PVSMS: A system for quantifying soiling effects and optimizing cleaning schedule in PV solar plants

Mounir Abraim [a,b,*], Massaab El Ydrissi [b], Hicham Ghennioui [a], Abdellatif Ghennioui [a,b], Natalie Hanrieder [c], Stefan Wilbert [c], Omaima El alani [a,b], Mohamed Boujoudar [a,b], Alae Azouzoute [d]

[a] *Laboratory of Signals, Systems, and Components, Sidi Mohamed Ben Abdellah University, Fez, Morocco.*

[b] *Green Energy Park research platform (GEP, IRESEN/UM6P), BenGuerir, Morocco.*

[c] *German Aerospace Center (DLR), Institute of Solar Research, Paseo de Almería 73, 04001 Almería, Spain.*

[d] *PV Materials Reliability and Durability group, National Renewable Energy Laboratory (NREL), Denver, CO, United States.*

*Corresponding author: abraim@greenenergypark.ma, mounir.abraim@usmba.ac.ma.

Abstract

Soiling of photovoltaic (PV) installations is an efficiency-limiting factor. It induces considerable energy losses and can even make PV projects economically unviable. A priori knowledge about the soiling phenomenon at a given site provides more guidance to PV project owners for effectively designing the solar field and accurately predicting the yield and profitability of the solar project. Soiling information can also improve the performance analysis of operational solar power plants. Recovering soiling losses begins with the installation of a reliable soiling monitoring system, followed by the implementation of optimized soiling mitigation or cleaning policies. In light of these facts, this work aims to provide a reliable and low-cost soiling monitoring station, named PVSMS (Photovoltaic Soiling Monitoring System). The working principle and detailed description of the hardware design are presented. The field validation of the proposed approach was performed by comparing the soiling loss data provided by PVSMS and the soiling loss on a real PV array, and it shows stable operation of the PVSMS and good agreement between the PVSMS data and the soiling losses quantified through the real PV array. A specialized soiling data analysis software tool has been developed to automate the soiling data analysis procedure and to assist operations and maintenance (O&M) teams in deciding on optimal cleaning dates. Furthermore, PVSMS has been used in a feasibility study of a large-scale PV project in a mining site. The result of this

application demonstrates that PVSMS can provide valuable insight into soiling behavior and can also be used to optimize cleaning strategy, estimate its related costs and economic benefits.

***Keywords**:* Photovoltaic, Dust deposition, Soiling monitoring, Sensor, Soiling mitigation, cleaning optimization.

Nomenclature

CC	Cleaning cost
DSL	Daily soiling loss
DSR	Daily soiling ratio
N_c	Number of cleaning operations
I_{sc}	Short circuit current
Q_{clean}	Output energy of clean solar field (kWh)
Q_{loss}	Energy loss due to soiling (kWh)
QS_{oiled}	Output energy of soiled solar field (kWh)
RL	Daily revenue loss due to soiling
RL_{acc}	Cumulative daily revenue loss from the last cleaning date
T_{module}	Back of PV module temperature
ΔSR	Soiling Rate

Abbreviations

ADC	Analog Digital Converter
DAQ	Data Acquisition
GEP	Green Energy Park
IEC	International Electrotechnical Commission
LED	Light Emitting Diode
MAD	Mean Absolute Deviation
NREL	National Renewable energy laboratory
O&M	Operation and Maintenance
POA	Plane Of Array
PV	Photovoltaic
PVSMS	Photovoltaic Soiling Monitoring System
RTD	Resistance Temperature Detector
SCADA	Supervisory Control and Data Acquisition

SSR	Solid State Relay

1. Introduction

The preferred regions for PV power plant projects are those with high solar potential; such areas tend to have a desert climate with a high concentration of dust in the atmosphere, water scarcity, lack of precipitation and extreme events such as dust storms [1], [2]. As a result, soiling of solar panels remains a major problem that causes significant yield and revenue losses in solar power plants [3]. The global solar energy losses due to soiling are expected to rise to around 4%-7% which will result in a revenue loss of as much as 7 billion euros for 2023 globally [4]. Soiling is a reversible type of degradation, which can be effectively mitigated through cleaning [4], [5]. Natural cleaning by precipitation can partially clean the solar field, but it may not always be enough to fully recover the performance loss, especially in areas with low levels of precipitation [6]. Red rain (precipitation with lots of particulates within the rain drops) can also cause a negative effect by increasing the accumulation of soiling [7], [8]. Other preventive soiling mitigation technologies, such as anti-soiling coatings, can lower the rate of soiling accumulation [9], [10], but cannot completely eliminate the need for cleaning operations [2], [4]. However, as necessary as they are, cleaning operations increase O&M costs, and consequently the price of electricity [11]–[13]. This implies that the cleaning operations should be optimized in a way that minimizes the cleaning cost and keeps the performance of the solar plant at an acceptable level. Deciding on the optimal cleaning policy requires reliable data on the soiling of the site of interest [14].

The most accurate source of soiling data comes from ground soiling measurement systems that are in close proximity to the solar site [15]. The International Electrotechnical Commission (IEC) standard 61724-1 for performance monitoring of photovoltaic systems [16] recommends the use of soiling measurement systems at any site with expected annual losses greater than 2%. Unlike other factors that impact solar system efficiency (e.g., temperature and irradiance), soiling is characterized by a very high spatial variability [17]–[19], which leads to non-uniformity in soiling rate even at the same site. For this reason, the IEC standard [16] also recommends the installation of multiple soiling measurement systems for solar systems with a capacity of more than 5 MW. The number of soiling measurement systems varies from 1 to 8 depending on the capacity of the solar system. Nowadays, with the rapid deployment of new large-scale solar PV projects

worldwide, the global PV installed capacity is expected to exceed 2.3 TW by 2026 [20]. Consequently, a significant number of PV soiling monitoring systems will be required to cover existing and newly installed PV capacity, making this market very active and rapidly expanding [14], [21]. Several companies have already taken advantage of this new opportunity and released solutions for PV soiling monitoring. Currently, different categories of soiling monitoring solutions are available. The most widely marketed are soiling stations that measure soiling losses directly from the electrical output of PV devices [14], [15]. A common type of a soiling measurement setup consists of two identical PV devices (PV modules or PV reference cells). One of them is cleaned regularly, while the other is left to naturally accumulate soiling. Soiling stations with PV modules are the most accurate solutions for soiling monitoring, as they mimic the soiling behavior of the real PV system. In addition, they are often used as a reference method to validate several other new soiling monitoring devices [22], [23]. The main limitation of these stations is the need for regular cleaning of the reference device. The task might be solved using automatic cleaning, but this presents two problems: the use of automatic cleaning units may not be sufficient to perform the cleaning adequately, and these cleaning systems may require regular maintenance. Replacing the reference PV module with a PV reference cell might reduce the complexity of the cleaning, since PV reference cells are much smaller. Therefore, if this is done, a simple cleaning nozzle or pressured water spray system could remove the accumulated soiling [24], but good cleaning results are still difficult to obtain. Also, the small sensing area of the PV reference cell may induce measurement uncertainties since the small areas are affected differently by soiling than PV modules themselves [7].

Recently, more innovative soiling monitoring solutions have been released to the market. These solutions use indirect measurement methods to derive the soiling losses. For example, the DustIQ optical soiling sensor offered by Kipp&Zonen measures the transmittance losses due to soiling through a photodiode that quantifies the scattered LED light it receives from the soiling particles accumulated on the sensor's glass panel [25]. Microscopic dust imaging has been reported in the literature as a method of soiling measurement [22], [26], [27]. However, the Atonometrics Mars soiling sensor is the only commercially available soiling measurement device that uses this method. DustIQ and Mars are advantageous in terms of cleaning requirements [28]. These sensors do not require regular cleaning because they do not incorporate a reference device to make the

measurements. Indirect soiling measurements were found to be less accurate than soiling stations [29]. This is due to the physical differences between these sensors and the real PV modules (e.g., glass texture, the sensing area). Furthermore, the variability of the solar spectrum and spectral response of each PV material results in a distinct soiling effect between PV technologies [30]–[32]. It is still necessary to conduct further research and improve the correlation between these sensors and the various PV technologies [21]. Therefore, other direct methods to measure soiling have been proposed. Two methods, that use the signal of a reference cell that is illuminated by a lamp have been presented [33], [34]. However, these sensors are still not available commercially.

Currently, when it comes to PV soiling monitoring and measurement systems, there is no one solution that fits all. The choice of a PV soiling measurement system depends on the requirements of the given application and the preferences of the project owner. Since it is a trade-off between data reliability and cleaning effort. For example, cleaning-free soiling sensors might be more beneficial in remote sites where regular cleaning cannot be assured, while soiling stations with pairs of PV devices are more useful in projects where on-site maintenance personnel are constantly available.

This study aims to address the growing demand for soiling monitoring and optimizing the cleaning of solar panels resulting from the significant increase in installed PV capacity worldwide. The proposed method is designed to be a comprehensive, reliable, low-cost, and easy-to-implement solution that can be utilized by O&M teams with commonly available components. The system has been engineered to comply with the IEC 61724-1 standard [16] while maintaining maximum flexibility. Unlike most existing PV soiling stations, the proposed system can be utilized with any type of PV installation, including fixed and tracking systems, as well as high-power output PV modules, and allows for the selection of PV modules similar to those used or to be used in the solar plant. The integration of a control circuit ensures that the system can be incorporated with any PV technology without inducing degradation of the PV modules. Additionally, a software tool has been developed to simplify and automate the raw soiling data processing procedure and provide solar plant managers and O&M teams with the information necessary to make informed decisions regarding cleaning dates based on the ground soiling data. PVSMS software takes into account the seasonal variability of soiling and the occurrence of natural cleaning events to make more effective cleaning decisions. This system can be used in feasibility studies for PV projects to accurately

predict the future yield of the solar plant, determine the project's profitability, and mitigate the financial risks associated with underestimation of O&M costs. The algorithms used for data analysis and cleaning decision-making approach are described in detail.

This paper is organized as follows: section 2 describes the hardware design and the interconnection between the different components. Section 3 depicts the experimental setup and field validation results of the proposed system. Section 4 details the data analysis procedures and the cleaning decision approach implemented in the software tool. Section 5 is an application example of the proposed system in soiling assessment for a PV project feasibility study at a mining site. The interpretation of the soiling measurements is presented. The recommended cleaning dates based on these measurements, the energy saved and the economic gain are discussed. In section 6, conclusions and perspectives are given.

2. PVSMS: A detailed description

PVSMS is a system designed to quantify the impact of soiling in solar PV plants. It is suitable for independent installations or as a complementary device to any new or existing weather station. It is also designed to operate with all PV panel technologies, including brand new PV modules that are characterized by high power output. This system was designed to be simple, low-cost, and easily deployable at multiple points in a PV installation to accurately determine the spatial variability of soiling in large-scale solar plants and it can be used on operational PV facilities or pre-construction study sites. It is well known that the soiling effect can differ from one PV technology to another [35]. To this end, PVSMS is designed to allow the selection of PV modules that are identical to those in the PV system or to those that will be used in pre-construction studies, thus ensuring that the soiling measured accurately represents the effect of soiling on the PV system under study. PVSMS is also capable of processing the measured data and estimating the daily energy loss due to soiling, as well as helping O&M teams to decide on the best time to clean the solar power plant.

Fig. 1 shows two views of a PVSMS set-up as it appears at the Green Energy Park (GEP) installation in BenGuerir, Morocco. As shown, PVSMS is composed of two PV modules: the reference (clean) PV module must be kept clean through regular cleaning, either manually or automatically, while the second module (soiled) should only be subjected to the cleaning operations

performed on the entire PV installation. There is a soiling measurement box, which is used to derive the soiling data by measuring the short-circuit current (Isc) of both clean and soiled PV modules. The soiling effect is then determined by comparing the short-circuit current of the clean module (Isc_{clean}) with the short circuit current of the soiled module (Isc_{soiled}). In Fig. 1(b), to the right of the soiled PV module, is a PV reference cell, whose function is to measure the plane of array (POA). There are also temperature sensors (not visible here), which keep track of back-surface temperature of the PV modules. The measured parameters are recorded in the internal memory of the data logger as time series and are also transmitted via preferred communication channel (Ethernet, Modbus, Cellular communication, etc.) to the monitoring and data analysis platform installed on a computer where the user has the capability of visualizing the measured data in real time. This platform also includes a software tool that our team has developed to perform soiling data analysis and provide a decision on cleaning operations.

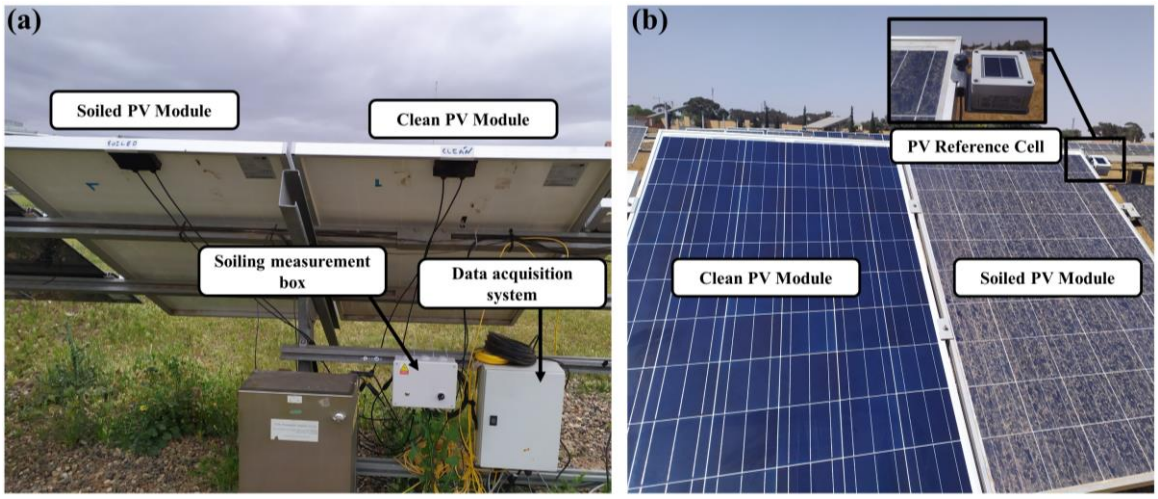


Fig. 1. (a) rear view, and (b) front view of a PVSMS installation.

The interiors of the soiling measurement box and the data acquisition system are shown in Fig. 2. Detailed descriptions of each component and the measurement approaches employed are provided in the following subsections.

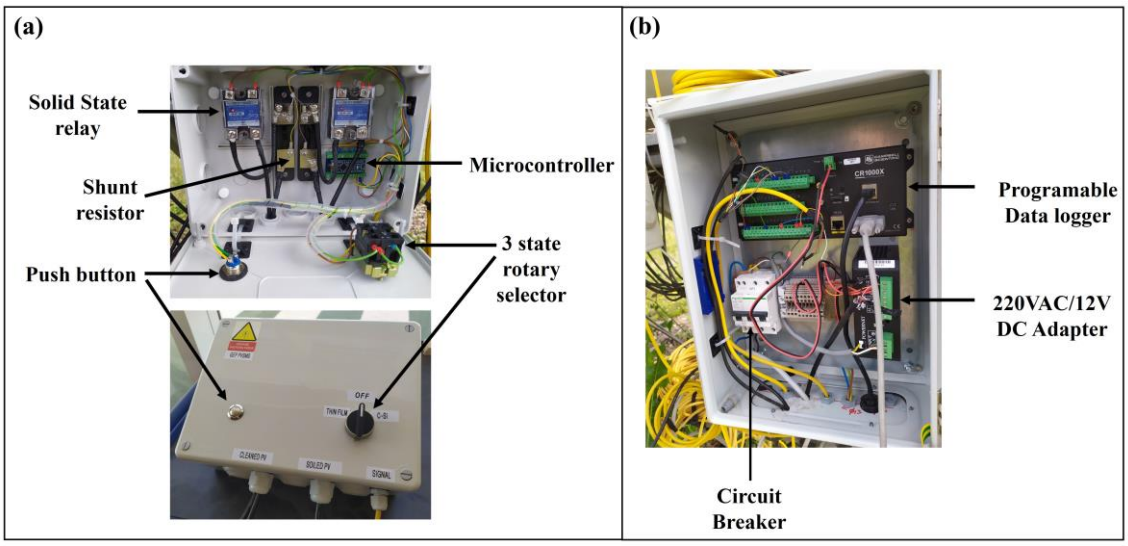


Fig. 2. The components of PVSMS, (a) Soiling measurement box, (b) data acquisition system.

2.1. PV soiling measurement

The soiling measurement system consists of measuring the short-circuit currents of the clean and soiled PV modules using a circuit configured in such a way that each panel is short-circuited with a high accuracy current-sense resistor (shunt resistor). The shunt resistors are very low resistance value resistors that provide highly accurate current measurement by measuring the voltage drop across the shunt resistor as a proportional metric of the current flow [36]. The short-circuit current is then determined using Ohm's law (Eq. 1):

$$I_{sc} = \frac{U_{sh}}{R_{sh}} \tag{1}$$

Where U_{sh} is the measured voltage drop across the shunt resistor, and R_{sh} is the resistance of the shunt. The temperature correction is applied to the I_{sc} measurements using Eq. 2 [37].

$$I_{sc\_Corr} = I_{sc} \times \left(1 + \left(T_{\text{module},0} - T_{\text{module}}\right) \times \alpha_{IscMod}\right) \tag{2}$$

Where I_{sc} is the short-circuit current without temperature correction, I_{sc_Corr} is the corrected short-circuit current, $T_{modulel,0}$ is the module temperature under standard test conditions (STC) which is typically 25°C, T_{module} is the measured PV module temperature, and α_{IscMod} is the

module temperature coefficient for the I_{sc} parameter provided by the manufacturer. The temperature measurement of clean and soiled PV modules is performed using a PT-1000 resistance temperature detector (RTD) taped to the backside of the PV modules, and connected to a conditioning circuit (voltage divider), so that the output signal of the temperature sensors can be read as a voltage signal (Fig. 3).

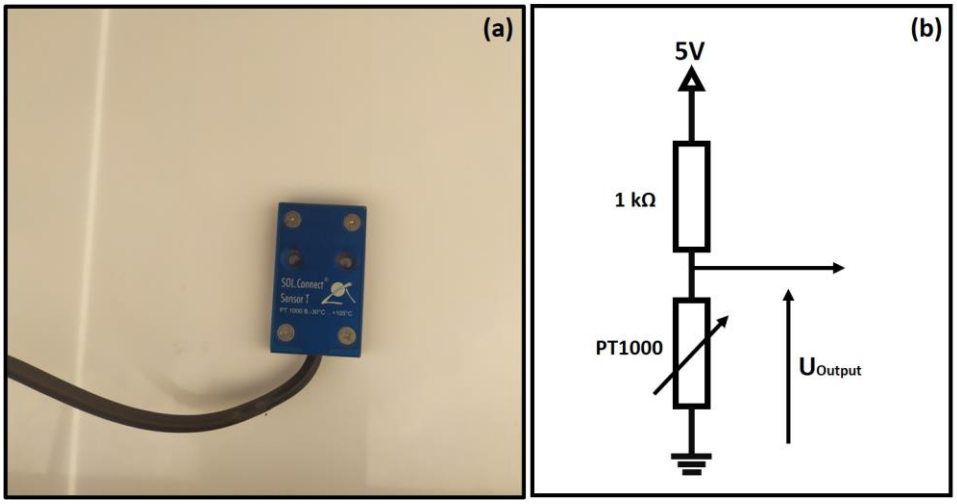


Fig. 3. (a) PT1000 temperature sensor taped to the backside of the PV module. (b) PT1000 conditioning circuit (voltage divider circuit).

The soiling measurement configuration used is in compliance with method two of the soiling measurement, entitled "short circuit current reduction due to soiling", international standard IEC 61724-1 [16]. The metric used to quantify the PV soiling is the soiling ratio SR, which is defined as the ratio of the output power of a soiled PV module to that of an identical clean PV module [16]. The PV soiling ratio is also assumed to be the ratio of the temperature corrected of the PV modules short-circuit currents (Eq. 3):

$$SR = \frac{I_{sc\_Corr,Soiled}}{I_{sc\_Corr,Clean}} \quad (3)$$

Where, $I_{sc\_Corr\_Soiled}$ is the corrected short-circuit current of the soiled PV module, and $Isc_{\_Corr\_Clean}$ is the corrected short-circuit current of the clean PV module. It should be noted the

selection of PV modules should be based on their capacity to generate an equivalent short-circuit current under the same conditions.

The short-circuit current was chosen as a metric to quantify soiling since it is widely used in the literature for this purpose [21], [38]–[40], as it is strongly correlated with the effective irradiance reaching the cells of the PV modules and as it can be easily measured [41]. Therefore, the effective irradiance reduction due to soiling can be easily determined by comparing the short-circuit current of the clean and soiled PV modules. Studies such as Gostein et al. [42] found that using short-circuit current as a soiling metric is accurate in the case of uniform soiling accumulation, and that this metric may underestimate the actual loss due to soiling in PV installations with severe non-uniform soiling. Although maximum power has proven to be more accurate and precise in cases involving non-uniform soiling, it is more complex, more expensive, and requires more sophisticated components.

To perform the short circuit measurements for PV soiling quantification in accordance with the recommendations of the international standard IEC 61724-1 for performance monitoring of photovoltaic systems [16], the two PV modules should not be held between measurements in an electrical state that could cause or increase the degradation rate. In the case of crystalline silicon modules (C-Si), the panels are held at the open circuit in between measurements and only short-circuited for a short period of time each minute to perform the measurements, while for thin-film modules, both panels are kept short-circuited. For this purpose, a three-state rotary selector is integrated, allowing the on-site operators to choose the PV technology under test. The signal from the rotary selector is transmitted to a microcontroller, which controls two solid-state relays (SSRs) according to the chosen PV technology. The rotary selector can also be used to select the permanent open circuit state (OFF), to prevent arcing caused by high current flow that can pose a risk to operators or damage PV module connectors when connecting or disconnecting PV modules. Fig. 4 demonstrates the interconnection between the different components.

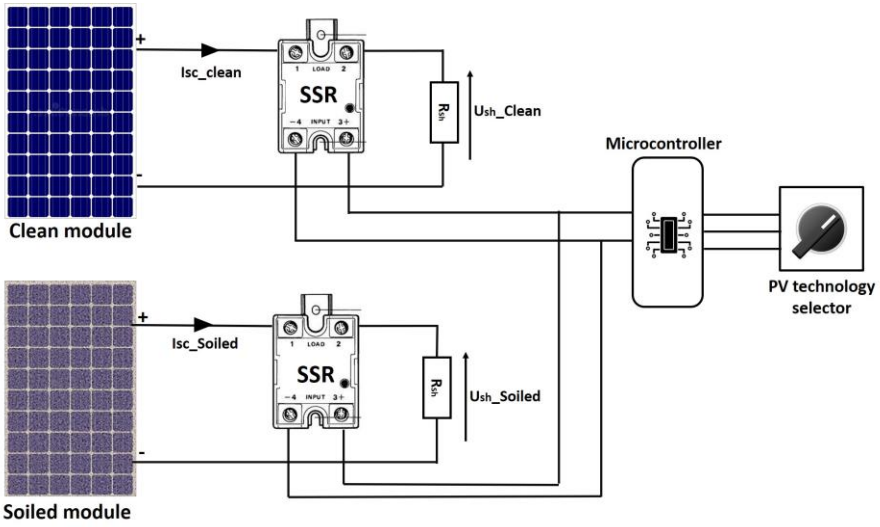


Fig. 4. The interconnection between the different components of the soiling measurement box.

A push button is also integrated (Fig. 2) to facilitate analysis and interpretation of soiling data. This push button is activated by the on-site operators. This allows a signal to be recorded in the data table that signifies that the cleaning or maintenance work has taken place. A code can be used by the on-site operators and the person in charge of data analysis (e.g., one impulse for cleaning the reference panel, two impulses for cleaning both panels and three impulses for maintenance interventions).

The push button short-circuits the wire when it is pressed and opens when unpressed. In order to generate high impulses, it is necessary to connect the push button to a pull-down circuit. The basic conditioning circuit for a push button is shown in Fig. 5.

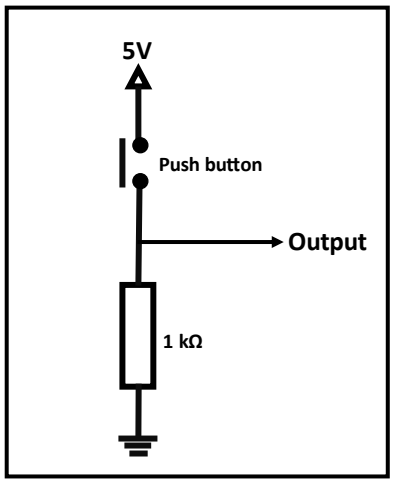


Fig. 5. Push button conditioning circuit (interfacing in pull-down mode)

2.2. Solar irradiance measurement

The effective solar irradiance or the so-called plane of the array (POA) is measured using pyranometers or PV reference cells. One of the main differences between these two devices is that pyranometers have a flat spectral response and measure the actual solar irradiance available. The PV reference cell mimics the spectral response of PV panels and measures only the portion of solar irradiance that can be absorbed by the PV cell materials [43], [44]. Also, the incidence angle and temperature dependence of the reference cell signal is not ideal, but might correspond to that of a given PV module. For the targeted application irradiance measurements can be obtained by selecting high-quality, newly calibrated PV reference cell with technology similar to that of the PV panels under test [45]. The PV reference cell is used to measure irradiance due to its low cost compared to a thermopile pyranometer, and to ensure that the measured irradiance corresponds to the irradiance absorbed by each particular PV technology. As can be seen in Fig. 1, the PV reference cell is attached to a holder that is fixed to the frame of the PV module, to guarantee that the sensor is properly mounted in the same plane as the PV modules under test. PVSMS is capable of functioning in PV plants with tracking systems, where the irradiance sensor must be attached to the tracking system for proper exposure to the same irradiance as the PV modules.

In order to measure solar irradiance, the PV reference cell used must meet the requirements for short-circuit current linearity as a function of irradiance according to IEC 60904-10 [46]. The irradiance measurement is influenced by the temperature of the PV cell. To correct this temperature dependence, the PV reference cell is equipped with a PT1000 temperature sensor (see Fig. 6). The corrected POA is calculated according to Eq. 4.

$$POA_{Corr} = POA \times \left(1 + \left(T_{Cell,0} - T_{Cell}\right) \times \alpha_{IscRC}\right) \quad (4)$$

Where POA_{corr} is the corrected plane of array irradiance, POA is the measured plane of array irradiance without correction, $T_{Cell,0}$ is the PV reference cell temperature under STC (typically 25°C), T_{Cell} is the measured PV reference cell temperature, and α_{IscRC} is the temperature coefficient for the I_{sc} parameter of the reference cell provided by the manufacturer.

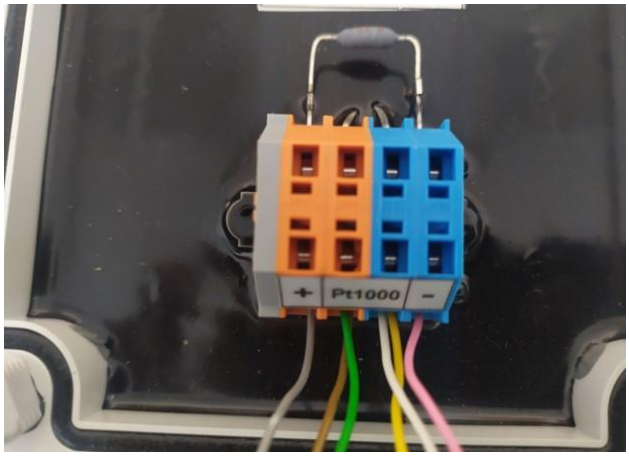


Fig. 6. The PT1000 temperature sensor integrated into the PV reference cell.

2.3. Data acquisition system

The data acquisition (DAQ) system is used to measure signals from sensors that monitor physical phenomena, and it is mandatory for any monitoring application. In the present system, a Campbell Scientific CR1000X data logger was used as the DAQ system (see Fig. 2-b). To read analog voltage sensors, the CR1000X data logger is equipped with 8 differential inputs (or 16 single-ended inputs). Voltage measurements are made using a 24-bit analog-to-digital converter (ADC). The ADC can be individually configured to set the gain and voltage

measurement range for each analog input. The measured voltage is then used to calculate the data quantities. The data logger is programed to take multiple measurements and store the average of each minute to be in line with the recommendations IEC 61724-1 standard [16]. The raw data are also transmitted via the available communication link (Ethernet, Modbus, cellular modem, etc.) to a server or local computer where the measurements can be monitored in real time. In the case of sites with no communication network, the data can be saved internally and retrieved later via a USB port. Fig. 7 shows the block diagram of the DAQ system and the interconnection with the other components of the system.

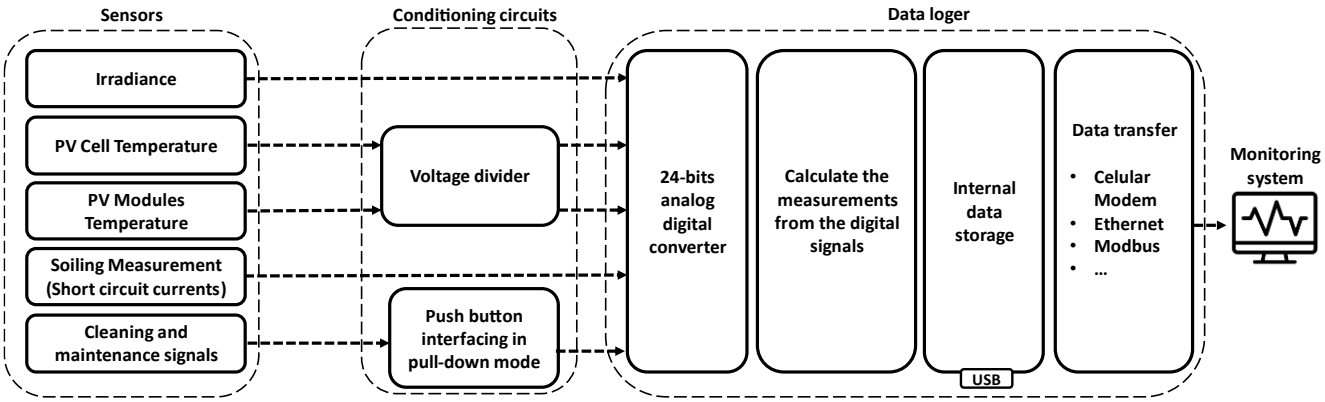


Fig. 7. Overview of the DAQ system and interconnection with other system elements.

3. Experimental validation of PVSMS

This section provides the validation results of the PVSMS soiling station. The outdoor validation experiment was conducted at the Green Energy Park (GEP) Research facility (see Fig. 8). PVSMS soiling station and a polycrystalline PV system were installed at the same location and under the same conditions from June 18 to September 30, 2022.

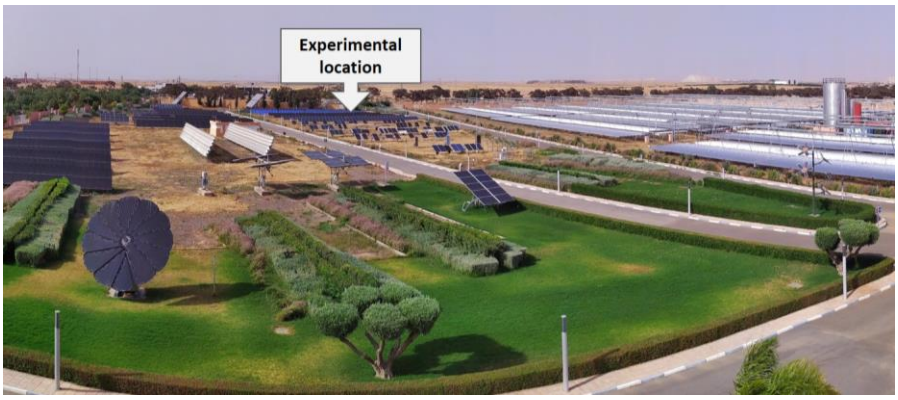


Fig. 8. The Green Energy Park research facility, BenGuerir, Morocco.

The polycrystalline PV system was divided into two strings with 19 modules per string (module specifications at STC are shown in Table 1). One string was cleaned every two days and the second string was left uncleaned (see Fig. 9). The PV system is connected to GEP's supervisory control and data acquisition (SCADA) system to monitor its production and store the data on the internal server. The daily energy generated by the soiled string Q_{soiled} is then compared to the daily energy generated by the clean string Q_{clean} to determine the daily soiling loss of the PV array (DSL_{array}) according to the Eq. 5.

$$DSL_{array} = \left(1 - \frac{Q_{Soiled}}{Q_{Clean}}\right) \times 100\% \quad (5)$$

To determine the PVSMS daily soiling data, the 1-minute SR is used to determine the daily soiling ratio (DSR_{PVSMS}). It is worth noting that only SR data between 10 am and 4 pm and under sufficient irradiance (POA>500 W/m^2) were considered to avoid insignificant soiling measurements due to low irradiance (Eq. 6).

$$DSR_{PVSMS} = \frac{1}{N} \sum_{t=10a.m}^{4p.m} SR_t \quad (6)$$

Where SR_t is the considered 1 minute soiling ratio, and N is the number of the daily selected data points. The daily soiling loss (DSL_{PVSMS}) is then calculated according to Eq. 7.

$$DSL_{PVSMS} = (1 - DSR) \times 100\% \quad (7)$$

It is worth noting that days exhibiting a high rate of change in I_{sc} as determined by the difference between consecutive data points, are excluded and linearly interpolated to eliminate insignificant data caused by cloud passages.

Table 1. The characteristics of the PV module at STC.

Technology type	Polycrystalline
Maximum power (P_{MAX})	250 W ±3%
Maximum power voltage (V_{MP})	30.8 V
Maximum power Current (I_{MP})	8.13 A
Open circuit voltage (V_{OC})	38.5 V
Short circuit current (I_{SC})	8.71 A

Fig. 9. The validation experimental setup.

The DSL of the PVSMS was compared to that of the PV array. It should be noted that both the PV system and PVSMS use the same PV module for a meaningful comparison. Fig. 10 (a) displays the DSL measured by the PVSMS and the DSL determined from the PV array as a function of time and Fig. 10 (b) shows a scatter plot of the DSL measured by the PVSMS and the DSL derived from the PV array. As shown in this figure, the DSL increases linearly (soiling accumulation). However, occasional rainfall (blue dashed lines) partially removes the accumulated soiling, which explains some of the DSL reduction instants. The field test was conducted by comparing the DSL measured by the PVSMS and the PV array, demonstrating the stability of the PVSMS in the harsh climate of BenGuerir. The results showed good agreement between the PVSMS and PV array measurements, with an R^2 value of 94.8% and a mean absolute deviation (MAD) of 1.3%.

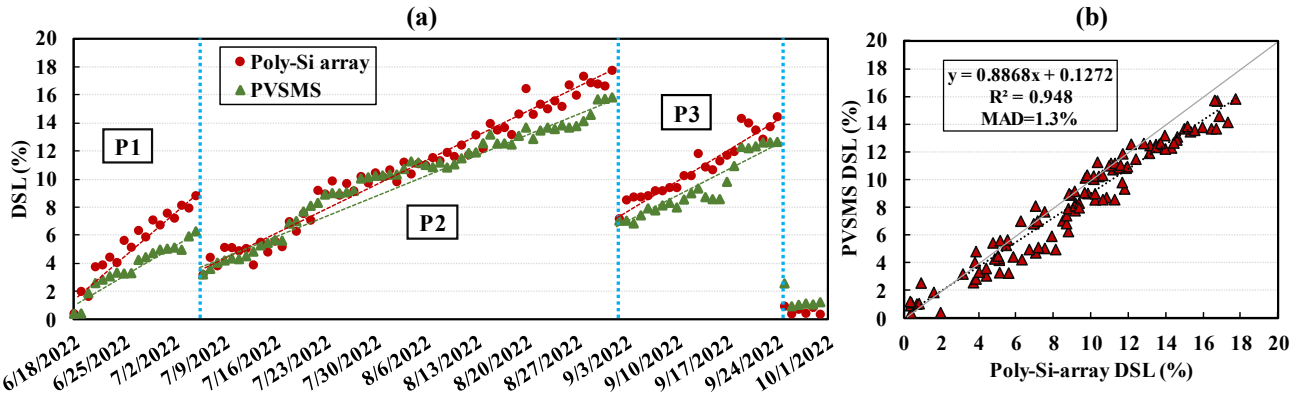


Fig. 10. (a) The PVSMS DSL compared to DSL of PV array as a function of time. (b) Scatter plot of the PVSMS and PV array DSL.

For a more detailed comparison, during the field test, the focus was put on 3 periods, denoted by P1, P2 and P3 (see Fig. 10 (a)). The selection of these periods was made in between occasional natural cleaning events where clear linear trends could be identified. Soiling loss rate (ΔSR: %/day) was determined for each period and is estimated as the slope of the linear regression of PVSMS and PV array soiling loss data as a function of time. Table 2 summarizes the ΔSR measured by the PVSMS and PV array for each selected period, along with the corresponding weighted average ΔSR values that have been calculated based on the duration of each period. The use of a period length weighted average ΔSR was selected as this metric has been proposed as a more robust representation of soiling characterization [47]. The resulting weighted average ΔSR, obtained from the measurements of the PV array and PVSMS, is utilized to calculate the absolute difference ΔSR between these two measurements. This serves as a general evaluation of the accuracy of the PVSMS and aligns with the methodologies employed in the literature for evaluating commercially available soiling sensors in field conditions [48].

As shown in Table 2, there are differences between the ΔSR measured by the PVSMS and the PV array for each particular period, which is expected to occur because soiling is a very complex phenomenon and many factors influence the soiling measurement. For instance, the non-uniform spatial distribution of soiling can result in varying readings when comparing two soiling stations within a single solar site, with differences that can reach up to 2-3 times [17], [49]. In this study the PV array and the PVSMS are located in close proximity to each other, but not in exactly the same place. Furthermore, PV array output power is affected by sky conditions, irradiance

fluctuations, and PV modules temperature, which may degrade the correlation. It is also noteworthy that the short-circuit current of a PV module presents a good approximation of the effective irradiance and can be used as a low-cost metric to quantify the soiling loss. When soiling is uniformly distributed across all cells in a module, the decrease in short-circuit current can be used to estimate the reduction in total module power output. However, a soiling distributed non-uniformly over the surface of PV modules can cause power losses that cannot be quantified accurately by short-circuit current measurements [50]. From Table 2, it can be seen that a mean absolute difference ΔSR of about 0.05%/day compared to a weighted average ΔSR of 0.29 %/day. Therefore, it can be concluded that the PVSMS has the capability to accurately monitor soiling losses and provide a reliable onsite soiling characterization.

Table 2. The soiling loss rate ΔSR (%/day) for PVSMS and the PV array based on the selected periods.

Period	**Period length (days)**	**ΔSR_{PVSMS} (%/day)**	**$\Delta SR_{PVArray}$ (%/day)**
P1: June 18th – July 5th, 2022	18	0.30	0.43
P2: July 6 – September 1st, 2022	58	0.20	0.24
P3: September 2nd – September 24th, 2022	23	0.29	0.30
The ΔSR weighted average value (%/day)		**0.24**	**0.29**
The absolute difference ΔSR (%/day) ($\Delta SR_{PVArray}$ - ΔSR_{PVSMS})		**0.05**	

4. PVSMS software tool

A specialized desktop software tool was developed to visualize and process the incoming raw measurements (see Fig. 11). It is common knowledge that cleaning is necessary to maintain solar plant efficiency. Nonetheless, cleaning dates are a strategic decision for PV plant operators, as they determine the profitability of the plant. Therefore, cleaning dates must be carefully chosen to maximize energy yield and minimize O&M costs. The main objective of the PVSMS software tool is to help PV operators, managers and O&M teams in deciding the optimal cleaning dates. To determine the best cleaning dates, it is first necessary to estimate the daily energy and revenue loss due to soiling. Then, the cleaning decision algorithm could make use of these results along with other economic inputs to decide whether a cleaning operation is needed. The following subsections provide more details on how the PVSMS software processes the raw data to estimate energy and revenue losses due to soiling and how the cleaning decision algorithm works.

Fig. 11. PVSMS desktop software.

4.1. Estimation of energy and revenue loss due to soiling

To estimate daily energy loss, the daily soiling ratio DSR should first be calculated from 1-minute SR data measured by PVSMS according to Eq. 6.

To estimate the DC power output of a given PV plant, the National Renewable Energy Laboratory (NREL) PVWatts DC power model was applied [51] (Eq. 8).

$$P_{Clean} = \frac{POA_{Corr}}{1000} \times P_{dc0} \times (1 + \gamma_p \times (T_{\text{module\_C}} - T_{\text{module,0}})) \quad (8)$$

Where POA_{corr} is the temperature corrected measured plane of array, P_{dc0} is the DC rating of the installed PV plant, γ_p is the power temperature coefficient, T_{module_C} is the measured clean PV module temperature and $T_{module,0}$ is the reference module temperature under STC (25°C). It is assumed that the efficiency of the PV system decreases linearly with increasing temperature, governed by the power temperature coefficient γ_p. This coefficient depends on the selected PV module technology.

Since soiling is considered, the PVWatts DC power model has been modified to also include the soiling parameter through multiplying the POA by the DSR and also by considering the temperature of the soiled PV panel. Thereby, the DC power output of a soiled PV solar field could be estimated (Eq. 9).

$$P_{Soiled} = \frac{(DSR \times POA_{Corr})}{1000} \times P_{dc0} \times (1 + \gamma_p \times (T_{\text{module\_S}} - T_{\text{module,0}})) \quad (9)$$

Since the raw data was measured with a time step of one minute. Therefore, the AC energy E_{AC} (in kWh) can be estimated according to Eq. 10.

$$E_{AC} = P_{DC} \times \left(\frac{1}{60 \times 1000} \right) \times \eta_{inverter} \quad (10)$$

Where P_{DC} is the estimated DC power and η is the nominal inverter efficiency. It should be noted that the user has the option to adjust the inverter's efficiency value, as it varies by make and model.

The daily AC energy generated by a clean solar field Q_{clean} and soiled solar field Q_{soiled}, is then determined as the daily sum of the calculated AC energy E_{AC}. The daily energy loss due to soiling Q_{loss} is defined as the difference between the energy of the clean solar field Q_{clean}, and the produced energy when soiling is accounted Q_{soiled} (Eq. 11).

$$Q_{loss} = Q_{clean} - Q_{soiled} \quad (11)$$

The daily revenue loss due to soiling (RL) is defined as the daily energy loss due to soiling Q_{loss} multiplied by the electricity price E_{Price} (Equation 12).

$$RL = Q_{Loss} \times E_{Price} \quad (12)$$

The PVSMS software is configured to perform the calculations every midnight by processing the raw data of the previous day, and generate a daily report with all necessary outputs.

4.2. Cleaning decision making algorithm

Cleaning is a strategic decision that impacts the profitability of the solar plant. Deciding on the best cleaning dates would increase the efficiency of the solar plant, while reducing O&M costs. This starts with the installation of a system capable of providing the parameters and reliable data to implement the appropriate cleaning strategy. To this end, PVSMS includes all the necessary hardware and software components to assist solar plants managers and O&M teams in soiling measurement campaigns and to optimize cleaning activities.

The approach implemented in PVSMS software is to clean when the payback from increased energy production is sufficient to make the reduction in soiling worthwhile. Therefore, the cumulative revenue loss due to soiling since the last cleaning date RL_{acc} is compared with the given cleaning cost CC on a daily basis. Once RL_{acc} exceeds CC, then an alert is sent to O&M teams to clean the solar plant. The soiled PV module of the PVSMS has to be cleaned along with the solar plant. The natural cleaning agents, such as rainfall, can effectively clean PV modules. As a result, the RL_{acc} is reset to zero following each cleaning operation or after any natural cleaning event that results in a free acceptable solar panel cleaning (DSR > 0.99). Fig. 12 shows a flow chart that describes the steps taken to decide on the cleaning dates.

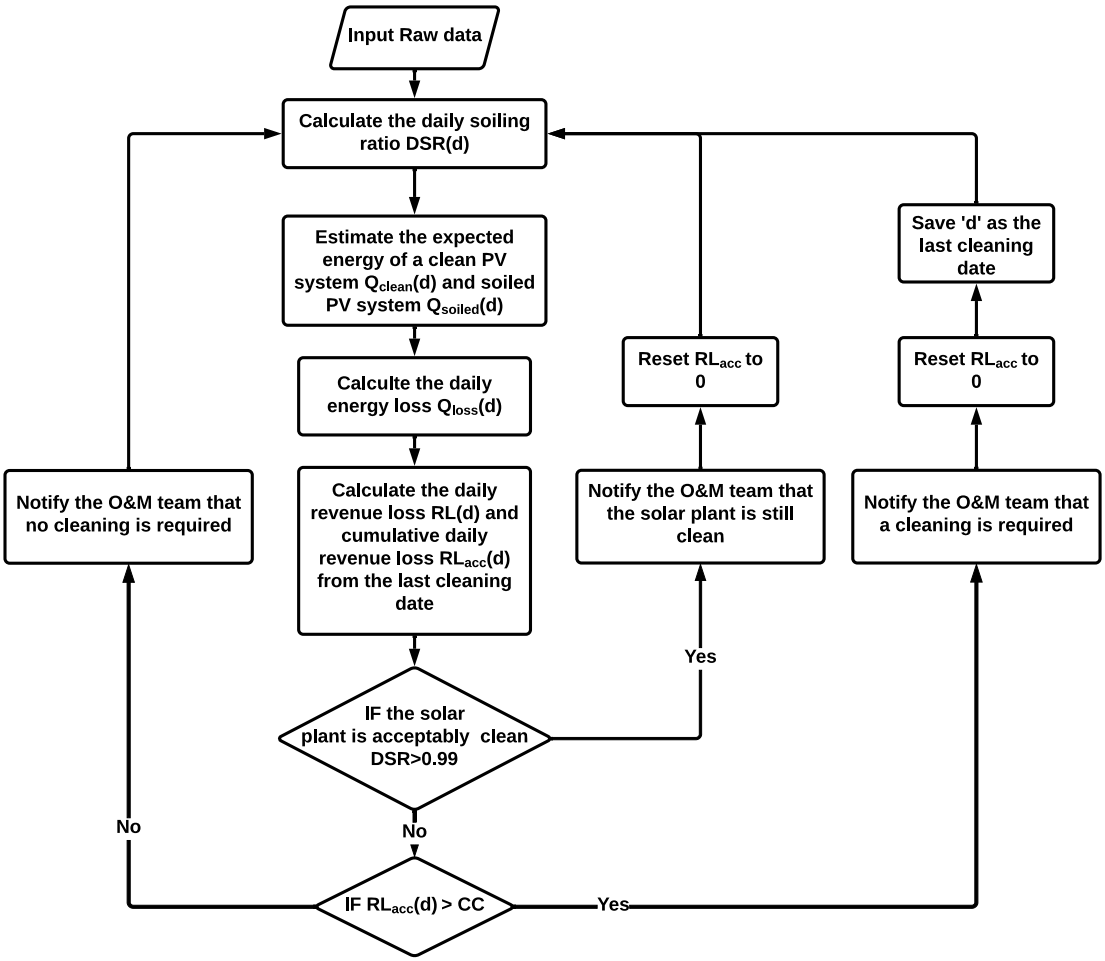


Fig. 12. Cleaning decision making algorithm in the case of operational PV solar plants.

In the case of feasibility studies, the soiled PV module of the PVSMS is left without cleaning for the entire measurement campaign. Therefore, once RL_{acc} exceeds CC, a specialized Python function is executed to simulate a manual cleaning operation based on the measured DSR. This function calculates the daily change in soiling ratio DSR_{diff} by subtracting the next day's DSR from the current day's DSR. Negative values of DSR_{diff} indicate a soiling accumulation, while positive values indicate a cleaning event. The DSR that corresponds to the PVSMS proposed optimal cleaning dates DSR_{opt} is created by resetting DSR_{opt} to '1' to mimic a manual cleaning operation. Otherwise, the calculated DSR_{diff} of the previous day is added to the DSR_{opt} of the previous day to estimate the DSR_{opt} of the current day. Fig. 13 shows a flowchart of the steps followed to simulate the DSR_{opt} and to decide on the best cleaning dates in the case of feasibility studies.

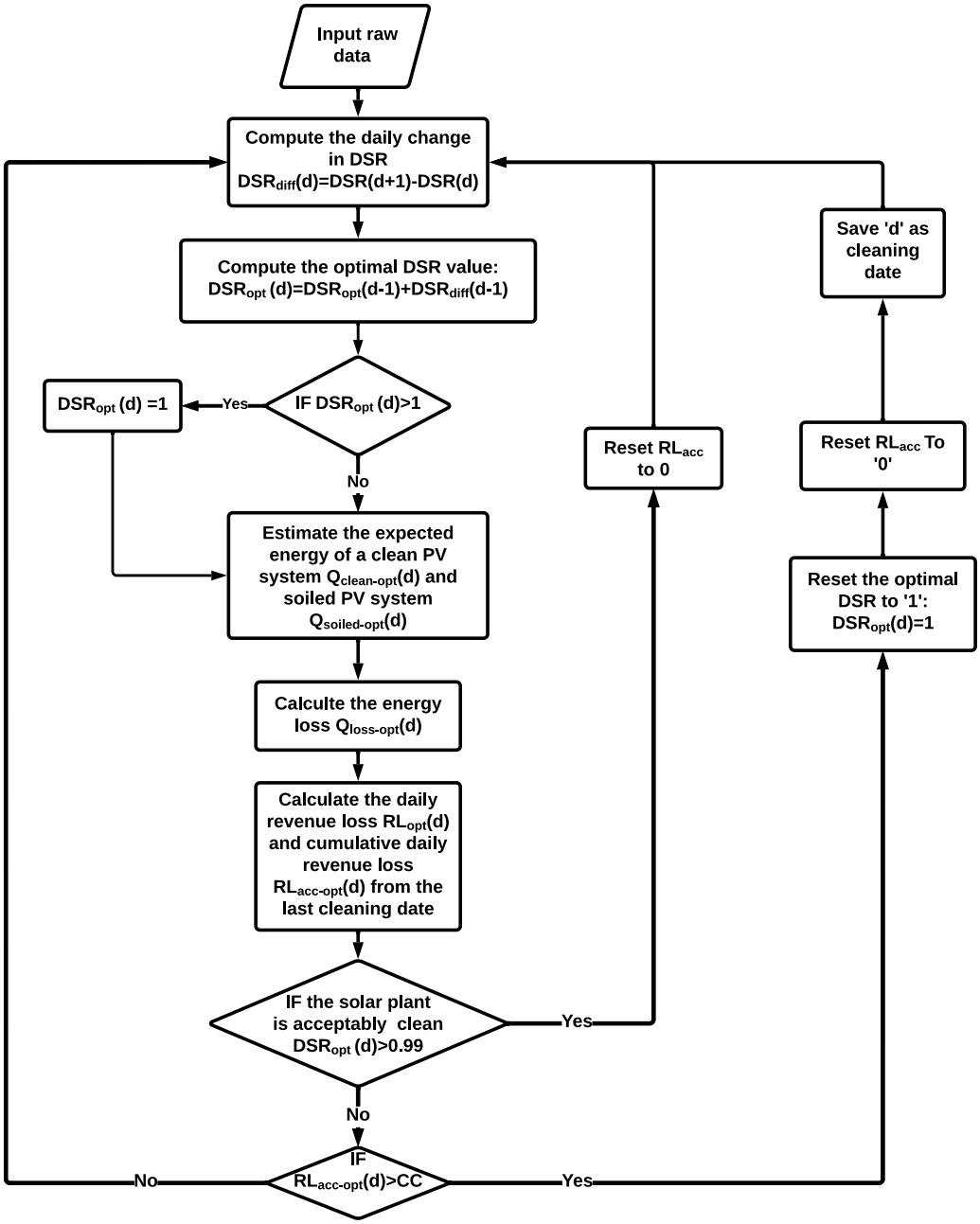


Fig. 13. Cleaning decision making algorithm in the case of feasibility studies.

The developed cleaning decision approach has advantages over conventional cleaning optimization methods. For instance, the average DSR value over a given period of time (monthly or yearly) is typically used to create soiling profiles and to simulate the performance of solar installations under soiling conditions [52], [53]. However, this assumption is not ideal

because it underestimates the day-to-day variability of soiling behavior [2]. Furthermore, soiling is a seasonal phenomenon [54], so the cleaning decision algorithm must take this into account. The present approach allows that the cleaning decision varies according to the seasonality of soiling and natural cleaning events that can provide free cleaning of the solar power plant.

The methodology presented in this study lacks a predictive component for determining cleaning schedules. Subsequently, there exists potential for further improvement in the cleaning decision-making process. The integration of a forecast of future weather conditions, particularly precipitation and air dust levels, at the site would enhance the cleaning decision-making and result in a more optimized outcome. It is noted that scheduling cleaning prior to rain or high dust concentrations would not be a viable option.

5. PVSMS field application: soiling assessment in mining site

The Moroccan mining industry is willing to adopt solar energy as its primary energy source. Consequently, many large-scale PV projects are planned to be deployed in the near future. Site assessment is a necessary step before the implementation of any solar project. Most mining sites are close to high dust emissions. Soiling is therefore a key parameter to evaluate at these sites in order to have a preliminary idea of the losses due to soiling, the frequency and the cost of cleaning. This section presents a case study of the soiling measurement campaign for a feasibility study of a solar PV project conducted at a mining site using PVSMS. Fig. 14 shows the measurement setup where the PVSMS is connected to two PV modules to measure the I_{sc}. In this study, PV modules that are of the same type as those intended for use in a future solar plant have been utilized. The specifications of the PV modules under STC are documented in Table 3. The temperature of the PV module's back surface was measured using a PT1000 temperature sensor. The POA was measured with a pyranometer. All relevant data was recorded and stored in a data acquisition system for subsequent analysis.

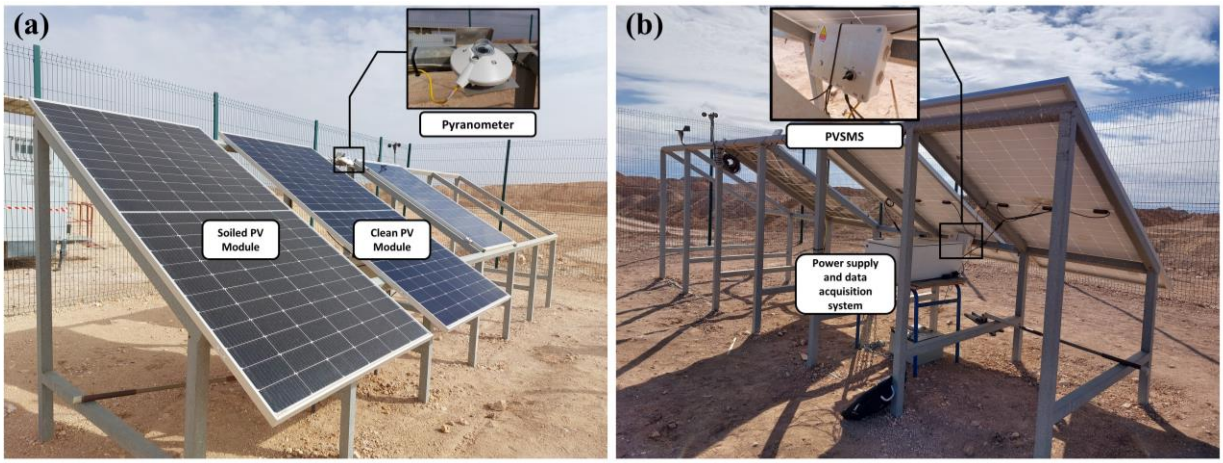


Fig. 14. PVSMS installed in a mining site.

Table 3. The PV module specifications used in the PVSMS setup at the mining site at STC.

PV cell type	Monocrystalline
Maximum power (P_{MAX})	540 W
Maximum power voltage (V_{MP})	41.64 V
Maximum power current (I_{MP})	12.97 A
Open circuit voltage (V_{OC})	49.60 V
Short circuit current (I_{SC})	13.86 A
P_{MAX} temperature coefficient (γ_p)	-0.350 %/°C
I_{SC} temperature coefficient (α_{IscMod})	+0.045 %/°C

Preliminary results of the soiling measurement campaign, estimated energy and revenue loss due to soiling, and recommended cleaning dates are detailed in the following subsections.

5.1. Soiling measurement campaign

The soiling measurement campaign was conducted from August 01 to October 31, 2022. The PVSMS clean reference PV module was cleaned daily, during early morning hours, to ensure reliable soiling quantification and to avoid shading of the PV modules. The measurement campaign is still ongoing to cover a full year period and to obtain a more complete picture of the seasonality of soiling at the study site. However, in this work, only data from the first 3 months are presented. Fig. 15 shows the daily soiling loss DSL measured by PVSMS and the daily total rainfall data obtained from a nearby weather station. As shown, the rain events make it possible to partially recover the performance. During non-rainy days, the DSL generally

increases over time, as soiling tends to accumulate continuously. However, the DSL can still decrease even in the absence of rainfall. This may be due to other natural cleaning factors such as wind that can remove soiling particles from the surface of PV modules. Although the study period only lasted for three months, the soiling rate accumulation shows a significant variability. To assess this variability, four periods have been defined (P1 to P4). The daily soiling rate (ΔSR: %/day) was estimated for each period as the slope of the linear regression of DSL as a function of time. Table 4 summarizes the ΔSR for each defined period and the weighted average ΔSR values that have been calculated based on the duration of each period. It can be noticed that P1 has the highest ΔSR value (0.25%/day) during the entire period. The DSL reaches a value of 7.48% in 30 days. This can be explained by the fact that this period represents the dry season of the year, which is characterized by lack of precipitation and high dust aerosol loads in the atmosphere. Periods P2 to P5 exhibit less significant ΔSR values and more occasional rain events, as these periods correspond to the start of the wet season, which is generally associated with more frequent rain events and lower dust aerosol loads in the atmosphere, leading to a lower rate of soiling accumulation. It is worth noting that the soiling rate accumulation in mining sites is also influenced by the scheduling of mining operations, which were relatively low in intensity during the study period (as evidenced by ΔSR weighted average value of approximately 0.17%/day).

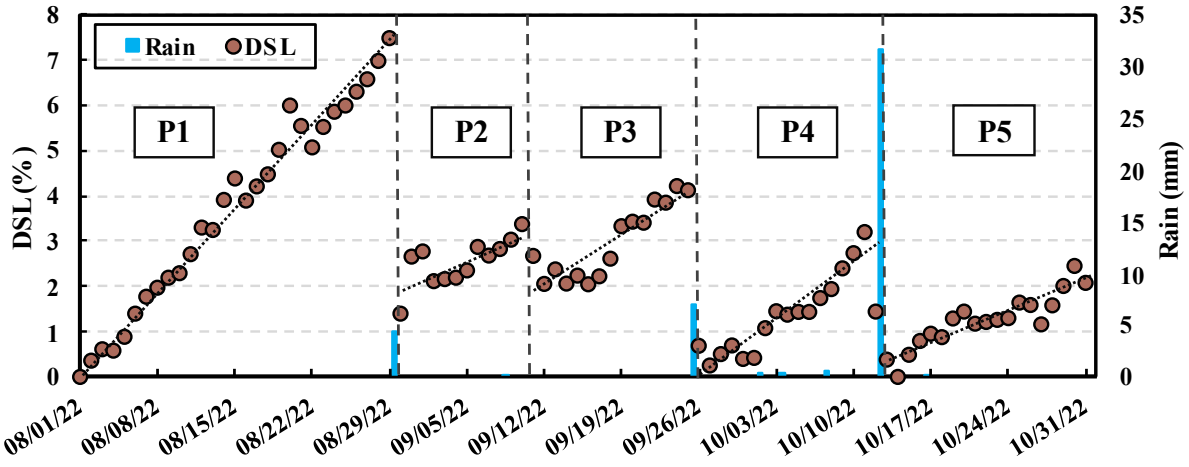


Fig. 15. The DSL measured by PVSMS at the mining site.

Table 4. Summary of measured ΔSR (%/day) for each defined period.

Period	Period length (days)	ΔSR (%/day)
P1: August 01st – August 30th, 2022	30	0.25
P2: August 31th – September 10th, 2022	11	0.11
P3: September 11th – September 25th, 2022	15	0.16
P4: September 26th – October 12th, 2022	17	0.15
P5: October 13th – October 31st, 2022	19	0.10
The ΔSR weighted average value (%/day)	**0.17**	

To recap, the ΔSR varied significantly over the study period. This means that the assumption of an average value of the soiling rate is not realistic, and could lead to an inaccurate soiling assessment of a given site and will certainly result in a bad decision, especially in terms of cleaning schedules.

5.2. PVSMS output results

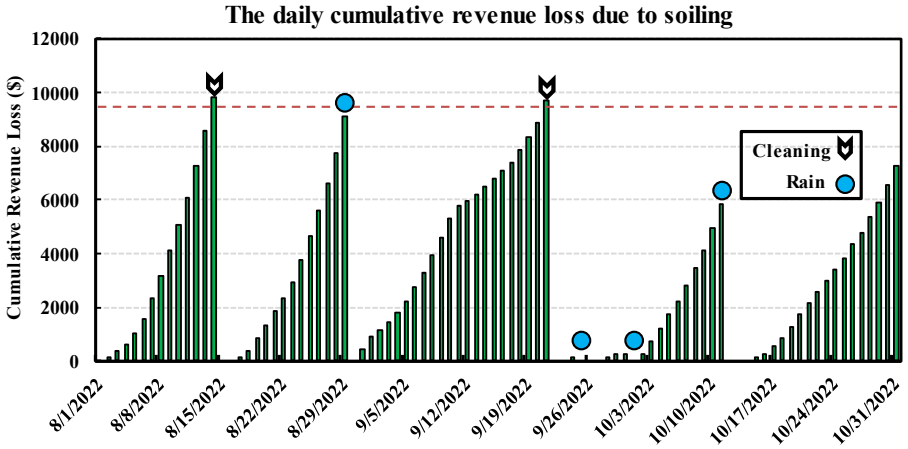
The raw measurement data were processed and analyzed by the PVSMS software tool to simulate the daily energy yield of a 44 MWp solar PV plant and to estimate the daily energy and revenue loss due to soiling accumulation. The calculation input parameters used in this work are detailed in Table 5. It should be noted that the input parameters must be chosen carefully for more accurate results, as each solar plant project requires a different technical and economic analysis. In this case, the technical specifications were chosen to match the design and sizing of the planned solar plant. Regarding the economic inputs, the local electricity price and cleaning cost were used [2]. Local costs are expressed in US dollars converted from Moroccan dirhams using a conversion factor of $0.11 per 1 Moroccan dirhams.

Table 5. The PVSMS calculation input parameters.

PV plant capacity	44 MWp
I_{SC} temperature Coefficient (α_{IscMod})	+0.045 %/°C
P_{MAX} temperature Coefficient (γ_p)	-0.350 %/°C
Inverter nominal efficiency	95%
Electricity Price	0.16 $/kWh
Cleaning cost	9460 $

The estimated daily cumulative revenue loss RL_{acc} is then used to decide the optimal cleaning dates. In this study, the CC is set at $9460. Therefore, as soon as RL_{acc} becomes higher than

529 this value, it is recommended to perform a cleaning of the solar system and the RL_{acc} is reset to
530 zero after each cleaning operation. The data presented in Fig 16 depicts the daily cumulative
531 revenue loss attributed to soiling (RL_{acc}) for the recommended cleaning dates. As shown in Fig.
532 16, the optimal cleaning dates, as determined by the decision algorithm, are August 14 and
533 September 21, since RL_{acc} exceed the CC (marked in red dashed line in Fig. 16). The decision
534 algorithm reset the RL_{acc} after any rain event that brought the station performance back to an
535 acceptable level, allowing for a costless cleaning on certain dates (e.g., August 31 and October
536 12). In the case of feasibility studies, the information on the number of days between two
537 successive cleaning operations (cleaning period) within each season is more relevant than the
538 resulting exact cleaning days. This is due to the fact that the cleaning dates depend on when the
539 evaluation is started, while the cleaning period depends more on the rate of energy loss due to
540 soiling during each season. Anticipating the seasonal variability of the cleaning cycle can assist
541 in accurately estimating O&M costs and efficiently allocate personnel and resources.
542 Nevertheless, in this study, only two cleaning dates have been proposed based on a limited
543 dataset of three months. As a result, it is not feasible to determine the seasonal patterns of the
544 cleaning cycle. It is worth noting that the PVSMS cleaning decision algorithm suggests the
545 adoption of a dynamic cleaning policy, which is considered more realistic compared to a fixed
546 cleaning frequency. This is attributed to the fact that soiling rates tend to vary, and natural
547 cleaning events may occur occasionally.



548
549 Fig. 16. The daily cumulative revenue loss due to soiling in the case of optimal cleaning dates.

The measured DSR and DSL and the proposed DSR_{opt} and DSL_{opt} profiles are shown in Fig. 17. The cleaning operations are marked with a dashed line. As can be seen. The initial cleaning was advised only after 14 days, while the next cleaning is considered necessary after 39 days since the previous cleaning. This can be justified by the fact that the first period was characterized by a lack of precipitation and a high soiling rate (about 0.25%/day), while the rest of the study period experiences some occasional rain events that recover the efficiency and also has a lower soiling accumulation rate (between 0.10%/day and 0.16%/day). It should be noted that the energy loss due to soiling does not only depend on the soiling rate but also on the solar resource of the site, since the energy loss will not be noticeable if a low level of solar irradiance reaches the solar collectors [2]. Therefore, it is not meaningful to decide on cleaning days based only on soiling data (e.g., DSL or DSR thresholds).

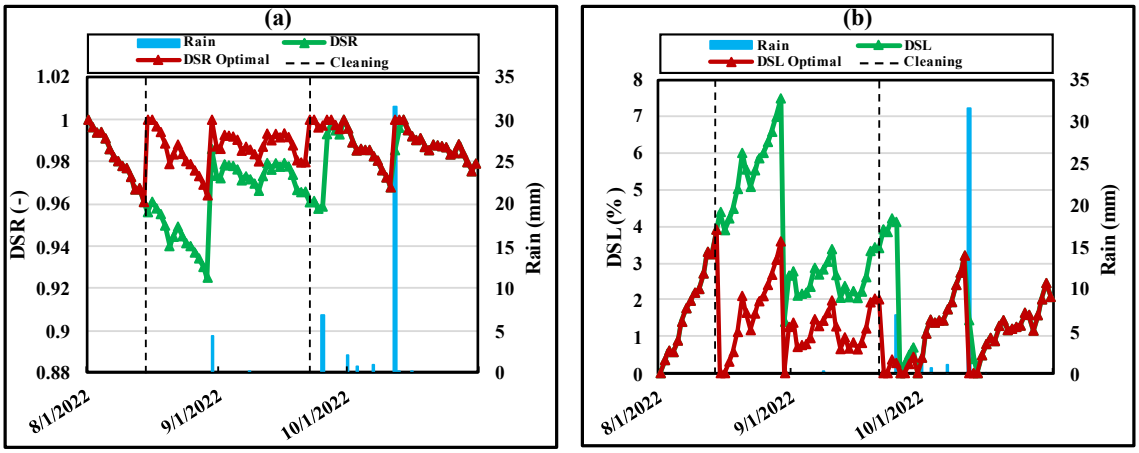


Fig. 17. (a) The measured DSR and the simulated DSR_{opt}, and (b) the measured DSL and the simulated DSL_{opt}.

Fig. 18 illustrates the daily energy and revenue losses due to soiling under two conditions: no cleaning and proposed optimal cleaning. The purpose of this figure is to demonstrate the detrimental impact of soiling and the importance of adopting an appropriate cleaning policy. The results show that the highest daily energy loss rate occurs in August. This result is consistent with expectations since this period is characterized by increased soiling accumulation and abundant solar irradiation. These conditions typically result in substantial energy loss due to soiling. In general, in the absence of any rainfall, energy loss accumulates, representing the overall impact of soiling throughout the exposure period without any cleaning

intervention. This trend is particularly visible in August, where the energy in the absence of cleaning activities reach up to 17.45 MWh, and the total energy loss during this month was approximately 265.2 MWh. However, the energy loss due to soiling was significantly mitigated by the precipitation on August 31. Therefore, this precipitation resulted in a free self-cleaning operation that reduced the energy loss due to soiling.

During the period from August 31 to the end of the study period, the daily energy losses profile exhibited less severity in the absence of cleaning operations. This trend can be attributed to the lower ΔSR values recorded during this period, as indicated in Table 4. Nonetheless, it is important to acknowledge that the maximum daily energy loss observed during this period was still significant, reaching a value of 10 MWh. Furthermore, the total energy loss during this period amounted to approximately 238.7 MWh.

These findings show the necessity of soiling assessment studies and the importance of applying an appropriate cleaning policy that effectively balances between the revenue losses caused by soiling and the cleaning costs. As shown in Fig. 18, the proposed cleaning dates effectively manage the accumulation of soiling and energy losses within acceptable limits, while optimizing the frequency of cleaning and decreasing the associated costs. Notably, the highest daily energy loss due to soiling recorded when the recommended cleaning operations were performed was approximately 8.3 MWh, and the total energy loss during the entire period was 264.5 MWh.

The daily revenue loss due to soiling increases over time due to the cumulative effect of soiling. The daily revenue loss exceeded $2700 at the end of August and about $1600 on September 23. However, when the proposed cleaning is applied, the revenue loss is considerably reduced, as the highest daily revenue loss recorded is approximately $1338.

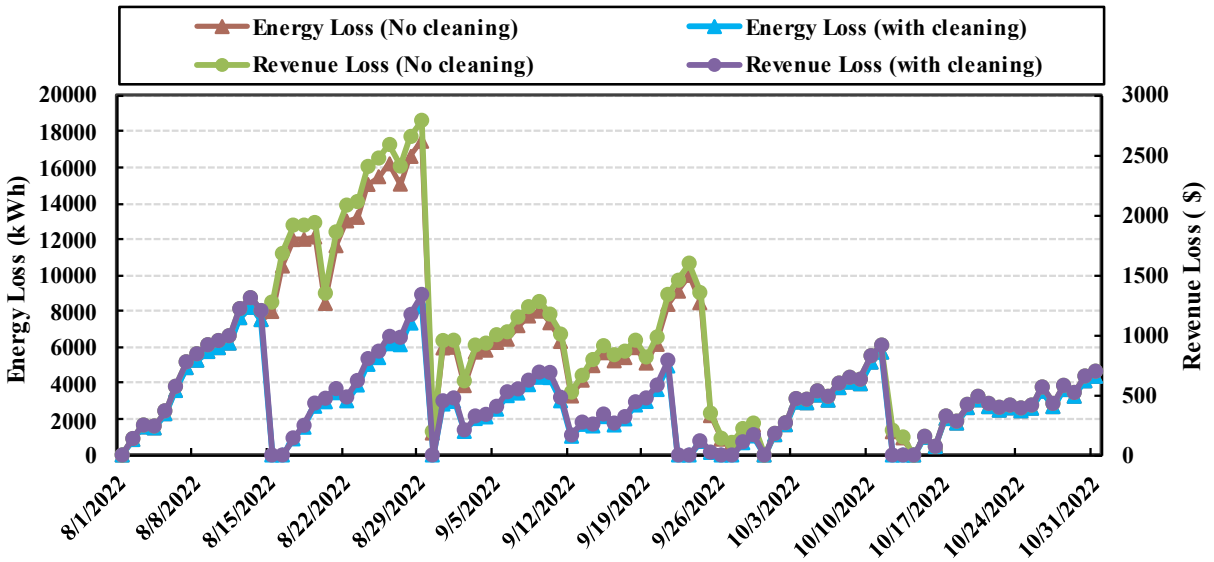


Fig. 18. The daily energy loss and revenue loss due to soiling in case of no cleaning operation and if the proposed cleaning is applied.

To further emphasize the benefits of optimal cleaning operations, the total produced energy for both no-cleaning and optimal-cleaning scenarios are determined and are given in Table 6. It can be clearly observed that by applying the optimal cleaning operations, 245.35 MWh of energy is saved. Nevertheless, the saved energy is not an accurate metric to evaluate the effectiveness of a cleaning policy. The reason is that frequent cleaning will certainly lead to greater energy savings, but also to increased cleaning costs. This shows the importance of determining the net revenue of a solar power plant by including the revenue from the energy produced as well as the cleaning costs. The net revenue is defined as a simplified case as follows.

$$\text{Net\_Revenue} = (Q_{Total} \times E_{Price}) - (N_C \times CC) \tag{13}$$

Where Q_{Total} is the total energy produced by the solar plant over the study period. E_{Price} is the electricity price. N_c is the number of cleaning operations and CC is the cleaning cost. It should be noted that in the process of determining the net revenue of the solar plant, other costs could be involved. However, this work is more focused on optimizing cleaning operations, so only cleaning-related costs are involved.

The net revenue of the proposed solar plant over the study period was estimated for both the proposed cleaning schedule and the no-cleaning scenario, and the results are given in Table 7. As can be seen, although there are zero cleaning costs (N_c=0) in the no-cleaning scenario, the net revenue is still less than the net revenue in the optimal cleaning scenario where 2 cleaning operations were performed (Nc=2). This is thanks to the proper choice of cleaning dates that ensures a trade-off between revenue loss and the cost of cleaning. The total economic gain of the cleaning operations was found to be approximately $20336. The economic gain found in this study corresponds to a period of 3 months. A longer period will certainly lead to a more significant economic gain.

Table 6. The total produced energy for the no-cleaning and optimal-cleaning scenarios.

	No cleaning	optimal cleaning
Total produced energy (MWh)	19589.23	19834.59
Saved energy (MWh)	245.35	

Table 7. The economic impact of optimal cleaning.

	No cleaning	Optimal cleaning
Net Revenue ($\$\times10^3$)	3134.278	3155.614
Cleaning economic gain ($\$\times10^3$)	20.336	

6. Conclusions and perspectives

The majority of commercial and large-scale PV plants are situated in desert, arid, and semi-arid regions, with more expected to be built in the future. These areas are vulnerable to high levels of dust and have limited rainfall and water resources, making soiling accumulation a critical factor that must be properly managed. Cleaning is the most effective way to address this issue. Accurate measurements of soiling are essential for selecting the appropriate cleaning schedule, as well as for performance analysis and yield prediction.

This work introduces the "PVSMS" (Photovoltaic Soiling Monitoring System), a reliable, low-cost and simple soiling monitoring solution that could be easily built using simple and widely available components. The PVSMS can be used in operational solar power plants or in the feasibility phases of solar projects, complementing existing solar weather stations. Its design

supports new brands of high-power PV modules and its internal control enables the use of any PV technology, allowing the selection of PV modules similar to those used or intended for use in solar power plants, while avoiding PV module degradation. This approach makes it possible to mimic the actual soiling behavior on the solar power plant and to provide more reliable soiling data.

A specialized software tool has been developed to facilitate the analysis of raw PVSMS data to help solar plant managers and O&M teams monitor plant performance, process the daily raw data, determine the current soiling loss, and select optimal cleaning dates that achieve a reasonable balance between cleaning costs and soiling revenue loss. The decision-making approach is based on a dynamic cleaning policy that takes into account the seasonality of soiling and the pattern of natural cleaning events. In addition, this software tool is able to assess the soiling rate of a study site during the feasibility stage of a solar project, predict future yield, provide preliminary information on optimal cleaning strategies, estimate the revenue loss due to soiling and calculate the corresponding cleaning costs.

To evaluate the reliability of the PVSMS, a comparison was made between the daily soiling loss detected by the PVSMS and the actual soiling loss on a PV installation located at the same site. This field test demonstrated a stable operation of the PVSMS and strong agreement between the measurements obtained by the PVSMS and the PV array, as evidenced by the R2 value of 94.8% and the MAD value of about 1.3%. In addition, the average absolute difference (ΔSR) was found to be 0.05%/day, compared to a weighted average ΔSR of 0.29%/day. These findings convincingly demonstrate that PVSMS can provide accurate monitoring of soiling losses and reliable characterization of site soiling conditions.

Preliminary results of a 3-months field application of PVSMS for soiling assessment in a feasibility study of a 44 MWp solar power plant at a mining site have been presented. The results indicate that the ΔSR varied significantly over the study period. In the month of August, a ΔSR of around 0.25%/day was recorded, leading to a total energy loss of 265.2 MWh, assuming no manual cleaning is performed. The daily energy loss profile exhibited less severity from August 31 to the end of the study period due to lower ΔSR values recorded during this period (ΔSR between 0.10%/day and 0.16%/day). Nonetheless, the total energy loss during this

period was still significant, amounting to approximately 238.7 MWh. The cleaning decision approach implemented in this study suggests two cleaning operations. The first cleaning operation is recommended after 14 days, while the next operation is required 39 days after the last cleaning operation. The recommended cleaning dates result in 245.35 MWh of energy savings and $20336 of economic gain. These results suggest that optimized cleaning schedules of solar panels is crucial in mitigating energy losses caused by soiling. Thereby improving the economic viability of solar power plants.

This work presents the initial version of PVSMS, which requires further improvements that can be addressed in subsequent versions. For instance, the need to include a low-cost and effective automatic cleaning device for the reference PV module to reduce the need for regular cleaning. Moreover, the integration of numerical weather prediction (NWP) models to forecast rainfall and dust loaded atmosphere and dust storm events, which will certainly improve the efficiency of the decision, as cleaning before heavy rain or dust storm is not recommended. Furthermore, to remediate the problem of non-uniform soiling distribution in large-scale solar power plants, IEC 61724-1 recommends installing multiple soiling stations. For this purpose, the current approach could be improved to give more flexibility in the input parameters and data analysis procedure so that cleaning decisions and recommendations would be given based on the soiling data and the specifications of each zone of the solar plant. These improvements could be the subject of future works.

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