from Article No. 2 supported the objective of validating the performance of the DUSST sensor and as compared to Article No. 1, this work demonstrated functionality in a range of outdoor locations and ambient conditions. Nearly identical field soiling rates were measured compared to traditional soiling stations in both California and Utah. The field results also demonstrated DUSST designs performed under extreme temperatures (-12 °C to 40 °C) and rain and snowfall. As is expected in working through the process toward commercialization, weaknesses were exposed such as a higher-than-expected performance variation with ambient temperature and susceptibility to lens soiling. The results suggested that next iteration designs should include 1) a high aspect ratio collimating tube to better protect LED lenses from soiling, 2) optical designs where focal length is not strongly dependent on temperature, 3) A flash circuit or pulsed light to minimize power consumption for remote sites that must run on battery power, 4) an option for measuring light intensity variation to reduce signal noise, and 5) eliminate of the heat sink (due to a flashed circuit) which reduces complexity and cost.

Article No 3, "Selection of the Optimal Wavelengths for Optical Soiling Modelling and Detection in Photovoltaic Modules" specifically supports the portion of objective 1.2 focusing on a successful patent application. As a prerequisite to a patent, inventors must demonstrate unique features of the invention compared to the existing state-of-the-art. A review of existing patents showed other inventions that similarly claimed to measure soiling losses but none of these patents stated that the measurements from the invention could distinguish soiling losses adjusted to various PV semiconductors or reconstruct the soiling transmittance spectrum. These specific claims were made in the patent applications contained in this thesis and article No 3 specifically supports achieving these claims.

While previous work by Fernandez [14] mathematically demonstrated that transmission losses at single wavelengths could be used to estimate soiling losses for PV devices, Article No 3 focused on going beyond this previous study in the following ways: 1) applying an outdoor soiling measurement campaign to evaluate the accuracy of estimating soiling losses via single and multiple wavelength measurements of transmission losses, 2) examining the benefits of more complex soiling spectral transmittance models for estimating soiling losses, and 3) evaluating such models in connection with specifically estimating soiling losses for PV devices of various semiconductors.

An experimental investigation was conducted over 46 weeks in Jaen, Spain where glass coupons were allowed to soil outdoors and periodic spectrally resolved transmittance measurements were conducted. These measurements showed that soiling transmittance losses increase in the blue region of the spectrum (shorter wavelengths) as compared to the red region (longer wavelengths) and the drop in the blue region increases with increasing soiling deposits. This implies that when calculating soiling losses for a given PV device per transmission losses at a single wavelength (as is the case with the basic configuration of DUSST), estimation error is related to the intensity of soiling losses, the incoming solar spectrum, and the given PV semiconductor. The data were then used to compare the accuracy of estimating soiling losses per three soiling spectral transmittance models: 1) transmittance is assumed to be flat an equal to the transmittance at a single wavelength (baseline DUSST device), 2) empirically fitting of a single exponential model based on transmittance at two measured wavelengths, or 3) empirically fitting of a single exponential model based on transmittance at three measured wavelengths. Generally, soiling loss estimates improved when measuring transmission losses at two versus one wavelength, and when measuring at three versus two wavelengths but the results were complex (depending on all the factors previously noted) and therefore are difficult to summarize with a single comparative numerical metric. Considering silicon PV and an optimum single wavelength measurement, all three models performed similarly for the reference irradiance and a blue rich spectrum (the average MAE for the 46-week data set was less than 0.1%). In the case of the red rich spectrum the single optimum wavelength model resulted in a MAE slightly above 0.1% while the two and three wavelength models were each progressively better. Alternatively, if a single wavelength measurement was conducted at 550 nm rather than an optimum value the MAE increased to a range of 0.3% to 0.5% depending on the irradiance spectrum.

In summary, the work presented in Article No. 3 demonstrated the following:

1) Optimal wavelengths can be selected for estimating soiling losses via a one, two, three wavelength model.
2) The above optimal wavelength choices are dependent on the PV semiconductor to which the soiling losses will apply, the intensity of soiling losses, and the incoming solar irradiance.
3) Generally, increasing the number of wavelength measurements from one up to three results in error reduction when estimating soiling losses.

These findings directly relate to the accuracy of measuring soiling losses per an optical soiling detector (DUSST) based on one, two, or three monochromatic light sources as well as the optimal choices of the monochromatic light sources. Additionally, these findings substantiated the claims within the patent application that the invention could distinguish soiling losses adjusted to various PV semiconductors or reconstruct the soiling transmittance spectrum.

5.2.3 Objective 2.1: Evaluate metrics for seasonal variation in PV soiling and the forecasting of optimal cleaning periods.

Article No 4: "Extracting and Generating PV Soiling Profiles for Analysis, Forecasting and Cleaning Optimization"

Object 2.1 was achieved through Article No 4 cited above. In this work soiling loss profiles were extracted per the SRR method described in [18] from nine soiling stations in California and Arizona as previously described in [33]. The SRR method outputs a median annualized soiling loss as well as a median soiling rate from all the stochastically generated soiling profiles for the data set. Comparatively, the fixed rate precipitation (FRP) model from [15] determines the soiling rate by fitting the slope of the soiling ratio for the longest valid dry period in the data set. FRP then combines this soiling rate with rainfall dates to create a sawtooth soiling profile for the site (100% recovery per rain above a set threshold followed by linear reduction per the soiling rate until the next rain). It is worth distinguishing that the SRR is a methodology for extracting soiling information but as described in the literature it is not a forecasting tool. Alternatively, the FRP allows for forecasting soiling profiles when rainfall data is available. In practice the PV industry has commonly forecasted soiling using the sawtooth concept from the FRP model coupled with historic rainfall data and a fixed soiling rate determined from a wide range of inputs. Both the original FRP work [15] and the stochastic profiles per SRR [18] show that soiling rates can vary across a data set (see the varying slopes in Figure 2), typically seasonally, but each method produces only on representative soiling rate. In this work we consider the use of monthly metric to capture seasonal variation of soiling rates and these monthly values are combined with rainfall or cleaning events to generate a modified FRP soiling forecast. This monthly metric is call the monthly mean (MM) soiling rate ($R_{s,m}$), with the value for a month *m* calculated as:

$$R_{s,m} = \frac{\sum (R_{s,i} \cdot n_{day,i})}{\sum n_{day,i}} \qquad (1)$$

where $R_{s,i}$ is the soiling rate for each *i*th-dry period occurring in the month *m* during the whole data collection, and $n_{day,i}$ expresses the number of days the dry period lasted. MM is then compared to generating the soiling profile using the soiling rate from the "Longest" soiling period (FRP baseline), the median soiling rate from SRR, the mean soiling rate from SRR, and a weighted mean soiling rate (weighted by the number of days in each soiling period). All the generated sawtooth patterns were then compared against the soiling profile directly extracted for each of the nine sites per RMSE. For seven of the nine sites RMSE was lowest for MM compared to the other metrics while for one site MM was tied with "Longest" for lowest RMSE and for the final site "Longest" slightly outperformed MM.

In Article No 4, cleaning optimization was examined per the most convenient cleaning day (MCCD). Energy recovery per cleaning depends on both the level soiling per the cleaning date as well as the number of days until the next natural cleaning event (typically a rainfall). If the energy recovered between the date of cleaning and the date of the next rainfall generates revenue above the cleaning cost, then a cleaning is justified. While it is simple to retroactively examine data and determine a cleaning was justified, in practice it is difficult to determine a cleaning should occur because this requires forecasting the next significant rain event. In this work we retroactively determined one cleaning event or MCCD per the existing year of data for five of the nine soiling stations (four were excluded due to having generally low soiling losses that do not justify cleaning). Historic 30-year rainfall data was then coupled with two stochastic weather-generation algorithms (Markov model and Spell-Length model) to forecast a one-year rain profile for each site. These rain profiles were evaluated against several precipitation metrics previously shown to correlate with soiling losses [2]. While the results were preliminary and only related to one year of ground data, the Spell-Length model showed lower RMSE than the Markov model. The forecasted rain profiles were also coupled with the soiling rate metrics (described above) to generate sawtooth soiling profiles where a MCCD could be extracted. This MCCD was then compared to the MCCD retroactively extracted from the 5 sites. The results showed that regardless of weather-generation algorithm or soiling rate metric, the forecasted MCCD was within 5-6 weeks of the actual MCCD. While this result is not of high enough accuracy to plan a specific O&M cleaning it does provide an expected window when cleaning is likely.

In summary the work presented in Article No 4 demonstrated the following:

1) Extracting a monthly soiling rate metric rather than a single annual rate can reduce RMSE when modelling soiling through a sawtooth model.

2) Stochastic weather-generation algorithms were examined for the first time to forecast site-specific rainfall patterns. These rainfall patterns were then be used with soiling rate information to examine optimal cleaning dates to minimize soiling losses. The results were preliminary but suggest a methodology that can be explored in more depth for sites that have more years of soiling data.

5.2.4 Objective 2.2: Evaluate models for detecting changes in soiling rates across periods that have been segmented by detectable cleaning events.

Article No 5: "Improved PV Soiling Extraction through the Detection of Cleanings and Change Points"

Objective 2.2 was achieved through Article No 5 cited above. An article leading to up to Article No 5 was published in the conference proceedings of the 47th Photovoltaic Specialists Conference in 2020 PVSC2020 (see section 5.3 O.4) that demonstrated that existing PV extraction models such as FRP [15] and SRR [18] could be improved by further segmenting data beyond rainfall or cleaning events. The basic assumption of both FRP and SRR is that a single soiling rate can sufficiently model the daily soiling ratio between two cleaning events. A simple example of where this assumption fails is when a dry season is followed by a rainy season before the next dry season. In this case the daily soiling ratio typically abruptly shifts upward to near 1 or 100% (no soiling) at the start of the rainy season but then the soiling ratio remains near 100% until the rainy season comes to an end where a new downward trend or significant soiling rate can be fit. FRP examined the use of a predetermined grace period length to account for these scenarios but selecting one value for the grace period does not account for varying lengths of the rainy season or no rainy season at all (a single rainfall cleaning). There are other natural reasons why the soiling rate can significantly change between two cleaning events and the PVSC2020 publication demonstrated that applying a segmented piecewise regression between cleanings improved upon the SRR and FRP models. Article No 5 followed in this same approach but also compared three change point detection algorithms to the existing piecewise-linear regression: 1) Prune Exact Linear Time (PELT), 2) Facebook Prophet Algorithm (FBP), and 3) Bayesian Estimation of Abrupt Change, Seasonality and Trend (BEAST). Each of the algorithms was graphically compared to the baseline SRR with cleaning only segmentation and then against each other per RMSE for nine soiling stations [33] and one PV site in Spain. Although further segmentation of data should always provide improvement in fitting criteria, graphical results confirmed cases where there was an obvious need for further segmentation. The additional segmentation provided a 40% reduction in RMSE in the best-case scenario but there was no obvious best-case model as the results varied by site. Piecewise regression and FBP showed the highest improvement on average across the sites (RMSE reduction of 20%) but there is room for tuning each of the models and therefore future work should still consider a range of models. The graphical results clearly showed benefit to the models, but it was noted that if one was only extracting an average soiling ratio there was no benefit to the additional model complexity. Alternatively, it was shown that if the goal was to extract dates for optimum cleaning, further segmentation of the data provided a large benefit. Similarly, one would expect if extracting mean monthly soiling rate (as in Article No 4) the additional segmentation would provide more accurate seasonal metrics.

In summary Article No 5 evaluated piecewise-linear regression and three change point algorithms for detecting changes in soiling rates across periods that were already divided based on cleaning events. All models showed the ability to capture real instances in the data sets where soiling rates significantly changed. None of the models proved to be an obvious winner considering the small number of data sets. Future work should continue to investigate piecewise-linear regression and various change point algorithms for better segmenting soiling profiles in periods with statistically distinct soiling rates.

5.2.5 Objective 2.3: Evaluate modelling improvements for automated detection of PV system cleaning events.

Article No 6: "Automated Detection of PV Cleaning Events: a Performance Comparison of Techniques as Applied to a Broad Set of Labeled PV Data Sets"

Objective 2.3 was achieved through Article No 6 cited above. As discussed in the introduction, the SRR algorithm by Deceglie [18] sought to automate the process of extraction of soiling loss trends from PV system data but as noted in [21, 22] SRR has significant limitations. The step of cleaning detection requires user tuning and accuracy is impacted by noise. Specifically, the user can adjust "α" where cleanings are a positive "*delta*" in the rolling median PI where *delta* must be greater than $Q3 + \alpha(Q3-Q1)$; Q stands for quantiles which are calculated for the entire time series of "delta" and $(Q3-Q1)$, is known as the interquartile range or IQR. Article No 6 is specifically focused on systematically testing alternate methods to this portion of the SRR algorithm with the intent to remove the need for user tuning. To evaluate potential improvements to the cleaning detection model, Article No 6 provides a data set of 22 PV PI signals (shared with the community for ongoing evaluations) that have been labelled by three soiling analysts for cleaning events per a documented rubric. These 22 systems are then used to test the following methods to improve upon the default SRR cleaning detection:

1) Consider a wide range of variations for α and the number of days (*day_scale*) used in calculated the rolling median of the PI within the existing SRR algorithm where cleanings are detected using IQR (here distinguished as *SRR-IQR*).
2) Applying irradiance filtering on a daily basis to remove noisy PI data prior completing cleaning detection.
3) Applying a rolling-window outlier filter on the PI data prior to completing cleaning detection.
4) Determining a cleaning event as a sufficiently high *delta* in relation to the 40-day rolling median of the absolute day-to-day deviations in the PI (here distinguished as *SRR-MAD*).
5) Detect cleaning events using change point detection from the Python Ruptures library.

All methods were quantified per the F_1 score (ranges from 0 to 1 where 1 is 100% correct identification of cleaning dates) for their accuracy in correctly identifying labelled cleanings while not false identifying additional days in the data set as cleanings. Roughly 1000 combinations of the above methods and tuning parameters were considered via the F_1 score. The default parameters within SRR-IQR resulted in $F_1 = 0.36$ while tuning α and *day_scale* improved to $F_1 = 0.63$. Prefiltering PI data based on the rolling-window filter and irradiance filter improved the tuned SRR-IQR results to $F_1 = 0.75$ and $F_1 = 0.76$ respectively. The best performing score was $F_1 = 0.79$ resulting from combining irradiance filtering with the SRR-MAD. The best performing change point algorithm resulted in $F_1 = 0.56$ and no clear set of parameter choices were found for tuning the change point algorithms.

In summary Article No 6 demonstrated significant improvement over the baseline approach to detecting cleanings in 22 labeled data sets, where a 43% absolute improvement was achieved in the mean F1 score (0.36 to 0.79) when going from the default SRR approach in Rdtools to the optimized SRR-MAD with irradiance filtering. Similarly, a 40% absolute improvement was achieved in the mean F1 score (0.36 to 0.76) when the irradiance filter was applied to a tuned version of SRR. While these results suggest a path to full automation of cleaning detection, caution should be taken as the results are based on 22 PV systems which were hand labeled. Future work should include continued testing while increasing the data set size and incorporating feedback from the PV soiling community on the methods applied in labeling the data set.

5.3 Other Publications Related to the Thesis

[O.1] M. Muller, J. Morse, F. Almonacid, E. F. Fernandez, L. Micheli, "Design and Indoor Validation of "DUSST": a Novel Low-Maintenance Soiling Station," Proceedings of the 35th European PV Specialist Conference, 2018.

[O.2] M. Muller, J. Morse, F. Almonacid, E. F. Fernandez, L. Micheli, "Indoor and Outdoor Test Results for "DUSST", a Low-Cost, Low-Maintenance PV Soiling Sensor, *46th Photovoltaics Specialist Conference,* 2019.

[O.3] Z. DeFreitas, A. Ramirez, B. Huang, S. Kurtz, M. Muller, M. Deceglie, "Evaluating the Accuracy of Various Irradiance Models in Detecting Soiling of Irradiance Sensors," 46th Photovoltaics Specialist Conference, 2019.

[O.4] L. Micheli, M. Muller, E. F. Fernández, and F. M. Almonacid, "Change point detection: An opportunity to improve PV soiling extraction," in Proc. IEEE 47th Photovolt. Specialist Conf., 2020.

6. CONCLUSIONS AND FUTURE WORK

The first half of this thesis focused on developing and patenting a novel low-cost, low-maintenance optical soiling sensor (DUSST). A patent was successfully published due to the prototyping, validation testing, and supporting research associated with this thesis. DUSST results were as follows:

1) DUSST devices were tested with three different monochromatic light sources (single wavelength LEDs) projected onto a silicon PV cells. Artificial soiling with three dust types demonstrated a R^2 of 0.98 or greater when correlating DUSST determined transmission losses to spectrophotometer measured transmission losses.
2) Coupons were naturally soiled outdoors in Jaen, Spain and DUSST measurements per a 530 nm LED and a silicon PV detector compared to spectrophotometer transmission losses with a R^2 of 0.94 and RMSE of 1.4%
3) Several DUSST design iterations were tested in chambers from -25°C to 40 °C and then deployed in climatically diverse outdoor locations, including California, Utah, Colorado, and Riyadh Saudi Arabia.
4) Design iterations included: 1) A single wavelength LED, 2) A single wavelength LED with a photodiode on the LED for intensity feedback, 3) A high intensity 7-white-LED with lens protection, and a 7-white-LED design that included a reference sensor for noise cancelation.
5) Outdoor testing proved functionality within exposure to rain and snow as well as ambient temperature extremes from -12 °C in Utah and above 40 °C in Saudi Arabia.
6) Near identical soiling rates were measured as compared to state-of-the-art PV soiling stations at multiple location with the longest co-measured soiling trend being greater than 3 months in California.
7) Outdoor and chamber testing also indicated the need for design improvements such as: A) a high aspect ratio collimating tube to protect the LED(s) from soiling in dirty environments, B) Selection of optics that minimize temperature dependence, C) a pulsed operation of the LEDs to avoid any self-heating and for lower power consumption for battery operated systems, and D) reduce complexity and cost by eliminating the heat sink (possible due to pulsed LED operation).

In addition to the lessons learned from prototype testing of DUSST, the 46 weeks coupon soiling campaign and associated modelling in Jaen, Spain demonstrated the benefits of constructing a DUSST sensor with two or three distinct monochromatic LEDS. Generally, increasing the number of wavelength measurements from one up to three results in error reduction when estimating soiling losses. As silicon in the most prevalent PV technology installed around the world, future work should consider building and validating a DUSST device with three distinct LEDs as calculated for silicon.

In the second half of this thesis several steps were considered to improve the current state-of-the-art PV soiling modelling. First, extracting a monthly soiling rate metric rather than a single annual soiling rate was shown to reduce RMSE when modelling soiling through a modified FRP model. Second, stochastic weather-generation algorithms were examined for the first time to forecast site specific rainfall patterns. These patterns were then subsequently applied with soiling rate information to examine optimal cleaning dates. The results were preliminary but suggest a methodology that can be explored in more depth for sites that have more years of soiling data. Next, piecewise-linear regression and three change point algorithms were tested for further segmented soiling trends beyond just cleaning events. Graphical results demonstrated that further segmentation of the data sets captured real changes in soiling rates that occurred due to extended rainy seasons, changes in wind patterns and airborne particulates, and for other reasons. Both the piecewise-linear regression and the Facebook Prophet algorithm showed an average reduction of 20% in the RMSE across the soiling sites examined. Future work should continue to examine all algorithms tested as the results were based on a small number of sites and each had only a year of data. Finally, filtering and algorithm improvements were considered for automatically detecting cleaning events within PV time series data. A publicly available data set was developed for 22 PV systems with prelabeled cleaning events. Using this data set, a 43% absolute improvement was achieved in the mean F1 score (0.36 to 0.79) when going from the default SRR approach in Rdtools to the optimized SRR-MAD with irradiance filtering. Similarly, a 40% absolute improvement was achieved in the mean F1 score (0.36 to 0.76) when the irradiance filter was applied to a tuned version of SRR. Future work should include working with the PV community to expand the publicly available validation data set as well as attempting to repeat the above results on a larger and more diverse data set. An additional goal is to work with the community to go beyond prelabeled cleaning events to include prelabeled soiling fits within the data set. Such a data will allow a more complete testing and comparison of various algorithms to extract a full set of soiling rates and soiling metrics from PV data. These efforts can provide the PV community with more complete tools for de-risking the uncertainty associated with PV soiling.

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8. PATENT AND JOURNAL PUBLICATIONS

Publication 1: A. Fernandez-Solas, L. Micheli, M. Muller, F. Almonacid, E. Fernandez, Design, characterization and indoor validation of the optical soiling detector “DUSST”, Solar Energy, Vol. 211, pp 1459-1468, 2020.
https://doi.org/10.1016/j.solener.2020.10.028

Summary: Nowadays, photovoltaic (PV) technology has reached a high level of maturity in terms of module efficiency and cost competitiveness in comparison with other energy technologies. As PV has achieved high levels of deployment, the development of devices that can help to reduce PV operation and maintenance costs has become a priority. Soiling can be cause of significant losses in certain PV plants and its detection has become essential to ensure a correct mitigation. For this reason, accurate and low-cost monitoring devices are needed. While soiling stations have been traditionally employed to measure the impact of soiling, their high cost and maintenance have led to the development of innovative low-cost optical sensors, such as the device presented in this work and named “DUSST” (Detector Unit for Soiling Spectral Transmittance). The thermal characterization of DUSST’s components and the methodology used to predict soiling transmittance losses are presented in this study. The results show that the losses can be predicted with an error lower than 1.4%. The method has been verified with an experimental campaign with naturally soiled coupons exposed outdoors in Jaén, Spain.

Publication 2: M. Muller, L. Micheli , A. Solas, M. Gostein, J. Robinson, K. Morely, M. Dooraghi, Y. Alghamdi, Z. Almutairi, F. Almonacid E. Fernandez, An in-depth field validation of “DUSST”: A novel low-maintenance soiling measurement device, Prog. Photovoltaics Res. Appl. March 2021.
https://doi.org/10.1002/pip.3415

Summary: This study presents indoor and field validation results for two versions of the “DUSST” optical soiling sensor, intended to be a low-cost and low-maintenance device for measuring photovoltaic soiling losses. Indoor testing covers irradiance calibration and temperature dependencies which are necessary to achieve high accuracy, low uncertainty field measurements. Field testing includes an array of different environments including: Saudi Arabia, California, Utah, and Colorado. DUSST versions include a configuration with a 530 nm LED (discussed in previous work) and a unit with 7 white LEDS and a polycarbonate collimating optic. The new design increases light intensity fivefold and demonstrates a single linear calibration coefficient is effective to measure soiling losses as high as 75%. Field data from Utah and California demonstrate that daily soiling loss measurements and soiling rate calculations closely match both reference cell and full-size module measurements of soiling losses and soiling rates. Corrective methods employed on the Utah DUSST sensor suggest that it is possible to achieve measurement errors as low as ±0.1% at two standard deviations. Field data from both Colorado and Saudi Arabia demonstrate that LED lens soiling can occur and that further design optimizations are needed. The lesson learned from all the field deployment locations suggest directions for future design improvements.

Publication 3: L. Micheli, E. F. Fernández, M. Muller, G. P. Smestad, and F. Almonacid, "Selection of optimal wavelengths for optical soiling modelling and detection in photovoltaic modules," Sol. Energy Mater. Sol. Cells, vol. 212, August, 2020. https://doi.org/10.1016/j.solmat.2020.110539

Summary: Soiling impacts the photovoltaic (PV) module performance by reducing the amount of light reaching the photovoltaic cells and by changing their external spectral response. Currently, the soiling monitoring market is moving toward optical sensors that measure transmittance or reflectance, rather than directly measuring the impact of soiling on the performance of photovoltaic modules. These sensors, which use a single optical measurement, are not able to correct the soiling losses that depend on the solar irradiance spectra and on the spectral response of the monitored PV material. This work investigates methods that can improve the optical detection of soiling by extracting the full soiling spectrum profiles using only two or three monochromatic measurements. Spectral transmittance data, measured with a spectrophotometer and collected during a 46-week experimental soiling study carried out in Jaén, Spain, was analysed in this work. The use of a spectral profile for the hemispherical transmittance of soiled PV glass is found to significantly improve the soiling detection, returning the lowest errors independently of the PV materials and irradiance conditions. In addition, this work shows that it is also possible to select the measurement wavelengths to minimize the soiling loss detection error depending on the monitored PV semiconductor material (silicon, CdTe, a-Si, CIGS and a representative perovskite). The approaches discussed in this work are also found to be more robust to potential measurement errors compared to single wavelength measurement techniques.

Publication 4: L. Micheli, E. F. Fernandez, M. Muller, and F. Almonacid, "Extracting and generating PV soiling profiles for analysis, forecasting, and cleaning optimization," IEEE J. Photovoltaics, vol. 10, no. 1, pp. 197–205, Jan. 2020.
https://doi.org/10.1109/jphotov.2019.2943706

Summary: The identification and prediction of the daily soiling profiles of a photovoltaic site is essential to plan the optimal cleaning schedule. In this article, we analyze and propose various methods to extract and generate photovoltaic soiling profiles, in order to improve the analysis and the forecast of the losses. New soiling rate extraction methods are proposed to reflect the seasonal variability of the soiling rates and, for this reason, are found to identify the most convenient cleaning day with the highest accuracy for the investigated sites. Also, we present an approach that could be used to predict future soiling losses through the implementation of stochastic weather generation algorithms whose ability to identify in advance the best cleaning schedule is also successfully tested. The methods presented in this article can optimize the operation and maintenance schedule and could make it possible, in the future, to predict soiling losses through analysis based only on environmental parameters, such as rainfall and particulate matter, without the need of long-term soiling data.

Publication 5: L. Micheli, M. Theristis, A. Livera, J. Stein, G. Georghiou, M. Muller, F. Almonacid, E. Fernandez, "Improved PV soiling extraction through the detection of cleanings and change points," in IEEE Journal of Photovoltaics, vol. 11, no. 2, pp. 519-526, March 2021.

https://doi: 10.1109/JPHOTOV.2020.3043104.

Summary: Photovoltaic (PV) soiling profiles exhibit a sawtooth shape, where cleaning events and soiling deposition periods alternate. Generally, the rate at which soiling accumulates is assumed to be constant within each deposition period. In reality, changes in rates can occur because of sudden variations in climatic conditions, e.g., dust storms or prolonged periods of rain. The existing models used to extract the soiling profile from the PV performance data might fail to capture the change points and occasionally estimate incorrect soiling profiles. This work analyzes how the introduction of change points can be beneficial for soiling extraction. Data from nine soiling stations and a 1-MW site were analyzed by using piecewise regression and three change point detection algorithms. The results showed that accounting for change points can provide significant benefits to the modeling of soiling even if not all the change point algorithms return the same improvements. Considering change points in historical trends is found to be particularly important for studies aiming to optimize cleaning schedules.

Publication 6: M. Muller, K. Perry, L. Micheli, F. Almonacid, E. Fernandez, “Automated detection of PV cleaning events: a performance comparison of techniques as applied to a broad set of labeled PV data sets, Prog. Photovoltaics Res, Vol. 30, no. 5, pp. 567-577, May 2022.

https://doi.org/10.1002/pip.3523

Summary: Extracting accurate soiling loss information from PV production data first requires segmenting the time series data per natural or manually occurring cleaning events. Maintenance logs are often incomplete, rain data is often unavailable, and the debate on rain thresholds for cleaning and dew or wind cleanings is still ongoing. The present work aims to overtake these issues by improving automated methods to detect these cleaning events and therefore improve extraction of soiling loss information. Time series power production data from 22 PV inverters were labeled for natural or manually occurring cleaning events. The data sets were carefully selected to include varying degrees of soiling, cleaning events, and noise. Several algorithms, including filtering logic and change point detection, were examined for efficacy at detecting the labeled cleanings. All the methods introduced except for changepoint detection showed significant improvement at detecting the labeled cleaning events per the mean F1 score. Furthermore, the highest performing cleaning detection algorithm achieved an absolute increase in the mean F1 score of 43% over the default version of the Rdtools Stochastic Rate and Recovery (SRR) algorithm. The highest performing algorithm included irradiance filtering and a cleaning detection threshold, adjusted based on the 40-day centered rolling median of the absolute day-to-day deviations in the daily performance index (PI). These improvements are promising as cleaning detection is an essential step in the automated analysis of photovoltaic soiling.

Publication 7: Fernández, E.F., Muller, M.T., Almonacid, F., Micheli, L., "Record of Invention: Low cost and low maintenance soiling spectral deposition detector," 2017.

Summary: Soiling deposition causes power losses to photovoltaic devices which increase the cost of solar energy. It is valuable to measure soiling losses in order to improve estimates of power production and to determine operation and maintenance schedules. The widely available soiling stations depend on water cleaning, manual cleaning or covering of a clean photovoltaic device in order to compare the measured output to a soiled photovoltaic device. A device has just been developed that does not require a clean device and estimates soiling loss through a reflection on the back side of a soiled surface. The proposed device provides a new low cost and low maintenance method to determine the photovoltaic soiling losses. Indeed, the invention proposed here does not require cleaning and relies on a different measurement to estimate the full spectral transmittance of soiling. This new device has lower noise to signal ratio thanks to the nature of the measurement procedure. The low cost, low maintenance and high reliability are achieved by using standard and well-known electronic components, widely used by the industry. This novel product can find application in any PV system worldwide, helping PV owners to reduce the impact of soiling, decreasing the power losses and increasing the energy production and economic revenues.

Publication 8: Fernández, E.F., Muller, M.T., Almonacid, F., Micheli, L., "Methods and systems for determining soiling on photovoltaic devices," 2019.
USPTO. 2019/0312548 A1

Summary: An aspect of the present disclosure relates to radiating light on to a front surface of a glass pane comprising a first surface and a second surface defining a thickness between the first surface and the second surface, wherein the first surface is substantially parallel to the second surface; detecting a transmittance of the light through the glass pane; comparing the transmittance through the glass pane to a reference transmittance value corresponding to a clean reference glass pane; and determining, using the transmittance and the reference transmittance, a soiling metric of a photovoltaic module.

Publication 9: Fernández, E.F., Muller, M.T., Almonacid, F., Micheli, L., “Methods and Systems for Determining Soiling on Photovoltaic Devices,” 2020.
US 10,734,946 B2

Summary: An aspect of the present disclosure relates to radiating light on to a front surface of a glass pane comprising a first surface and a second surface defining a thickness between the first surface and the second surface, wherein the first surface is substantially parallel to the second surface; detecting a transmittance of the light through the glass pane; comparing the transmittance through the glass pane to a reference transmittance value corresponding to a clean reference glass pane; and determining, using the transmittance and the reference transmittance, a soiling metric of a photovoltaic module.