AIP | Journal of
Renewable and Sustainable Energy

Dust accumulation effect on efficiency of Si photovoltaic modules

R. E. Cabanillas and H. Munguía

Citation: J. Renewable Sustainable Energy **3**, 043114 (2011); doi: 10.1063/1.3622609
View online: http://dx.doi.org/10.1063/1.3622609
View Table of Contents: http://jrse.aip.org/resource/1/JRSEBH/v3/i4
Published by the American Institute of Physics.

Related Articles

Characterization of metastabilities in Cu(In,Ga)Se2 thin-film solar cells by capacitance and current-voltage spectroscopy
J. Appl. Phys. 110, 094506 (2011)

A light emitting diode based photoelectrochemical screener for distributed combinatorial materials discovery
Rev. Sci. Instrum. 82, 114101 (2011)

Plasmonic reflection grating back contacts for microcrystalline silicon solar cells
Appl. Phys. Lett. 99, 181105 (2011)

Study of organic photovoltaics by localized concentrated sunlight: Towards optimization of charge collection in large-area solar cells
APL: Org. Electron. Photonics 4, 235 (2011)

Study of organic photovoltaics by localized concentrated sunlight: Towards optimization of charge collection in large-area solar cells
Appl. Phys. Lett. 99, 173305 (2011)

Additional information on J. Renewable Sustainable Energy

Journal Homepage: http://jrse.aip.org/
Journal Information: http://jrse.aip.org/about/about_the_journal
Top downloads: http://jrse.aip.org/features/most_downloaded
Information for Authors: http://jrse.aip.org/authors

ADVERTISEMENT

AIPAdvances

Submit Now

Explore AIP's new open-access journal

• Article-level metrics now available

• Join the conversation! Rate & comment on articles

Downloaded 07 Nov 2011 to 79.131.205.35. Redistribution subject to AIP license or copyright; see http://jrse.aip.org/about/rights_and_permissions

JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY **3**, 043114 (2011)

Dust accumulation effect on efficiency of Si photovoltaic modules

R. E. Cabanillas[1,a)] and H. Munguía[2,b)]
[1]*Department of Chemical Engineering, Engineering Division, University of Sonora, Hermosillo, Sonora 83000, México*
[2]*Department of Physics, Natural and Exact Science Division, University of Sonora, Hermosillo, Sonora 83000, México*

(Received 29 March 2011; accepted 15 July 2011; published online 9 August 2011)

We experimentally studied the electrical efficiency effects of naturally forming atmospheric dust deposits on commercial photovoltaic panels. The variable considered for measurements was the electric potential for three commercial silicon modules: monocrystalline, polycrystalline, and amorphous. A mathematical model was developed to determine maximum potential as a function of temperature and of total incident radiation. The study presents two essential parts: the naturally deposited dust particles and the variation in maximum electric potential between clean and dirty modules. The results indicate that the maximum reduction in potential is around of 6% for monocrystalline and polycrystalline modules and of 12% for the amorphous silicon. © *2011 American Institute of Physics*. [doi:10.1063/1.3622609]

I. INTRODUCTION

Due to their versatility, low maintenance, and long lifetime, photovoltaic (PV) modules are a very attractive alternative for small, off the grid energy projects. In recent years, the use of these devices in the greater Sonoran Desert region has increased considerably. The principle uses are for communication, illumination, water pumps, etc. One continually hopes that the application of photovoltaic modules becomes more common in less remote, including on grid, locations.

The design of PV-solar plants requires knowing with precision the behavior of photovoltaic modules and their limits. There are two environmental conditions that adversely affect the efficiency of the modules: the high temperatures and the accumulation of dust on the surface.[1,2] It is well known that temperature affects the conversion efficiency of the silicon solar cells. Higher temperatures reduce the conversion efficiency.

The temperature effect was analyzed in detail in a previous work,[3] where three types of photovoltaic modules: monocrystalline, polycrystalline, and amorphous were studied under extreme temperature conditions that are characteristic of the region of the state of Sonora. That study found that the dust layer accumulated on the modules affects their performance. A series of experiments were conducted in order to clearly define the problems that cause the losses in power. The evaluation of the electrical efficiency due to the effects of dust on the modules was permitted with information previously obtained. Previous works by Al-Hasan[4] and Nahar[5] present studies concerning the electrical power decrease in modules due to dust accumulation, under controlled conditions. Our focus was to perform this study under natural operating conditions.

This study was carried out in the city of Hermosillo, Sonora, where not only is there a high level of solar incidence, but also an elevated presence of dust.

II. STUDY OBJECTIVES

To study the effects on electrical performance of photovoltaic modules due to naturally forming dust deposits on the surface.

[a)]Electronic mail: rcabani@iq.uson.mx.
[b)]Electronic mail: hmunguia@fisica.uson.mx.

III. METHODOLOGY AND EXPERIMENTAL SETUP

An arrangement of three types of commercial photovoltaic modules was used: amorphous, monocrystalline, and polycrystalline. These modules were located on the roof of the Chemical Engineering Department at the University of Sonora and operated under real environmental conditions. For each module, a circuit was designed and constructed to measure the maximum electrical power generated. An automatic data acquisition system was created in order to monitor temperature and solar radiation. The modules were mounted on a solar tracker so that the radiation always arrived at a direction normal to the modules plane. The clean modules were left to accumulate dust for weeks until there was sufficient dust to conduct tests. Then the deposited dust was collected in order to be evaluated. During every day of testing, the potential maximum and associated parameters were monitored. The tests conducted on the accumulated dust are described after the report.

In order to measure the incident radiation on plane of the modules, a solid state radiation sensor type Licor was mounted to the solar tracking platform. A thermocouple type T was adhered to the back of every module as well.

As mentioned previously, two control circuits were designed to measure the voltage and current: one to simulate a variable charge and the other for the sequential selection (commutation) of the modules.[6] The circuits are controlled by a data acquisition system through a program created for this project. Once a module has been selected, the circuit load simulator performs a current "sweep" from zero (open circuit) to the short-circuit. Upon finishing the sweep, the circuit commutator changes to the next module and repeats the current sweep of charge. The experimental system design is shown in Figure 1. The program that controls the circuits and acquisition of data repeats in 15 min intervals and every run has duration of approximately 2 s. Every run of the program gathers the following parameters:

- Ambient temperature
- Solar radiation in the modular plane
- Temperature of modules
- Voltage and current of each module.

In addition, the program reports the date, hour, and minute of every charge carried out. The maximum potential is calculated from current-voltage (*I-V*) curves. The current-voltage curves were measured with a charge simulator device, which sweep in 22 points, and the data are recorded. Figure 2 depicts an example of the sweep. Each day the process starts up at eight o'clock in the morning and stop 12 h later. The tests were made during 90 days, from August to December (summer to autumn). The monitoring process was continuous all over the study period.

In order to measure the range in sizes of the dust particles, an LS Particle Size Analyzer brand Coulter model Fraunhofer LS 100Q (based on laser diffraction technology) was used.[7] A Leica Microscope, model DMLS, was used to study the morphology of the dust.

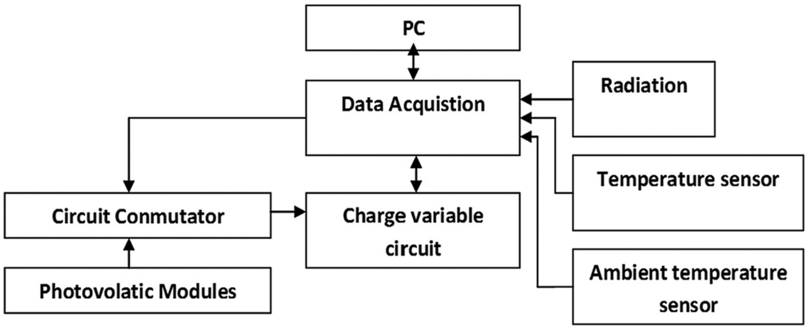

FIG. 1. Block diagram of the experimental system of measuring maximum potential.

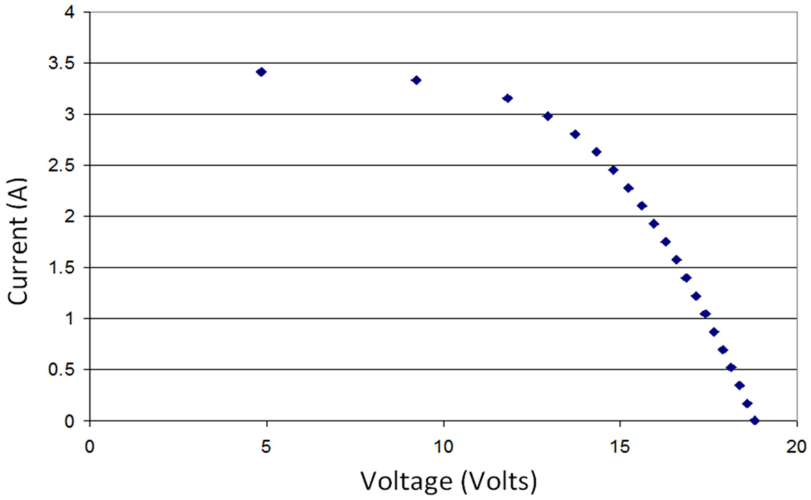

FIG. 2. *I-V* curve obtain from the modules in operation using the constructed charge simulator.

IV. RESULTS

A. Study of dust

The density of accumulated dust was determined to have an average value of 2.59 gr/cm^3. The density per surface area was also determined to be 1.177, 1.238, and 2.326 gr/cm^2 for the monocrystalline, polycrystalline, and amorphous, respectively.

The dust was analyzed with the LS particle size measurement system (Laser diffraction technology), which determined the distributions of the numerical fractions, surface area, and volume as a function of the particle size (diameter of particle). It is important to note that the fractions are not absolute values, but are relative to the totals in each case. The corresponding percentages are presented in Figures 3, 4, and 5. Figure 3 shows the relative distribution of the number of particles and it is possible to appreciate the most significant ranks in sizes. The size of the particles' diameter measures between 0.4 μm and does not reach 400 μm (356 μm to be precise). The system is capable of measuring particle sizes from 0.4 μm up to 1000 μm, which means that the lower limit borders the range of dust found in this study, but the upper limit is well within the system's capable range. The distribution of the fractions of the surface area of the particles is presented in Figure 4. There are two maxims values, the greater near 0.829 μm and the other at 13.61 μm. Finally, Figure 5 presents the distribution of the fraction of particles per volume. In this case, particles that have a diameter around 19.76 μm have major influence on the total volume.

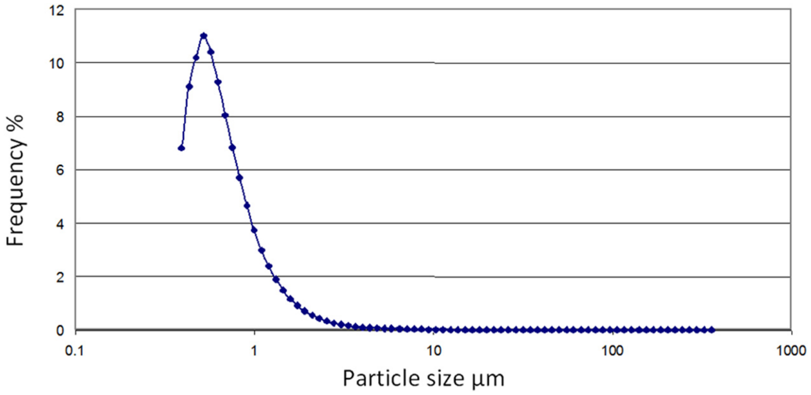

FIG. 3. Number of particles distribution.

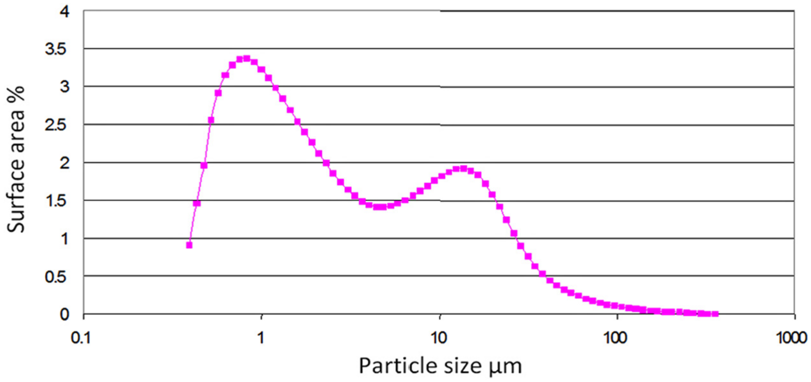

FIG. 4. Distribution of the area of the particles.

B. Morphology of the dust

Photographs of the dust are showing in Figures 6 and 7 with 20× and 40× magnification, respectively. By examining these photos can be conclude that the dust has various forms, but in general, the dominant form is spherical. Also, the dust particles have distinct transmittance indices; some are completely opaque, while others have a specific degree of transparency. The principal components, in order of importance, of the dust collected are clay, sand, soot, mushrooms, spores, and vegetable fibers. These conclusions were determined by experts in materials, agronomy, and chemistry.

C. Maximum power (MP)

The three photovoltaic modules were left to collect dust for long periods of time (around 20 days), such that the maximum power performance could be evaluated with naturally formed dust deposits. The modules were cleaned at noon (when the solar radiation varies the least) and the quantity of dust deposits was measured. Monitoring and data acquisition were continuous between samples.

Figure 8 shows the electrical performance of the maximum power of the amorphous module during a day in which it was cleaned. There is a jump in power at 12:30 h, after the cleaning was made. At the moment of increased power, the solar radiation value did not change significantly; therefore, the change in power is almost solely due to the removal of dust. The quantity of power measured just before 12:30 h was 20.13 W corresponding to the dusty conditions, the next data after the cleaning were 23.46 W. The difference between readings is an increase in power of 14% (including correction for change of temperature and/or solar radiation).

A graph of variations of MP and direct solar radiation during a test day are showing in Figure 9 for monocrystalline module. The increase of value of MP due to cleaning surface is

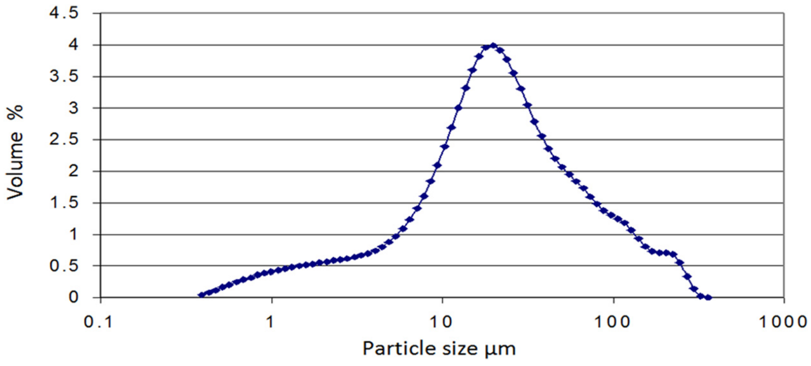

FIG. 5. Distribution of the volume of the particles.

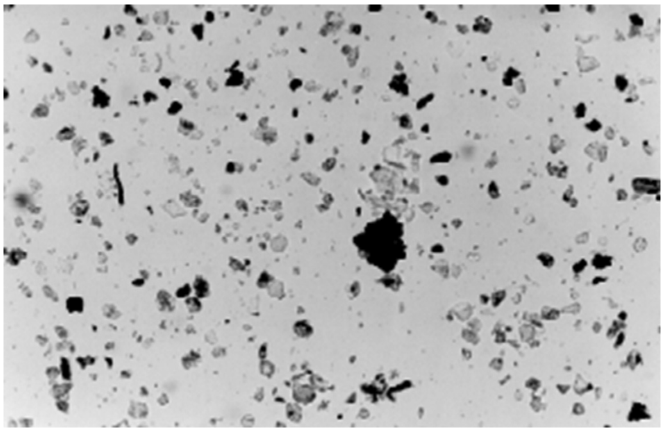

FIG. 6. Photograph of collected dust magnified 20×.

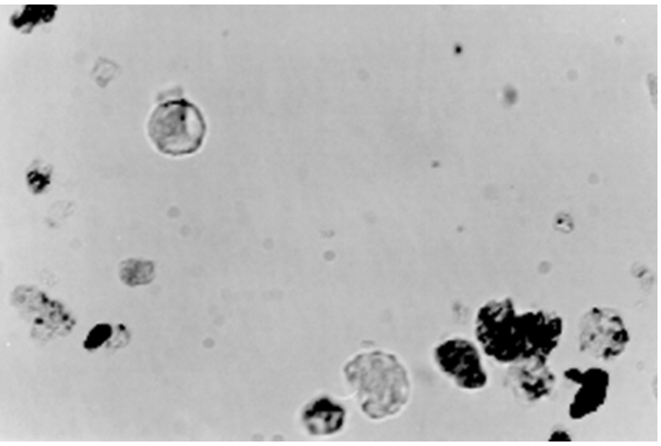

FIG. 7. Photograph of collected dust magnified 40×.

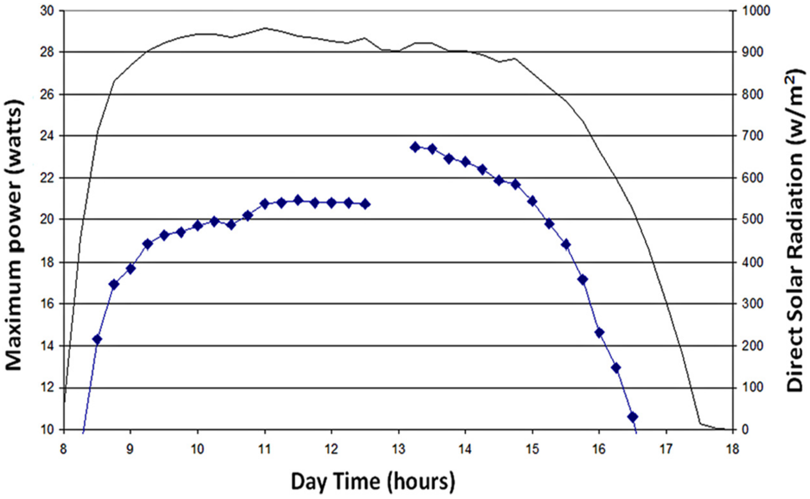

FIG. 8. Graph of solar radiation and the maximum power for the amorphous silicon module.

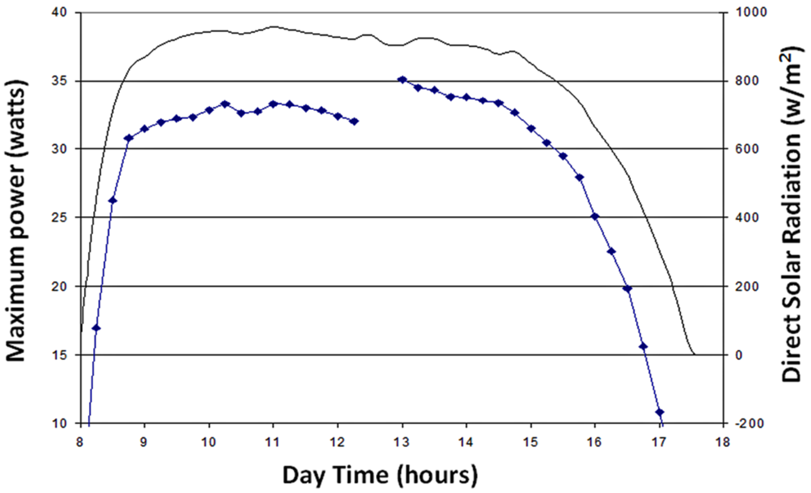

FIG. 9. Graph of solar radiation and the maximum power for the monocrystalline silicon module.

evident but a little lower than amorphous module. In this case, the power prior to cleaning was 32.1 W, while after the module was cleaned, MP changed to 35.1 W, which is an increase in power of 8.5%. Finally, Figure 10 shows the electrical performance of maximum power for the polycrystalline photovoltaic module. Here, the increase in power is of 5.2%.

After modeling the performance of the modules, a mathematical correlation is proposed that can be utilized in the calculations of photovoltaic systems,

$$P_{Max} = aR^{b}T_{Mod}^{c}, \tag{1}$$

where P_{Max} is the maximum power of the module, **R** is the solar radiation incident to the normal plane of the surface of the modules, and $\mathbf{T_{Mod}}$ is the temperature of the module. In which **a** is a factor that multiplies the radiation and temperature, **b** is the exponent of radiation, and **c** is the exponent to the temperature.

In previously experimental study, Espinoza[8] used a similar mathematical expression to fix data for the same array of modules only for the temperature effect. That model was validated for 20–85 °C and for one sun. The values of constants obtained by Espinoza are presented in Table I.

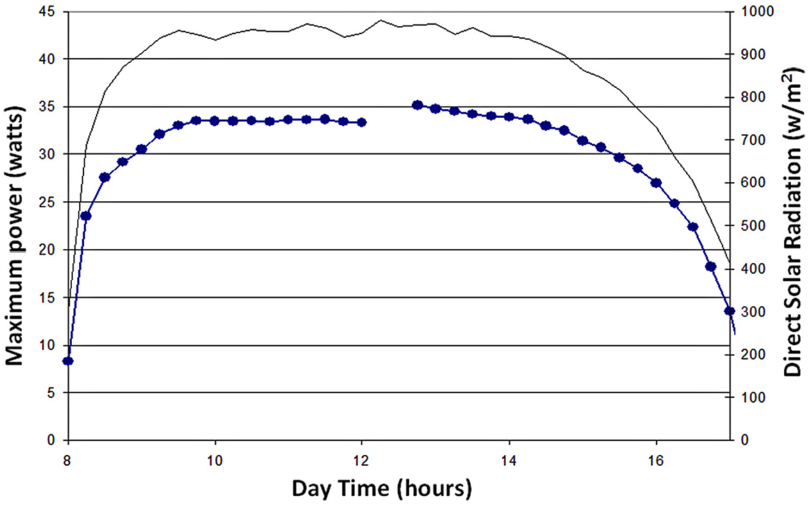

FIG. 10. Graph of the solar radiation and the potential maximum for the polycrystalline silicon module.

TABLE I. Values for the constants reported by Espinoza (Ref. 8).

Constants	Amorphous	Polycrystalline	Monocrystalline
a	0.066	0.28159	0.2822
b	0.9766	1.022	0.939
c	−0.18978	−0.52089	−0.4029

The exponent of **R**, the constant **b**, is approximately one, which means that the solar radiation is directly proportional to the maximum power. In contrast, the constant **c** (exponent of the temperature) has a negative value, which indicates an increase in temperature reduces the power; this agrees with major studies reported in the literature.[9,10] Finally, the constant **a** is related to the characteristics of each solar module manufacturing.

For the purpose of this work, **b** was considered a fixed value of one ($\mathbf{b} = 1$), the value of the constant c was calculated for every module under clean conditions, and the value of the constant **a** was left open (floating), with the assumption that this coefficient will include the effects due to dust and could quantitatively represent the effects on the power.

Five cleaning events were analyzed in around 80-days-long experiment, with 15 days between each taking samples. Due we did not control the quantity of deposited dust, the value of parameter **a** might change but always the value will decrease. We calculated how to change the parameter **a** between dirty and cleaning modules. A resume for these experiments is showing in Table II, where the change of parameter **a** is presented in percent.

The average change of parameter **a** in monocrystalline module was 4.74%, it was the lower value of change for three modules. The polycrystalline module was affected in 4.94% and 10.42% for amorphous module. Both mono and poly modules showed almost the same behavior with a maximum of around 6% and minimum of 4%, in contrast, amorphous module had a maximum of around 12% and minimum of 8%. These results are consistent with the amount of dust density per surface area obtained for each module (1.177, 1.238, and 2.326 gr/cm^2 for mono, poly, and amorphous, respectively).

V. CONCLUSIONS

A. Characterization of dust

There exists a distribution in the size of the dust particles deposited naturally on the photovoltaic modules, which range goes from 0.4 to 400 μm (356 μm is the precise value). That is to say, particles larger than 400 μm were not encountered. The most numerous particles, 11% of the total, has a diameter of 52 μm. The particles that present the largest fraction of the total volume, which have the greatest impact in causing shadows, have a diameter around of 19.76 μm.

TABLE II. Percentage of change of the parameter **a** for five cleaning events.

Test Number	Monocrystalline	Polycrystalline	Amorphous
1	4.3	4	10.6
2	4.1	4.5	11.7
3	5.1	6.4	8.1
4	3.9	5.4	11.8
5	6.3	4.4	9.9
Max.	6.3	6.4	11.8
Min.	3.9	4	8.1
Average	4.74	4.94	10.42

The microscopic study of the dust recollected from modules shows that not all the particles are completely opaque. In fact, a significant portion (studies to determine the statistical fraction has not been done) of the observed particles have certain grade of transmittance. Further studies should include transmittance factors. The morphology of the particles of dust present irregular forms though tends to be spherical.

The modules demonstrate the distinct capacities of retaining dust, the amorphous module tending to have the ability to retain twice as much dust as the monocrystalline and polycrystalline modules. This can be explained by the material used to cover the modules. While the amorphous possesses an undulating plastic cover, the monocrystalline and polycrystalline modules have a glass cover. Solar panels with plastic coverings, therefore, require cleaning maintenance more frequently.

This study was performed in Hermosillo, Sonora, a dry area particularly susceptible to the affects of dust. The size and form of dust particles are unknown for different regions and further studies are recommended for various environments.

B. Maximum power

It is evident that the maximum electrical power is increased when the modules are cleaned. With the goal of isolating the effects due to dust from other possible influences as temperature, a mathematical model (1) of maximum power was utilized and proved to be very consistent (Espinoza[8]). This model involves the effects due to temperature and radiation, leaving the linear effects (as is assumed to be the effect of dust) to the coefficients of the independent variables. Utilizing the model mentioned as a base, the amorphous module was affected by dust no less than 8% and as great as 13%. In the cases of the monocrystalline and polycrystalline modules, the reduction of maximum power had values between 4% and 7%.

It should be kept in mind that the operating conditions for the three modules were all the same: all placed on a thermal-mechanic sun tracker, all left the same time without cleaning, and all operated under the same atmospheric conditions. Hence, we can conclude that the dust naturally deposited is greater on modules with plastic coverings than modules with glass sheets. The density of dust ranging from 1.4 to 2.3 $\mathrm{gr/m^2}$ had a reduction of electrical power in ratio 2:1. This relation confirms the assumption that dust affects the maximum electrical potential linearly.

With the goal of better understanding the dust effect on the photovoltaic modules, we suggest for further works to study in depth the hypothesis the factors not presented in this study such as: the particles transmittance, the formations of groups of particles which contrasts monolayer hypothesis would be not correct (as some author suggest), and finally the grade of saturation of dust on the covered surfaces as a result of the interaction between particles and sheets materials.

ACKNOWLEDGMENTS

The authors want to thank the contribution of Osvaldo Espinoza and Rafael Yari Cabanillas to the realization of this work.

[1] M. Mani and R. Pillai, Renewable Sustainable Energy Rev. **14**, 3124 (2010).
[2] A. Y. Al-Hasan and A. A. Ghnoeim, Int. J. Sustainable Energy **24**, 187 (2005).
[3] R. E. Cabanillas, H. Munguia, and O. Espinoza, "Evaluación del efecto de altas temperaturas en la eficiencia eléctrica de módulos fotovoltaicos comerciales de tres tipos (amorfo, policristalino y monocristalino)," in XXV National Solar Energy Congress, Asociación Nacional de Energía Solar (ANES), San Luis Potosí, México, 2001.
[4] A. Y. Al-Hasan, Sol. Energy **63**, 323 (1998).
[5] N. M. Nahar and J. P. Gupta, Sol. Wind Technol. **7**, 237 (1990).
[6] J. I. Acedo, "Efecto del polvo sobre la eficiencia eléctrica de módulos fotovoltaicos de silicio," B.S. thesis, Universidad de Sonora, 2002.
[7] See https://www.beckmancoulter.com for manufacturer and product.
[8] O. Espinoza, "Efecto de altas temperaturas sobre la eficiencia eléctrica de módulos fotovoltaicos de silicio," B.S. thesis, Universidad de Sonora, 2001.
[9] K. Bücher, Sol. Energy Mater. Sol. Cells **47**, 85 (1997).
[10] E. Skoplakia and J. A. Palyvos, Sol. Energy **83**, 614 (2009).