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# Soiling of Photovoltaic Modules: Comparing between Two Distinct Locations within the Framework of Developing the Photovoltaic Soiling Index (PVSI)

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**Abstract:** This article evaluates the impact of dust accumulation on the performance of photovoltaic (PV) modules in two different locations inside Egypt, Cairo and Beni-Suef. Two identical PV modules were used for that purpose, where each module was exposed to the outdoor environment in order to collect dust naturally for a period of three weeks, each in its corresponding location. The approximate dust density on each of the two PV modules was estimated. Moreover, the electrical performance was evaluated and compared under the same indoor testing conditions. The results show a better electrical performance and less dust density for the PV module located in Cairo compared to that located in Beni-Suef. The results further provide an indication for the impact of soling in different locations within the same country through a clear and simple procedure. In addition, it paves the way for establishing a Photovoltaic Soiling Index (PVSI) in terms of a Photovoltaic Dust Coefficient, as well as a Photovoltaic Dust Interactive Map. The product of such concepts could be used by the Photovoltaic systems designers everywhere in order to estimate the impact of dust on the future performance of PV modules in small and large installations in different regions around the globe, and during different times of the year as well.

**Keywords:** photovoltaic (PV); soiling; photovoltaic soiling index (PVSI); photovoltaic dust coefficient; photovoltaic interactive dust map; dust accumulation

## 1. Introduction

Renewable energy technologies deployment has witnessed an exponential growth worldwide. By the year 2017, the power sector added 167 gigawatts (GW) of renewable energy capacity globally, which constitutes a constant strong growth rate of 8.3% over the previous year and a continuation of previous growth rates since 2010 averaging 8% per year [1]. Regarding generating electricity from the sun using photovoltaic (PV) technologies, it is foreseen that there will be a massive expansion and utilization of the Photovoltaic technologies in various applications [2]. This would require rigorous standards, specifications, and maturely designed systems in order to get the most out of this widely utilized technology.

Nevertheless, in order for a PV system to work efficiently and effectively, several technical and environmental parameters have to be taken into consideration. The major technical parameters that affects the PV system functionality are several: The material properties of the PV cells, IV characteristics of the PV modules, as well as the efficiency of the inverters, charge controllers, and the rest of the Balance of System (BOS) components [3]. Several installation factors have to be taken into consideration as well: PV modules tilt angle, tracking, cables lengths, and the adherence to the relevant electrical codes and standards [4]. Moreover, there are significant environmental parameters that affect the PV system performance directly: Incident solar irradiance, air temperature and the associated PV module temperature during operation, air humidity, wind speed, and dust accumulation (soiling). In fact, dust accumulation on the surface of PV modules constitutes a form of shading that leads to the reduction of their output power, in addition to accelerating their degradation in case of leaving them for prolonged periods without proper maintenance and scheduled frequent cleaning [5]. This makes the soiling of PV modules as one of the most significant environmental phenomena that affect the performance of PV modules. In that context, many studies in literature can be found studying the factors that affect the accumulation of dust particles on PV modules surfaces [6,7]. Moreover, in a recent research work, it has been demonstrated that different research articles present several case studies, where several environmental, optical, and electrical parameters have been evaluated and compared [8]. However, although all of the studies are in accord with the fact that dust accumulation affect the performance of PV modules significantly, there are differences in the demonstrated loss percentages of electrical performance and output power. This has been attributed to the variations in the experimental setups and the equipment used, the measured parameters, the type of electrical characterizations and testing (indoors or outdoors), the variation in the geographical and climatic profiles where the dust accumulation occurs, and the demonstration of results [8,9].

For this, each study within the PV soiling research is significant, as each work is achieved under different environmental circumstances, in addition to the existence of several variations within the experimental and analytical formulation of the research problem in hand. In that sense, several research lines in literature can be found tackling the PV soiling issue from many distinct angles, for example, Costa et al. [10] presents periodic literature review in order to compile and assess the most recent and up-to-date publications related to soiling of PV modules. Recently, Menoufi [8] has presented a novel concept through an empirical research work (The Photovoltaic Soiling Index—PVSI) calling for the standardization of the soiling studies related to PV systems so that their results could be compared. In that same sense, the development of a Photovoltaic Soiling Index (PVSI) has been suggested so that the PV systems designers will be able to access the PV soiling data easily, and thus conduct their design taking into consideration the intricate details of soiling in different regions and during different times of the year. Other studies in literature can be found focusing on dust mitigation, where they mainly vary between several active and passive techniques. Said et al. [11] presented a review of the effect of climatic conditions on the performance of PV modules, particularly the soiling issue, where they reviewed the past, current, and future approaches for mitigating the effect of dust in that regard. Many other studies in that regard can be found examining self-cleaning coating solutions and their durability (passive dust mitigation techniques) and mechanical cleaning as well (active dust mitigation techniques) [12–18].

In reference to tackling the soiling studies from experimental viewpoints related to studying the effect of dust accumulation on the performance of PV modules, several research works have been achieved in different locations around the globe, within different times of the year, and in different environmental and experimental circumstances. Conceição et al. [19] investigated the soiling of PV modules in southern Europe taking into consideration the seasonal variations and their effect. Jian and Lu [20] demonstrated the effect of surface temperatures on the dust particles deposition on the surface of PV modules. Schill et al. [21] studied the impact of soiling on the shape of the IV curves of PV modules in a test site located within the Gran Canary Island in Spain. Kazem and Chaichan [22] investigated the energy losses caused by dust deposition on PV modules in Northern Oman. Said and Walwil [23] studied the effect of dust accumulation on the overall glass transmittance of PV modules, examined the spectral transmittance of anti-reflective coated glass, and conducted a characterization of the physical and chemical properties of dust particles deposited. Pulipaka et al. [24] adopted a regression model in order to examine the loss of PV modules output power caused by soiling at various levels of irradiances, where a neural network model was developed from the obtained experimental data. Javed et al. [25] used an artificial neural network in order to model the correlation among environmental variables and daily change in the PV power output loss caused by soiling in Doha (Qatar). Figgis et al. [7] conducted a study that investigated the effects of some environmental and physical variables on the condensation of soiled PV surfaces: Relative humidity, surface dew point temperature difference, hygroscopic dust content, and surface wettability. Gholami et al. [26] conducted a seventy-days experiment in order to evaluate the impact of soiling on the electrical performance of PV modules in Tehran (Iran). Fountoukisa et al. [27] conducted a research in order to evaluate the effect of dust on the performance of PV modules during a twelve months period in Qatar using experimental field measurements and modeling, where they developed a nonlinear correlation between specific environmental parameters (relative humidity, dust particles mass, and PV electrical losses). You et al. [28] developed a framework that predicts the energetic and economic effects caused by soiling of PV modules, where they studied the effect of relative humidity, precipitation, and tilt angle, in addition to introducing a relative net-present value in order to determine the optimal cleaning interval for the soiled PV modules.

Within such context, it has been found that only a few case studies about soiling of PV modules were reported from the African Region and the Gulf area relative to other regions of the world [8]: It has been shown that during the last two decades, specifically from 1990 and up to 2017, almost half of the PV soiling studies emerged from Asia, where the majority of studies were from the Kingdom of Saudi Arabia (KSA), Malaysia, and India. The KSA has been found to be the country that generates the largest number of studies not only in Asia but among the rest of the world as well. For Egypt, two significant case studies have been reported: Menoufi et al. [9] have studied the impact of dust accumulation on the electrical performance of PV modules at the East Bank of the Nile (Beni-Suef, Egypt) for a period of three months. Elminir et al. [29] conducted a seven months experiment in Cairo (Egypt) in order to examine the impact of PV modules tilt angle on the soiling density over their surfaces. In a study similar to the latter one, Abdeen et al. [30] studied the impact of tilt angle on soiling in Aswan (Egypt), but in terms of comparing the electrical performance of the tested PV modules.

In fact, Egypt has many arid and desertic areas, as well as a significant expansion within its solar Photovoltaic projects among other African countries [31,32]. Several countries in the Gulf Cooperation Council have set their solar energy targets and stated executing them as well [33]. This demands the scientific community in the region to lead more research and initiatives in the different research lines concerning the soiling of PV modules. Hence, as a contribution to this field of studies in that specific region, this article discusses the difference between the impact of dust accumulation on the performance of PV modules in two different locations inside Egypt (Cairo and Beni-Suef).

In such context, there are some interesting research studies in literature that deal with comparing the impact of soiling on PV modules in two or more different locations, each according to its intended target: Micheli and Muller [34] investigated over one hundred environmental and meteorological indicators and compared them with the performance of twenty PV soiling stations installed in the United States of America (USA). The study aimed at determining the extent of the ability of the investigated parameters to predict the soiling losses occurring on PV systems. Accordingly, it has been concluded that the annual average of the daily mean particulate matter values recorded by monitoring stations deployed near the PV systems are the best soiling predictors for PV systems. Tanesab et al. [35] gathered dust samples from the surface of PV modules installed in two different locations (Australia and Indonesia), deposited the collected dust artificially on the surface of three PV modules technologies, electrically characterized them through indoor testing preparations, and studied the morphology of the dust samples from the corresponding locations. The focus in such study was mainly to correlate between the dust morphologies and the related electrical performance. Referring to the case study presented in this article, as demonstrated in the following section, two actual PV modules were placed and used to collect the dust from two distinct outdoor locations (natural dust deposition). This is in order to take into consideration the natural dust deposition that occurs due to the natural exposure of the PV modules to the outdoor environment as a part of an actual operating PV system. Moreover, this research is considered to be an advancement and one more step within the context of introducing and clarifying the Photovoltaic Soiling Index (PVSI) that has been previously introduced [8]. The proposed Photovoltaic Soiling Index would help the PV designers and researchers have a reliable estimation for the impact of dust on the performance of PV modules in a specific region and during a determined time of the year. This could be achieved through having information about a Photovoltaic Dust Coefficient for different PV module technologies, as well as having accesses to Photovoltaic Interactive Dust Maps. In that regard, the aforementioned concepts and their future elaboration is entailed within the body of the present article, in order to serve as a base and a reference for the wide scale establishment of the suggested Photovoltaic Soiling Index (PVSI) practical implementations.

## 2. Materials and Methods

Two identical PV modules with the characteristic shown in Table 1 were used for the corresponding experiment. Each of the two PV modules was placed at a horizontal position on the rooftop of a building, each in its corresponding location: One in Cairo (30.0444° N, 31.2357° E) and the other in Beni-Suef (29.0661° N, 31.0994° E). The two cities are characterized by their hot desertic climate throughout the year. Each of the two PV modules was left exposed to the outdoor environment for three consecutive weeks without cleaning (from the 1st until the 21st of August 2018).

**Table 1.** Specification of each of the identical photovoltaic (PV) modules used in the experiments.

| Parameter | Value |
|---|---|
| Maximum Power (Watt) | 5 |
| Power Tolerance (%) | 0/+3% |
| Maximum Power Voltage—$V_m$ (Volt) | 18.36 |
| Maximum Power Current—$I_m$ (Ampere) | 0.27 |
| Open Circuit Voltage—$V_{oc}$ (Volt) | 22 |
| Short Circuit Current—$I_{sc}$ (Ampere) | 0.29 |
| Maximum System Voltage—VDC (Volt) | 1000 |
| Dimensions (mm) | 260 × 220 × 18 |
| Weight (kg) | 0.8 |
| Test Condition | 1000 W/m$^2$, AM 1.5, 25 °C |

The PV modules were positioned horizontally in order to allow for the maximum amount of dust accumulation on their surfaces. Such placement would be an indicator for the worst-case scenario of dust accumulation on the surface of a PV module each in its corresponding region [36]. After the dust accumulation period, the two PV modules were tested under the exact same conditions using the simplified indoor testing station shown in Figure 1.

The testing station comprised a Xenon lamp that was used for simulating the incident solar irradiance, where the incident light values were measured using a specialized probe. The probe was placed on the left of the wooden frame in order to measure the same level of irradiance received by the horizontal surface of the tested PV module. The ambient room temperature and the PV module surface temperature were recorded using a datalogger and two calibrated T-type thermocouples. The current, voltage, and power measurement were registered using an IV source meter. In order to estimate the dust density in terms of weight per square meter on the PV modules surfaces, glass slides were placed on the top of each PV module during the dust accumulation process. Each glass slide was weighted before and after the dust accumulation [9].

The usefulness of the indoor testing configuration is that both of the irradiance and temperature—the most influencing parameters on the performance of PV modules—can be controlled, or in other words, maintained and measured at desired and well determined levels during capturing the IV characteristics of the tested PV modules. This would result in reliable and accurate comparisons regarding the impact of dust accumulation—as an independent variable—on both of the PV modules. From a distinct related perspective, it is worth mentioning that a recent study has concluded experimentally that the dust accumulation density hardly has any effect on the operating temperature of a PV module [37].

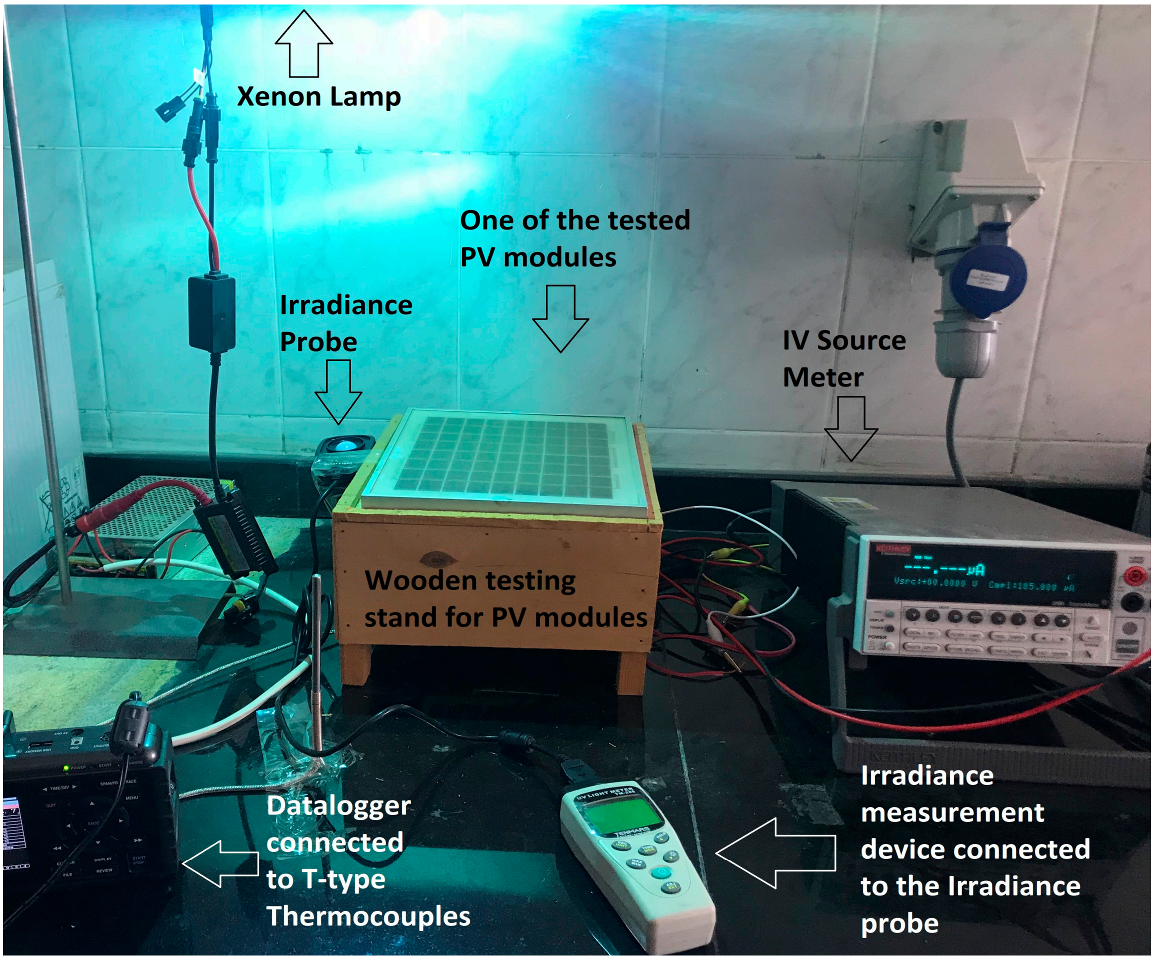



**Figure 1.** The indoor testing station for the PV modules.

Regarding the outdoor experimentations, it can be found that several studies in literature were conducted to examine the impact of dust under typical and normal operating conditions taking into consideration several parameters: Geographic location, climatic profile, and season of the year [38]. The experimental measurements and the related comparisons in that latter approach have to be carefully executed, as the environmental conditions would vary greatly from day to day regarding the ambient temperature, solar irradiance, wind speed, and humidity. This is in addition to the impact of more complex phenomena that comprise many interrelated and interdependent factors such as high wind and storms. In brief, the studies in literature vary in two aspects regarding the main theme of the adopted methodology: The dust accumulation aspect (natural accumulation through outdoor exposure, or artificial deposition through indoor controlled deposition) and the electrical characterization aspect (outdoor measurement under the sun, or indoor measurements under a solar simulator) [8]. In the present article, the dust accumulation process occurred outdoors (natural dust accumulation) and the electrical characterizations were executed indoors (indoor measurements under a solar simulator).

## 3. Results and Discussion

The apparent dust accumulation on the surface of the two PV modules is demonstrated in Figure 2. It can be noticed that the Beni-Suef PV module (right) appears shadier than the Cairo PV module (left). This can be considered as a preliminary indication that the amount of dust accumulated on the surface of the Beni-Suef PV module is larger than that on the surface of the Cairo PV module. This can be attributed to the more arid and desertic climate of Beni-Suef compared to Cairo, which causes a faster rate of dust accumulation on the surface of the PV modules.

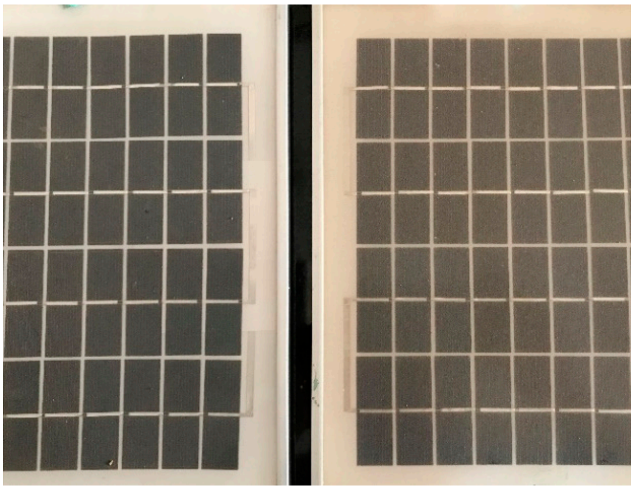


**Figure 2.** Cairo PV module on the left and Beni-Suef PV module on the right.

Such claim was confirmed by the dust slides that were fixed on the top of each PV module (Table 2), where it is shown that the amount of dust per square meter on the surface of the Beni-Suef PV module (0.0424 gm/cm$^2$) is larger than that of the Cairo PV module (0.0366 gm/cm$^2$). Although the dust has been accumulated previously in Beni-Suef in a previous experiment [9], the results could not be interpolated herein, as the dust accumulation—in the present study and the previous one—occurred during two different times of the year and for varied periods of time. In addition to that, the dust accumulation could differ throughout the years according to the constantly changing environmental and climatic profile of each region [8]. This could make the dust accumulation patterns during a summer season in a year differ from the dust accumulation during the same season in the following year. This is one of the technical motives for establishing a Photovoltaic Soiling Index (Photovoltaic Dust Coefficient and Photovoltaic Interactive Dust Map) that incorporates continuous monitoring of the dust accumulation on the surface of PV modules throughout the days and years, taking into consideration any potential changes in the annual dust accumulation patterns.

**Table 2.** The dust weight on each of the glass samples, demonstrating the corresponding weight per unit area.

| | **Beni-Suef Glass Slide** | **Cairo Glass Slide** |
|---|---|---|
| Slide weight before dust (gram) | 4.5528 | 4.4722 |
| Slide weight After dust (gram) | 4.5952 | 4.5088 |
| area of slide (7.62 × 2.54 cm$^2$) | 19.3548 | 19.3548 |
| Weigh of dust per unit area (g/cm$^2$) | 0.0424 | 0.0366 |

Figure 3 shows the IV curves of the tested PV modules. It is noted that the Beni-Suef PV module shows lower electrical performance during the electrical measurements compared to the Cairo PV module: The short circuit current and open circuit voltage of the Beni-Suef PV module is less than that of the Cairo PV module by 26% and 8%, respectively. This can be attributed to the larger amount of dust that is accumulated on the surface of the Beni-Suef PV module in comparison to the Cairo PV module.

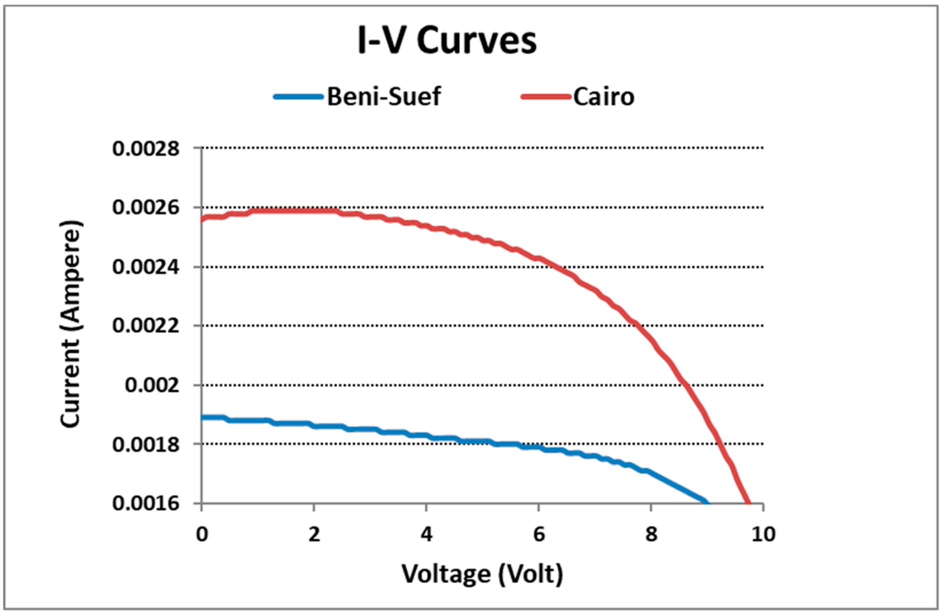



**Figure 3.** IV (Current–Voltage) curves of the tested PV modules.

Figure 4 shows the P–V curve of the tested PV modules. The overall maximum power produced by the Beni-Suef PV module during the test is estimated to be 15% less than that of the Cairo PV module. The corresponding correlation herein is essential in developing a Photovoltaic Soiling Index in terms of a Photovoltaic Dust Coefficient, that is, the electrical behavior and performance of the PV modules would be estimated for different dust densities over their surfaces, under the same controlled indoor testing conditions. This would help in treating the soiling of PV modules as an independent environmental variable that is being taken into consideration during choosing a specific PV technology for a corresponding system. That is, each PV technology/brand would have its own Photovoltaic Dust Coefficient. Such implementation would be analogous to the temperature coefficient rates that are present in the thermal characteristics section inside the datasheets of the commercial PV modules [39], which are developed and benchmarked in several specialized research laboratories [40].

From another perspective, it could be concluded that the electrical performance of a PV module in Cairo outperforms that of a PV module in Beni-Suef under the same dusty and soiling conditions. However, such claim would only be valid if both of the dusty PV modules were electrically characterized using controlled indoor experimentations, which is the case of the present research. In other words, although the dust accumulated in two different locations, the testing was conducted indoors under the same controlled conditions (temperature and irradiance, as demonstrated in Figures 5 and 6) for the sake of knowing the subtle difference that dust accumulation had on the performance of the two PV modules without any bias from other environmental factors.

On the other hand, if the same two PV modules were electrically characterized outdoors, each in its corresponding location where the dust accumulated (Cairo and Beni-Suef), then the results could differ radically from those generated in the present study. This is because the outdoor electrical characterization in such case is not only affected by the soiling as the sole environmental indicator, but by other outdoor location-related environmental parameters that are present at the moment of the electrical characterizations as well: Air temperature, PV surface temperature, irradiance, wind speed, and humidity. In that latter scenario, the performance of PV modules could be compared using identical testing stations to be installed in the locations required for establishing the comparison, taking into consideration the measurements of all the location-related environmental parameters, not only the electrical characterization results.

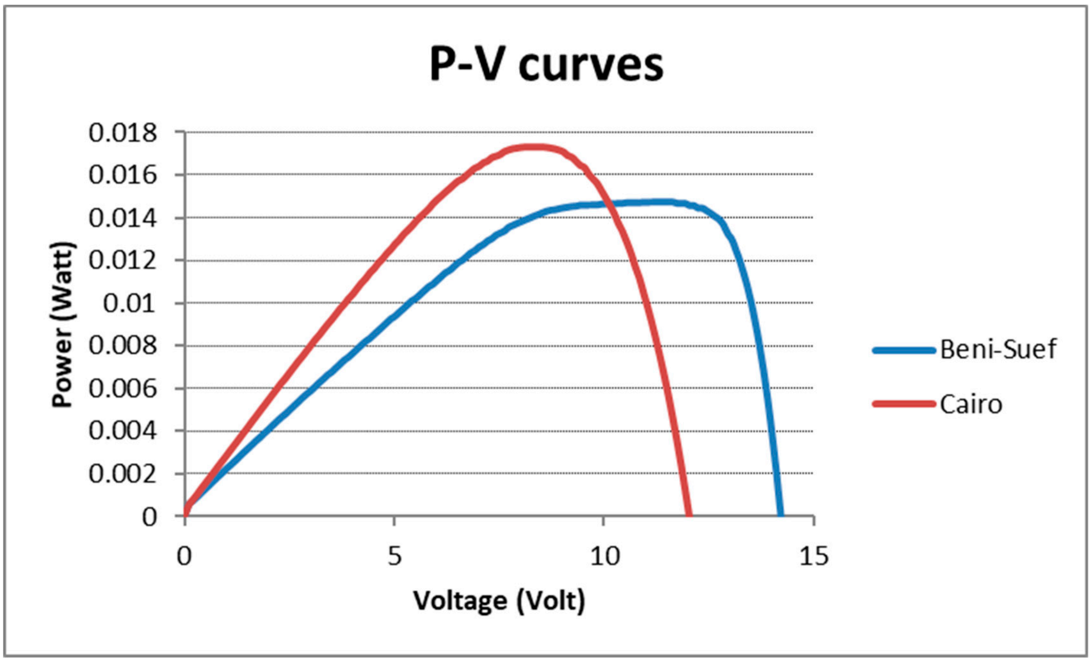



**Figure 4.** P–V (Power–Voltage) curves of the tested PV modules.

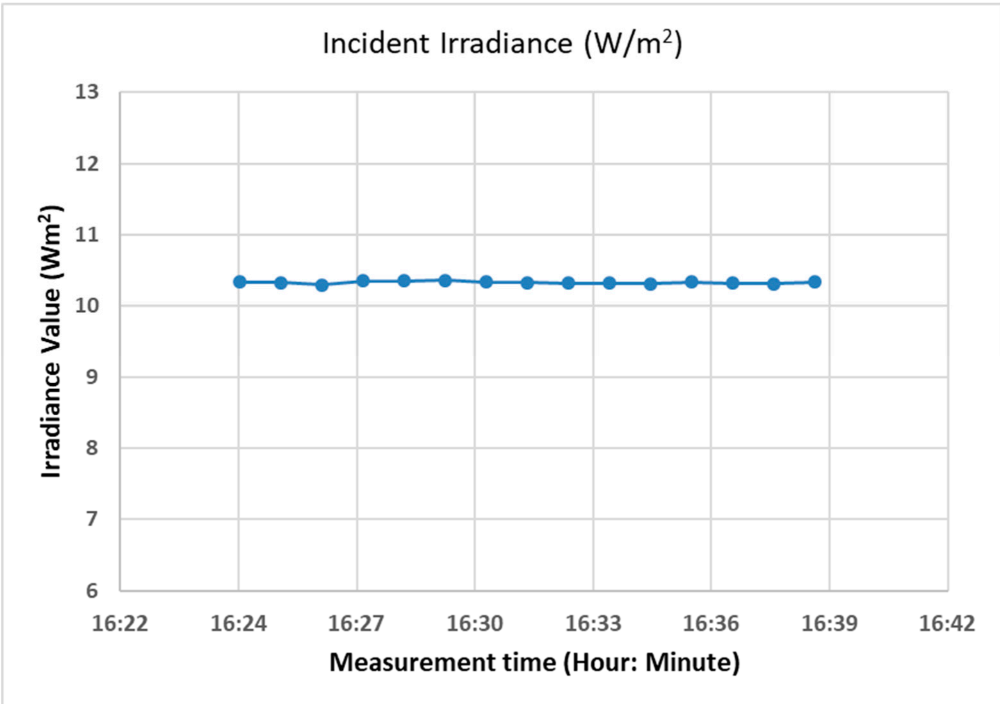
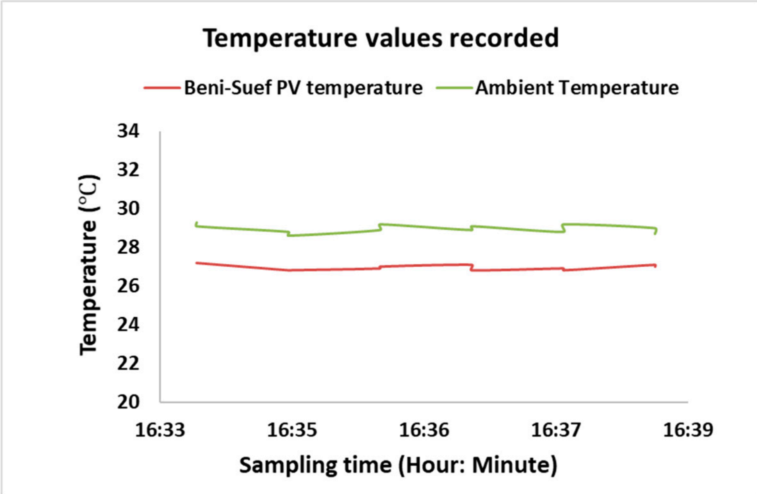
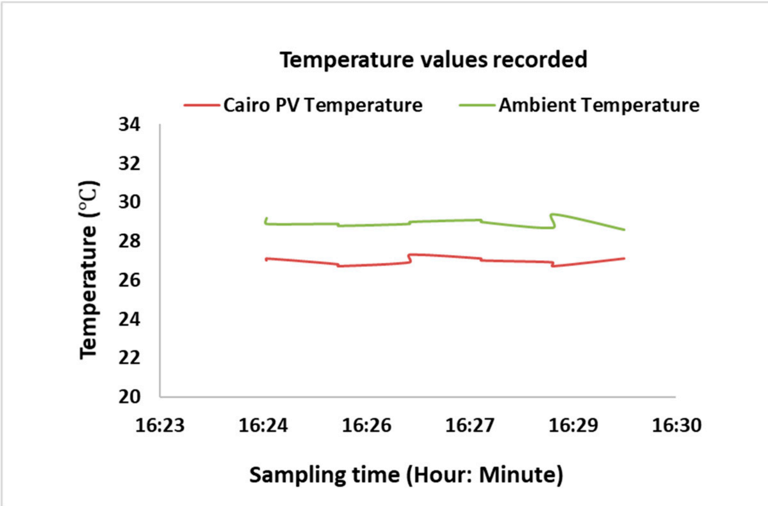



**Figure 5.** Measured incident irradiance during the electrical characterizations and measurements.

Within that same context, a Photovoltaic Soiling Index in terms of a Photovoltaic Interactive Dust Map [8] could be developed, where the PV systems designers could retrieve the soiling information in specific locations and during different times of the year based on the readings developed by those testing stations. This would also—like the Photovoltaic Dust Coefficient explained previously—treat the soiling of PV modules as an independent environmental parameter to be taken into consideration during the design of the PV systems.




(**a**)




(**b**)

**Figure 6.** (**a**,**b**) Measured temperature of the indoor testing environment and the PV modules surface temperatures during the electrical characterization and measurements.

This would also help in providing further indications of the necessary measures required for the cleaning frequency [41] of a corresponding PV system in a specific location, in relation to its annual energy production plans whether it is a grid-connected or a stand-alone PV system. In such case, the Photovoltaic Soiling Index in the form of a Photovoltaic Interactive Dust Map would resemble the technical arrangements that has been achieved for the Photovoltaic Geographical Information System (PVGIS) in order to retrieve information that supports estimating the impact of solar irradiance and temperature on the performance of PV systems in several locations around the globe [42]. In other words, the inclusion of the Photovoltaic Soiling Index within the interactive maps of a geographical information system such as the PVGIS would enable the PV systems designers to have an overarching perspective regarding the temperature, irradiance, soiling patterns, soiling daily density, and the associated overall impact on the performance of the PV modules that are to be installed in a specific location and during a determined time of the year.

Hence, in brief, the Photovoltaic Soiling Index in terms of a Photovoltaic Soiling Map could be speculated as the loss percentage of voltage and power output per day of dust accumulation in a specific region. After that, the average loss of voltage and power output percentages per gram per month of accumulated dust could be estimated, as well as per year. This will require placing the tested PV module each in a specific location, taking into consideration the measurements of current, voltage, and power output reading every day at a specific hour (at noon, for example), together with the other spatial environmental parameters (wind speed, humidity, solar irradiance, etc.). Moreover, such testing scheme could be further elaborated for a period of over five years, in order to have an idea about the possible variations of the loss of voltage and power outputs of PV modules due to potential environmental profile and climatic changes in each location throughout the years, which would create a new correlation between the changes of the soiling patterns and the environmental profile changes in terms of the electrical performance of PV modules.

In addition to that, the Photovoltaic Soiling Index in terms of Photovoltaic Dust Coefficient could be achieved inside specialized indoor characterization laboratories with the aim of achieving a benchmark. In such case, determined amounts of dust could be artificially deposited on the surface of the tested PV module on several stages, where each stage represents a specified amount of dust that is evenly distributed on the surface of the tested PV module, representing one gram of dust per layer. Then, the voltage and power output loss could be calculated as a percentage per gram of deposited dust. The characterization and components of the deposited dust could be varied according to the nature of the particulates in each region.

## 4. Conclusions and Recommendations

This article presents a case study that compares the impact of soiling on the performance of PV modules in two distinct locations inside Egypt (Cairo and Beni-Suef). The PV modules were exposed to the natural environment outdoors for a period of three weeks, each in its corresponding location. The indoor electrical characterization results show that the Cairo PV module outperforms the Beni-Suef PV module, where it demonstrates higher values of short circuit current, open circuit voltage, and maximum power when tested under the same conditions. This has been attributed to the fact that during the three weeks periods, more dust has been accumulated on the Beni-Suef PV module than that on the Cairo PV module, due to the desertic and arid nature of Beni-Suef region compared to Cairo; therefore, more accumulated dust caused more shading, leading to more electrical performance losses of the Beni-Suef PV module compared to the Cairo one. However, further studies are needed in that regard in order to examine deeply the morphology and characterization of the dust particles and the significance of their impact on the shading patterns on the surface of PV modules in different locations throughout the years. In addition to that, in order to examine the practical and real-time impact regarding each location, each of the corresponding PV modules has to be tested and electrically characterized outdoors, each at its corresponding location. Identical testing stations could be used for that purpose, where they can operate and execute the electrical characterization simultaneously, taking into consideration the measurements of the unique environmental parameters of each location (temperature, wind speed, humidity, etc.). This would provide a global perspective about the significance of impact of dust on the performance of PV modules under real operating conditions in distinct locations. From a practical design viewpoint, and within the Photovoltaic Soiling Index concept and perspective, the further elaboration of this research is recommended to be as follows:

(1) Allowing the dust to be naturally accumulated on the surface of PV modules due to outdoor exposure in distinct locations then performing an indoor standardized electrical characterization would support the development of a Photovoltaic Dust Coefficient [8]. Such coefficient can be used in order to determine the rate of loss of electrical power produced by PV modules in terms of the dust density over their surfaces (i.e., rate of change of the PV electrical power output per gram weight of accumulated dust). The Photovoltaic Dust Coefficient can be developed for different types of PV modules technologies in specialized benchmark laboratories, similar to the benchmarking process achieved for developing a Photovoltaic Temperature Coefficient for the different technologies and brands of PV modules [40].

(2) Exposing the PV modules outdoors in order to allow natural dust accumulation on their surfaces while monitoring their performance continuously together with the other location-related

environmental parameters (air temperature, wind speed, humidity, etc.) would help in developing a Photovoltaic Interactive Dust Map for a specific region [8]. This can help the PV designers worldwide in estimating the power output losses that can be caused due to the dust accumulation on the surface of PV modules in a specific region and during a specified time of the year, exactly as they can recognize the solar irradiance and average temperature in that same context [42]. Therefore, during the design phase, the energy production plan of a PV system can be estimated accordingly, taking into consideration a global perspective of the dust accumulation phenomena and the necessary cleaning frequency required.

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