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Effect of dust accumulation on the transmissivity and performance of photovoltaic modules: a three-dimensional numerical study

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Abstract. The efficiency of photovoltaic modules (PV-Ms) is mainly affected by dust accumulation and variations in solar irradiance. This three-dimensional numerical study, performed using COMSOL Multiphysics based on the finite element method (FEM), investigates the combined influence of these factors on the performance of PV modules. The analysis considers dust densities from 0 to 45 g/m² and irradiance levels between 100 and 900 W/m², with a wind speed of 1 m/s and an ambient temperature of 26°C. The results show that dust deposition slightly decreases the module temperature by about 0.5 % at low irradiance and 1.6 % at high irradiance, leading to small increases in electrical efficiency (EEF) of about 0.06%. However, solar irradiance remains the dominant parameter, significantly increasing the module temperature and reducing the EEF by approximately 13.4% for a clean module and 12.9% for a dust-covered module.

1 Introduction

In recent decades, growth in global population and rapid industrialization have brought about a significant increase in energy consumption. With fossil fuels gradually being exhausted and causing serious environmental damage, the changeover to clean and renewable energy sources has become urgent [1]. Among these sources, PV technology stands out as a promising solution, capable of efficiently transforming sunlight into electricity while reducing carbon footprint. This technology, thanks to the modularity and reliability, is assuming at the present time an important role in the sustainable energy strategy of many countries. The actual output of PV-Ms depends, however, on climatic conditions and the environment in which they work [2]. Among the most important factors external to the plants, the accumulation of dust on the surface of the PV-Ms is one of the main causes of decrease of output. The layer of dust formed reduces considerably the transmission of direct solar radiation to the cells resulting in less generation of power and general efficiency. This effect is specially marked in semi-arid and arid centres, as North Africa and the Middle East, where the solar potential is among the highest in the world [3].

Several studies have examined the impact of dust accumulation on PV-Ms under various environmental conditions. For example, Kayri and Bayar [4] found that clay, limestone, and urban dust significantly reduce PV-M efficiency, with losses increasing over time and reaching up to 78% after six months without cleaning. Elamim et al. [5] observed in

Mohammedia, Morocco, that natural dust accumulation decreases electricity production by about 7–12% and reduces glass transmissivity due to silicon and limestone particles that also retain heat. Fatima et al. [6] reported that non-uniform dust distribution limits incident radiation and power generation, while cleaning modules twice a week can effectively reduce losses to around 7%. Warsama and Selimli [7] showed that higher dust density and smaller particles decrease both energy and exergy efficiencies, whereas larger particles mitigate these effects. Qu et al. [8] demonstrated that increased dust density, irradiance, and tilt angle can together reduce glass transmissivity by nearly half and cause power losses of about 50 %.

A review of the literature shows that the majority of studies on how dust affects PV-Ms are mainly experimental, which restricts our ability to comprehend the underlying mechanisms and make accurate predictions. There are extremely few numerical studies that allow for parametric and in-depth examination. Furthermore, despite the fact that environmental factors like solar irradiance and dust deposition can have a substantial impact on PV-M efficiency, few researches have looked at their combined effects. This study uses COMSOL Multiphysics to create a 3D numerical model based on the FEM in order to fill in these gaps. The objective is to thoroughly and quantitatively evaluate the simultaneous impact of dust and solar irradiance on the thermal and electrical behavior of PV-Ms, thus providing actionable results for the optimization and maintenance of PV-Ms.

2 Methodology

2.1 PV module structure and materials

In this study, a monocrystalline PV-M measuring 1200 × 545 mm was used. Its structure consists of five main layers: a protective Tedlar sheet, a first layer of EVA, monocrystalline silicon PV cells, a second layer of EVA, and, on the surface, a sheet of tempered glass (Fig. 1). These layers provide protection, mechanical stability, and transmission of solar irradiance. The metal frame, which ensures the rigidity of the module, was not included in the thermal analysis because its influence was considered negligible [9]. The numerical simulations are based on the thermophysical characteristics of each layer, which are listed in Table 2.

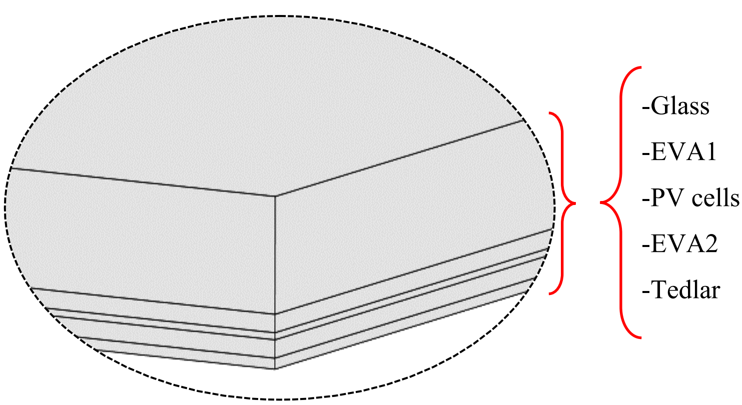

Fig. 1. Schematic representation of the structure of the PV-M studied.

Table 1. Thermophysical data for the layers of the PV-M [10–12].

Material	Thickness (mm)	C (J/kg.K)	k (W/m.K)	ρ (kg/m^3)
Backsheet	0.3	1250	0.14	1200
Glass	3.2	750	1.04	2200

EVA	0.5	2400	0.29	935
Silicon	0.192	703	163	2329.1

2.2 Numerical Simulation Methodology

A computational method based on COMSOL Multiphysics software was used to analyze the PV module's thermal behavior. Internal conduction between the component layers, natural convection with the ambient air, and radiation exchange between the various surfaces are the three basic modes of heat transfer that are included in the established model [13]. Ignoring the spaces between the PV cells, the module is depicted as a homogeneous layered structure made up of five successive levels [14]. It is believed that the temperature of the outside air is uniform [15]. Incident solar radiation is absorbed by every material in the module, and any energy that is not transformed into electricity is transformed into heat [15]. Thermal radiation is simulated by considering that the front face exchanges with the sky and that the rear face emits towards the ground [15]. Due to more limited heat exchange at the rear of the module, the convection coefficient for this face is taken to be half that applied to the front face [16].

2.3 Performance analysis

The EEF of PV-Ms is calculated using the following equation [17]:

$$\eta_{PV} = \eta_{ref} \cdot (1 - \beta_{ref} \cdot (T_c - T_{ref})) \tag{1}$$

Where η_{ref} corresponds to the reference efficiency of the module set at 12%, β_{ref} denotes the temperature coefficient of the PV cell (0.0045%/°C), T_{ref} represents the reference temperature equal to 25°C, and T_c indicates the actual temperature of the cell.

The electrical power delivered by a PV-M can be determined using the following equation [18] :

$$P_{PV} = \eta_{ref} \cdot \tau \cdot \alpha_c \cdot G \cdot A_{PV} \cdot (1 - \beta_{ref} \cdot (T_c - T_{ref})) \tag{2}$$

Where G denotes incident solar irradiance, τ denotes the transmissivity of the glass (0.96), and α denotes the absorptivity of the cells, set at 0.9.

To evaluate the effect of dust, equation (12) [12] relates the degree of soiling to the transmittance of the glass in order to determine the transmission factor.

$$\tau = \tau_0 \cdot [1.01645 - 0.09885 \cdot \ln(J_d + 1.18102)] \tag{3}$$

Where J_d denotes the mass of dust deposited (g/m²), and τ_0 and τ correspond respectively to the transmittance of clean glass and that of dirty glass.

2.4 Mesh independence study

For the PV-M studied, a mesh independence test was conducted to determine the configuration offering the best thermal stability while optimizing numerical performance. The analysis evaluated the influence of varying the number of mesh elements on the temperature of the PV cells and on the calculation time, rather than limiting itself to mesh density alone. The simulations were performed under constant irradiance (900 W/m²) and ambient temperature (26°C) conditions. The results presented in Fig. 2 indicate that the calculation time varies greatly depending on the mesh, while the thermal accuracy remains stable beyond a certain level of refinement. Thus, an Extra Fine mesh (Fig. 3) was chosen for the following simulations, ensuring a balance between accuracy and calculation time.

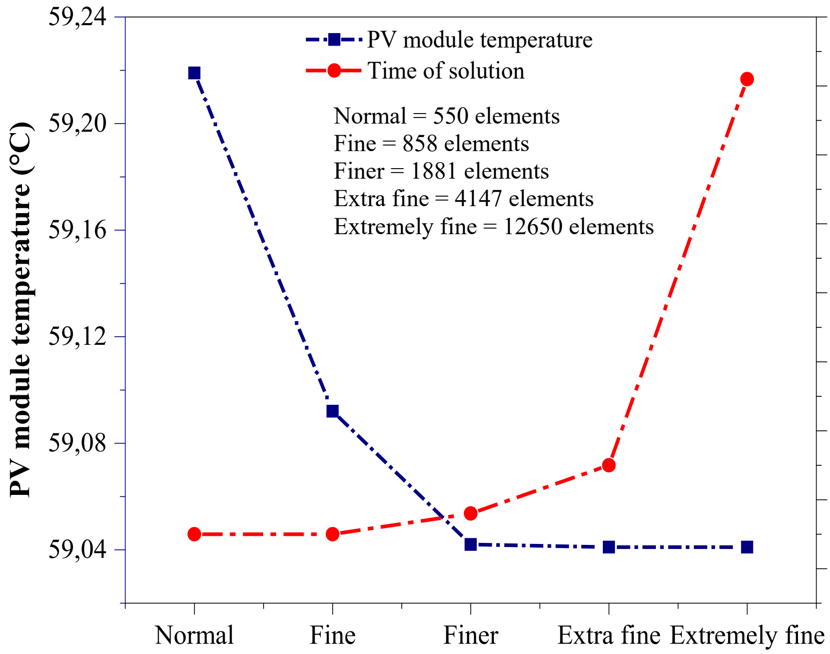

Fig. 2. Impact of mesh density on PV cell temperature and simulation time.

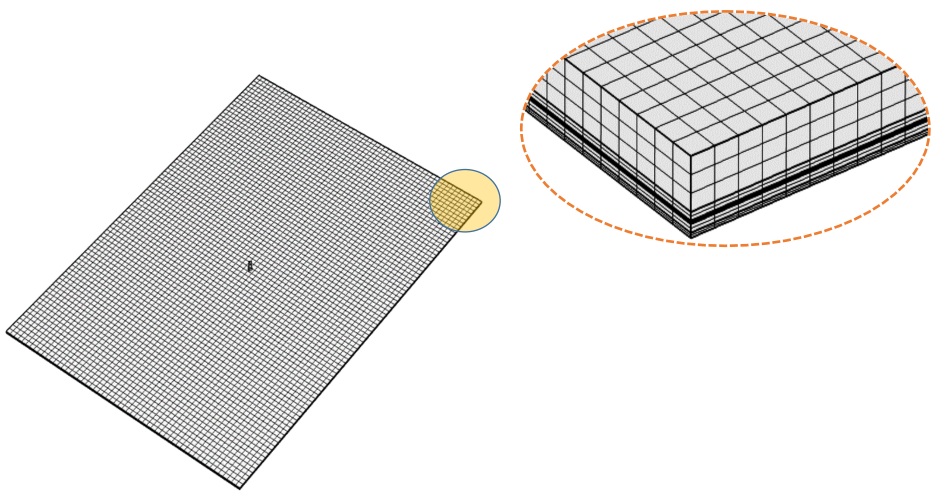

Fig. 3. Mesh configuration studied for the PV-M.

2.5 Validation of numerical model

The reliability of the numerical model is confirmed by its validation using experimental data. The model used in this study has already been validated using experimental data in article [12], showing excellent agreement between numerical and experimental results.

3 Results and discussion

The object of the present work is to study the influence of the dust, as well as of the joint influence of the dust plus the solar radiation, on the PV-Ms. In order to reproduce there being different real working conditions, the solar radiation was produced varying between 100 to 900 W/m^2, while the ambient temperature and wind speed were kept constant at 26°C and at 1 m/s respectively. The dust deposited on the module surface varied between 0 to 45 g/m2. The analysis covered variations in electrical power, module temperature and EEF of the PV-M.

Fig. 4 shows that the temperature of the PV-M gradually decreases as the amount of dust deposited on its surface increases. This decrease, of approximately 0.967 °C when the dust mass increases from 0 to 45 g/m², is explained by the reduction in absorbed solar radiation, with the dust acting as a partial barrier. This behavior highlights a thermo-optical effect whereby the dust layer alters the energy balance between the module's thermal absorption and emission. However, although this decrease in temperature leads to a slight improvement in EEF (0.053 %), the attenuation of the incident light flux limits the overall performance gain. Similar trends have been observed by Zhao et al. [19] and El Alami et al. [12], confirming that dust, depending on its composition and particle size, can both reduce module heating and slow down PV conversion.

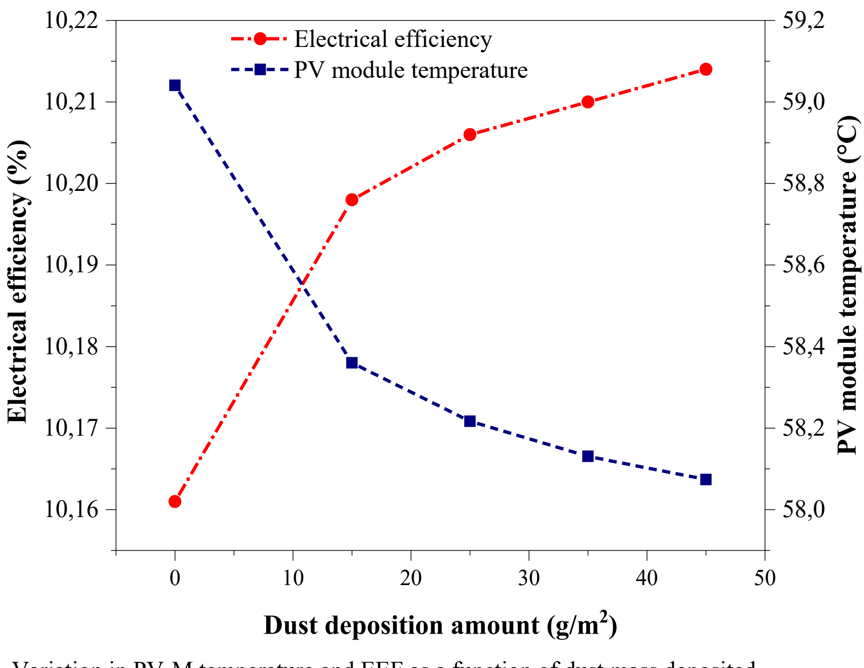

Fig. 4. Variation in PV-M temperature and EEF as a function of dust mass deposited.

As shown in Fig. 5, the electrical power of the PV-M gradually decreases as the amount of dust deposited on its surface increases, recording a drop of approximately 0.256 % when the dust mass increases from 0 to 45 g/m². This decrease is mainly due to the reduction in solar radiation reaching the active surface of the cells. The dust layer acts as a partial screen that diffuses and reflects part of the incident light flux, thereby reducing the amount of photons absorbed and, consequently, the short-circuit current. In other words, the reduction in the current generated outweighs the improvement in output voltage associated with cooling.

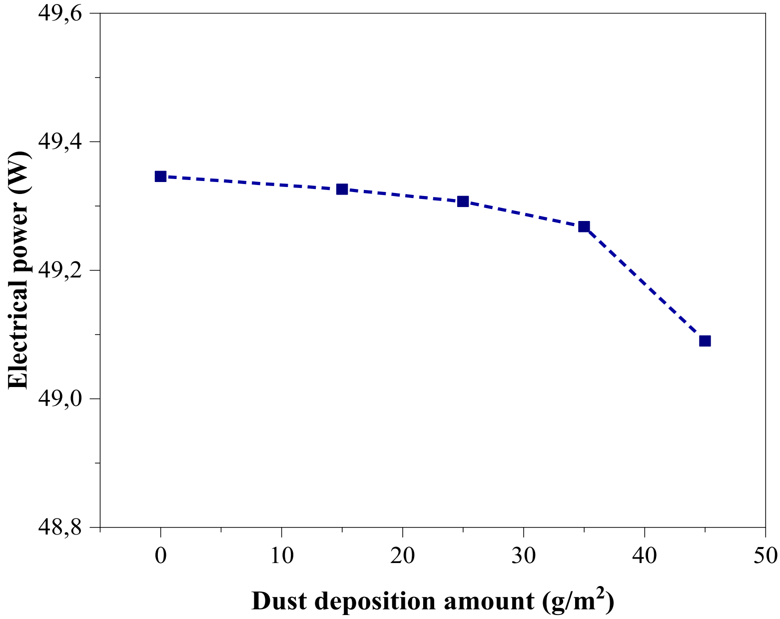

Fig. 5. Influence of the amount of dust deposited on the electrical power of the PV-M.

Fig. 6 illustrates the evolution of the PV-M temperature as a function of solar irradiance and the amount of dust deposited on its surface. It is clear that the module temperature increases with irradiance, reflecting greater absorption of solar radiation by the photovoltaic cells. For a perfectly clean module with 0 g/m² of dust, the temperature rises by 29.08°C when the irradiance increases from 100 to 900 W/m². In contrast, for a module covered with a layer of 45 g/m² of dust, the temperature only increases by 28.25°C under the same conditions. This difference, although small, can be explained by the attenuating effect of the dust, which reduces the amount of radiation actually absorbed by the active surface of the module and thus limits its heating. In addition, dust accumulation can influence the temperature distribution on the surface of the module, resulting in lower thermal gradients compared to a clean module.

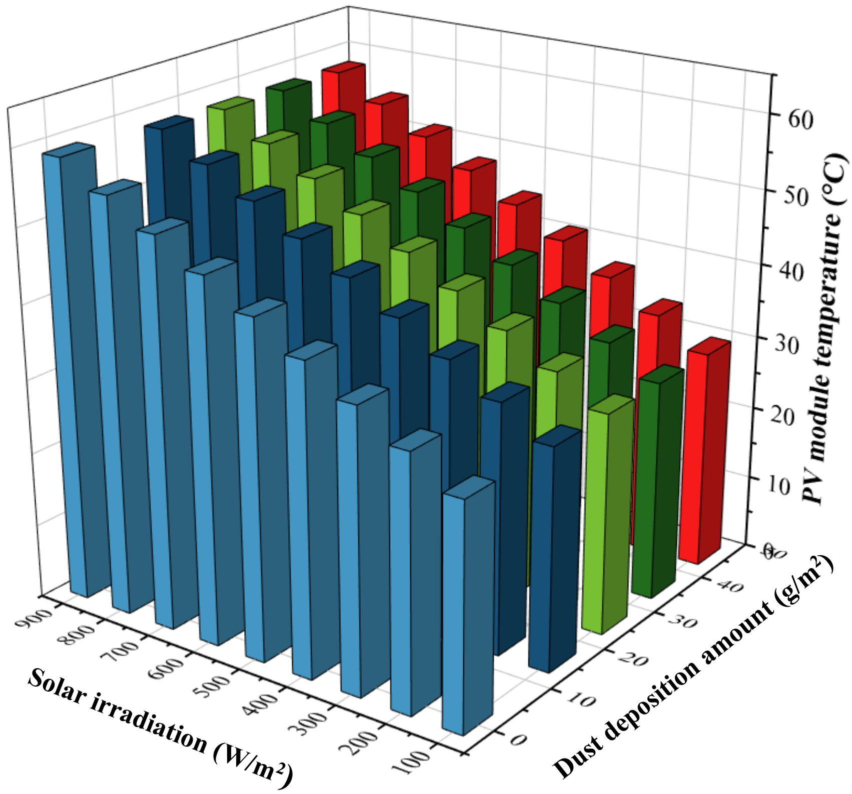

Fig. 6. Influence of solar irradiance and dust quantity on PV-M temperature.

The analysis presented in Fig. 7 highlights a clear trend whereby the EEF of the PV-M decreases as solar irradiance increases, regardless of the amount of dust deposited on its surface. This decrease in efficiency is due to the cells heating up under high irradiance, which causes a decrease in output voltage and thus reduces the overall efficiency of the module. For a clean module with 0 g/m² of dust, the efficiency decreases by 1.571% when the irradiance increases from 100 to 900 W/m². When the surface is covered with 45 g/m² of dust, the decrease is slightly less pronounced and the efficiency varies by 1.525%. This difference can be explained by the attenuating effect of the dust, which slightly reduces the amount of radiation absorbed by the cells, thus limiting their heating and the impact on EEF.

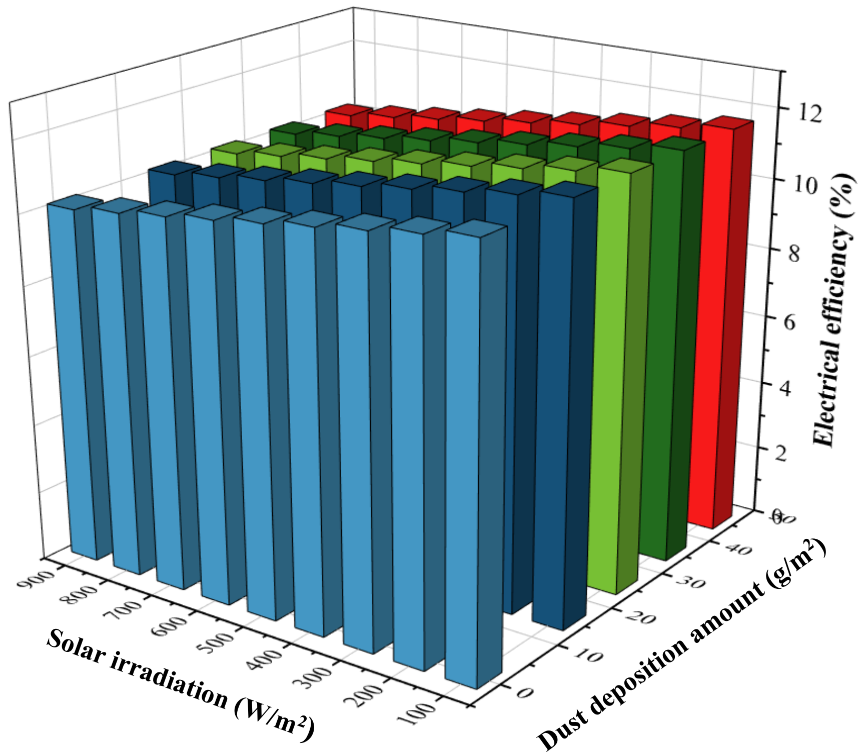

Fig. 7. Combined influence of solar irradiance and dust on the electrical power of PV-M.

4 Conclusion

This numerical study, conducted in 3D using COMSOL Multiphysics and based on the FEM, evaluated the effect of dust and solar radiation on PV-M performance. The results show that dust accumulation of up to 45 g/m² causes a slight decrease in module temperature, from 0.14 °C in low radiation conditions to 0.97 °C in high radiation conditions, resulting in a slight increase in EEF from 11.732% to 11.739%. On the other hand, the increase in irradiance from 100 to 900 W/m² remains the dominant factor, leading to a significant increase in temperature and a decrease in efficiency, from 11.732% to 10.161% for a clean module and from 11.739% to 10.214% for a dust-covered module. These results highlight the importance of simultaneously considering the effects of dust and solar radiation in order to optimize the performance of PV-Ms, and underscore the need for regular cleaning to limit the impact on electricity production.

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