Waterless cleaning technique for photovoltaic panels on dual-axis tracker

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Abstract

Several soiling mitigation solutions and cleaning techniques have been developed to maintain high efficiency of photovoltaic (PV) panels. First of its kind, the investigation of the adaptability of the cleaning systems to solar trackers has been performed. The majority of these systems are dedicated to fixed installations whereas only few systems that can be adapted to solar trackers as presented in the updated cleaning systems background. For this reason, this paper presents an innovative approach which consists of combining trackers with an integrated cleaning system that has been designed. Based on the conducted experimental study, a maximum of 7% in soiling losses has been found for the PV generator of 4 kWp equipped with a dual-axis tracker installed in Rabat-Morocco over almost one year. Consequently, a reduced cleaning prototype has been realized and tested to evaluate the energy recovery based on the performed cleaning. The automatic cleaning has presented a similar efficiency with the manual cleaning with a slight difference of 0.95 pp and an increase of energy of 11.5% in the arid region. Through the economic analysis carried out taking into account the gain in energy production, the automatic cleaning cost was 0.14 €/kWh. It has been found that the cleaning technique based on the telescopic arm would be more effective if the tracker is installed in an arid region where soiling is higher than Rabat. In this case the payback time of the cleaning solution is faster (8 to 9 years), hence its profitability.

1. Introduction And Background

Solar energy as a source of renewable and a clean energy has known a significant growth over the last few years. In fact, the great potential in solar energy especially in the MENA (Middle East and North Africa) region needs to be massively exploited to cover the electricity demand which is increasing over the years. Morocco is an example of countries having a considerable solar potential with 3000 hours/year of sunshine and an average irradiation of more than 5 kWh/m² per day (Othieno and Awange 2016). The Moroccan Kingdom has therefore launched special projects for clean energy based on solar energy (Aarich et al. 2018; Cantoni and Rignall 2019). However, soiling is a challenge that faces solar technologies (Dahlioui et al. 2022a). It is manifested by the accumulation of dirt on the surface of solar panels and can cause significant power losses. A daily and monthly power reduction in some areas can reach respectively more than 1% and 80% (Kazem et al. 2020). This makes maintaining or enhancing the performance of the solar power plants through low cost and ecological soiling mitigation techniques the trend today (Costa et al. 2017; Gupta et al. 2019a).

Indeed, water-based cleaning methods are nowadays the most commonly used in cleaning of solar collectors (Fernández-García et al. 2014; Kazem and Chaichan 2019), but they are considered as less sustainable since they require an important amount of water for large reflective areas especially in a region suffering from water scarcity (Bouaddi et al. 2018). As detailed by (Jamil et al. 2017), different cleaning techniques were the result of the awareness to keep the solar panels constantly clean and improve their performance. Figure 1 presents a classification of the cleaning techniques that can be divided into three categories. Each category will be detailed in the following section.

In this paper, a recent review on the cleaning and soiling mitigation techniques has been done. A focus has been given to the investigation of the adaptability of the mechanical cleaning solutions to solar trackers. Based on this rigorous analysis, an innovative cleaning technique has been designed, realized and tested. Moreover, in this work, the soiling losses for dual-axis tracker have been evaluated for the site of Rabat under real environmental conditions. The second section of this paper presents the evaluation of the manufactured cleaning system based on an artificial soiling.

1.1. Natural cleaning

The first category concerns the natural cleaning which can be done by rainfall, wind and dew depending on the climate conditions. No cost is required by natural cleaning but it has been reported as being not effective for small dust particles (Gupta et al. 2019b). The efficiency of cleaning by natural events depends on the amount of rainfall (rain or dew) and the wind direction. It has been reported in Qatar that an amount of 3 mm of rainfall can ensure an efficient cleaning and restore the initial state of solar panels (Elminir et al. 2006; Javed et al. 2020). Less than this amount can lead to a partial cleaning. The effect of rainfall can be affected positively or negatively by wind velocity (Hee et al. 2012). Indeed, high wind speed with presence of rain enhance the cleaning of the solar panels by blowing rain to remove the dust out of the panel. The effect can be reversed in absence of rain and, depending on wind direction, the dust can be blown on the surface and lead to dust accumulation.

In the work of (Jiang et al. 2018), the cleaning of PV panels by wind has been analyzed and it has been found that large particles with diameter larger than 1 μm were effectively removed by wind due to the low required resuspension velocity compared with small particles. In the same work, the wind velocity that can lead to a natural cleaning is ranged between 0.82 to 2219.8 m/s. Regarding the cleaning by dew, an important amount of dew water is observed on the solar panels which leads to their self-cleaning especially in early mornings (Dahlioui et al. 2019). The effect of this latter as a cleaning agent has not been well investigated in literature. A recent review has been recently published aiming to exploit dew in soiling mitigation (Dahlioui et al. 2022a).

1.2. Corrective cleaning

Manual cleaning

Manual cleaning requires human resources (labor), material such as soft brushes for dry cleaning as well as water in the case of wet cleaning. Karcher (kaercher.com/us/) which is a company specialized in the cleaning products, has developed cleaning brushes made by natural and nylon bristles that avoid micro-scratches to be created on the solar glass surface. These brushes can be fitted with air pressure cleaners.

As benefits, the manual cleaning is considered the most efficient method to recover PV performance and it can be performed whenever required (Gupta et al. 2019b). However, it requires high cost and water which is limited as well as scratches may be produced. According to the study of (Fernández-García et al. 2014), the use of demineralized water and a brush was the most effective compared with a jet of air or water with high pressure. The use of detergent is not required since it does not increase the effectiveness of cleaning.

Mechanical systems

The corrective cleaning category includes as well mechanical techniques that can be fully automatic or semi-automatic. Mechanical cleaning systems denote any cleaning technique with motorization able to replace the physical effort provided by the operator. They are characterized by a large dust removal force, fast operation, good environmental adaptability and control performance (Lu et al. 2013). According to the system dimensions (motorization axes), the mechanical solutions are divided into three categories; single dimension, two dimensions and autonomous robots.

According to literature, the cleaning combined with tracking may increase the efficiency of the solar panel by 50% (Abhilash and Panchal 2016). However, the most of these cleaning solutions are dedicated to fixed panels and they showed less degree of adaptability to the trackers as shown clearly in Table 1. In order to make these solutions appropriate to trackers, it will be necessary to rely on their adaptation, which will involve a high investment cost and makes the cleaning solution economically less attractive. Few systems that show more adaptability to tracker systems as the case for Hector and Ecoppia T4 (Hardt et al. 2011; 2019a). However, the need for operators is required to perform the distribution tasks for the fleet of solar power plants. Several solutions are in the research stage, furthermore, they show more adaptability to trackers (Tejwani and Solanki 2010; Singh and Ravi 2014) since they perform a rotation of 360° during the day, which results in sliding of cleaning system twice over the PV modules. For the autonomous cleaning robots, they are still the most appropriate for the tracking system as they move without restrictions on a given surface and, with a single robot, a large area can be scanned. However, the passage of a slightly heavy robot on hard soils may not ensure effective cleaning (Juzaili et al. 2017). According to what has been cited earlier, a real gap in cleaning systems dedicated to solar tracker is highlighted. Hence the need to take the obtained improvements points into consideration and propose a cleaning technique integrated into solar trackers.

Table 1 Commercial and near commercial mechanical cleaning systems of solar panels, [V]: Verified; [NV]: Not Verified; [A]: Adaptive; [VA]: Very Adaptive

Cleaning system*	Autonomy	Simplicity of design	Adaptable for trackers	Adaptability	Economic feasibility for trackers	Comments
Nomadd (Services 2019)	V	V	NV	NV	NV	The need of twin mounted rails. To be used, this system requires that the PV modules should form a row
SolaRobot (2019b)	V	NV	NV	NV	NV	The cleaning system should be guided by rails
SunPower	NV	NV	NV	A	NV	Effective for one-axis tracking solar PV panels
Greenbotics GB1 (Dailygreen.it 2013)	NV	NV	NV	NV	NV	Complicated structure which is not compatible with trackers in general
Geva-Bot (Geva-Bot 2019)	NV	V	NV	A	NV	Not compatible with a tracker composed of many modules mounted in wide rows
Washpanel (Verdi 2019)	V	V	V	A	NV	This cleaning system does not require rails and it accepts wide rows. But if the tracker is composed of multiple rows, the use of this system is not considered low cost.
Hector (Hardt et al. 2011)	V	V	V	VA	V	This cleaning system is developed for the cleaning of Heliostats in CSP plants
SunBrush (SunBrush 2019)	V	V	V	A	NV	Adaptable for a wide row of PV modules. Multiple units are needed for a tracker composed of many rows.
Solmaks (Solmaks 2019)	V	NV	NV	NV	NV	The use of this system requires rails
Miraikikai (2019c)	NV	V	V	VA	NV	The autonomy of this cleaning system is relative since it needs one operator to be placed on the PV modules surface
Sinfonia Resola (Sinfonia 2019)	NV	V	V	VA	NV	As a cleaning robot, it needs to be placed on the surface which is subject to cleaning
Aerial Power (Aerialpower 2019)	VV	NV	V	VA	V	One drone can be used for many trackers. However, it will involve a lot of time in cleaning since it uses a small brush.
hyCLEANER (2019d)	V	NV	V	VA	V	The need for an operator to place the system on the PV panel surface as well as a long time to clean a considerable surface
PSE-BOSON(Solrenen 2019)	V	V	NV	A	V	This system presents a smart correction of moving position in real time as well the advantage of turning back after failing to pass an obstacle to 3 times (Security)
Ecoppia T4 (2019a)	V	V	V	A	V	As a cleaning robot, it needs to be placed on the surface which is subject to cleaning

* *The names of the cleaning techniques mentioned in the table correspond in most cases to the names of the companies. Note that the use of these names is only to compare the compatibility of these techniques with the tracker presented in this work and it does not present any publicity interest.*

Electrodynamic screen (EDS)

As a corrective cleaning method, the electrodynamic screen has been proposed and tested in different environments and adopted as the main dust removal by the National Aeronautics and Space Administration (NASA) on Mars and Moon missions (Horenstein et al. 2013). The EDS uses traveling-wave effects to deter dust out from the panel surface. The principle of EDS is based on the manufacture of electrodes on a substrate (Fig. 2). The electrodes are either transparent or very thin in order to minimize the shading effects. In order to insulate the electrodes from the air, a transparent dielectric cover is placed over the electrodes. This dielectric layer becomes the outermost layer thus requiring protection from dirt or even its mitigation (Guo et al. 2018). During field operations, dust deposition occurs on the air side of the dielectric cover, so that the activation of the EDS can repel the deposited dust, taking advantage of the electrostatic charges carried by the dust particles (Kawamoto and Guo 2018). The dielectric blanket is a thin sheet which is bonded to the electrodes / substrate through an adhesive, or applied as a coating (Kawamoto and Shibata 2015). The activation of the EDS consists in applying a high alternative voltage to the electrodes, which leads to an alternative electric field. The electrically charged dust that has settled on the air side of the dielectric cover can then be pushed out of the EDS. This latter can be either a self-contained thin structure that covers the front surface of a solar panel or a component integrated into the solar module (Guo et al. 2018).

The EDS is considered faster compared to other methods cleaning. However, there is a risk of screen degradation due to ultraviolet (UV) rays (Deb and Brahmbhatt 2018b). Also, the system involves high voltage supply to generate electric field, thus reducing the generation efficiency by 15%. It has been also reported that the EDS is not effective for wet or cemented dust particulates (in presence of dew), and so it is less efficient for small sized particles (Guo et al. 2018).

1.3. Preventive soiling mitigation

The preventive methods include different approaches aiming to repel the dust out from the panels surface based on the treatment of the surface properties (He et al. 2011). This first category of soiling mitigation focuses on special coatings that can be super-hydrophilic (Son et al. 2012) or super-hydrophobic (Nguyen-Tri et al. 2019). The second part is dedicated to tilt angle and tracking effect as a soiling mitigation approach.

Super-hydrophilic coating

The common super-hydrophilic coating is based on Titanium dioxide TiO2, which has hydrophilicity and photocatalytic activity (He et al. 2011). This preventive approach has two phases. The first one is a photocatalytic process which TiO_2 film reacts under the UV radiation leading to splitting the dust particles. Then, because of the hydrophilicity, the rainfall will diffuse to the whole surface instead of get together and rinse the dust. Several works have been developed related to the preparation, doping and amendment of this material. This self-cleaning method cannot be used in solar cell array because they worked mostly in desert region where the occurrence of rain is very limited.

The performance of the hydrophilic coating has been improved by using an automated mechanical vibrator as demonstrated by (Al-Badra et al. 2020). Indeed, the results showed only a decrease of 12.94% in PV panels efficiency while the one of coated PV only has reduced by 24.46%.

Super-hydrophobic coating

Inspired by the Lotus leaf (Przybylak and Maciejewski 2016) with a hydrophobic effect and less wettability, has raised a great interest among the research community because of its capability to be reproduced as coatings for self-cleaning by developing Nano-structures and micro-structures (Xiao et al. 2017). The hydrophobic coating consists of forming a layer which is considered as a barrier so that water accumulates on the substrate in a spherical shape without being adhered to the substrate surface. These spherical water droplets could roll off easily on the treated tilted surface thus leading to its self-cleaning. Indeed, it has been reported in literature (Park et al. 2011) that the contact angle (CA) can be enhanced by reaching more than 150° (Fig. 3).

Many works are ongoing with a great focus to improve the non-wettability property of the hydrophobic coating as well as the lifetime and durability concerns especially for real environmental conditions (Sarver et al., 2013b). In fact, the lifetime of the coating is considered very limited. A durability study conducted in Denmark on candidate coatings has shown that they started to degrade after only two weeks outdoors, and this degradation was manifested by the contact angle decrease (Oehler et al., 2020).

Tilt angle and tracking effect

Soiling is highly affected by a surface's tilt angle. Indeed soiling rates significantly decrease at steep tilt angles (Sarver et al. 2013b; Anana et al. 2017). In Portugal, a model based on irradiance and soiling data has been developed to set tilt angle configurations to maximize the energy production (Conceição et al. 2018). For large solar field, the different tilt angle configurations could be concretized by movable tilt angle frames which present better costs optimization rather than single or dual-axis trackers. Since soiling can reach higher rates during the night (Ilse et al. 2018), stowing the PV modules equipped with solar tracker vertically or upside at night can significantly reduce soiling (Figgis and Ilse 2019) as well. In case of trackers, many stowage positions have been proposed to mitigate soiling (Ilse et al. 2019). It has been found that facedown position is obviously more opportune (Sayyah et al. 2014).

1.4. Synthesis

In order to restore the losses in optical performance due to soiling phenomenon, several cleaning techniques can be adopted in solar power plants as presented in Table 2.

Table 2
Summary of the cleaning and soiling mitigation techniques with their advantages and disadvantages

Soiling mitigation techniques		Advantages	Disadvantages
Natural	Rain	- Free of charge	- Availability
	Wind		- Climate site dependent
	Dew		- Less efficient for birds dropping and cemented dust
Manual	Labor	- Efficient	- High costs - Micro-scratches
Corrective	Electrodynamic Screen (EDS)	- Faster compared to other methods	- Screen degradation due to UV
	Mechanical systems	- Fast operation, good environmental adaptability and control performance	- Less adaptability to solar trackers - Maintenance costs - Less efficient for fine dust particles
Preventive	Trackers/Tilt angle	- Efficient in soiling mitigation compared to fixed structures	- Economic applicability for large solar field
	Anti-soiling coatings	- Passive (no energy requirements) - Efficient	- Durability concerns

2. Experimental Study

2.1. Methodology

At the RDI (Research, Development & Innovation) Solar Energy Platform (Barhdadi 2016), the dual-axis tracker of HeliosLite has been installed and which is characterized by Roll and Tilt mechanism illustrated in Fig. 7. This type of kinetic is named also as fixed horizontal tracking mechanism where the tilt axis is fixed and contained in the horizontal plane (Martínez-Hernández et al. 2020). Sixteen multi-crystalline silicon modules of two different manufacturers are mounted on the dual-axis tracker shown in Fig. 4. In order to evaluate the soiling losses for the dual-axis tracker, an experimental study has been conducted. In this section, one PV module will be subject to regular cleaning three times a week, while the adjacent module will accumulate soils naturally. The output of the modules is recorded using the power optimizers P300W of SolarEdge mounted on the back of each of the modules. The optimizers are connected with the inverter SE4K of the same brand. The soiling ratio (*SRatio*) and soiling losses (*SL*) are calculated using the formula of Eq. 1 (Zorrilla-Casanova et al. 2011)

$$SRatio = \frac{P_{max1}}{P_{max0}}$$

1

$SL(\%) = \ (1 - SRatio) \times 100$ (2)

where $P_{max0} \text{and} P_{max1}$ are respectively the maximum power output of clean PV module and the soiled PV module.

2.2. Soiling losses for dual-axis tracker

The $SRatio$ measurements have lasted for more than 10 months from February 19 to December 03, 2018. Figure 5 presents the evolution of this parameter as well as the reported rainfall during this period. It has been noticed that *SRatio* did not significantly decrease during the three first months of exposure. This can be explained by the significant rainfall (up to 40 mm with an average of 20 mm) during this first period of the study. During the dry period ranging from July 02 to August 27, 2018, *SRatio* has significantly dropped at a SRate of about 0.1%/day as presented by the red line. Rain events have occurred at mid-September (4.3 mm), recovering partially *SRatio*. It can be deduced that a cleaning frequency once a year during the dry period, is sufficient given the frequent rain events in this site. Soiling losses have been calculated for the mentioned dry period as shown in Fig. 6. It has been found that *SL* are ranging from 2–7% for PV with tracking with an average of 4.8%. Similar results have been found in Tudela-Spain (Garcı et al. 2011) which is characterized by a semi-arid climate as the site of Rabat in Morocco. In fact, this dual-axis tracker is characterized by an upward stowage position which is reported in literature as having a significant impact on maximizing soiling compared to face-down (Roth and Pettit 1980; Sayyah et al. 2014). Since gravitational settling is the primary mechanism for dust deposition, the dust accumulation is highest under this condition. But this data has been reported without referring to the type of the installation climate. In fact, this stowage position contributes to the accumulation of dew water, particularly during the night, thus making it possible to moisten the dirt which flows in the morning with the tilting of the tracker from the horizontal position into vertical. In fact, this tilting should be done in early morning (at sunrise) to avoid hard layers of dust to be formed on the PV panels surface that are difficult to remove (Alnasser et al. 2020). The described cleaning approach using dew, has led to promising results as found in our recent work (Dahlioui et al. 2022b). The average of SL recorded of 4.8% would be more mitigated with the use of an integrated cleaning system into the dual-axis tracker.

3. Development Of An Innovative Cleaning Technique For Dual-axis Tracker

3.1. Functional analysis

As mentioned before, most of the mechanical cleaning systems are not adaptable for all situations especially in our case as shown in Table 1. Indeed, the proposed solution has to be appropriate to the mechanical support architecture illustrated in Fig. 7 (HeliosLite 2019) especially with the mobility of the metallic components of the motion transmission chain indicated by red circles. For the reason, it was essential to carry out a functional analysis (Fig. 9) which aims to express the true need of the solution in terms of functions that must be stated, grouped and characterized. Other important functions are to be considered related to cost and sustainability. In other words, the proposed cleaning solution should be low cost and ecological. In the case of a cleaning with contact, this latter should avoid the formation of micro-scratches.

3.2. PV cleaning technique based on the telescopic arm

The design of the cleaning system based on the telescopic arm in the form of a chisel meets all the criteria of the functional analysis presented above. Indeed, we opted for the telescopic arm in the form of a chisel given its rigidity and the fact that we are going to use arms of reduced lengths instead of a single fixed arm, hence the problem of flexion at the extremities of the tracker. Therefore, keeping the arm always horizontal on the surface of the modules as well as ensuring effective cleaning were among the determining criteria for our design proposal for this system.

The arm narrows and deploys using an electric jack to reach the ends of the tracker and then a translational motion is occurred. To be able to rotate from one panel to another, a stepper motor has been proposed to be coupled to a conical gear in order to transform the direction of the rotation. The end of the arm is connected by a mounting connection to rotating nylon brush to prevent scratching on the surface of the PV modules. The proposed brush has a diameter of 400 mm, a large diameter to optimize the number of displacements of the brush on the PV modules surface. The cleaning using this type of brush can be performed on a dry surface as it can be done on a humid surface especially in early mornings where the amount of dew is quite important [8]. As for the time of cleaning, in order to exploit the quantity of dew formed, the cleaning will be performed early morning when the tracker is still in the stowage position (horizontal). Figure 9 is illustrating the architecture of the proposed cleaning technique designed for the real dimensions of the dual-axis tracker. The telescopic arm with chisel form will be fixed in the middle of the tracker's bar by a fixing connection.

3.3. Telescopic arm dimensioning

In Fig. 10, an illustration of the telescopic arm position when the tracker is in the horizontal position. Some data related to the tracker are used in this dimensioning as the distance between the PV module and metal central bar (h). The diagonal of the 4 PV modules will be designated by (D). One of the lozenge angles is designated by (β). For a good appearance of the parameters on the figure, each parameter is indicated by color adjacent to the parameter in question.

In order to calculate the minimum length (*a*) of the telescopic arm, a mathematical approach has been followed. The length (*a*) will be calculated based on Eq. 3 so that the arm does not cross with the metal bar of the tracker that we already mentioned in Fig. 4.

$$\cos\beta = \frac{h}{a}$$

3

For the case that the telescopic arm is completely narrowed, $\beta = 5°$ and referring to Eq. 3:

$$h = a = 208mm$$

4

By adopting the following hypothesis for a lozenge represented by Eq. 3, where $d_1, \ d_2$ and α, β are respectively the diagonals and the angles of the lozenge. A condition limit has been as well adopted which is $d_1 < d_2$.

$$\begin{cases} \alpha + \beta = \frac{\pi}{2} \\ d_1 + d_2 = Cte \end{cases}$$

5

To calculate the number of lozenges that will compose the telescopic arm, the 4 modules diagonal (*D)* has been determined using the dimensions of a standard PV module. Eq. 6 presents the total number of lozenges. N refers to the number of bars of length (*a)* constituting the telescopic arm. Considering that $D = 3565$ mm, the telescopic arm will be composed of 9 lozenges made of aluminum profile with a length of 208 mm each.

$$N = \frac{D}{a}$$

6

3.4. System control

Since the system must be controlled and its use needs to be secure, safe and autonomous, the automated control is extremely required. For the control of the system, a GRAFCET (Control Functional Graph Steps and Transitions) diagram has been developed as shown in Fig. 11. It describes the functioning of the system and represents the developed automatism to control the cleaning system. This diagram contains all the actions and transitions since the beginning of the command which is related to the automatic starting conditions until the shutdown. The principle of cleaning of a panel will be the same for the other panels mounted on biaxial tracker, which means four control loops; each loop corresponds to the rotation of the telescopic arm from one panel to the other with an appropriate angle.

3.5. Demonstration prototype

3.5.1. Overview of the realized system

The purpose of making a demonstration prototype of the cleaning technique is to do tests before investing in the development of the final version of the product. It also makes it possible to validate the technical choices before going into production. Through this reduced prototype, the efficiency of the cleaning technique will also be evaluated. It should be noted that the choice of components for this reduced prototype strongly depends on what is available on the market. Instead of using two PV modules for each side as illustrated in Fig. 12 and Fig. 13, only two panels for the whole system have been used since the purpose of this realization is testing the cleaning technique and not to reproduce the PV system with its tracking system. Technical data of the PV modules are presented in Table 3.

3.5.2. Control of the realized prototype

The control of the cleaning solution presented in Fig. 14 is based on the use of an Arduino Uno board. This card is in charge of processing the various information detected by the Bluetooth sensor, a start button or other components of the system. Since the cleaning system consists of three motors of different voltages, the use of the relay-based board is necessary. This 5V relay board is connected to the DC motor of the rotating brush with a voltage of 12V as well as the motor of the jack which ensures the translation of the telescopic arm on the surface of the PV panels. As for the rotation motor which moves the arm from one panel to another, it is directed via a reference TB66 stepper motor driver. It should be noted that the cleaning solution integrated on the full-size tracker would be supplied by the PV modules mounted on the tracker itself. Since the prototype produced would be powered from the grid, an AC/DC transformer has been added to the system.

3.6. Tests of the proposed cleaning technique

3.6.1. Experimental methodology for artificial soiling

The purpose of this section is to test the cleaning carried out by the proposed cleaning based on the telescopic arm with an artificial soiling. The panel surface has been covered manually using a sieve in a homogeneous way, with the dust collected from the ground, to simulate the soiling that occurs in outdoor conditions. Note that the operation is done by the same person and with the same amount of dust to be able to keep the same tests conditions. It would be more convenient to use the test bench that has been already designed and tested locally for dust deposition (Laarabi et al. 2018), however the dimensions of the PV modules (71.1 cm x 32 cm) are bigger than the dust container. The density of dust is 70 g/m² as measured before experiment (Fig. 15). The cleaning technique performance will be evaluated based on measuring the output characteristics of the PV modules with the technical data presented in Table 3. A multimeter has been used to measure the open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}). The PV modules are placed in horizontal to simulate the worst-case scenario of dust accumulation. Figure 16 presents the methodology followed in this section.

Table 3
Technical data of the PV modules used for the tests of the cleaning technique

Technology	Polycrystalline Silicon
Rated Power (Pmax)	40 W
Voltage at Pmax	18.2 V
Current at Pmax	2.20 A
Open-circuit Voltage (Voc)	22.5 V
Short-circuit Current (Isc)	2.31 A
Maximum System Voltage	DC1000 V
Standard test conditions	AM1.5, E = 1 kW/m², Tc = 25°

3.6.2. Results of artificial soiling

The test results of the artificial soiling are shown in Fig. 17. Actually, *SL* were 31% after covering the surface of the PV panel. A manual cleaning has been done as previously explained in leading to only 2.58% in *SL*. Note that this latter was a water-free cleaning that may not restore all the efficiency because of the very small particles that cannot be efficiently removed by manual cleaning (Mohamed et al. 2018; Syafiq et al. 2018).The panel has been newly covered with the same amount of dust to test the realized cleaning system. Through the cleaning carried out by the cleaning system (Fig. 18), the losses due to soiling have been reduced to 3.53%. Indeed, the difference between both automatic and manual cleaning was only 0.95 pp. It should be noted that the automatic cleaning carried out is without water with a very fine brush. However, some fine particles remain on the PV panel surface. Note that the surface of the panel is swept only once in order not to scratch it, as well as to optimize the energy consumed by the motors. Unlike the manual cleaning where we could re-clean the same surface. For the reasons previously mentioned, the difference between both cleaning methods is well justified.

As mentioned before, a lack in literature related to the cleaning techniques dedicated to solar trackers has been highlighted, so rare are the works that have discussed the cleaning efficiency of cleaning systems combined with tracking. For instance, (Tejwani and Solanki 2010) developed a cleaning system based on sliding a rotating brush has provided 15% more energy output as compared to PV module without cleaning. Another work has reported the possibility to adapt the water-free cleaning technique to solar trackers which has demonstrated an increase in energy yield of 6.31% considering the cost of the prototype (Deb and Brahmbhatt 2018a). However, the evaluation of the energy increase should take into consideration the cost of the adjustment of the cleaning system to the tracker architecture or providing 4 cleaning units. While, one unit of the cleaning technique presented in this paper, is sufficient for 16 PV modules mounted on the dual-axis tracker. It should be noted as well that no cleaning technique proposed for the dual-axis tracker so far, hence the novelty of this work.

3.6.3. Economic analysis

The economic analysis is an essential part of this work to evaluate the success of the cleaning system. It assesses the profitability and degree of feasibility of the cleaning system, including its ability to recover investment and operating costs as quickly as possible. A study of the cost impact for a real case was performed for the dual-axis tracker previously described of 4 kWp installed in Rabat. The cost the proposed cleaning system (C_{CS}) is the total of the initial cost ($C_{initial}$) and the maintenance cost $\left(C_{maintenance}\right)$. This latter is calculated based on the cost of energy consumption $\left(C_{w}\right)$ of the solution with a frequency of cleaning of once a month and spare parts replacements. Indeed, the cleaning frequency depends on the geographical area where the PV plant is implemented. In this case, the worst-case cleaning frequency has been adopted to calculate the energy losses due to soiling (E_{loss}). The cost of electricity losses (C_{El}) is calculated by Eq. 10, where (C_{oE}) is the cost of electricity per kWh (Majeed et al. 2020).

$$C_{CS} = C_{initial} + C_{maintenance}$$

8

$$C_{maintenance} = C_{material} + C_{w}$$

9

$$C_{El} = E_{loss} \times C_{oE}$$

10

$$E_{loss} = E_{gc} - E_{gs}$$

11

where (E_{gc}) and (E_{gs}) are respectively the energy generated at clean state and soiled state of the PV modules mounted the dual-axis tracker.

C_{CS} of the proposed cleaning solution was taken to be 1150 € on the lifetime of 25 years which is the common period for the operation of PV plants. Considering the automatic cleaning recovery calculated in previous section that can be obtained using the proposed cleaning solution of 3.53%, the gain in energy (or loss in case of absence of cleaning) is 330.44 kWh over the year as can be deduced from Fig. 19 and Fig. 20. In other words, the gain in energy is only the difference between the produced energy in the clean state of a reference PV module, multiplied by the number of modules mounted on the biaxial tracker, and the energy produced in soiled state of the dirty PV module. Therefore, the automatic cleaning cost will be 0.14 €/kWh which is not profitable in terms of payback time compared to the system lifetime. In fact, the cost of the solution should provide a return on investment in less than 10 years. In other words, since in desert and arid sites, soiling is more pronounced then the return on investment is expected to be faster. For this reason, a projection has been made on an arid region where soiling is higher. Indeed, in an arid region, an average soiling losses of around 12% during the dry period of 3 months has been found (Azouzoute et al. 2019). Considering that in the arid area, the rain events are rare, it has been deduced that 12% is an annual average. Assuming that the same tracker is implemented in similar region, the gain in energy after cleaning would be 930.8 kWh, thus an increase of energy of 11.5%, which implicates 130.3 €/year. So, a payback time would be 8 to 9 years. Table 4 is a summary of the performed economic analysis. It can be deduced that this cleaning solution based on the telescopic arm would show a very important economic attractiveness if only it is implemented in a desert climate where the soiling reaches higher rates.

Table 4
Gain obtained by cleaning using the solution designed for Rabat Region and in the case that the installation is in an arid area

	Rabat site	Arid site
Average soiling losses (%)	4.8	12
Energy consumed by the cleaning system (kWh)	21	
Lifetime of the cleaning system (years)	25	
Price of the solution to be paid (€/kWh)	0.14	
Gain in energy production (kWh)	330.44	930.8
Payback time	24	≈ 9

4. Conclusion

Soiling is among the most challenging topics which receive a lot of attention in the research community regarding its significant effect on energy production. This paper brings to the literature an innovative approach to improve the performance of solar installations. It is not only a question of using a tracking system to maximize the production of PV modules but to integrate an automatic and low cost cleaning system for a higher production.

According to the intensive research carried out and presented in this work as updated background, only few cleaning systems that showed their adaptability to the tracker studied in this paper. However, this adaptability is relative since it will be necessary to invest more to make these cleaning systems completely appropriate to the dual-axis trackers. Therefore, it is of utmost importance to present an innovative cleaning solution to tackle the challenge of soiling especially for countries with great potential in solar energy as the case of Morocco.

The evaluation of the soiling losses for the PV modules mounted on a dual-axis tracker has been done for almost a year at the site of Rabat. For the same tracker, an innovative cleaning technique based on a telescopic arm has been presented. It has been also detailed in this paper, an artificial soiling approach followed to evaluate the gain in energy production using the realized cleaning technique. This implies an increase in energy yield of 3.53% if the solution is implemented in Rabat site and up to 11.5% in an arid region. Considering the cleaning cost, including the initial and maintenance costs, which is 0.14 €/kWh, through the economic analysis performed in this work, it has been found that the cleaning system is not profitable at the site of Rabat where higher soiling losses do not exceed 7%. However, it would present a very important economic attractiveness if the dual-axis tracker is implemented in desert areas where high soiling levels are frequently reached.

As mentioned before, the presented cleaning system has been designed to work on a dry surface of PV modules as it can ensure a humid cleaning especially in early mornings where the amount of dew is important and the tracker is still in the stowage position. As perspectives, it is recommended, before implementing the solution into the real size tracker, to test the realized prototype under real conditions in arid or hyper-arid climates to well evaluate its effectiveness and profitability.

Declarations

Ethics Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors contributions

DD: conceptualization, methodology, formal analysis, investigation, resources, data curation, writing - Original Draft. SMA: conceptualization, methodology, formal analysis. BL: methodology, formal analysis. AB: resources, funding acquisition, review & editing, supervision, validation.

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Competing interests

The authors declare no competing interests.

Availability of data and materials

All data generated or analysed during this study are included in this published article

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Figures

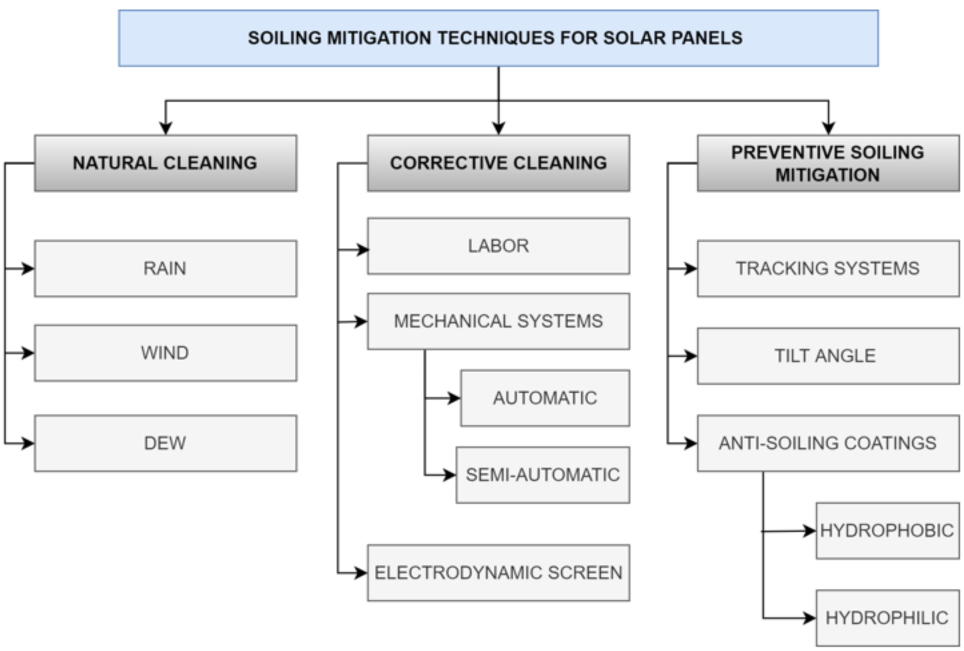

Figure 1

Overview of the different sub-categories of soiling reduction techniques for solar panels.

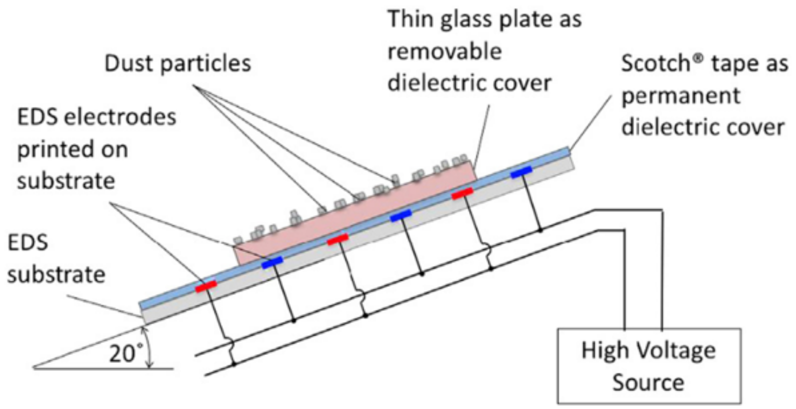

Figure 2

Schematic view of an Electrodynamic Screen (Guo et al. 2018)

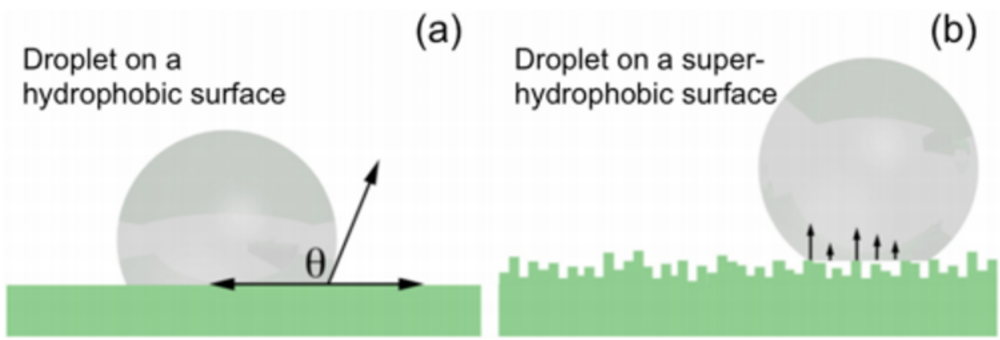

Figure 3

Schematic of (a) water droplet on normal hydrophobic surface with contact angle greater than 90° and (b) water droplet on a super-hydrophobic surface with a contact angle ⩾150°. A super-hydrophobic surface is defined as a surface that has a water CA angle ⩾150°. Micro- and nano-structuring a surface amplifies the natural tendency of the surface to achieve super-hydrophobicity (Schaeffer et al. 2015)

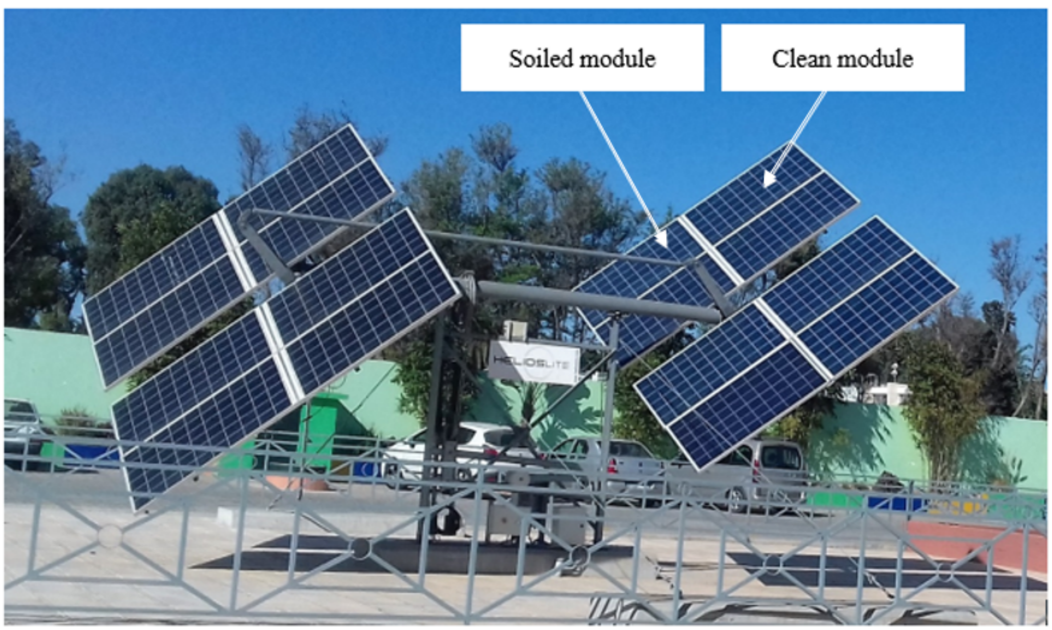

Figure 4

HeliosLite dual-axis tracker installed in the RD&I solar platform

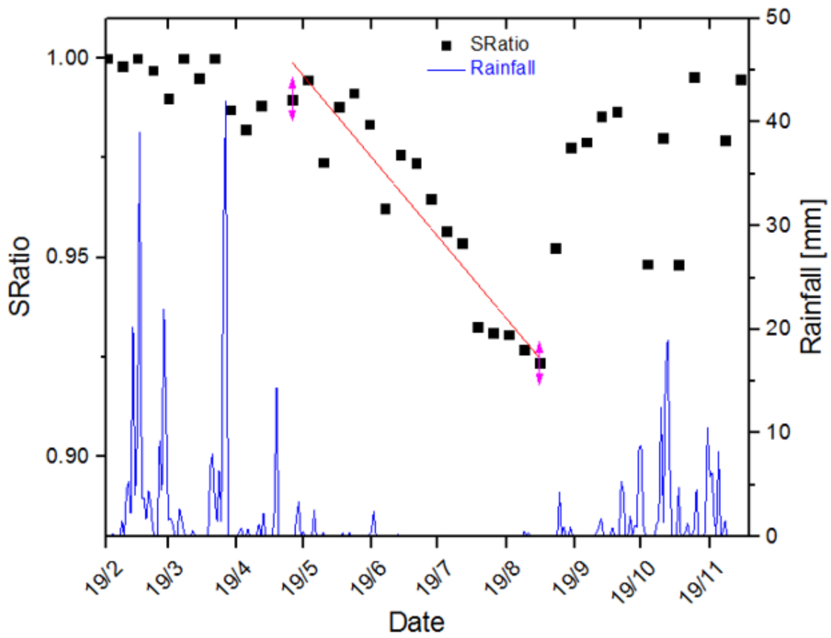

Figure 5

Evolution of SRatio of PV modules mounted on dual-axis tracker in Rabat, data ranging from February 19 to December 03, 2018. The SRate is displayed by a red line corresponding to the period with absence of rainfall

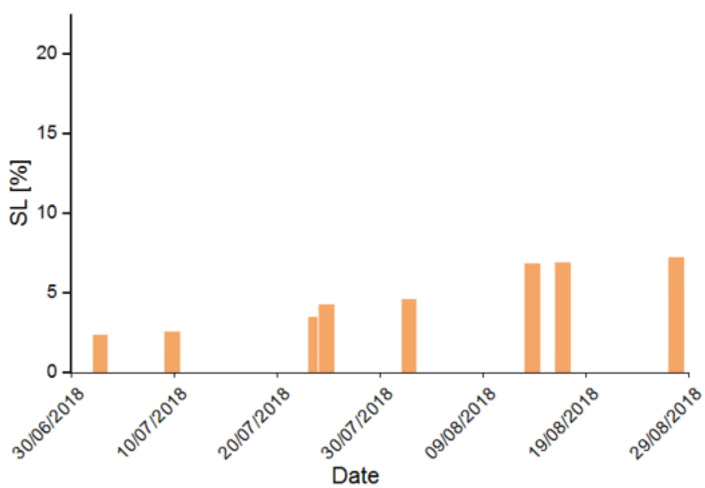

Figure 6

Daily Soiling Losses (SL) for PV on dual-axis tracker in clear days

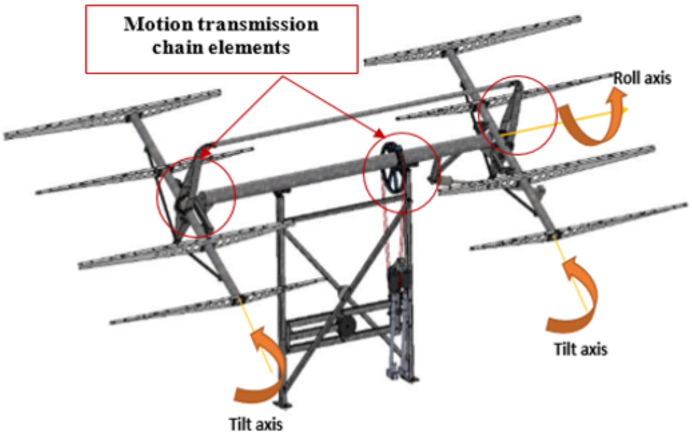

Figure 7

Architecture of the dual-axis Tracker from the documentation provided by HeliosLite (HeliosLite, 2019)

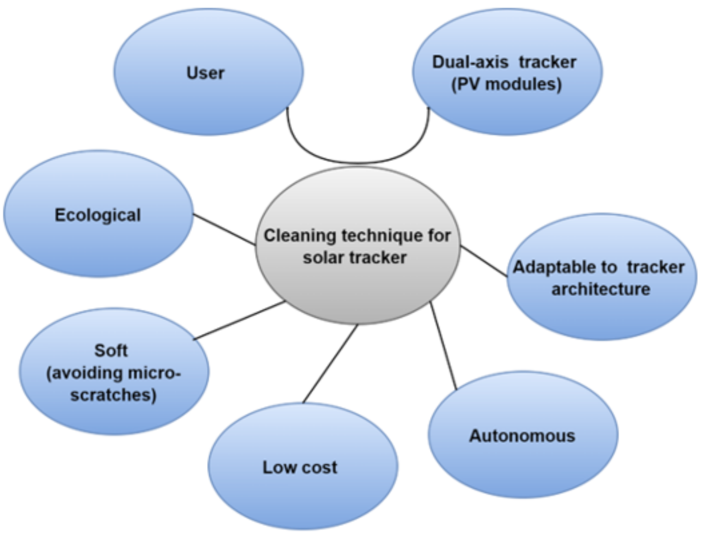

Figure 8

Different functions involved in the functional analysis of the proposed cleaning system

Figure 9

Location of the cleaning system on the middle bar of dual-axis tracker

Figure 10

Dimensioning of the telescopic arm taking into account the real dimensions of the tracker

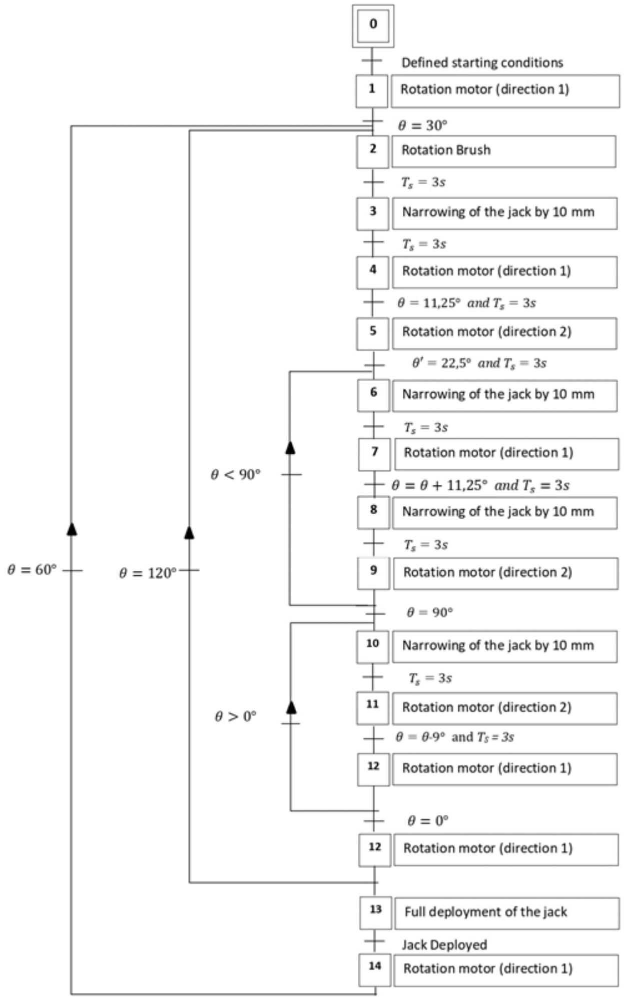

Figure 11

GRAFCET representation of the control system

Figure 12

Top view of the realized prototype of the cleaning technique based on the use of telescopic arm.

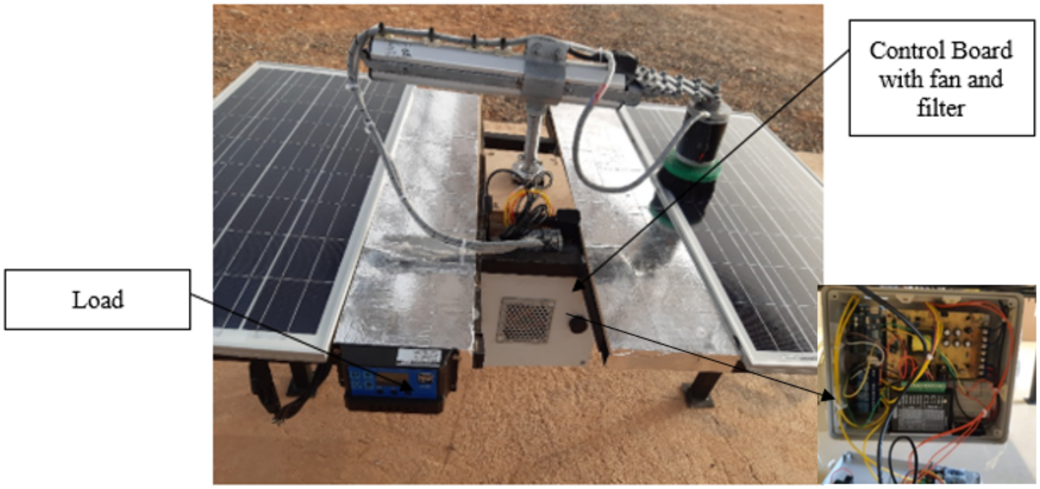

Figure 13

A focus on the control board and its location in the realized prototype

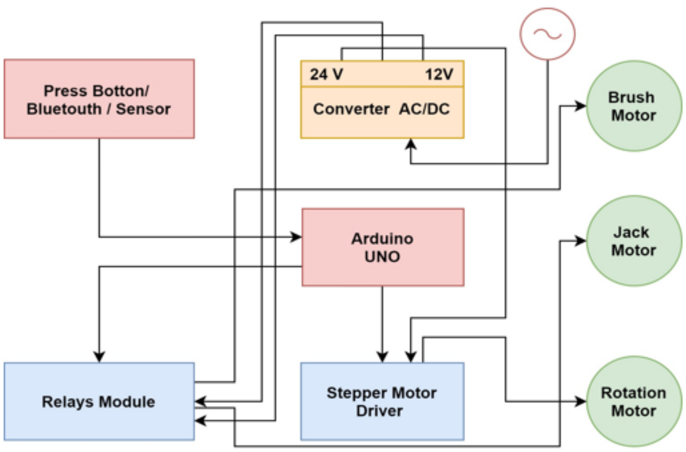

Figure 14

Block diagram of the cleaning system control proposed to be integrated into the dual-axis tracker

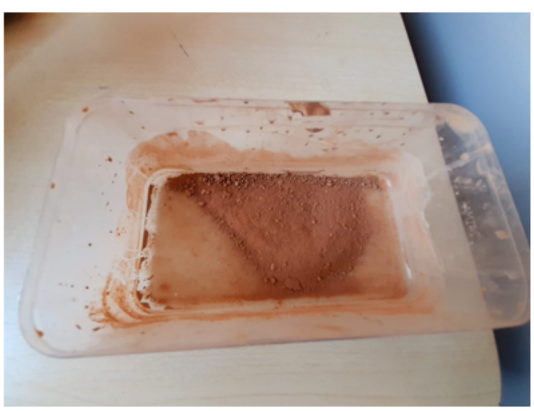

Figure 15

Dust used in the artificial soiling weighted by the precision electronic balance Texas with an accuracy of 0.01g

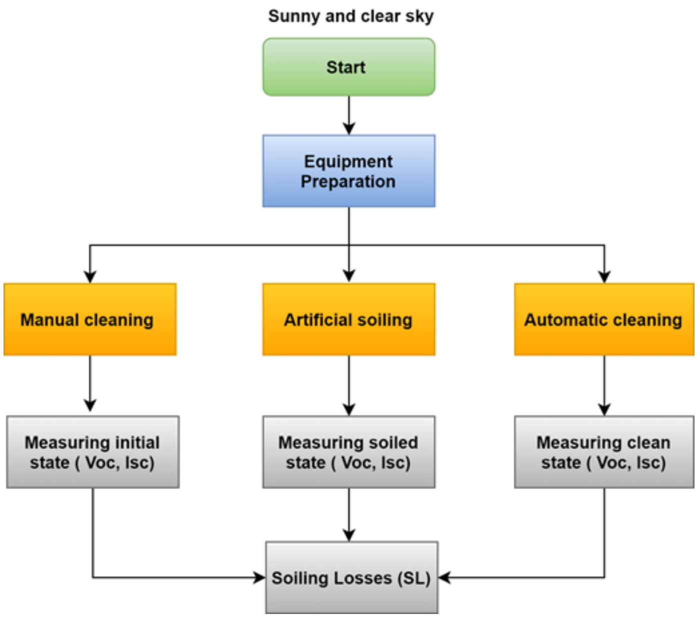

Figure 16

Methodology followed to test the realized cleaning technique

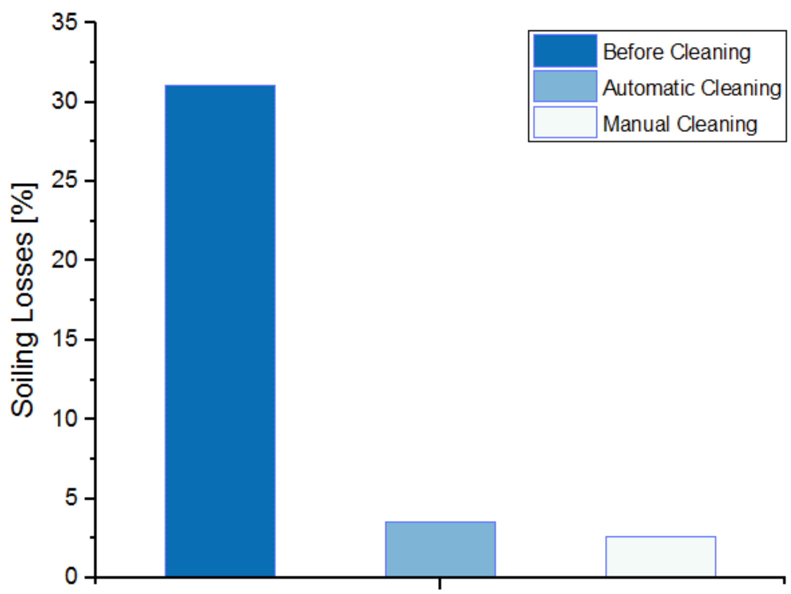

Figure 17

Soiling losses recovery by manual and automatic cleaning

Figure 18

View on the PV modules with artificial soiling during cleaning operation

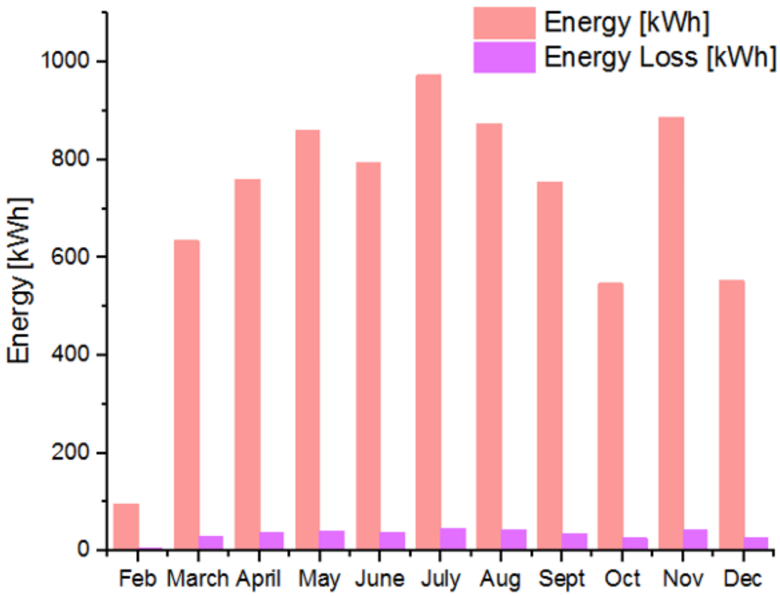

Figure 19

Evolution of monthly recorded produced energy for a clean state of the modules and the corresponding losses due to soiling for the site of Rabat from February to December 2018

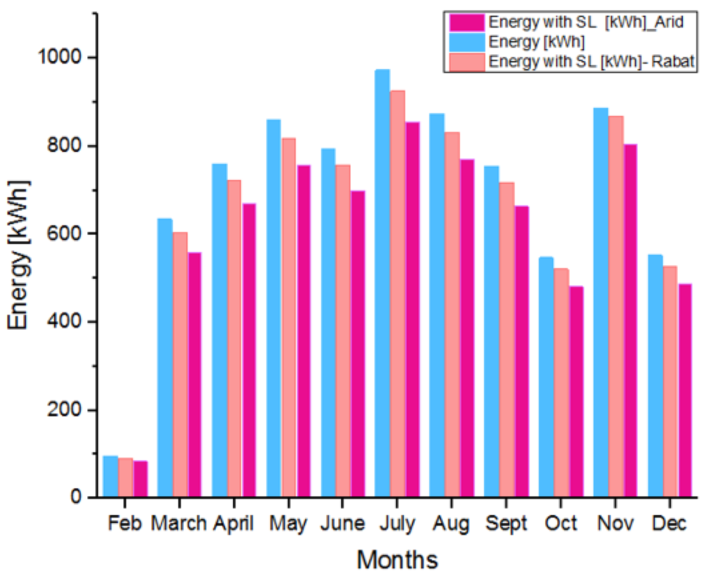

Figure 20

Comparison of the energy produced with and without soiling based on the recorded energy for the site of Rabat, the energy with soiling loss in the arid region was calculated based on the soiling losses found in the arid region