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SERENDIPV

Suspect Soiling Issues in Your PV Plant? Engage with European Experts to Find a Solution

SerendiPV Innovations on Soiling Detection

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1 Introduction to SerendiPV

SERENDI-PV aims to increase PV-generated power penetration in European grids by addressing modelling, diagnostics, & quality control. The project focuses on accurate modelling for new PV technologies, enhancing energy yield assessments. It also innovates in advanced fault diagnosis emphasizing predictive maintenance for PV inverters & batteries. Improved understanding of component failures & aging will enable anticipation. Better quality controls will increase project quality & lifetime, reduce performance uncertainty, & improve bankability.

2 Introduction

Even with optimized cleaning procedures, estimations [0] of financial losses due to soiling show an increase over the last years, from 4 billion euros in 2018 up to 7 billion euros in 2023, as shown in Figure 1:

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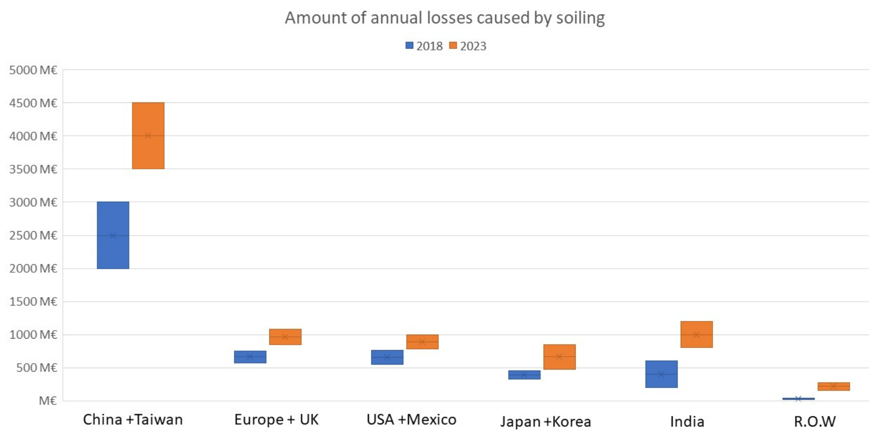

Figure 1: Estimation of annual losses caused by soiling

Due to the impact of soiling on the energy production of a PV plant, it is critical to continuously measure and monitor the level of soiling. Several solutions or techniques are available today. Some are commercially available, and some are under development. They can be split in three categories:

- Software methods based on the analysis of monitored electrical and environmental data.
- Software methods based on the analysis of pictures.
- Dedicated soiling sensors.

Figure 2 shows three approaches positioned according to two considerations, which are the time needed to learn and the accuracy of the estimates obtained. As a rule, the data analysis required around 70 days (2-3months) of data because part of them are not exploitable and various filters are applied to get rid of noise. The treatment and interpretation of electrical data is stochastic which means that the result is included in one interval of uncertainty. On the opposite, the Imagery analysis is based on pictures taken from the sky thanks to UAVs and therefore this gives a quick and accurate estimate of soiling on each PV panel of the solar farm. The compromise between these two axes is the measurement kit, which provides data directly related to the soiling. These kits do not require training, however the daily soiling ratio obtained must be averaged over few days rolling periods in order to mitigate the normal variations related to measurement uncertainty.

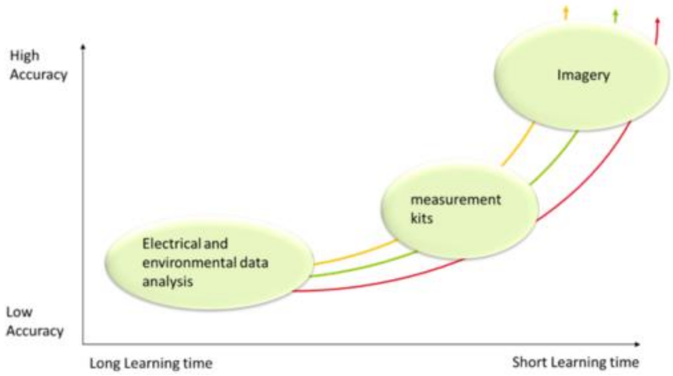

Figure 2: schema of the three soiling quantifying approaches

Note: There are others approaches, for instance one of them estimates the soiling impact by taking into account meteorological data and the concentration of airborne particles measured by satellites (i.e., Queeri Solar Atlas April 2021).

3 Software Methods for Detecting Soiling

3.1 State of the art

Up to now for the scientific community, soiling is assumed to accumulate at a fixed rate (i.e., linear) during the deposition periods [1]–[3]. Some authors have suggested exponential soiling deposition models [4].

Two soiling extraction models have been presented in the literature; the oldest is the fixed rate precipitation (FRP) model [1] and more recently the stochastic rate and recovery (SRR) model [2]. The FRP model, which requires a performance metric and the rainfall pattern as inputs, generates a soiling profile by applying the same fixed soiling rate to all dry periods [1]. This simple model based only on the precipitation would not be able to detect non rainfall-related cleanings. The SRR model calculates the soiling rates between each pair of consecutive cleaning events and generates a number of potential soiling profiles by using a Monte Carlo simulation [2].

According to these models, Photovoltaic (PV) soiling profiles exhibit a saw tooth 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. To sum up, these models might fail to capture the change points (CP) and occasionally estimate incorrect soiling profiles. Significant benefits have been obtained by introducing a change point analysis in soiling extraction models [5] [6]. As such, changes in deposition rates can be detected, cf. figure 3.

CPs are generally classified as “continuous” or “discontinuous” [7]. In the first case, only a change in the slope occurs (cf. figure 3), whereas in the second case, a step is present (cf. figure 4) caused by a cleaning event.

Cleanings days are identified in those dates in which a positive shift in the performance data larger than Q3 + 1.5 IQR (Q3=third quantile, IQR=inter quantile) occurred.

It has been demonstrated that the CP approach can analyze historical soiling trends more accurately than a CO (clean only) approach for many cases, and that profiles generated by this method fit better to reality.

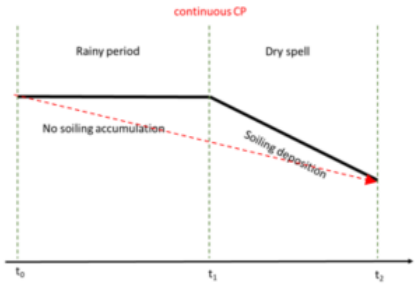

Figure 3: continuous change point

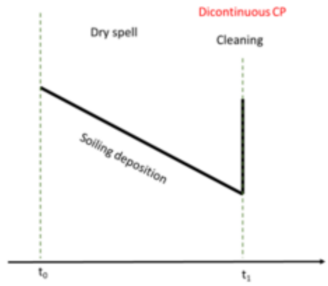

Figure 4: discontinuous change point

3.2 Innovations in SerendiPV

Since 2022, CEA has been developing another approach termed Stochastic Quantifying Soiling Loss (SQSL), which aims to improve the soiling profile extraction. On one hand, like SRR approach, the SQSL method does not require any environmental data, or any other information like for instance artificial cleaning operation. It calculates the impact of soiling directly from the electrical data measured in solar power plants. On the other hand, unlike SRR, it does not look for CP or CO days, but considers a performance metrics (PM) profile. The PM is a ratio between relative current (DC current / STC DC current) and relative irradiance (G/ STC G). A PM profile should be composed of different periods, divided into 3 types:

- A cleaning day (C.D) is one day when the performance metrics (PM) of the day after is greater than the PM of the day plus a threshold value,
- A stable Period (St.P) consists of days when, for each of them, the PM is sufficiently close to that of the previous day. The end of this period is identified according to 2 criteria: the day when the difference in PM with that of the previous day is greater than the threshold as described previously or the day when the difference in PM with that of the 1st day of the period is greater than the same threshold. In the latter case, we speak of a Stable Evolutionary Period. (St/E.P)
- A soiling period (S.P) is composed of the other days, those that are neither included in the stable periods nor identified as cleaning days.

Once each period family has been characterized, the Monte Carlo method is used to generate many random PM profiles based on the probability distributions of different parameters such as frequency and duration distributions, soiling rate distributions, etc.

Statistical analysis of the distribution of these PM profiles makes it possible to estimate the most likely average soiling ratio as well as the uncertainty interval. From there, it is possible to choose from the most pessimistic to the most optimistic scenario according to the desired risk level. Uncertainty intervals can be reduced significantly if a correlation between certain parameters or if seasonal effects are detected. Indeed, it is easy to add conditions or equations in the profile generator to better adapt it to reality.

The other strong point of the SQSL method is to allow the generation of future soiling profiles, to identify in advance the cleaning frequencies and dates that are typically more cost effective. This could be done simply by integrating in the SQSL algorithm, predictive parameters that would affect certain characteristics of the period families. The identification of these predictive parameters is a complex specific study that can advantageously be fed by the results obtained with the SQSL method.

4 Devices for Measuring Soiling

4.1 State of the art

Soiling sensors are supposed to be installed in the same configuration (tilt, azimuth, clearance) as the PV modules of the plant. They can be divided in two groups of devices:

4.1.1 Devices using PV cells and/or PV modules

The principle is the determination of a soiling ratio by comparing a “soiled” cell or module, as it is continuously exposed to its environment to a reference “clean” cell or module. The reference element can be cleaned regularly (and automatically) if also exposed, or protected by a cover, which can be moved (automatically) for the comparison of measurements. Most devices calculate the soiling ratio as the ratio of short-circuit currents of the soiled and reference PV elements. The current values may be corrected if the element temperature is measured. A soiling ratio equal to 1 indicates the absence of soiling, whereas a soiling ratio equal to 0 shows a complete soiling blocking totally the light. If soiling is not homogeneously spread over the surface of a PV module, the short-circuit current may not be relevant to account for the real effect of soiling on the electrical behavior of the module; power measurement would be more appropriate, even if more complex to do. IEC-61724 standard recommends soiling measurement within two hours of solar noon or for angle of incidence lower than 35° on a tracker.

Atonometrics’RDE 300: the device is composed of a PV module (soiled element) and a reference cell (clean element). The latter is also exposed to the environment, but a washing unit can spray water on the cell to clean it. Soiling ratio is calculated from corrected short-circuit currents of both elements.

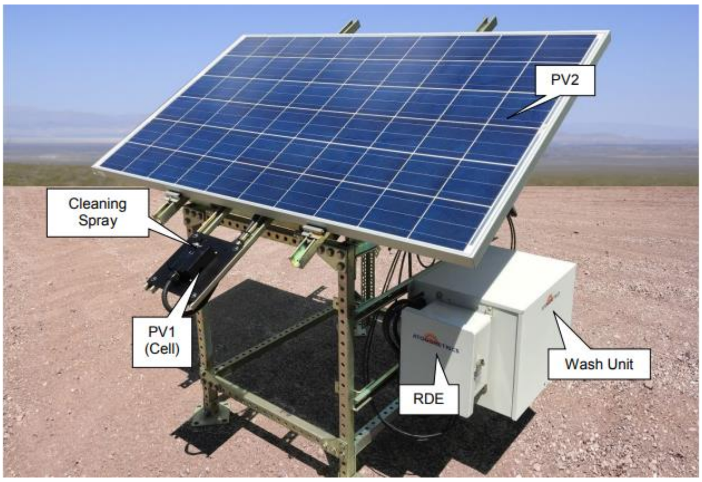

Figure 5: Atonometrics’RDE device (Source: Atonometrics)

Extel Energy: the device is composed of two large PV cells; one is exposed to dirt and the other one is portected by a cover, which opens for the compared measurements.

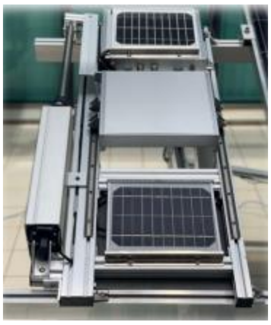

Figure 6: Extel's device (Source: Extel Energy)

Fracsun's ARES: the device is composed of two large PV cells, which are exposed to dirt. Two sprinklers, connected to a water tank, can spray water on the bottom cell to clean it.

Figure 7: Fracsun's device (source: Fracsun)

Other devices, like Campbell Scientific's DustSens and NRGsystems' kit, use also 2 PV cells/modules for comparison, but the reference one has to be cleaned manually.

4.1.2 Optical Devices

This category of devices doesn't use any PV cell or module but analyses the disturbances of light rays on a glass window.

Kipp&Zonen's Dust-IQ: the device is composed of 2 sensors and a PV cell or calibration. It doesn't require sunlight for soiling loss estimation as it measures the transmission loss on light rays emitted by blue LEDs through the sensor window, on which soil is accumulated. Kipp&Zonen recommends soiling measurement within two hours of solar zenith. Site calibration regarding the dust type is required.

Figure 8: Kipp&Zonen's device (Source: Kipp&Zonen)

Atonometrics' Mars: a camera system, consisting of an image sensor and microscope lens captures the image of the shadow generated by the soil particles accumulated on the top glass window. The soiling loss is then determined from this image by a processor. The device doesn't need any site calibration.

Figure 9: Mars device (Source: Atonometrics)

4.2 Innovations in SerendiPV

As presented before, the most common methods for estimating electrical energy losses due to soiling are to use optical sensors or to compare the short-circuit current of two solar devices (clean vs dusted). These approaches may be sufficient to calculate soiling irradiance losses, but are not designed to address the real effective power losses that soiling cause in PV modules. In fact, as soiling deposition is dominated by prevailing winds, dust patterns are usually non homogeneous (see Figure 10) [8].

This kind of dust distributions create "steps" in the I-V curve of the modules, affecting the maximum power point, P_M, much more than the I_{SC}. As an example, Figure 11 presents the I-V curves of the PV modules shown in Figure 10 , before and after being cleaned. Loss in P_M is 26% higher than I_{SC} loss (1.7% in absolute terms). Furthermore, it is worth mentioning that, when modules affected by different soiling patterns are connected in series, additional losses can be measured (Wp losses in the figure) when considering the MPP losses.

Figure 10: Picture of the most usual soiling deposition in a PV plant, dominated by prevailing wind. This type of soiling causes "steps" in the I-V curve of the modules.

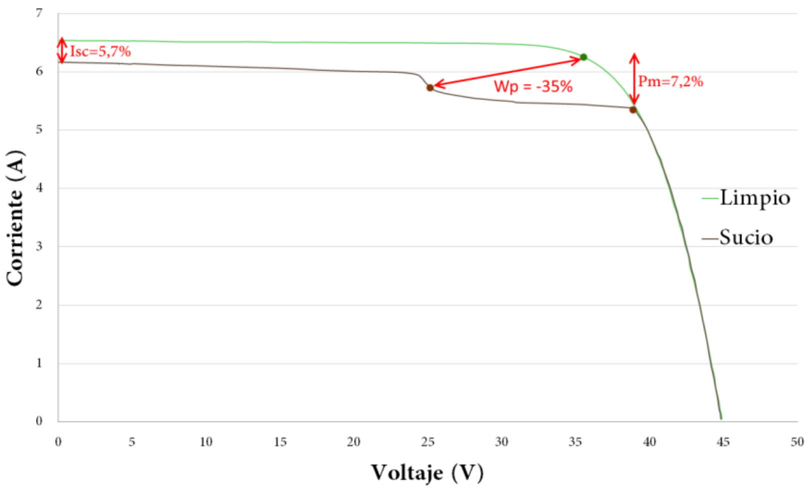

Figure 11: Example the I-V curves of the modules shown in Figure 10, before and after being cleaned. Losses in PM, ISC, and at the operation point, WP, are presented.

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As a consequence of the above, the SerendiPV consortium has only considered developing soiling sensors for addressing the effective power affection in PV modules. Moreover, two further characteristics have to be considered:

- Automaticity: soiling sensors that include auto cleaning options allow having soiling affection data without relying on site interventions, which is obviously very practical in some cases.

- Representativeness: automatic soiling sensors are, up to date, not able to be integrated in real PV arrays, but part of an independent static semiportable structure (i. e. Atonometrics' approach), what derives in not fully representative dust accumulation patterns (for example, when comparing to tracking structures). In addition, manual dry cleaning usually is more reliable than automatic wet cleaning when dust deposition is significant (See Figure 12).

Figure 12: Example of dry (left) and wet (right) cleanings in modules with a significant dust affection. As it can be observed, wet cleaning does not achieve good results although thorough cleaning was applied.

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The SerendiPV consortium is developing two prototypes to tackle these characteristics one by one.

4.2.1 Prototype A: Soilratio

The CEA-INES has been working since 2015 on a concept for measuring the rate of soiling in an outdoor environment. The concept chosen by the CEA consists in protecting one of the two PV sensors with a cover between each measurement, to keep it as clean as possible. In this way, this sensor does not require any cleaning, which guarantees better accuracy and lower operating costs. The first demonstrator at modules scale was manufactured in 2017. At the beginning of 2021, an important step was reached with the manufacturing and testing of an industrial prototype, termed "Soilratio" (see figure 13).

Figure 13: evolution of CEA’s soiling kit

A new version of SoilRatio (I.e., V2 prototype) was designed and manufactured within Serendi-PV project and was installed in the field in PV plant. This last upgrade aims to improve the relevance of the soiling measure. In particular, it integrates specific multi-zone panels, each zone being an independent sensor, thus allowing a more precise identification of the soiling type. The post treatment algorithm collects these multi-zones measures and extrapolates them to the whole PV plant considering the electrical architecture, in particular the bypass diodes, to calculate the real electrical impact on the whole PV installation.

4.2.2 Prototype B: E-Dust

QPV has developed a soiling sensor based on the use of two PV modules (clean and dusted) from the same batches, installed in the same structures and exposed to the same wind and tracking conditions as the rest of PV modules that make up the PV plant. Again, the full I-V curve of both modules is simultaneously and periodically measured. As a comparative measure is carried out, no specific calibration is needed, as the system auto calibrates itself when both modules are cleaned.

	
(a)	(b)

Figure 14: (a) Clean and dusted modules connected to an E-Dust prototype installed in a PV plant in Chile. (b)View of the installation of the E-Dust prototype.

5 Case studies

Real examples of how these SerendiPV innovations have been used are presented in this section.

5.1 SW methods on monitoring data

The SQSL approach, previously described, was applied on monitoring data of a vertical bifacial PV plant available in the partners' portfolios. A performance metric PM was calculated from DC current and irradiance (on both sides) measurements. A Dust-IQ device is also installed on site; it indicates a very low level of soiling over the August-September testing period:

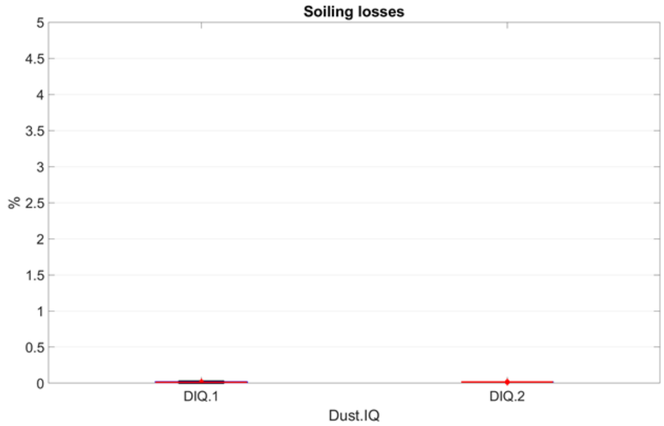

Figure 15: soiling loss ratio of the Dust-IQ sensors

The result of SQSL method on two individual modules (note: modules are connected to microinverters), for which irradiance and temperature measurements are available, is as follows:

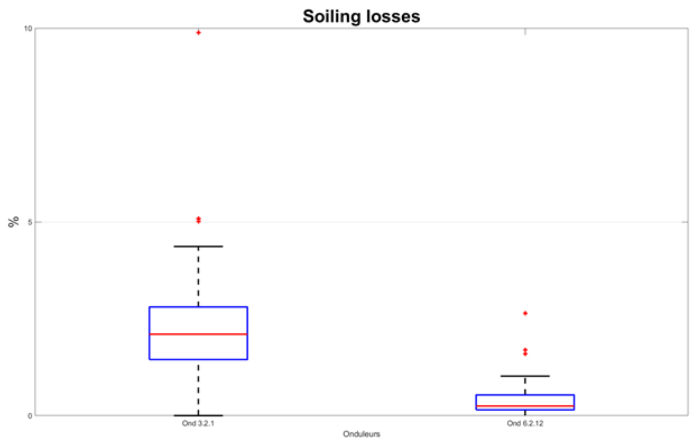

Figure 16: soiling loss estimation on two modules (about 2% and 0% respectively)

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These first results are compliant to measurements as they are in the range of uncertainty of the sensors.

For the first module, we can relate the soiling ratio and the rainfall impact:

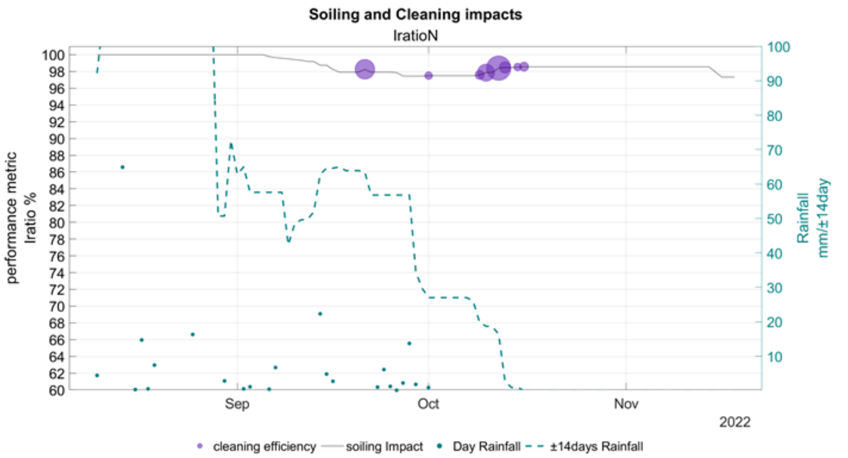

Figure 17: soiling ratio and rainfall impact

The rainfall impact looks very little, which may be expected for vertical modules.

5.2 Soiling devices (Soilratio)

Figure 18 and 19 show the kind of analysis provided by the Soilratio kit installed at CEA-INES' facility.

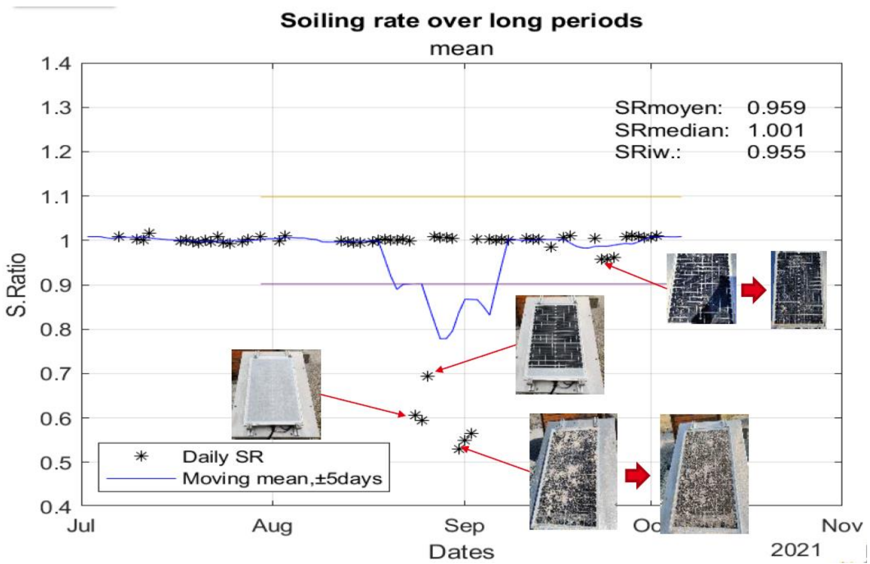

Figure 18: Example of SoilRatio v1 prototype testing results with artificial soiling at CEA-INES' facility

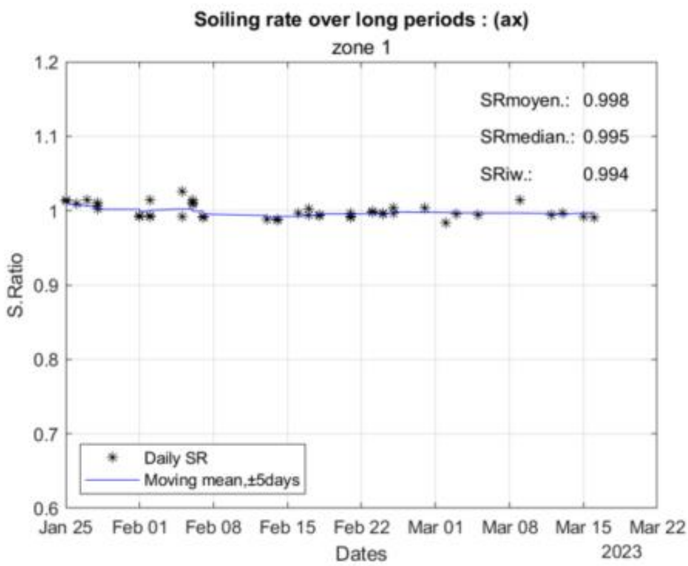

Figure 19: Example of SoilRatio v2 prototype testing results at CEA-INES' facility

5.3 Soiling devices (E-dust)

Figure 20 shows the evolution of a dirty and a clean module along a day, as measured by an E-Dust prototype installed in a PV plant in Portugal. Beyond the performance anomalies (as the tracking deviation) significant differences in the soiling ratio are observed among different hours of the day (thus, among different incidence angles). These results make the case for continuous measurements, in order to obtain a more accurate soiling loss estimation.

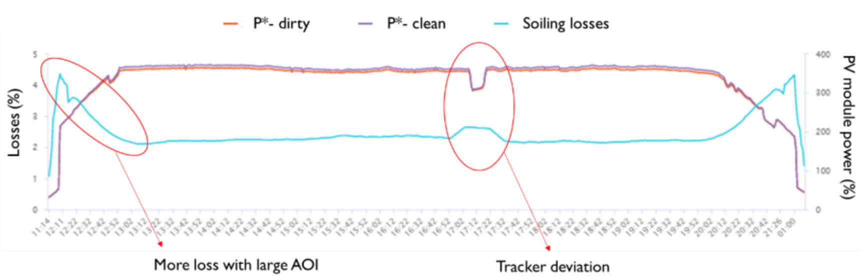

Figure 20: Evolution of a dirty and a clean module along a day

Commented [SV5]: Same behaviour for the clean and dirty module?

Figure 21 presents the daily evolution of the soiling ratio as measured by two E.Dust prototypes installed in two PV plants in Portugal and Chile. Together with the soiling ratio, real energy losses are calculated, based on the PV plant production.

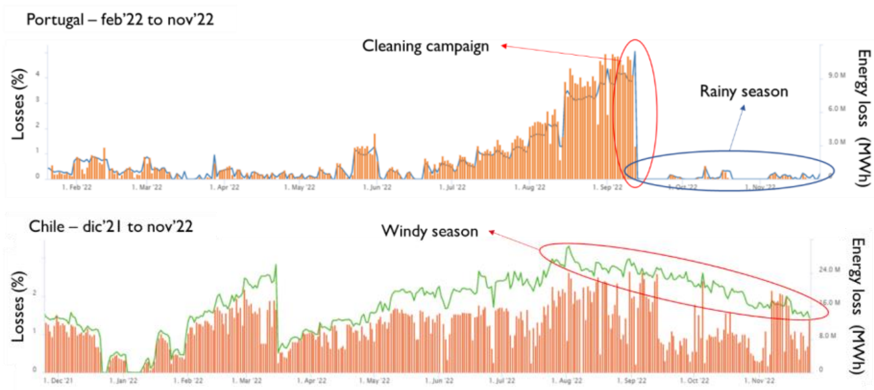

Figure 21: Daily evolution of the soiling ratio as measured by two E.Dust prototypes

6 Collaboration Call

6.1 What's in it for you?

We invite your organization to join an ambitious European research project dedicated to advancing the field of solar photovoltaic energy. This endeavor aims to design, test, and deploy cutting-edge technology to maximize the efficiency of photovoltaic power plants.

In this regard, your contribution can be instrumental. We are seeking partnerships with companies willing to share operational data from their photovoltaic plants. This data will significantly enhance our research efforts, providing real-world context to test our developments and innovations.

Several tools are currently under development for the simulation and monitoring data analytics on soiling on PV plants. These tools will be tested on your dataset after having received the data.

In return for your valuable input, we commit to sharing the results of our analysis. This will offer a unique opportunity for your organization to gain in-depth insights into your own systems. Through our professional and technical analysis, you will be better positioned to identify potential areas of improvement, optimize your operations, and ultimately increase the efficiency of your solar plants.

By participating, your company will not only contribute to pushing the boundaries of solar energy efficiency, but also stand at the forefront of the energy transition, strengthening your competitive advantage in the renewable energy market. We look forward to your positive response and a successful partnership.

All data shared will be handled in strict accordance with European data protection regulations, ensuring your information remains secure and used solely for the purposes of this research.

6.2 How to collaborate?

We are actively looking for the monitored operational data of PV systems of different typologies and installed all over the world, in order to further develop and validate our simulation models on soiling. If your data are of interest for the research group involved in the soiling PV monitoring, you could receive in-depth analyses for free that will contribute to a better understanding of the performance of your PV assets.

If you are currently modelling soiling on a PV plant, and if you are interested in sharing good simulation practices, and/or simulation codes, we encourage you to use our collaborative tools for development and get involved in PV modelling with the rest of the team. Interesting comparisons between different approaches could teach important lessons. The results of these data analyses, as well as the input data, will not be publicly released in order to preserve the critical commercial character of most of such data that will be provided by their owners, and to prevent their competitors from gaining access to the knowledge of the actual performance of their PV plants.

6.3 Data Requirement

The necessary data for proceeding in the analysis are:

- For SQSL method:
    - Description of the PV plant (electrical architecture)
    - PV module reference (datasheet)
    - Irradiance in the plane of array measurement
    - Location of sensors if numerous
    - Module temperature measurement (if not available, ambient temperature)
    - DC current measurement at plant, inverter or junction box level; if not available, DC power, otherwise AC power measurement

If you do not match all the criteria, please contact us to **contact@coplasimon.eu** and we could schedule a call to check if you are eligible to join a call.

How to send the data

The data can be sent to the specific partners, detailed in the call, or to **contact@coplasimon.eu.** These data will be shared among the mentioned SerendiPV partner exclusively and will be stored on private folders of the CKAN database of the Serendi-PV project.

7 REFERENCES

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Document History

Date	Version	Prepared by	Organisation	Approved by	Notes
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