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Influence of Dust Deposition on the Electrical Parameters of Silicon-Based Solar Panels Installed in Senegal (Dakar Region)

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Abstract

In recent years, photovoltaic (PV) modules are widely used in many applications around the world. However, this renewable energy is plagued by dust, airborne particles, humidity, and high ambient temperatures. This paper studies the effect of dust soiling on silicon-based photovoltaic panel performance in a mini-solar power plant located in Dakar (Senegal, 14˚42'N latitude, 17˚28'W longitude). Results of the current-voltage (I - V) characteristics of photovoltaic panels tested under real conditions. We modeled a silicon-based PV cell in a dusty environment as a stack of thin layers of dust, glass and silicon. The silicon layer is modeled as a P-N junction. The study performed under standard laboratory conditions with input data of irradiation at 1000 W/m^2, cell temperature at 25˚C and solar spectrum with Air Mass (AM) at 1.5 for the monocrystalline silicon PV cell (m-Si). The analysis with an ellipsometer of dust samples collected on photovoltaic panels allowed to obtain the refraction indices (real and imaginary) of these particles which will complete the input parameters of the model. Results show that for a photon flux arriving on dust layer of 70 μm (corresponding to dust deposit of 3.3 g/m^2) deposited on silicon-based PV cells, short circuit current decreases from 54 mA (for a clean cell) to 26 mA. Also, conversion efficiency decreases by 50% compared to clean cell and the cell fill factor decreases by 76% - 50% compared to reference PV cell.

Keywords

Dust Deposition, PV Cell, Fill Factor, Modeling, Ellipsometer

1. Introduction

The rapid growth of photovoltaic technologies in the world is very important and contributed to global electricity generation [1] [2]. Research and development in the field of solar energy continue to focus primarily on optimizing the efficiency of PV cells. With 3.000 hours of sunshine per year and global irradiation of 5.8 kWh/m^2/day, Senegal has a significant potential for the development of photovoltaic power generation [3] [4] [5]. Solar production is affected by several factors such as local environment, weather conditions, PV panel tilt angle, dust accumulated on PV cells, etc. [1] [2]. Among these different factors, deposition of dust on PV cell surfaces is a crucial element that affects their performances. In fact, after their manufacture, solar panels are installed and exposed in open air for electricity generation. Thus, the accumulation of dust on their surface gives rise to the thin layer. Thus, the layer with some thickness can mask exposure to sun and absorb some incident radiation beam. This led to a significant decrease in the electrical parameters [6] [7]. In addition, solar production is also affected by several factors such as local environment, weather conditions, PV panel tilt angle, dust accumulated on PV cells, etc. [8] [9] [10] [11]. Among these different factors, deposition of dust on PV cell surfaces is a crucial element to study. It is a natural phenomenon and depends on several parameters such as local environment and meteorological parameters [12] [13]. Senegal is close to Sahara Desert and this region is among the largest sources of dust in the world [14]. According to Paudyal and Shakya [15], decrease in electricity production due to dust deposits was 3.16% in one day, reached 10.41% in ten days and finally 15.74% in one month. Thus, Kaldellis and Kapsali [16] and Moehlecke [17] showed that solar energy production decreases significantly in presence of dust. For example, Chanchangi *et al.* [18] used a solar simulator and studied the effect of accumulation of 13 different samples (ashes, bird droppings, carpet dust, cement, dust, etc.) on the performance of PV modules. Afterwards, they noted a decrease of about 98% in short circuit current. Similarly, Adıgüzel *et al.* [19] found 15 g of dust on crystalline silicon modules, power loss of 62%. Moreover, Hachicha *et al.* (2019) [20] collected dust of different sizes (from 1.61 to 38.40 μm) and various shapes. They concluded that the yield decreases by 1.7% per g/m^2 of accumulated dust. In addition, Jiang and Sun [21] presented monocrystalline silicon (mc-Si), polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) technologies. Their results showed 0% - 26% yield reduction for dust deposits increasing from 0 to 22 g/m^2. In Senegal, Ndiaye *et al.* [6] exposed PV panels to natural climatic factors for one year and found maximum power decrease of 18% - 78% for polycrystalline and monocrystalline modules, respectively. Said and Walwil [22] noted an average reduction in short circuit current of about 13% after 5 weeks of exposure. In fact, several studies on factors affecting photovoltaic energy have been carried out worldwide [23], in Africa and particularly in Senegal. However, modeling studies focusing on interaction of solar radiation with dust deposited on surfaces of these PV cells are still missing. Therefore, a

comparative approach of two PV cells has been adopted in this work to study the influence of dust deposits on operating characteristics of PV cells. In addition, research and development in the field of solar energy continue to focus primarily on optimizing the efficiency of PV cells. This paper aims to contribute the improvement of performance of PV cells in Senegal. We study losses of short circuit current, power output, conversion efficiency and fill factor of PV cells as a function of dust deposit on their surfaces.

The paper is divided into three parts. The first part presents methodology (modeling). Then, the second part presents the results of simulations resulting from modeling of the losses of electrical parameters of silicon-based solar cell in presence of dust deposit on the surface. Finally, the last part presents the conclusion.

2. Methods

The monocrystalline silicon cell installed in a dusty environment is modeled as a stack of thin layers (dust/glass/silicon) as shown in **Figure 1**. This allows to evaluate the electrical losses of solar cells in presence of dust on the surface of PV modules. Reflection and transmission coefficients at the interface of these layers obtained from refractive indices of the dust. Thus, the dust refraction is obtained thanks to an ellipsometer that analyzes collected dust samples. Also, the global reflectance of multilayer system obtained from the Fresnel reflection and transmission coefficients. Thus, the refraction indices and global reflectances of the different layers will be used as input data for the model. The influence of dust on the energy production of silicon-based solar cell has studied. Silicon layer is considered as an N-P junction structure as shown in **Figure 2**. This model used to determine the current densities, various cell characteristics such as short-circuit current, open circuit voltage, power output, conversion efficiency and form factor of the PV cell in the presence of dust deposition on the PV surface in all N, P and space charge area (SCA) zones of the solar cell. When surface of cell is illuminated by flow of light, the cell creates charge carriers such as electrons and holes. Electron-hole pairs created in the space charge zone of P-N junction are immediately separated by a electric field in this region and carried
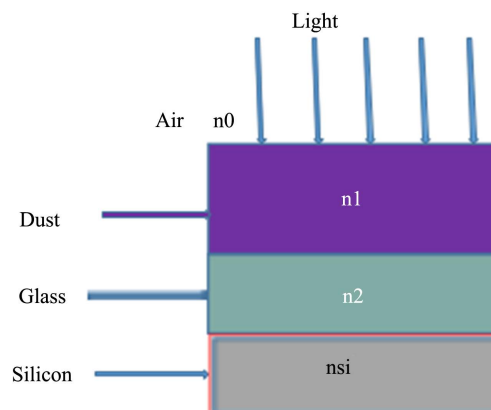

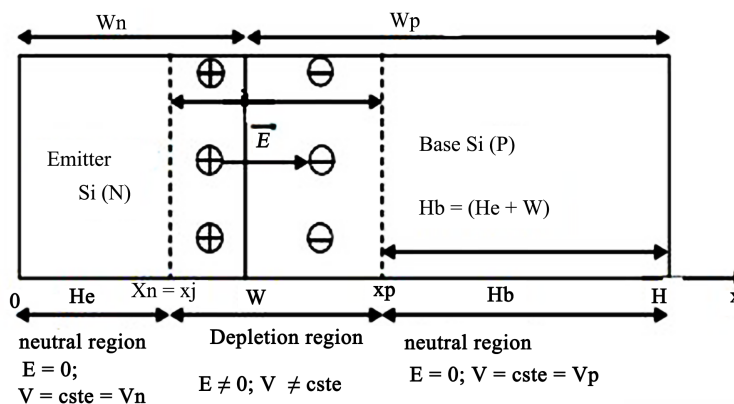**Figure 1.** Stacting of dust/glass/silicon.

Figure 2. Dimensions of Si(N)/Si(P) silicon-based solar cell.

into. They carried the neutral zones on either side of the junction. If the device is insulated, a potential difference appears across the junction and if it is connected to an external electric charge, free electrons must pass through the charge to recombine with positive holes; thus, current can be generated from the cells under illumination [24].

Thus, to study the influence of dust on energy production of silicon-based solar cell, the silicon layer considered as an N-P junction structure as shown in **Figure 2**. It allows to study the influence of dust on energy production of silicon-based solar cell.

In our study, the surface transport of minority carriers and consequently the surface current is neglected. The continuity equation allows to determine, at any point and at any time, the concentration of carriers in a semiconductor. When light illuminates the surface of the emitter with certain wavelength λ, there is an electron-hole pair generation whose generation rate $G(\lambda)$ is expressed by Equation (1) [24] [25]. This model developed by Mahfoud [26].

$$G(\lambda) = \alpha(\lambda) \cdot F(\lambda) \cdot \left[1 - R(\lambda) \right] \cdot \exp(-\alpha x) \tag{1}$$

$F(\lambda)$: Spectral flux of incident photons,

$\alpha(\lambda)$: Absorption coefficient of the material,

$R(\lambda)$: Reflection coefficient at surface of the material.

However, the pairs photogenerated carriers do not remain static and their continuity equation is written [27]:

$$D \cdot \frac{\partial^2 \delta(x)}{\partial x^2} + G(\lambda) - \frac{\delta(x)}{\tau} = 0 \tag{2}$$

D: Diffusion coefficient of minority carriers,

$\delta(x)$: Excess minority carrier's density,

τ: lifetime of electrons.

2.1. Density of Excess Minority Holders in the Base

Minority charge carriers generated (electrons) in P-type base of the photopile, under effect of illumination with monochromatic light, are electrons of charge

$-q$. Indeed, density of these generated carriers in the base is determined from continuity equation. Thus, when we consider phenomena of generation, recombination and diffusion of excess minority carriers in the base, this equation is written in a static regime [27]:

$$D_n \cdot \frac{d^2 \left(n_p - n_{p0} \right)}{dx^2} + G(\lambda) - \frac{n_p - n_{p0}}{\tau_n} = 0 \qquad (3)$$

$n_p - n_{p0} = \delta(x)$: density of the electrons generated in the base;

n_{p0}: density of electrons generated at equilibrium;

D_n: minority carriers' diffusion of electrons in base and n: electrons in base.

Indeed, this continuity equation admits for general solution as:

$$n_p - n_{p0} = A \cosh\left(\frac{x}{L_n} \right) + B \sinh\left(\frac{x}{L_n} \right) - \alpha \times F \times (1 - R) \frac{\tau_n}{\alpha^2 \times L_n^2 - 1} \exp(-\alpha x) \quad (4)$$

where L_n is the minority carriers diffusion length in the base and the coefficients A and C are determined by the following boundary conditions:

$$n_p - n_{p0} = 0 \qquad (5)$$

Thus, density of minority carriers is as follows [28]:

Boundary conditions:

- With $x = H_e + w$ and $x = H$, we have:

$$S_n \times (n_p - n_{p0}) = \frac{-D_n \times d(n_p - n_{p0})}{dx} \qquad (6)$$

$$
\begin{aligned}
n_p - n_{p0} = {} & \frac{\alpha \times F (1 - R) \times \tau_n}{\alpha^2 \times L_n^2 - 1} \times e^{-\alpha(H_e + w)} \times \Bigg[\cosh \frac{x - H_e - w}{L_n} - e^{-\alpha(x - H_e - w)} \\
& - \frac{\frac{S_n L_n}{D_n} \left(\cosh \frac{H_b}{L_n} - \exp(-\alpha H_b) \right) + \sinh \frac{H_b}{L_n} + \alpha L_n \exp(-\alpha H_b)}{\frac{S_n L_n}{D_n} \times \sinh \frac{H_b}{L_n} + \cosh \frac{H_b}{L_n}} \\
& \times \sinh \frac{x - H_e - w}{L_n} \Bigg]
\end{aligned} \qquad (7)
$$

τ_n: lifetime expectancy in the base,

w: width of the PN and S_n junction: recombination speed on the back surface,

H_e et H_b: width of the transmitter (P) and the base with $H_b = H - (H_e + W)$,

D_n: distribution ratio of excess minority shareholders.

In the issuer, the charge carriers obey the following continuity equation:

$$D_p \cdot \frac{d^2 \left(p_n - p_{n0} \right)}{dx^2} + G(\lambda) - \frac{p_n - p_{n0}}{\tau_p} = 0 \qquad (8)$$

$P_n - P_{n0}$: density of excess minority carriers and P_{n0}: density or concentration of excess minority carriers at thermodynamic equilibrium;

τ_p: lifetime of excess minority shareholders.

- Boundary conditions below, the equations below can be solved:
- At the junction ($x = 0$); the rear side ($x = H_e$) and $P_n - P_{n0} = 0$

$$\frac{D_p \times \mathrm{d}\left(P_n - P_{n0}\right)}{\mathrm{d}x} = S_p\left(P_n - P_{n0}\right) \tag{9}$$

$$p_n - p_{no} = \frac{\alpha \times F\left(1-R\right) \times \tau_p}{\alpha^2 \times L_p^2 - 1}$$

$$\times \left[\frac{\left(\dfrac{S_p L_p}{D_p} + \alpha \times L_p\right)\sinh\dfrac{H_e - x}{L_n} + \left(\dfrac{S_p L_p}{D_p}\sinh\dfrac{x}{L_p} + \cosh\dfrac{x}{L_p}\right)\exp\left(-\alpha H_e\right)}{\dfrac{S_p L_p}{D_p}\times\sinh\dfrac{H_e}{L_p} + \cosh\dfrac{H_e}{L_p}} - \mathrm{e}^{-\alpha x}\right] \tag{10}$$

S_p: front surface recombination velocities and D_p: hole diffusion coefficient ; L_p: hole diffusion length.

2.2. Calculation of the Density of the Photocurrent in the Base

In PN junction cell, photocurrent generated by charge carriers (electrons) is written [29].

$$I_{\mathrm{ph}} = q \cdot A \times \left(\frac{\partial\left(n_p - n_{p0}\right)}{\partial x}\right)_{x = H_e + w} \tag{11}$$

q is the electron elementary charge.

A: illuminated surface of cell and the corresponding photocurrent density is:

$$J_{\mathrm{ph}} = \frac{I_{\mathrm{ph}}}{A} = q \times D_n \times \left(\frac{\partial\left(n_p - n_{p0}\right)}{\partial x}\right)_{x = H_e + w} \tag{12}$$

$$J_n = \frac{q \cdot F\left(1-R\right) \cdot \alpha L_n}{\alpha^2 \cdot L_n^2 - 1} \times \mathrm{e}^{-\alpha\left(H_e + w\right)} \tag{13}$$

2.3. Calculation of Density of the Photo-Current in the Emitter

When we use the Equation (14), we found the photocurrent density in the emitter by using the Equation (15):

$$J_{\mathrm{ph}} = \frac{I_{\mathrm{ph}}}{A} = q \times D_p \times \left(\frac{\partial\left(n_p - n_{p0}\right)}{\partial x}\right)_{x = 0} \tag{14}$$

$$J_p = \frac{q \times F\left(1-R\right) \times \alpha L_p}{\alpha^2 \times L_n^2 - 1}$$

$$\times \left[\frac{\left(\dfrac{S_p L_p}{D_p} + \alpha \times L_p\right) - \dfrac{S_p L_p}{D_p}\cosh\dfrac{x}{L_n} + \left(\dfrac{S_p L_p}{D_p}\cosh\dfrac{x}{L_p} + \sinh\dfrac{x}{L_p}\right)\exp\left(-\alpha H_e\right)}{\dfrac{S_p L_p}{D_p}\times\sinh\dfrac{x_j}{L_p} + \cosh\dfrac{H_e}{L_p}} - \alpha L_p \mathrm{e}^{-\alpha x}\right] \tag{15}$$

2.4. Calculation of the Density of the Photo-Current in the Space Charge Zone (ZCE)

In this zone, photocurrent density is given by [27]:

$$J_{\text{zce}} = q \times F(1-R) \times \exp(-\alpha H_e) \times (1 - e^{-\alpha w}) \tag{16}$$

2.5. Total Photocurent Density

Total photocurrent density is sum of photocurrent densities of three zones (P-N-ZCE) of photopile and is written as follow [30]:

$$J_{\text{ph}} = J_n + J_P + J_{\text{zce}} \tag{17}$$

The photocurrent density over the entire spectrum is obtained by integrating J_{ph} current density over entire range of the solar spectrum used. Thus, J_{tot} is given by:

$$J_{\text{tot}} = \int_{\lambda_{\min}}^{\lambda_{\max}} J_{\text{ph}} \cdot d\lambda \tag{18}$$

All expressions used to calculate open circuit voltage (V_{co}), maximum power (P_m), conversion efficiency (η) obtained from [31].

$$P_m = V_{\max} \times I_{\max} \tag{19}$$

The Fill Factor (FF) and conversion efficiency (η) are expressed below as [32] [33].

$$\text{FF} = \frac{P_m}{V_{\text{co}} \times I_{\text{cc}}}; \eta = \frac{P_m}{P_i} = \frac{\text{FF} \times I_{\text{cc}} \times V_{\text{co}}}{P_i} \tag{20}$$

V_{co}, I_{c}, P_i; respectively, open circuit voltage, short circuit current and incident light power. V_m, I_m and P_m are respectively, voltage, current and maximum power.

3. Results and Discussions

In addition to standard parameters, we need the real and imaginary refractive indices of dust to feed our model. For this purpose, we collected samples of dust deposited on surface of the solar module in Dakar. These samples analyzed by ellipsometry to obtain optical indices of particles deposited in Dakar over a period of one year. Thus, **Figure 3** shows the variation of real (**Figure 3(a)**) and imaginary (**Figure 3(b)**) indices of dust deposited on the PV cell surfaces as a function of wavelength. They will be used as input parameters for the model. Indeed, imaginary refractive indices of the dust collected on the PV cell surfaces over the whole spectrum obtained by the ellipsometer are a bit high compared to the results of Colarco *et al.* [34]. They found mean imaginary aerosol indices above Dakar at shorter wavelengths. This difference in value is explained by the shift in the collection date and the composition of the dust which varies according to the weather and weather conditions. However, the refraction indices found in this study according to the work [35] [36] [37] [38] show the presence of pure minerals and clays in this composition. These confirm that indices provided by the ellipsometer correspond to dust indices of the locality. Moreover, according to work of Veselovskii *et al.* [39], the values of real dust indices of Dakar, Senegal could be between 1.35 to 1.65 and those of the imaginary indices between 0 to 0.02 and these values are quite close to those of the ellipsometer.
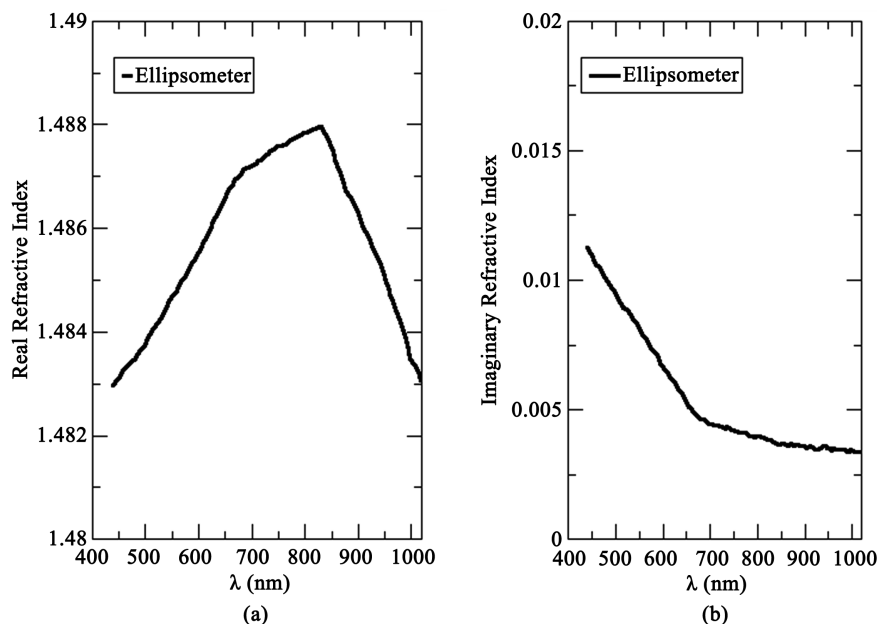
Figure 3. Refractive indices of Saharan dust. Real index of dust particles (a) Imaginary in dex of dust particles (b).

Figure 4 shows the evolution of photocurrent density (J) of the PV cell for different dust layer thicknesses varying from 30, 45, 55 and 70 μm corresponding respectively to dust deposit of 1.4; 2.1; 2.6 and 3.3 g/m². It represents J-V characteristic for different dust deposits on surface of PV cell. Short-circuit current of the cell decreases sharply as size of the dust layer increases. For a clean cell (black curve on **Figure 4**) without dust, short circuit current is 54.44 mA. However, as dust accumulate on the surface of these panels, there is gradual decrease in this short circuit current. For layer of 30, 45, 55 and 70 μm, short circuit current is 33.5, 32.44, 30.54 and 26.45 mA respectively. Indeed, when dust settles on the surface of cell, a large part of the light reflected and the photon flux arriving at the surface reduced. This leads to a decrease in the temperature inside the cell. According to Mahfoud [26], this decrease in short-circuit current is due to decrease in photon flux reaching the cell surface. Consequently, a dust layer 70 μm thick leads to 51% reduction of this current compared to that of the clean cell.

These results were consistent with Chanchangi *et al.* [18]. They showed that short circuit current of PV cells reduced by 46% when bird droppings deposited on PV surfaces. In addition, these figures show that deposition of dust on PV cells slightly reduces open circuit voltage as shown by Mani and Pillai [9]. Other results such as [40] [41] corroborate with our results. Their work showed that dust reduces short circuit current of solar cells. Moreover, according to Klugmann-Radziemska [42], short circuit current depends on irradiation. So, irradiation reaching the cell decreases with the increase of dust deposited on PV cell surface.

Figure 5 shows evolution of power produced by the silicon cell for different layers of dust deposited on cell surface as a function of the supply voltage. Clean
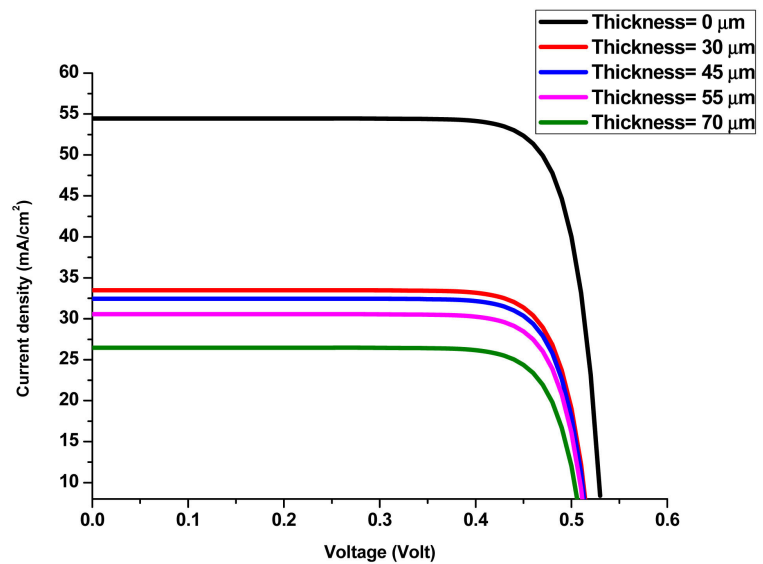
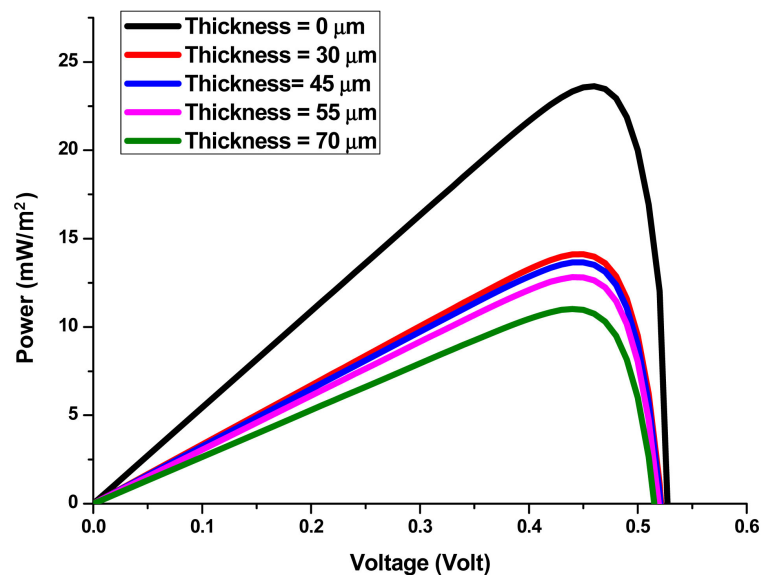**Figure 4.** Current-voltage characteristics of cell for different dust layer thicknesses.

Figure 5. Power-voltage characteristic of cell for different dust layer thicknesses.

cell (dust layer thickness 0 µm corresponds to dust-free cell) whose power output represented by the black curve and the green curve corresponds power output of the room cell when a dust layer of 70 µm (dust deposit corresponding to 3.3 g/m^2) deposited on surface of the PV cell. Indeed, they show a significant decrease from 23.62 mW/m^2 to 11 mW/m^2 for dust layer thicknesses ranging from 0 to 70 µm. Thus, we note a decrease of half of the power produced compared to that of the clean cell. These results confirm those of Majeed *et al.* [43]. Moreover, these curves show that when the thickness of the layer of dust deposited on the cell increases from 30, 45 and 55 µm (corresponding respectively to a dust deposit of 1.4, 2.1 and 2.6 g/m^2), the power output decreases respectively by 14.12, 13.66 and 12.816 mW/m^2.

Figure 6 shows current-voltage characteristics between clean cell (dust layer thickness 0 μm) and room cell (dust layer thickness 70 μm) (black curves) and power-voltage characteristics of the silicon-based photovoltaic cell between clean cell (dust layer thickness 0 μm) and room cell (dust layer thickness 70 μm) (blue curves). Indeed, they show that the maximum power point (PPM) (corresponding to 0.46 mA; 51.36 mW) of the clean cell increases from (0.44 mA; 25.038 mW) to unclean cell of dust deposit corresponding to 3.3 g/m^2. This decrease in production corresponds to a decrease in maximum power from 23.63 to 11.016 mW corresponding to a 53% decrease in production compared to the clean cell. These losses are quite low compared to results of Nimmo and Said [44] who noted 65% decrease. These differences in value could be due to different compositions of the Kuwaiti dust but also to climatic conditions. For variation of dust layer thickness from 0 to 70 μm, power loss of about 12.614 mW observed. Overall, this figure confirms results of Jiang and Lu [40] who showed that deposition of dust on PV cell surfaces decreases output power of the cell. According to Ndiaye *et al.* [6] decrease in cell power is due to the decrease in irradiance. Indeed, the illumination flux is reflected by dust layers.

Figure 7 shows conversion efficiency of silicon cell for different dust layers deposited on cell surface as a function of the size of dust layer. By increasing dust deposit on the cell surface by (30, 45, 55 and 70 μm) corresponding to 1.4, 2.1, 2.6 and 3.3 g/m^2 respectively, the conversion efficiency of PV cell increases from 23% to 11%. When layer of dust 70 μm (corresponding to a deposit of 3.3 g/m^2) deposited on surface of PV cell, conversion efficiency of the cell increases from 23% to 11%. Thus, we can see that half of the cells production is lost due to dust. These results corroborate to Chen et al, Guan *et al.* and Ramli *et al.* [32] [45] [46] They concluded that productivity efficiency of photovoltaic cells decreases when dust accumulates on their surfaces. These studies have shown that decrease in performance is due to reduced absorption of solar energy, as a small fraction of the solar radiation passes through the dust layer and reaches the surface of the PV module. Furthermore, according to Klugmann-Radziemska and Hegazy [42] [47], the decrease in efficiency is due to decrease in light transmission through the glass cover when dust accumulates on PV cell surfaces. According to Ndiaye *et al.* Rao *et al.* [6] [23] the decrease in efficiency could be due to the increase in temperature above the cell caused by the absorption of light by the dust layers.

Figure 8 shows the fill factor of silicon-based cell for different layers of dust deposited on cell surface. Indeed, this parameter provides information on quality of cell. For layer thickness variation from 0 to 70 μm, fill factor decreases from 76% to 50%. This decrease corresponds to 26% compared to clean cell. Thus, this curve confirms degradation caused by dust on surfaces of monocrystalline silicon cells. The reduction of this factor is favored by the increase in temperature on PV cell surface. It is due to absorption of photons and light by dust atoms according to Ahmed *et al.* [48]. The decrease of the fill factor could be due to the
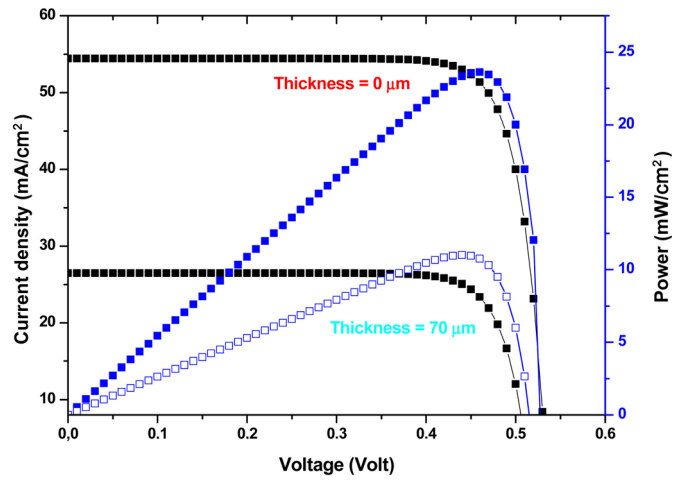
Figure 6. Current-voltage characteristic for clean PV cell (dust layer thickness 0 μm) and room PV cell (dust layer thickness 70 μm) (black curves); Power-voltage characteristic for clean cell (dust layer thickness 0 μm) and room cell (dust layer thickness 70 μm) (blue curves).
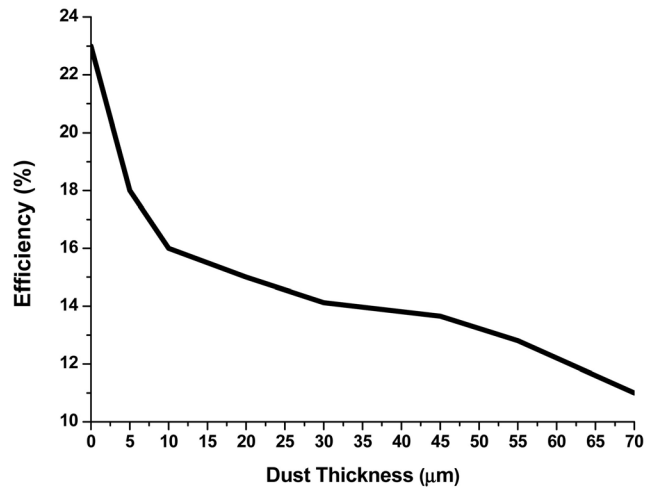

Figure 7. Cell conversion efficiency for different dust layer thicknesses.
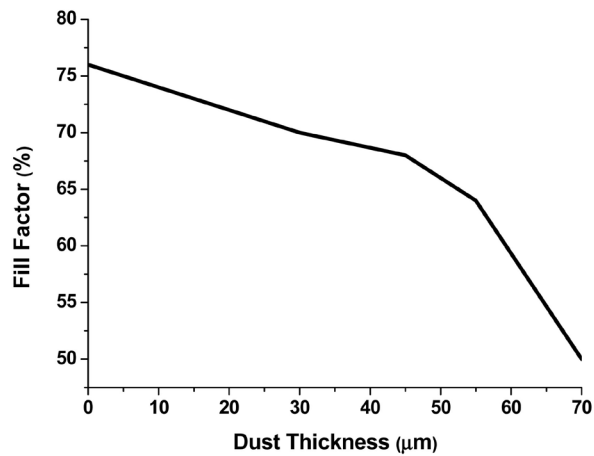

Figure 8. Cell form factor for different dust layer thicknesses.

increase in series resistance of the PV cell when the dust layer increases. Furthermore, the behavior of the curve could be due to the difference in size of dust particles or the structural properties of the collected dust [49] [50].

4. Conclusions

This work evaluated the influence of dust deposition on the electrical performance of silicon-based photovoltaic cells by a model. Thus, the analysis of loss of electrical characteristics as a function of dust is studied. Indeed, it allowed us to evaluate the losses of electrical characteristics such as production efficiency, power output, short-circuit current and fill factor of monocrystalline silicon-based photovoltaic cells as a function of dust deposited on the surface of these solar modules in Dakar, Senegal.

Firstly, this work showed that the deposition of dust on PV cell surfaces does not significantly change open circuit voltage. However, short-circuit current affected by this dust deposit with loss of about 51% for a dust layer of 70 μm (corresponding to dust deposit of 3.3 g/m^2) compared to clean cell current. Moreover, the main conclusion is that a cleaning of the cell should be considered in order to optimize its electrical performance from dust layer thickness of 70 μm (corresponding to dust deposit of 3.3 g/m^2).

However, it would be interesting to extend this work by introducing into this model, the influence of cell temperature but also by comparing it with experimental studies. In addition, the realization of multi-layers of dust and glass on the silicon cell could allow to measure the electrical parameters in real-time. This study also has limitations because type of dust is not specified and dust layers are assumed to be homogeneous. So, it would also make sense to take into account the binding of dust atoms on the surfaces of PV modules.

Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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