Assessing the optoelectronic behavior of soiled silicon photovoltaic cell under harsh environmental conditions*

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In the current study, a monocrystalline Si photovoltaic (PV) cell was modeled using solar cell capacitance simulator (SCAPS) to demonstrate the optoelectronic performance of the cell under harsh environmental conditions. Harsh conditions are simulated in terms of wind speed and temperature fluctuations within the presence of a dust layer. All models are evaluated with respect to a bare model with no dust layer accumulated and operating under standard test conditions (STC). Accordingly, the PV under-test characteristics have been estimated under continuous wind speed and temperature variations. An interesting behavior for the cell operation under relatively high temperatures with an accumulated dust layer was observed. The short circuit current increased by 61.5% with decreasing open-circuit voltage by 47.3%, showing an overall positive trend for the power harvested. Such behavior contradicts the average temperature performance of cells without dust layer accumulation. A detailed justification is illustrated, where the heat transfer rate with dust accumulation highlighted an incremental increase concerning the bare cell by 14.57%.

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Integrating solar cells in various critical applications has recently drawn attention to optimizing solar cells' efficiency for harsh environmental conditions[1-4]. In our case study in Egypt, 2 000 kW·hr/m^2 to 3 000 kW·hr/m^2 is estimated as an annual direct solar radiation[5]. Following such a perfect solar profile, Egypt is considered a good location for photovoltaic (PV) implementation[3,4]. However, the desert nature of the Egyptian land causes impacted the PV system sustainability. Dust accumulation on the PV surface may be considered a significant constraint that impacts the solar cell's performance[6-8]. Additionally, the wind speed effect on the PV surface and the temperature effect also influence the PV performance[9]. In the current investigation, we highlight the scope of dust accumulation as a natural problem due to environmental conditions. Dust accumulation showed an increasing trend during windy days, which can significantly increase PV performance degradation[10]. Wind speed variation changes the dust layer thickness according to the deposition rate, type and size of the dust particles, and location. Alternatively, the increase in the cell operating temperature affects the solar cell performance rapidly in different ways, and the effect when the dust layer is presented differs from that when it is not presented[11].

In previous work implemented in the Greek regions of Chania and Ligourio[12], a simple, coherent theoretical model was introduced to study the impact of varying environmental parameters, including but not limited to wind speed, and temperature, on the solar cell performance. Additionally, the study was extended to include outdoor measurements under the same variable environmental conditions to validate the respective theoretical analysis. Moreover, the study investigated the thermal loss mechanisms applied on a PV panel due to variable wind speed. The results agreed to match the results reported in the previous literature. The work did not consider the dust effect on the PV cell, which significantly influences the PV cell performance and is affected by wind speed and temperature[12].

Another early study carried out at the Solar Test Facility in Doha, Qatar, performed by Benjamin Figgis et al[13]. A pair of outdoor soiling microscopes (OSMs) had a 5 cm×5 cm glass collector surface for each one. Each OSM captures an image every 10 min. Wind speed was measured every 2 min with an elevation of 2 m. The experiment helped to calculate the deposition rate at different wind speeds. The data in this work was beneficial

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in calculating different dust layer thicknesses at different wind speeds.

The current study presents a p-i-n junction model for a solar cell using solar cell capacitance simulator (SCAPS) to study the carrier-transport and optical generation impact of the wind and temperature effect with the presence of a dust layer. The two experiments were discussed in detail at different temperatures and wind speeds. In the case of the temperature effect, the experiment was repeated, once with added dust layer and once without the layer. While utilizing the suggested model, the PV cell parameters have been estimated under continuous variation in wind and temperature, as well as the total output power of the cell under various harsh conditions.

The extracted data from Ref.[13] was utilized as an input to estimate the dust layer casemated thickness in terms of the deposition rate at various wind speeds. The dust layer effective density was calculated using the specific gravity of the dust particles in El-Sherouk City, Egypt (30, 07, 03, N-31, 36, 20, E). The location is where an experiment was at which a set of glass sheets was placed on a horizontal surface. At the same time, dust accumulations were observed for six successive weeks of weekly measurement[6,7]. The dust layer thickness was calculated at six weeks period experiment, different wind speeds, using the specific gravity 1 682 kg·m^{-3}. The overall expected variation in the accumulated dust layer as a function of the wind speed is plotted in Fig.1. The figure shows experimental data from Ref.[13] with the corresponding exponential fitting function.

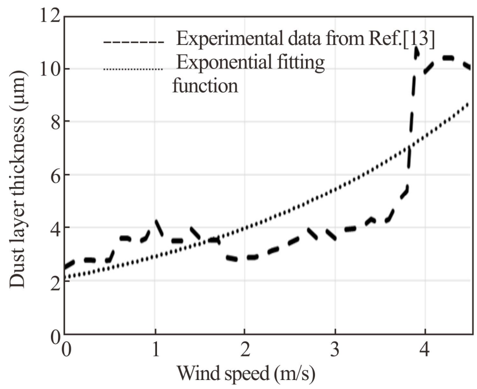

Fig.1 Dust layer thickness variation with different wind speeds

To investigate the temperature effect on a monocrystalline PV cell, the cell was modeled using SCAPS-1D as demonstrated in Fig.2. The cell temperature was tuned within 200—400 K. The SCAPS-1D is a drift-diffusion-based simulation tool. Herein, we utilized it to simulate the solar cell junction *J-V* characteristics[14]. The SCAPS-1D provides the capability of simulation the solar cells as a series cascaded layer, where the operating cell temperature can be tuned per iteration. The same experiment was repeated after adding a 2.517-μm-thick dust layer to the same model (see Fig.3). This layer is added in the direction of the incident irradiance. The thickness of the dust layer was determined based on the resultant dust layer thickness for a six-week experiment at 0 m/s wind speed[6,7].

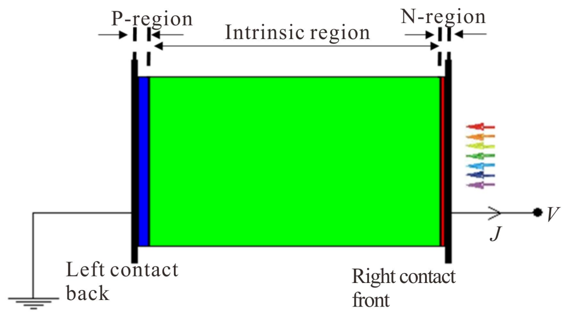

Fig.2 SCAPS model for the monocrystalline PV cell

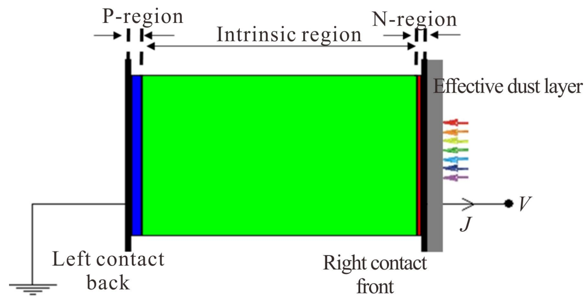

Fig.3 SCAPS model for the monocrystalline PV cell with adding a dust layer at 2.517 μm thickness

For the sake of studying the impact of a dust layer on the front contact of the solar cell, the materials composing the dust sample were clarified by the percentage of presence of each material, as in Refs.[6] and [7]. This data efficiently calculated the equivalent thermal conductivity of the dust layer. From a chemical perspective, the dust layer is a composite of a set of materials, and each has a thermal conductivity of k_{eff}. Herein, the practical medium theory is appropriate to determine the effective thermal impact of the accumulated dust layer. The effective thermal conductivity is given by

$$k_{\mathrm{eff}}=k_{\mathrm{m}}\frac{2\delta_{\mathrm{i}}(k_{\mathrm{i}}-k_{\mathrm{m}})+k_{\mathrm{i}}+2k_{\mathrm{m}}}{k_{\mathrm{i}}+2k_{\mathrm{m}}-\delta_{\mathrm{i}}(k_{\mathrm{i}}-k_{\mathrm{m}})},\qquad(1)$$

where k_{eff} is the effective thermal conductivity, k_{m} is the medium thermal conductivity, k_{i} is the inclusion thermal conductivity, and δ_{i} is the volume fraction of the thermal conductivity.

The wind speed significantly affects the dust deposition rate on the PV cell surface. The experiment showed increases in the dust layer thickness at different wind speeds starting from 0 m/s to 5 m/s. The particles in the experiment location have a specific gravity of 1 682 kg·m^{-3}. The specific gravity of the location was used to know the effective density of the dust. The effective density was used for six weeks (the same period as the experiment in Egypt) to get the dust layer thicknesses at different wind speeds. The dust layer thicknesses were calculated at each 0.1 m/s wind speed. As a result, the efficiency of the PV cell was affected, as demonstrated in Fig.4. The resultant dust layer thickness increased with the increase of the wind speed. This decreased the PV cell's overall efficiency by 71.2% at the end of the experiment, where thickness reached 18.69 μm at a wind speed of 5 m/s.

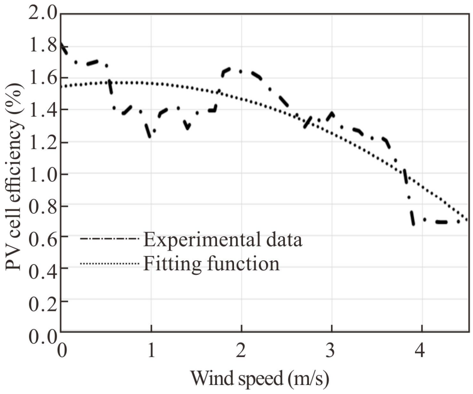

Fig.4 PV cell efficiency degradation while increasing the wind speed

The temperature affects the performance of the solar cell significantly[12]. Two cases are studied in this paper to show the effect of temperature. Firstly, the model in Fig.2 was simulated at different temperatures starting from 200 K to 400 K. Secondly, a 2.517-μm-thick dust layer was added to the same model (see Fig.3). The model was also simulated at temperatures ranging from 200 K to 400 K. The temperature variation results for the bare cell, without the dust layer, were reported in Fig.5. As previously reported in the literature, the output showed a decaying trend with increasing the operating cell temperature. After adding the dust layer, Fig.6 demonstrated an exciting behavior in cell *J-V* curves, varying the cell operating temperature. The results showed an enhanced current against temperature while still decaying voltage with temperature is observed as in the bare case (see Fig.5).

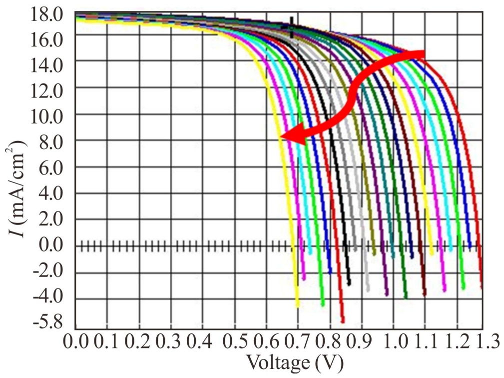

Fig.5 *I-V* curves for the studied temperature experiment without adding the dust layer on a PV cell with an area of 4.8 cm×1.2 cm (The red arrow indicates the increase in temperature)

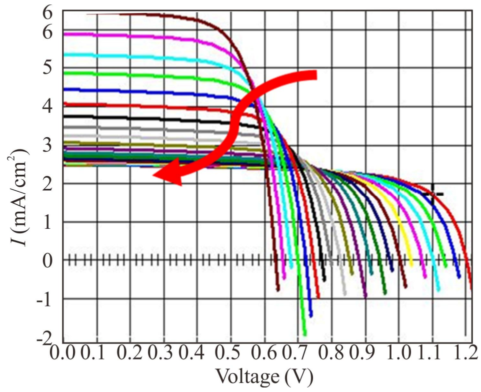

Fig.6 *I-V* curves for the studied temperature experiment with 2.517 μm thickness adding the dust layer on a PV cell with an area of 4.8 cm×1.2 cm (The red arrow indicates the increase in temperature)

The overall results showed a significant effect, especially in the short circuit current I_{sc}. When the model was simulated without a dust layer, the short circuit current I_{sc} increased from 17.46 mA/cm^2 at temperature of 200 K to 17.60 mA/cm^2 at temperature of 260 K. Then it decreased until 17.03 mA/cm^2 at 400 K, with results plotted in Fig.5. In the second step, a dust layer with a thickness of 2.517 μm was added to the model, as shown in Fig.6. Herein, significant variation in short circuit current is recorded. Comparing the two results (Figs.5 and 6), the temperature effect when the dust layer is added differs from that when it is not presented. The dust layer added decreases the temperature effect and unexpectedly increases in I_{sc}. The short circuit current increased from 2.49 mA/cm^2 at temperature of 200 K to 6.47 mA/cm^2 at temperature of 400 K. This means the dust layer enhanced the PV cell performance with the temperature increase. The short circuit current I_{sc} increased by 61.5%.

The efficiency of the PV cell decreased by 47.65% when the PV cell was directly exposed to the sun without a dust layer added. On the other hand, the efficiency increases by 26.24% when the dust layer is added at 2.517 μm. The two results were compared and plotted in Fig.7. Although the efficiency increases when a dust layer is added to the PV cell, the maximum efficiency value reached 2.84 mA/cm^2 at 400 K, while the efficiency decreased when no dust layer was added with the temperature increasing. The minimum efficiency value was 8.02 mA/cm^2 at 400 K, which is still higher than the maximum efficiency value by 64.5%.

The interpretation of the data shown in Figs.5—7 is very significant. To provide such a justification, the heat transfer module in Comsol Multiphysics was utilized to simulate the overall heat transfer for the cell under investigation. Two models were simulated, with and without the dust layer, where the thermal conductivity of the dust layer was previously estimated, using practical medium theory. The results in Fig.8 show the capability of the dust layer to speed up the heat transfer rate to the analysis of the bare cell. Herein, a 14.57 % enhanced rate of heat transfer is observed. However, as mentioned earlier, such an enhanced heat transfer rate does not reflect a natural enhancement in the cell operation as the overall cell efficiency is dramatically reduced due to dust accumulation. The system was simulated thermally to explore the technical and physical justification of the unusual temperature behavior simulated in Figs. 6 and 7.

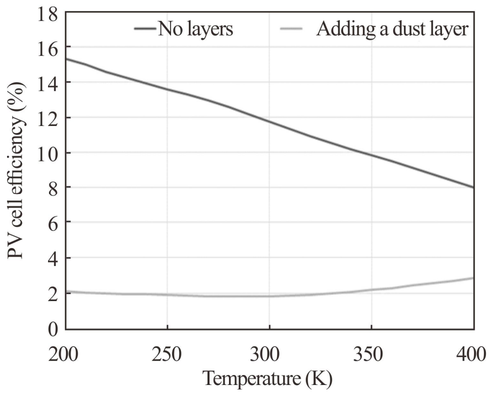

Fig.7 Efficiency performance with increasing temperature in the case of adding a 2.517-μm-thick dust layer

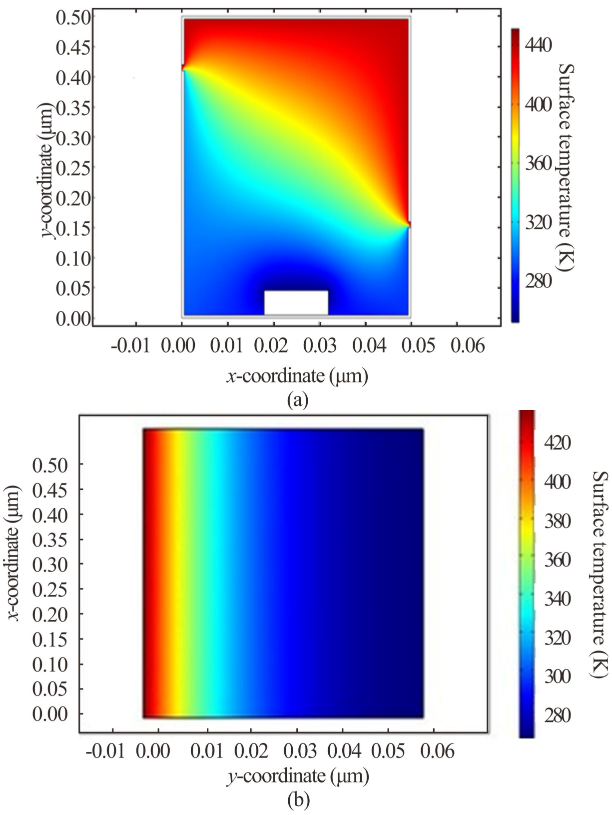

Fig.8 (a) Surface and (b) cross-sectional heat transfer model for a solar cell with a dust layer

In conclusion, the present study identifies the impact of operating solar cells under harsh environmental conditions. The term harsh indicates the operation under accumulated dust and fluctuation in wind speed and temperature. The solar cell's performance is simulated as *J-V* curves and efficiency curves, showing the expected degradation in cell performance due to an increase in wind speed and temperature. The effectiveness of the wind speed showed more than 70% degradation factor, while temperature behavior showed a fascinating increasing trend in efficiency. The unusual temperature response was physically justified with heat transfer models.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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