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Development of low power laser in-situ thickness measurement for correlating the dust thickness to the PV performance

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ABSTRACT

Maintaining the photovoltaic (PV) panels operating at their optimum performance is a critical objective for energy harvesting. However, dust deposition due to natural, vehicular, and construction work over a period on the panels reduces the performance of the system. The primary goal of this work is to develop an in-situ laser-assisted dust thickness measurement unit and correlate the deposited dust thickness to the PV panel performance. The performance of the PV panel for various dust samples and coating thicknesses is analyzed, and the results from this in-situ measurement were correlated to the PV module's electrical performance. In this study, the effect of dust thickness on the panel temperature and the developed modular system is calibrated with various industry-standard thickness measurement techniques. The developed system suggests that even a few microns of dust deposition are enough to drop the PV performance by 50%. To understand the holistic effect of the deposited dust on the PV panel, a modular integrated system is developed which measured not only dust thickness, but also dust-spectroscopic effect, temperature variation due to dust, and the decrease in the electrical performance of PV panel. Real-time monitoring and establishing the relationship of deposited dust thickness and PV performance helps to determine the panel cleaning frequency in large PV fields. These results lead to a reduction in human resources and resources utilized in the cleaning of PV panels. This portable, modular system could be used in site assessment of a new proposed PV field and scheduling plant maintenance in an existing PV field.

1. Introduction

Stable power conversion efficiency and the lifetime of the photovoltaic (PV) panel dictate the PV field performance. However, the lifetime of the PV panel is based on environmental factors like dust, relative humidity, temperature, and mechanical stress (Mani and Pillai, 2010). The performance of panels depends on the installation angle for a geographical location. The mode and type of dust accumulation also depend on the geological location and installation conditions (Smestad et al., 2020). investigated the soiling losses through an optical study. In this study, samples are collected from different locations of the globe and studied their effect on the PV performance.

Accumulation of dust and contamination is the biggest concern in PV power production. Once the dust is accumulated on the panels, it hinders the light from reaching the panel, thus effectively decreasing the performance of the panels. Many studies are conducted correlating dust and on solar PV performance (Rao et al., 2018). reported detailed review on dust effect on PV performance. Here various work on use of natural and artificial dust effect on the PV performance and theoretical modelling to speculate this effect is reviewed. Further, the scope of various techniques, methods and apparatus used in these performance measurements are also compiled. Another detailed review has been conducted by (Ilse et al., 2018) which provided a soiling effect from the bottoms up approach on the PV device perspective. Dust adhesion and energy required to dislodge is correlated to performance of the device and consequently to module performance.

(Aïssa et al., 2016) investigated the chemical aspect of the dust collected from a specific geographical location and its effect of the performance is correlated. Even the large spectral transmittance loss due to this specific dust chemistry is explained (Jaszczur et al., 2019).conducted study in Kraków, Poland, degradation of characteristics of polycrystalline modules due to natural dust under high wind and pollution atmosphere.

The study of the dust on the PV panels is focused on transmission loss due to deposited dust and their effect on the PV output. These studies are conducted by utilizing the spectroscopic method under broad source

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light (Smestad et al., 2020). investigated the effect of various soiling modes to loss of light transmission. PV performance was correlated to this transmittance and the dust size distribution (PSD) through the optical characterization of dust (Piedra et al., 2018). optical losses due to aerosol were measured by a developed technique. They validated their model by artificially coating dust on control substrates. In patent (Michael Gostein, 2019a) they utilized the optical reflection method, and (Michael Gostein, 2019b) used the optical imaging method to correlate the effect of dust on PV performance.

Currently, PV soiling monitoring stations are deployed, and comparative analysis is done between clean and dusted panels. The soiling monitor station in a PV field is locally deployed and needs regular maintenance (Michael Gostein, 2020). filed a patent for a PV soiling measuring device. This device includes a clean PV device and a soiled PV by comparing both the soiling effect in the PV field can be studied (Capdevila et al., 2016). carried out work in relating satellite-based solar insolation data and dust layer optical transparency for a period on various PV module setups. The deposited dust increases the temperature of the PV panels, which also reduces the performance of the panel. that the PV surface is relatively higher temperature when it is dirty. This increase is demonstrated by thermal imaging of the clean and unclean PV modules and its electrical performance has been studied by (Abderrezek and Fathi, 2017).

For the optimal performance of the PV, the dust accumulation should be minimal (Mondal et al., 2018). studied different cleaning methodologies for the PV panels. They concluded that cleaning can be achieved by various manual processes, but they seem to be energy-intensive and time-consuming efforts. An automatic robotic system is an alternate option that brings in issues of additional maintenance of the cleaning system (Jiang et al., 2016). developed a theoretical model to estimate the cleaning frequency based on the dust deposition velocity model (Majeed et al., 2020). developed a cleaning system with the minimum

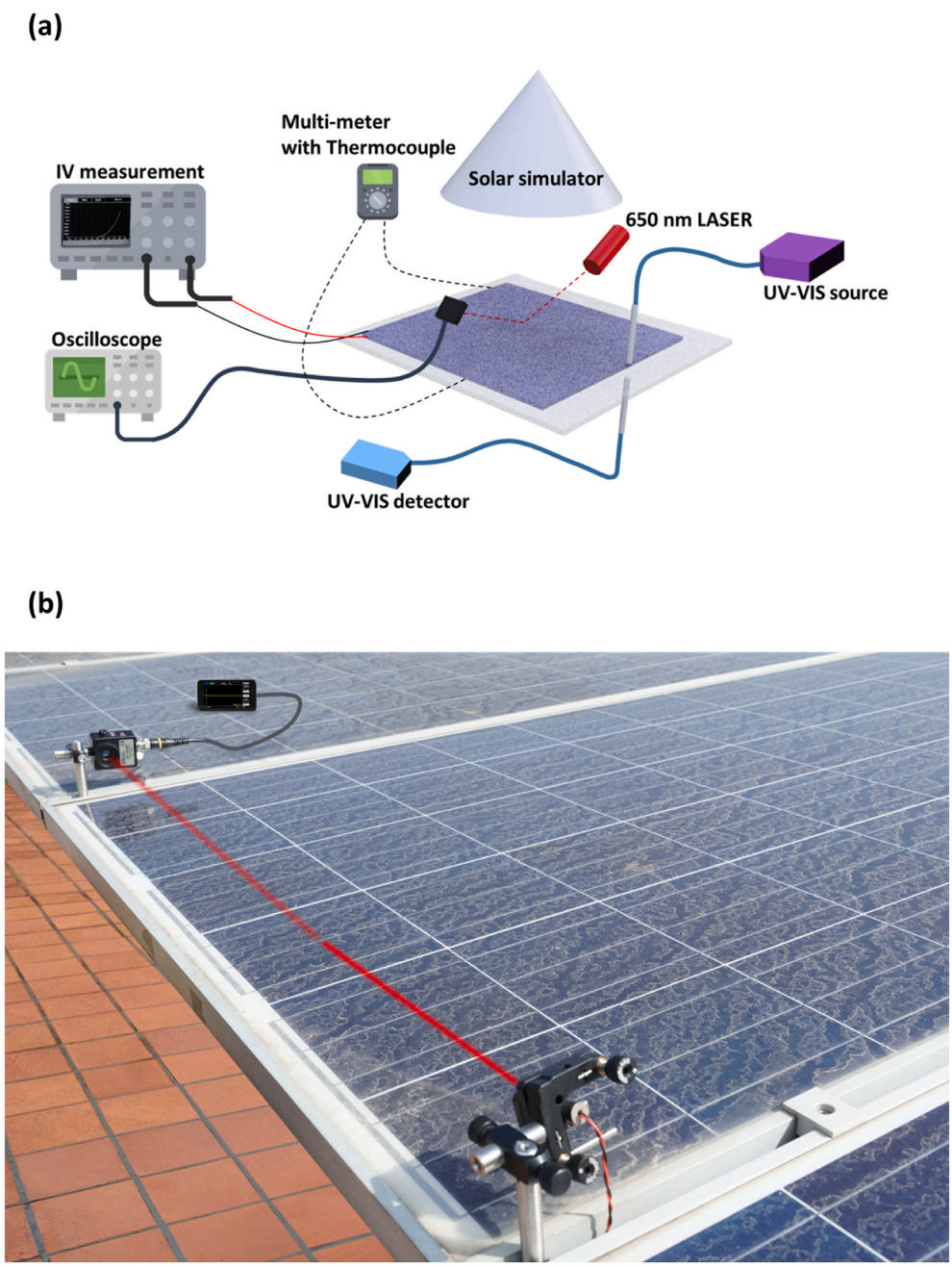

Fig. 1. (a)Experimental setup (b)Graphical representation of the final setup.

usage of water by recycling it. Determining the optimizing the cleaning schedule of the PV field will increase the panel lifetime and optimize the resources utilization.

The guiding factor for the cleaning of the PV is dictated by the power output from the PV panels. By understanding the thickness of the dust deposited on the PV panel in the field, the panel performance can be correlated. This correlation eliminates the panel or electrical connection malfunctions in large PV fields. This study aims to develop a laser-assisted in-situ dust thickness measurement and correlate thickness effect on the PV panel performance. Integrated in-situ dust thickness units with an optical spectroscopic technique are developed for understanding the soiling effect on PV panel electrical performance. In a single integrated setup, all the optical and electrical properties of the panel under various dust thicknesses are studied. The idea here is not only to measure the thickness coverage of the dust on the panel but to correlate the thickness to the power conversion performance of the panel.

2. Experimental setup

Experiential schematic for the dust particle thickness measurement integrated with spectroscopic and electrical characterization unit is shown in Fig. 1(a). Silicon panel of 0.19 × 0.09 m size is illuminated under a 500W solar simulator. Ocean Optics UV–Vis with a multimode fiber system is used to measure the transmittance and spectral response of the dust layers on the PV system. The diode laser of 650 nm with 5 mW output power and Thorlab photodetector is used to measure the thickness of the dust. Kethely 2450 module is used to measure the I–V parameters of the panel. Dust from different regions is utilized to study their effect and to calibrate the laser thickness monitoring unit. Dust collected from a dry rural area is denoted as DUST 1. The dust collected from outside and inside a PV field is denoted as DUST 2 and DUST 3. The black soil collected from the rural area is denoted as DUST 4. The dust from the Kuduremukh iron ore mining location is mentioned as DUST 5. These types of dust samples were chosen because this kind is the most common dust observed in many large PV testbeds in southern India (Wani et al., 2011).

3. Result and discussion

To study the dust effect, collected dust samples are redeposited on the PV panels. Multiple layers of dust are coated on the PV panel using a sieving process with 150 μm mesh. The covered dust particle size distribution is shown in Fig. S1 with a size distribution histogram in the supplementary information. Fig. S2 of Supplementary Information shows the result of morphology and composition of the deposited dust obtained using a scanning electron microscope and Energy Dispersive X-ray Spectroscopy (EDS) analysis. In addition to checking the versatility of the system, both red and black dry soil was used for the in-situ dust thickness measurements and their effect on PV panel performance.

Thickness measurement is carried out using a laser reflection technique. In this method, the 650 nm diode laser is illuminated on a dust-coated panel, and the reflected beam is detected using the Thorlabs photodetector. The dust particles can get ionized under higher power. Hence appropriate laser wavelength and power must be used so as not to get erroneous data. Therefore, here to measure the dust layer thickness, the lower power laser is used. A diode laser of class 3A at 650 nm wavelength having a maximum power output of 5 mW is used in this setup. This laser is used because of its low power and visible wavelength. 650 nm is an industry standard when it comes to thickness measurements due to low scattering and smaller form factors. Si detector is used to measure the reflected beam. The detector has a very high sensitivity of 0.5 A/W in this targeted wavelength range. Measurements are repeated for different dust samples and different thicknesses. The parameters of the system have remained constant in all the measurements. The measured thickness of the coated dust for different thicknesses is shown in Fig. 2.

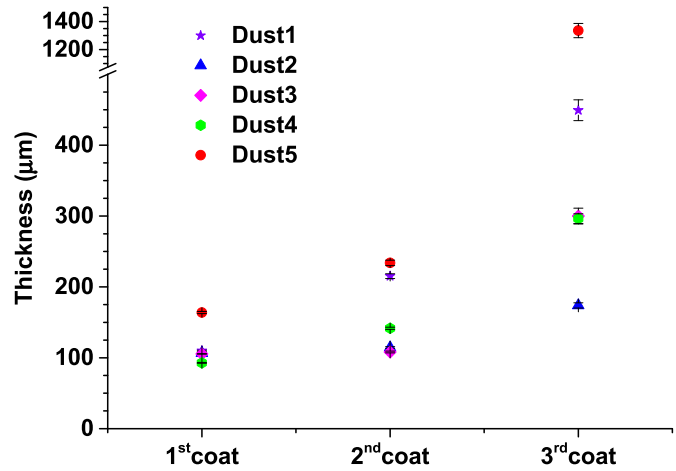

Fig. 2. Laser thickness profile for multiple dust coating.

Due to optical loss and the non-uniformity of the dust coating, small distribution in the measurement data is observed. By repeating the measurements multiple times, the average thickness of the coated dust on the panel is calculated. The average thickness of the first, second, and third coating is found to be 115 ± 0.76 μm,162 ± 2.3 μm, and 511 ± 17.42 μm and represented and t1, t,2, and t3. The laser thickness measurement unit is calibrated using Bruker's DektakXT Stylus Profiler, Olympus DSX1000 Digital Microscope, and Oxford screw gauge with various standard samples. The obtained results of these calibration samples are in Fig. S3 in the supplementary information. The values obtained using all the three commercial thickness measurement techniques with developed laser thickness technique setup have a standard deviation of fewer than 2.8 μm, suggesting the suitability of the developed in-situ laser technique for measurement of dust and pollution on PV panels. This simple measurement also helps with optimizing the cleaning schedule, use of clean potable quality water, and human resources.

Dust profile on glass encapsulation of the PV panel dictates the amount of light reaching the semiconductor and hence its performance. The light transmission characteristics of the dust-coated glass were evaluated simultaneously. The transmittance of the dust coating with various thicknesses is measured using an optical fiber-based UV–Vis spectrometer. The obtained measurements are shown in Fig. 3. The UV–Vis spectra show a reduction of light transmittance as the thickness of the dust coating increases. A significant transmittance reduction is observed in the visible region between 400 and 600 nm. Transmittance loss is less than 10% for an average dust thickness of 115.75 ± 0.76 and 168.65 ± 2.2 μm. However, once the thickness increases by more than 500 μm, the transmittance decreased by more than 30%. This observation is persistent in all dust samples. These results from transmittance spectra indicate even less than millimetres of dust particles on the PV panel, decreases the performance due to the reduction of light reaching the panel.

The dust-coated PV was illuminated with the solar simulator of 500 W, and its spectral response was acquired with a fiber-based UV-VIS spectrometer. Acquired spectra for various dust coating thickness are shown in Fig. 4. It is observed from Fig. 4(a) that as dust particle coating thickness is increased, the transmittance of the light decreases in the visible region between 400 and 600 nm. In the region of the higher (infrared) wavelength [700–900 nm], the transmittance of light increases as the dust particle coating increased, as shown in Fig. 4(b). IR transmittance for different dust thickness is measured in this study. 32% increase of the IR radiation transmittance is observed as the dust thickness increase. The percentage increase in the IR radiation is given in Fig. S4 of Supplementary Information. The results shown in Fig. 4 are observed in all dust samples utilized in this work. This result indicates

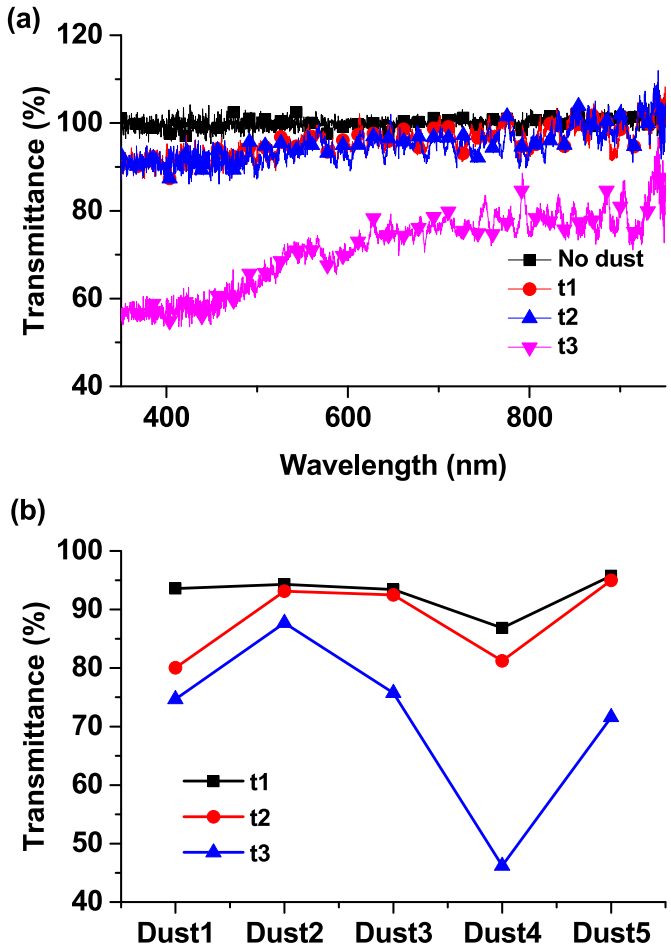

Fig. 3. UV Vis transmittance spectra for multiple layer coating of Dust on glass.

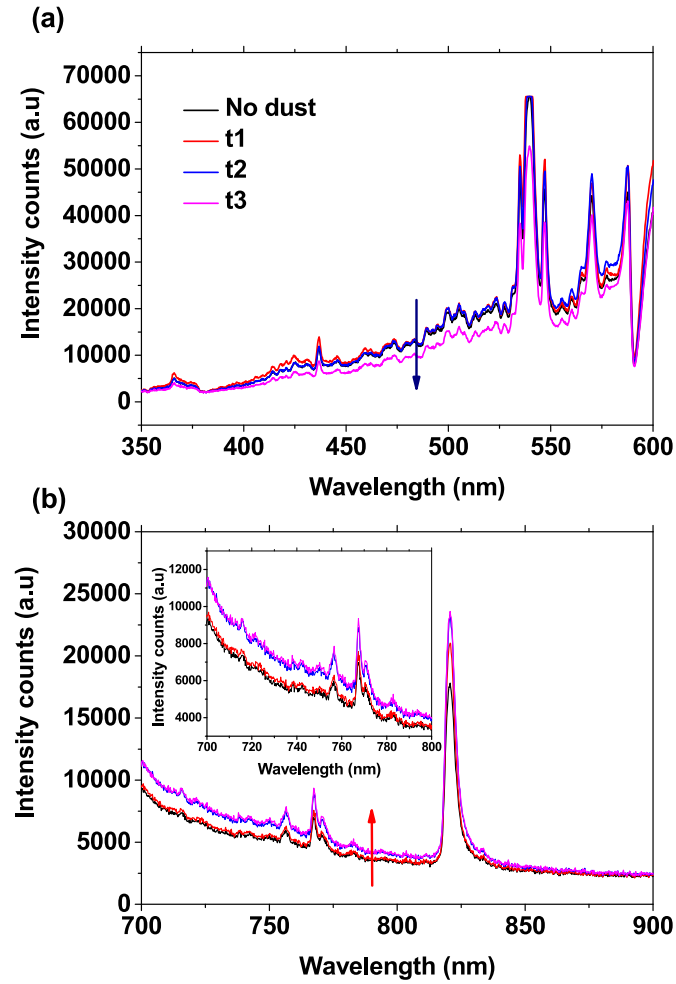

Fig. 4. Radiation spectra of the solar simulator for (a) UV and Visible wavelength (b) IR wavelength through coated dust.

that the higher portion of the infrared (IR) wavelength range is penetrating the panel, which is further detrimental to the performance and aging. Higher transmission of the IR radiation leads to a rise in the temperature of the panel in the long run.

Another vital aspect of the PV performance is the temperature at which devices operate. It is known that semiconductor device relation to temperature, as the temperature increases, the conversion efficiency decreases. Hence monitoring of the change in the temperature of PV arising due to dust deposition is also critical. These temperature measurements were carried out using two thermocouples at different locations on the PV panel. In Fig. 5, the effect of the dust coating on the measured temperature of the panel is shown. As the dust coating thickness increases, the surface temperature of the panel is observed to increase. Correlations between changes in temperature either positively or negatively with the dust chemistry should be evaluated for a holistic understanding of the problem.

The electrical performance of the PV panels under different dust for multiple coating thickness is studied. Fig. 6 shows the characteristic results of the PV panel under various dust coating conditions under 500 W illumination. As the thickness of the deposited dust layer increases the current density (Jsc), and the efficiency (EFF) substantially decrease, as shown in Fig. 6(a) and (c). The open-circuit voltage (Voc) and the fill factor (FF) did not change much, as shown in Fig. 6(d) and (b). The measured parameters of the PV are calculated and presented in Table T1 of supplementary information. As the dust thickness increases panel performance decrease due to less light transmittance. The current density of the panel reduces as the dust thickness increases. The dusty panel efficiency drops 50% compared to the cleaner panel.

I–V characteristics for different dust coating conditions are shown in

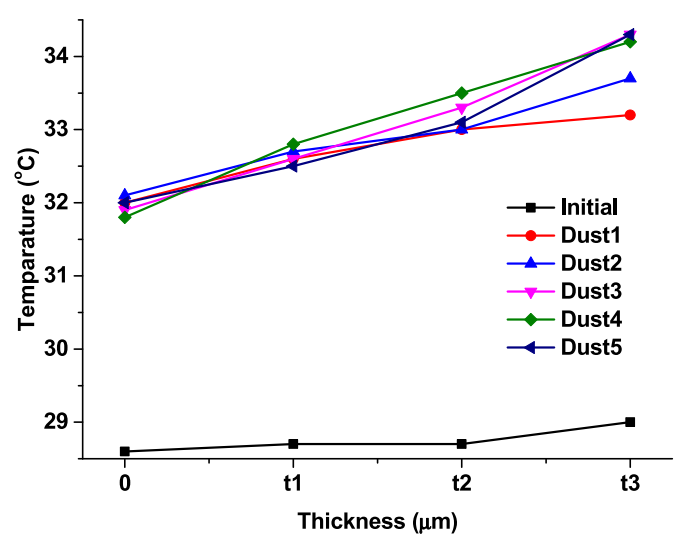

Fig. 5. Temperature of the glass vs. the thickness of the dust deposited.

Fig. 7. In Fig. 7, it is observed that as the dust coating thickness increases, the short circuit current decreases resulting in a reduction of the current density. In the inset of Fig. 7, magnified I–V characteristics are shown.

These results suggest that a critical thickness of the deposited dust

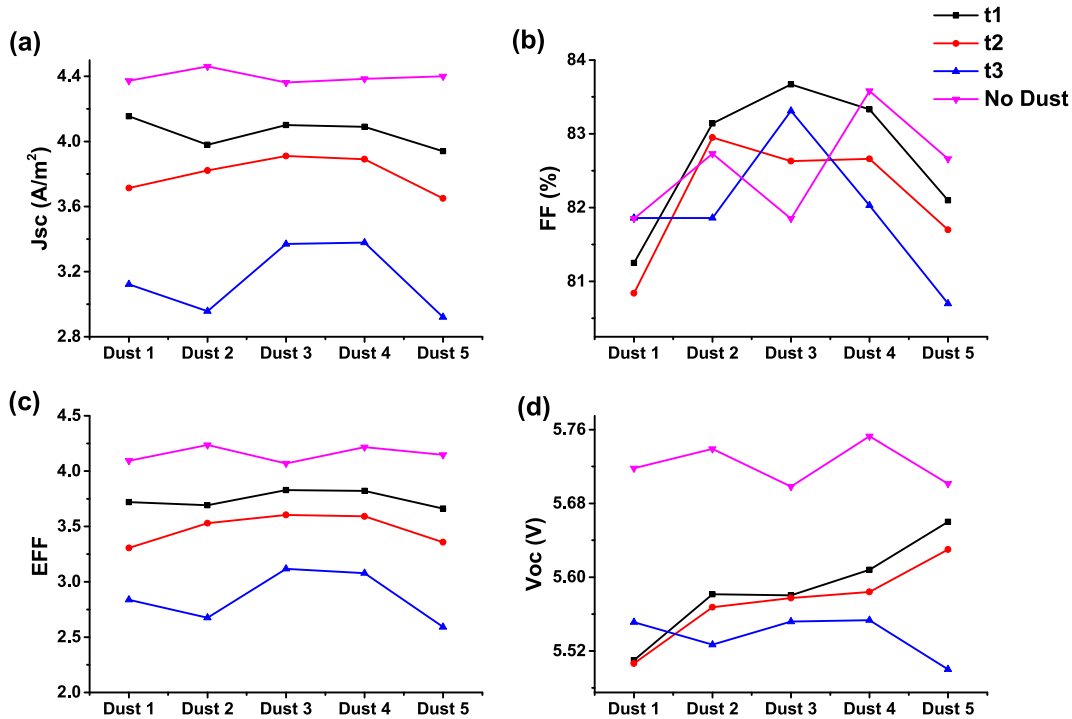

Fig. 6. (a) current density (b) fill factor (c) efficiency (d) voltage of the panel as a function of the thickness of the dust deposited.

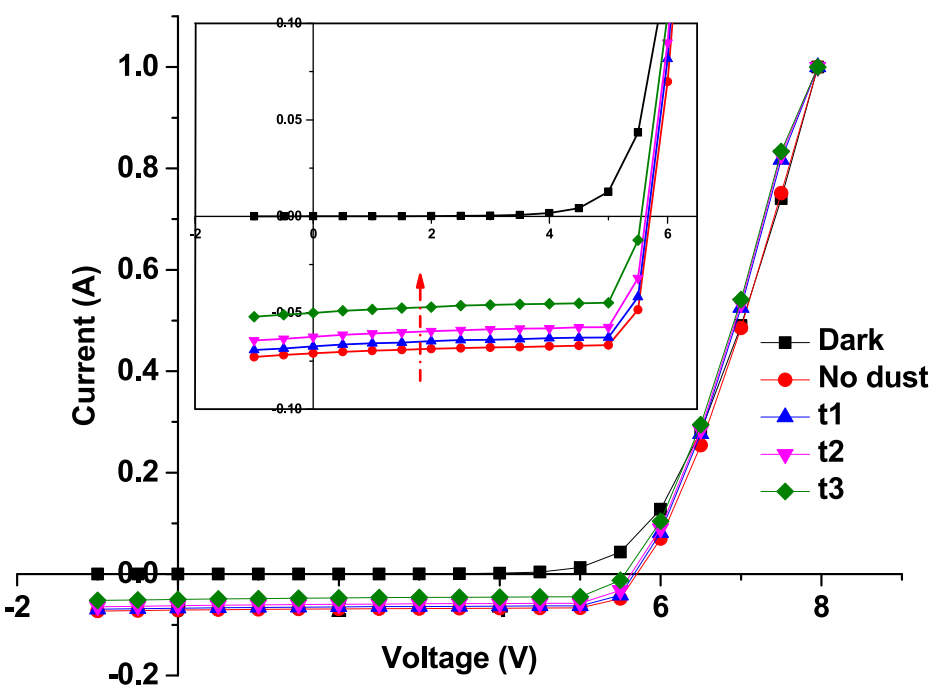

Fig. 7. I–V curve of the PV panel under deposited various dust thickness.

drastically affects the PV performance. The response of the developed system is correlated to the standard calibrated dust thickness deposited on the PV panel. Dust thickness to the PV panel performance is established in this study. The response of the developed system to the PV performance is statistically correlated. As the dust thickness increases, the correlated efficiency and the current density of the panels reduce as shown in Fig. 8. The measured response of the system to the PV parameter fits well in the measured range of 0–1000 μm of dust thickness. The measured and the statistically analyzed values are matching, indicating the suitability of this developed technique to evaluate the dust thickness in a large PV station to its electrical performance and consequently optimize the cleaning schedule.

The effect of dust on the PV panel is critical, as observed by the thermal and spectroscopic studies. These studies indicate the reduction in the power output of the PV panel to the deposited dust thickness. The thickness of the dust affects the performance of the PV panel, which is unavoidable under environmental conditions. The in-situ thickness monitoring of this dust deposition can be a simple solution for the

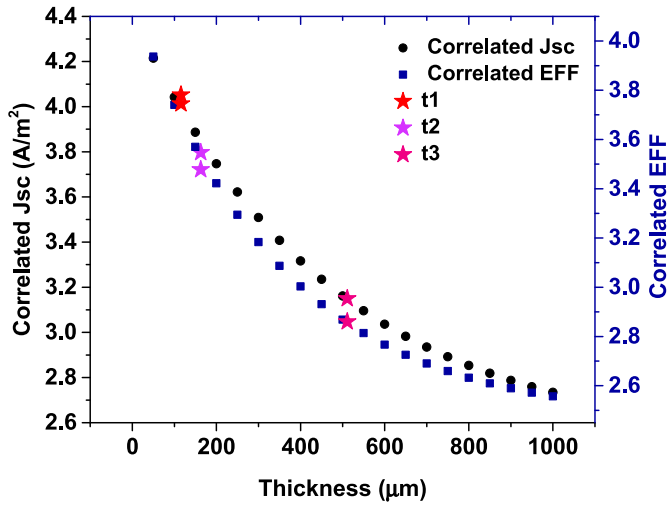

Fig. 8. PV panel current density and efficiency under different thickness of the dust deposited on it.

complex dust effect on the PV panel. By measuring the thickness of the dust on the PV panel, life and health can be accurately monitored. By this method, the cleaning period, resources, and the workforce to maintain the large PV Power Station can be optimized.

4. Conclusion

In this study, In-situ laser-assisted dust thickness measurement system is developed for PV soiling study. Optical and electrical measurements are carried out on the artificially deposited dust layers to correlate their effects on the performance of the PV panels. The study is carried out using a developed integrated in-situ setup with laser and spectroscopic techniques. The developed laser-based thickness monitoring system is portable; that can give representative information in a vast PV field. Higher accuracy of fewer than 2.8 μm is achieved using the simple in-situ laser measurement technique that can be adopted for the PV field. These obtained results were calibrated against commercially available high-precision laboratory techniques. The reliability of the system is analyzed with different dust types of dust for multiple thicknesses. A drastic change in the performance is observed for certain dust coating thickness, which indicates up to a critical dust coating thickness, PV performance does not get affected. The dust on the PV panel also increases the temperature at which PV panels operate. Dust thickness of 500 μm significantly increases the PV panel temperature by 2 °C resulting in a reduction in photocurrent and a drop in the panel conversion efficiency by 50%. As the thickness increases, IR radiation transmittance increases resulting in degradation of the panel. This information could be further used for better analytics and cleaning schedule, which consequently resulting in optimization of power generation and resource management. The correlation between dust thickness to panel performance is obtained, which helps in developing an efficient cleaning cycle for the large PV field. The correlation of the dust thickness to panel performance and its lifetime helps in understanding the effect of dust on the PV panels.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clet.2021.100332.

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