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Soiling-induced transmittance losses in solar PV modules installed in Kathmandu Valley

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Abstract

Renewable energy sources are fast emerging as more reliable supplement of conventional energy sources. Among the various renewable sources, solar energy is most sought after in today's world. Solar PV modules when installed in outdoor environments suffer from various factors which are generally unaccounted in laboratory testing. Energy generation from solar collectors is primarily dependent on the amount of incident radiation on their surfaces. Soiling on modules is known to reduce the transmittance of incident rays to solar cell and cause significant output power degradation. Soiling is closely associated with the various factors such as module tilt angle, site-specific climate, outdoor exposure period, humidity, wind speed, dust characteristics and material properties. This experimental work is aimed to study the transmittance losses encountered by solar PV modules and the corresponding power degradation. The experimental results show an alarming reduction in transmittance as high as 69.06% over the dry study period experiencing no rain. The power of dusty solar module decreases by 29.76% compared to the module cleaned on daily basis. Dust deposition density on the PV module accounted to 9.6711 g/m^2 over the study period.

Keywords: Solar energy, Soiling, Air pollution, Transmittance loss

Introduction

Scope of clean and renewable source of energy in developing countries is high. From economic to environmental benefits, renewable sources have a considerable role to play for the overall development. From mere alternatives in the race to provide human civilization with required energy, renewables have now stolen the march and are set to become the frontrunners in the coming decades. Renewable energy sources with the growing share in the energy mix globally are more than capable of meeting future energy requirements. Continuous research and development in the various dimensions of renewable energy sources are ongoing, and they are touted as the major shareholders for electricity generation in the coming future. Commonly known technologies include biomass, geothermal, solar, tidal, wave and wind energy systems. On the global scenario, due to easy and accessible amount of resource, solar energy has the significant market over other distributed renewable energy techniques, as denoted by the sharply reducing cost of PV systems all over.

Dust is simply defined as a particulate matter less than 500 μm in diameter which can comprise various suspended matters in the atmosphere from organic to inorganic particulates (Sarver et al. 2013). Dust is generated from various sources such as soil elements lifted by wind, volcanic eruptions, vehicular movement and pollution (Siddiqui and Bajpai 2012). Deposited particles on PV modules interfere with illumination quality by both attenuating and scattering incident light (Qasem et al. 2011). There is a strong variation in particle shape, size and constituents of dust according to regions throughout the world. Similarly, the deposition patterns, rates and characteristics are found to vary dramatically in different localities. Ambient conditions such as humidity/moisture gradients, variation in wind velocity direction and magnitude and seasonal variations affect the properties of dust as well as deposition rates (Sarver et al. 2013). Dust

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particles attach onto a surface due to gravity, electrostatic charge or mechanical effects (wind or water droplets). After deposition, they are held by the variation of electrical potential near the surface (charge double layer), surface energy effects and capillary effects, in addition to gravity and electrostatic forces (Qasem et al. 2011).

One of the major impacts of dust deposition is observed on the transmittance of solar modules. Transmittance is generally known by the degree of solar radiation passing through a module encapsulation (generally made of plastic or glass). The transmittance reduction due to dust deposition eventually leads to reduction on power generation from modules. Different studies have shown large performance variations from location to location as a function of exposure time (Siddiqui and Bajpai 2012; Aassem et al. 2012). El-Shobokshy and Hussein (1993), covered PV module surfaces with different dust types (i.e. limestone, cement, carbon) and found the short-circuit current was reduced to 20% of its initial value for the carbon accumulation with only 28 g/m^2, whereas same reduction was accounted with 73 g/m^2 deposition for cement, 125 g/m^2 for 50 μm, 168 g/m^2 for 60 μm and 250 g/m^2 for 80 μm limestone dust. It was specifically noted that the material composition of dust also affects PV performance. From the results, carbon particles absorb solar radiation more readily than the other dust types. Mailuha et al. (1994) focused the study on the effects of dust-deposited layer density and included tilt angle and solar intensity, and found that with the increment of solar intensity, the PV performance degraded due to decrement in dust accumulation. At 700 W/m^2, the reduction in power output was almost negligible; however, when the intensity dropped to 400 W/m^2, the reduction was nearly 25% of the initial power output. Continuous humid environment causes degradation in solar cell efficiency and causes the transmittance to decrease (Mekhilef et al. 2012). The results of study by Jiang et al. (2011), to investigate the output degradation of different types of PV modules with different surface materials caused by airborne dust pollution experimentally, indicated that dust pollution has a significant impact on PV module output. With dust deposition density increasing from 0 to 22 g/m^2, the corresponding reduction in PV output efficiency grew from 0 to 26%. The reduction in efficiency was found to have a linear relationship with the dust deposition density, and the difference caused by cell types was not obvious. Also the reduction in output power at relatively higher solar densities is much more severe. This phenomenon is probably attributed to relatively higher reflection effect of the deposited dust to light. Sometimes PV modules of same and different technologies are known to have a different power rating, so performance ratio could be the best platform for power rating comparison. An experiment found the performance ratio decreasing with the dust accumulation, and the ratio is expected to substantially improve once the modules were cleaned (Adinoyi and Said 2013). From various studies, the dust accumulated on the PV module surface is found to decrease the transmittance of incident light and ultimately decrease the solar energy received by the solar cells in PV modules. In a study conducted in Baghdad Saidan et al. (2015), the experimental results show that dust considerably reduces the maximum current from 6.9 to 16.4% depending on the time period of PV panels' exposure in dust-affected environment, i.e. from one day to one month. Elminir et al. (2006) in Egypt investigated the effect of dust on the transparent cover of solar sensor using several sensors and concluded that soiling on glass inclined of an angle of 0° and 90° from horizontal causes a reduction in the corresponding transmittance by approximately 52.54 and 12.38%, respectively. This shows that the tilt angle plays one of the major roles in determining the performance of PV modules. Hegazy (2001) studied dust deposition on glass plate surfaces with various tilt angles and also measured the transmittance of plate under different weather conditions and concluded that the degradation in solar transmittance primarily depends upon the tilt angle. Dust accumulation on a tilted glass plate located in Kuwait City was found to reduce the transmittance of the plate from 64 to 17% for the tilt angles ranging from 0° to 60°, respectively, after 38 days of outdoor environment exposure (Sayigh et al. 1985). Soiling on a glass plate tilted at 45° angle decreased transmittance by an average of 8% after an exposure period of 10 days in a research performed in India (Garg 1973). A study by Cano (2011) on the effect of tilt angle of PV modules on dust deposition in Arizona found that during the period of January through March 2011 there was an average loss due to soiling of approximately 2.02% for 0° tilt angle. Modules at tilt angles 23° and 33° also have some irradiance losses but do not come close to the module at 0° tilt angle. Tilt angle 23° has approximately 1.05% monthly irradiance loss, and 33° tilt angle has an irradiance loss of approximately 0.96%. The effect of dust deposition is evident at any tilt angle, but the magnitude is different with the solar module with low tilt angle being bound to more energy losses. Al-Hasan (1998) investigated the effect of the amount of accumulated dust on the efficiency of a PV module in the Kuwait climate on almost similar latitude to Kathmandu (latitude 30°). A linear relation has been proposed to correlate the degradation in efficiency with the amount of sand dust accumulated on the module surface. Paudyal and Shakya (2016) on the similar research have derived another regression equation relating the impact of various meteorological parameters as well as dust deposition density for Kathmandu. This relation could help PV system designers to reliably predict the effect of dust accumulation on PV module efficiency under real environmental conditions. Ndiaye et al. (2013) on their investigation on the effect of soiling in the performance of PV modules have highlighted the impact of dust on the current–voltage and power–voltage characteristics of PV modules with the advent of the mismatch effect. The maximum power (P_{max}), the maximum current (I_{max}), the short-circuit current (I_{sc}) and the fill factor are the most affected performance characteristics by the dust deposition on the PV modules surface. P_{max} output losses are observed to be from 18 to 78%, respectively, for the polycrystalline module (pc-Si) and mono-crystalline module (mc-Si). I_{max} loss can vary from 23 to 80% for, respectively, pc-Si and mc-Si modules. However, the maximum voltage output (V_{max}) and the open-circuit voltage (V_{oc}) are not affected by dust accumulation for both technologies studied. This shows that mono-crystalline modules are more prone to efficiency losses due to soiling effect. The variation of energy losses during the day depends on the optical transmittance due to the incidence angle of irradiance on tilted plane and refractive index of dust material (Semaouia et al. 2015). Experimental investigations conducted in Indonesia demonstrated a significant decrease in PV output power in relation to dust accumulation during a long period of dry conditions. Results of experiments show that dust accumulation after two-week exposure in the dry season caused a PV output power reduction of 10.8%. Two different weather conditions were considered to analyse the effect of local weather conditions on PV output power, rainy and cloudy conditions. Results from the experiment under a rainy condition showed that PV output power decreased by more than 40% when there was an average relative humidity of 76.32%, whereas during cloudy conditions the decrease in output power was more than 45% when there was an average relative humidity of 60.45% (Ramli et al. 2016). Analysis from Chin et al. 2011 shows that the efficiency of solar power system after incorporating the single axis tracker is higher than that of the fixed array system and the cost of electricity from a PV system is approximately equal to that of a diesel generator and cheaper than a grid extension when a single tracking system is introduced. The completed MATLAB model (Chin 2012) of the solar tracker with external disturbances was designed to provide a computer-aided design tool to determine the efficiency over the fixed solar panel, net current output, power generated and the types of PV systems that can be combined to give a required level of efficiency before actual implementation, where the experimental results show a similar behaviour in the power, the efficiency and the current output over the fixed solar panel when compared them with the simulation results.

Experimental set-up

Kathmandu Valley lies 1325 m above sea level, and due to high occurrence of calm and low wind speeds, the dispersion conditions in Kathmandu are poor (Shrestha 2001). The annual average daily global solar radiation for Kathmandu is 3.83 kW/m^2/day (Poudyal et al. 2012). The unique topographic features coupled with high emissions of pollutants make the valley particularly vulnerable to air pollution. The valley is surrounded by hills, forming bowl-shaped topography restricting wind movement and retaining the pollutants in the atmosphere. This is especially bad during the winter season (November–February) when thermal inversion occurs in the valley late night and early morning. Cold air flowing down from the mountains is trapped under a layer of warmer air and acts as a lid. As a result, the pollutants are trapped close to the ground for extended periods of time (CANN 2014). The polluting agents generated inside Kathmandu cannot be transported during the winter time and hence settled on the surface of solar modules installed in Kathmandu.

Experimental set-up was installed on the Institute of Engineering, Tribhuvan University located in Kathmandu Valley, Nepal, from the 13 August 2015 to 10 January 2016. Two 40 W each polycrystalline solar modules manufactured by Rahimafrooz Solar were installed on the Central Campus, Pulchowk, with tilt angle of 27° as shown in Fig. 1a. Power generation from those modules was constantly measured and stored in data loggers. Similarly, 150 microscopic slides of dimension 25.1 mm × 75.2 mm × 1.2 mm were placed with an array formation in similar tilt angle as shown in Fig. 1b, to the modules to measure dust deposition density as well as transmittance (Gandhi et al. 2014). Dust containing slides were measured for transmittance before cleaning using Cary 60 UV–Vis Spectrophotometer as shown in Fig. 2a, manufactured by Agilent technologies. The process was repeated after thorough cleaning of the slides to gather transmittance value of clean slide. Slides with dust accumulation were measured in electrical balance shown in Fig. 2b with 0.0001 gm sensitivity, at the rate of one slide per day. Slides were measured with dust first and again measured after the dust was thoroughly cleaned. The difference between two values gave the weight of dust. The quantity, obtained after subtraction of weight of clean slides from weight of dusty slides and divided by area of microscopic slide, gives the dust deposition density. During the study period, one module was cleaned daily, whereas the other was left to the natural soiling phenomena throughout. The P_{max} of both the solar modules were measured simultaneously. The variation in power output

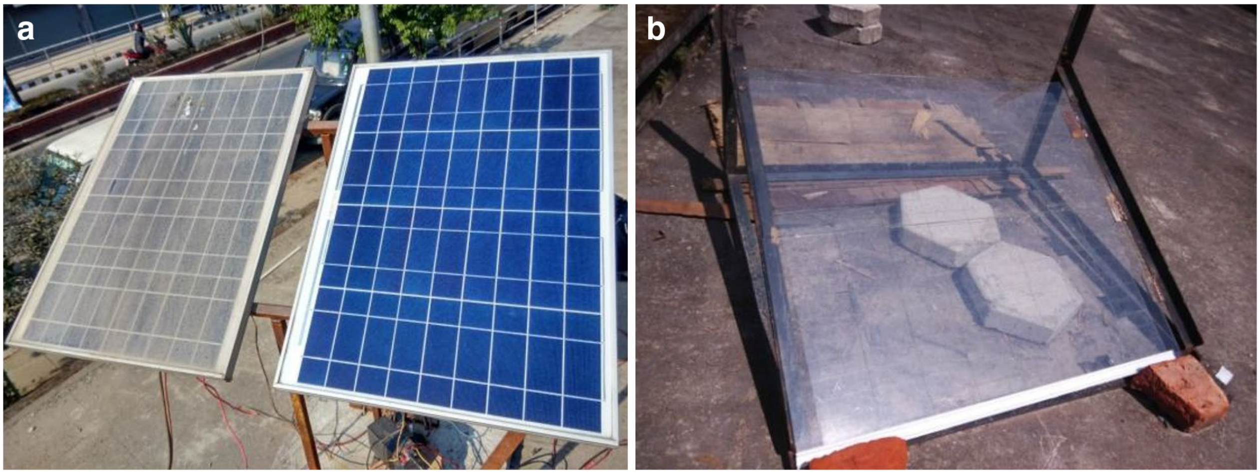

Fig. 1 a, **b** Experimental set-up for data collection

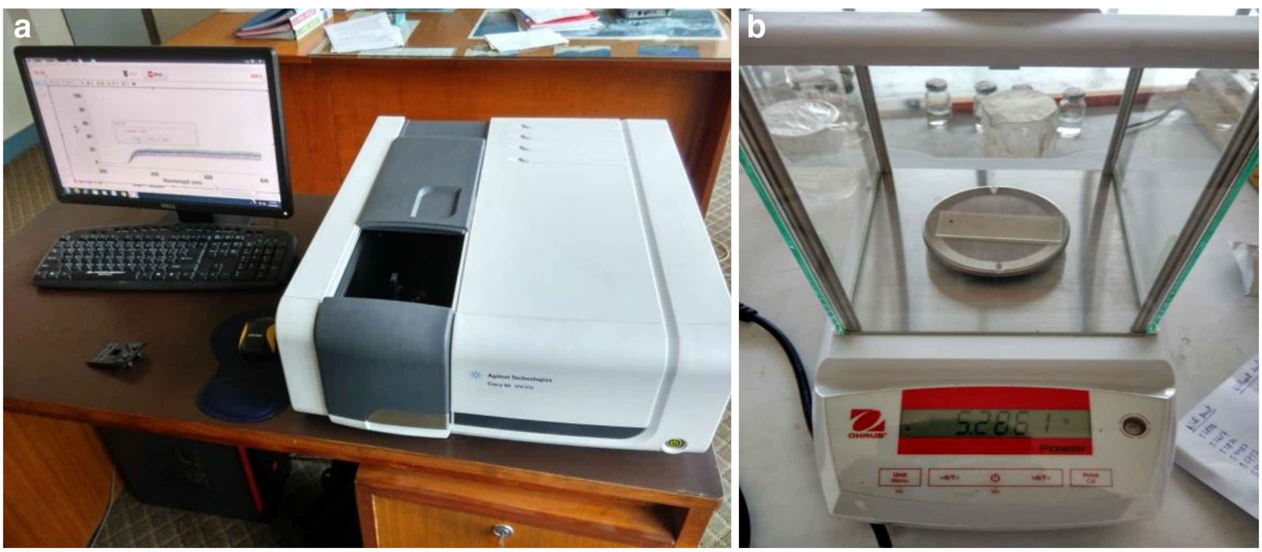

Fig. 2 a, **b** Transmittance and dust deposition density data collection techniques

of modules was signalled by the varying values of Imp and V_{mp} of both solar modules and recorded into the individual data loggers attached on each module.

Data for temperature, rainfall and humidity were collected from Department of Hydrology and Meteorology, Kathmandu, from the nearest meteorological site at Kathmandu airport. The values of P_{max} were calculated for each day from 9 am to 3 pm, from which average value per day was calculated. The daily average values of meteorological variables were taken from the nearest meteorological station. Statistical software NCSS11 was used for multiple regression analysis which was performed to calculate the combined effect of meteorological variables towards dust deposition density. The power output is dependent on other factors as well, apart from the irradiance, i.e. cell degradation losses. But since the modules are brand new, their performance reduction for a five-month period is not considered.

Results and discussion

Transmittance is generally defined as the ratio of incident light falling on a body to the light passing through it. As per the observation, the transmittance of the dusty slides decreases over time as dust deposition density increases. The increment of dust deposition density meant the dust layer on the glass surfaces got thickened with time which in turn blocked the solar energy transmitting through it. So dust deposition density and transmittance are inversely related to each other. Transmittance was measured for the wavelength between 200 and 800 nm. For simplification, transmittance value was taken on 3 different values: 750, 600 and 450 nm. Figure 3 denotes the transmittance reduction graph of dusty samples in 750 nm wavelength.

Another factor to consider is the solar density. It is found that the reduction in output power at relatively lower or higher solar densities is much more severe. This phenomenon is probably attributed to relatively higher reflection effect of the deposited dust to light as the certain portion of already low value of irradiance gets reflected by the accumulated dust layer (Jiang et al. 2011).

The rainfall, humidity and temperature data which were available from Department of Hydrology and Meteorology are shown in Figs. 4, 5 and 6, respectively. Whereas the Fig. 7 depicts the value of power collected by dataloggers in a clean and dusty module setup.

Dust deposition density increases as the time period of exposition increases. Natural cleaning actions of rainfall, wind speed and dew are evident in the graph as these agents lowered the dust deposition density as shown in Fig. 8. Some high values of dust deposition density are due to the bird dropping in the dust slide.

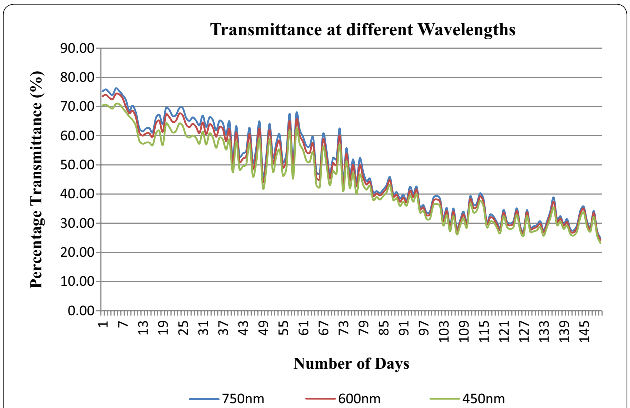

Fig. 3 Measured transmittance at different wavelengths

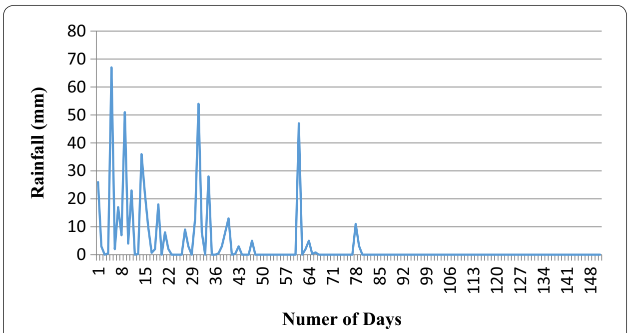

Fig. 4 Rainfall during the study period

Cumulative effect of meteorological parameters on dust deposition density

Research by Paudyal and Shakya (2016) shows a negative correlation between humidity and dust accumulation. Humidity and dust deposition density are known to involve more than one variable (Qasem et al. 2011). Wind speed can promote raised and suspended dust movement, thus promoting higher rate of dust accumulation due to surface collusion (Qasem et al. 2011). And other remaining variables such as temperature and rainfall are also known to play significant role in dust deposition. Here, the relation of all the meteorological variables under consideration with respect to dust deposition density is studied using multiple regression analysis. Cell temperature, humidity, rainfall and ambient temperature

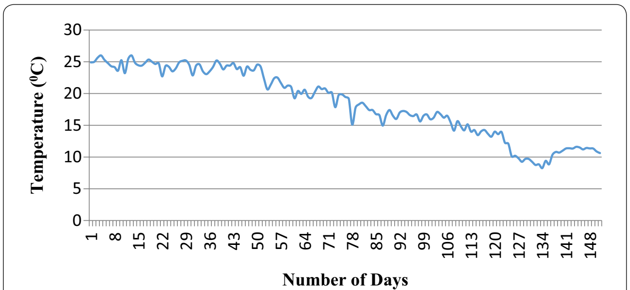

Fig. 5 Temperature variation during study period

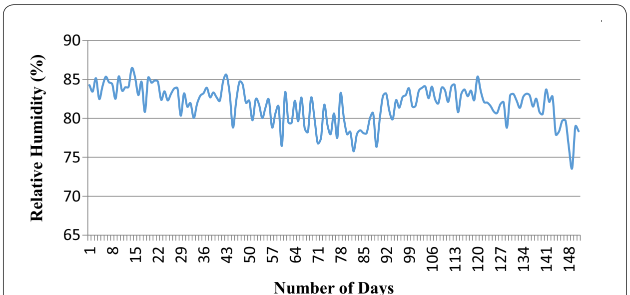

Fig. 6 Average humidity for the study period

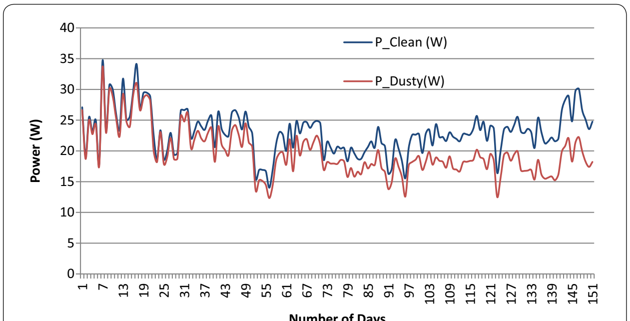

Fig. 7 Power output from clean and dusty solar modules

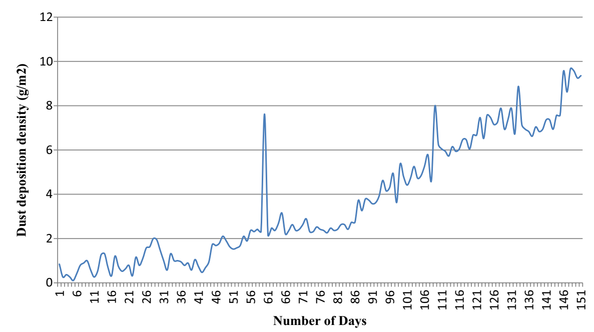

Fig. 8 Measured dust deposition density

are the independent variables for regression analysis. The operation resulted in the statistical results as given in Table 1.

The regressed model takes the form of the following equation

$$Y = A + \beta_1 * X_1 + \beta_2 * X_2 + \beta_3 * X_3 + \beta_4 * X_4, \quad (1)$$

where Y = dust deposition density on modules, A = regression coefficient, X_1 = rainfall (mm), X_2 = ambient temperature (°C), X_3 = humidity (%), X_4 = module temperature (°C).

Equation (1) reduces to the form

$$Y = 13.3843 - 0.0064 * X1 - 0.3656 * X2 - 0.0074 * X3 - 0.0642 * X4. \quad (2)$$

Effect of dust deposition density on transmittance

Dust deposition density has adverse effect on the transmittance as shown in Fig. 9. As shown in the numerous experiments performed, most notably on the research works of Elminir et al. (2006) and Gandhi et al. (2014), the strong dependence of dust deposition on the transmittance and on energy yield is verified. The reduction in transmittance in the glass samples increased before saturating as shown in Fig. 3 (Elminir et al. 2006). The correlation coefficient (r) and coefficient of determination (r^2) of −0.8690 and 0.7552 indicate a strong linear relationship between these parameters. Humidity can be considered another major factor as long expositions to humid environment cause the encapsulate delamination and is known to affect the transmittance property of laminating surface.

Table 1 Statistical parameters of multiple regression for model

Parameters	Value
R^2	0.8632
Adjusted R^2	0.8595
Coefficient of variation	0.2770
Mean square error	1.014345
Square root of MSE	1.007147

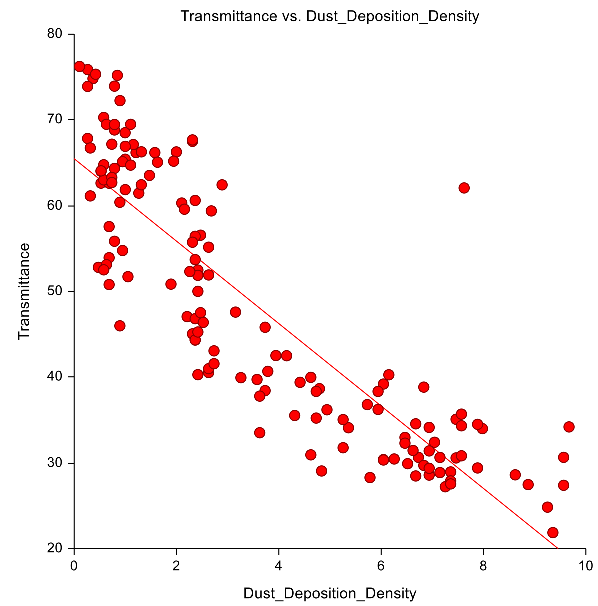

Fig. 9 Effect of dust deposition density (gm/m^2) in Transmittance (%)

Percentage transmittance loss

Percentage transmittance loss is given by Eq. (3), where τ_c is the transmittance observed for the clean glass samples and τ values depreciate due to dust deposition, that is, by prolonged exposure

$$\%\tau_{\text{reduction}} = \left(1 - \frac{\tau}{\tau_c}\right) * 100. \quad (3)$$

Basic result evident is that transmittance reduction percentage also increases with increasing days of exposure. Figure 10 depicts the percentage of transmittance loss which was mere 2.52% at the first day of experiment which rose up to 69.06% at the final day of experiment at 750 nm wavelength. The graph shows high variations in transmittance loss at the middle, which can be attributed to the formation of dew in prevalent climatic conditions. Dew promotes dust accumulation on flat surfaces and subsequent evaporation reinforces dust adhesion; in fact, it sometimes forms a solid, packed cement-like composite (Elminir et al. 2006).

Effect of transmittance on power output reduction

Over the period of study, the power output of modules decreased continuously due to dust accumulation, which resulted in reduction in transmittance. As shown in Fig. 11, the correlation coefficient (r) of −0.8904 indicates

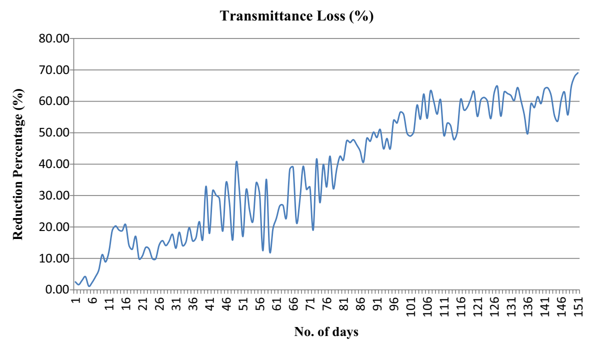

Fig. 10 Percentage loss in transmittance

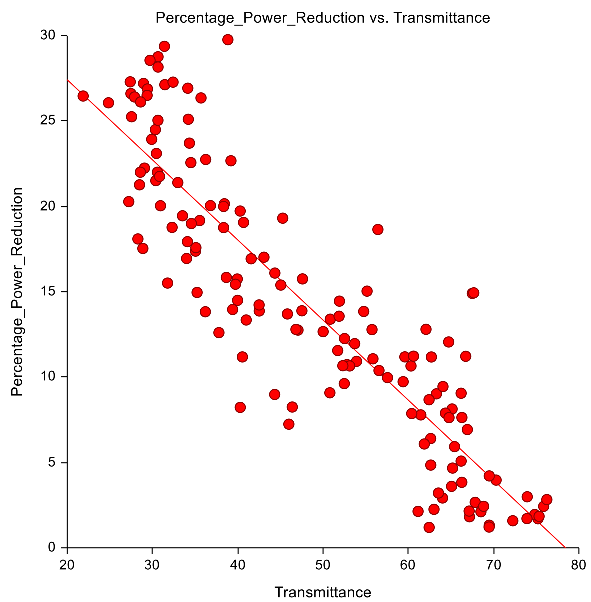

Fig. 11 Effect of transmittance on power output reduction

strong negative linear relation among these variables. Reduction in transmittance of module surface increases the output power reduction percentage of the solar modules as they are inversely related to each other. As the dust layer on the surface of PV module became thicker, the transmittance loss became alarmingly higher which triggers higher loss of module output power (Weber et al. 2013).

Conclusion

The correlation of dust deposition density with transmittance and eventually correlation of transmittance with power reduction were investigated in this paper. Dust deposition plays a crucial role in obstructing the solar irradiance reaching solar cells and reduces the transmittance of the encapsulate lamination leading to thus reduction in power generation. Voltage generated from the modules was not altered to significant levels. The dust deposition density ranging from 0.1047 to 9.6711 g/m^2 and the power reduction of 29.76% with respect to 69.06% transmittance loss can be considered high in the span of 5 months. The study enlightens the dire need of incorporating a proper cleaning device or mechanism in existing solar PV systems installed in the areas exposed to relatively high dust deposition conditions during dry season of Kathmandu to reduce power loss due to soiling. As the laminate encapsulation of the solar modules contains pores to reduce the reflectance of the solar radiation, some dust may be present in such pores which require careful cleaning. Thus, the proper cleaning mechanism for such cases should be selected and applied. Since the transmittance losses due to soiling are highly pronounced, the research shows the system design of the solar PV systems must incorporate the possible power loss from the transmittance reduction due to soiling.

Authors' contributions

BRP is a lead author and corresponding author of the research article. He contributed to performing research activities, data collection, data analysis and writing of the research article. SRS played an integral part of this research process. He contributed to the design of this research and supervision of all the related works. DPP played another integral part of this research. He contributed to the formulation of transmittance measurement, compiling and verification of the manuscript and data analysis. DDM was another prominent contributor of this research as he contributed to the formulation of transmittance measurement, analysis of the results and managing the data collection facility. All authors read and approved the final manuscript.

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Competing interests

The authors would like to confirm that there are no any competing interests associated with this publication and the research has been carried out for a purely academic purpose.

Availability of data and materials

The data and materials are available anytime from the author, as per request.

Consent for publication

The research contains the data exclusively measured for the academic research. All the contributing authors are the participants of the research and hence the article is formulated in the consent of all authors.

Ethics approval and consent to participate

Not applicable.

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