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(Research Article)

Impact of small particulate deposition on solar photovoltaic (PV) module performance

Anil Kumar Sisodia *

Department of Physics, Government Bangur Post Graduate College, Pali, affiliated to Jai Narayan Vyas University, Jodhpur (Rajasthan)-306401/India.

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Abstract

The accumulation of dust and particulate pollutants on solar PV modules significantly reduces their performance efficiency. Fine particles, such as carbon, cement, and ash powder, cause more severe efficiency drops compared to coarser materials like brick powder. These pollutants obstruct light transmission and amplify thermal effects, with carbon powder and cement dust posing the greatest challenges due to their fine particle size and high solar radiation absorption capacity. Even small quantities of carbon particles result in substantial performance degradation, highlighting their critical impact. To sustain long-term efficiency, the development and implementation of effective cleaning methods and protective measures are essential for mitigating these detrimental effects.

Keywords: Pollutants; Soiling; PV sites; Shadow effect; Power loss; Transmittance loss

1. Introduction

Figure 1 Settlement of various type of pollutants from different sources

Normally, Solar panels are typically installed in open environments, where they encounter a range of natural obstacles that can affect their performance. The efficiency of photovoltaic (PV) devices is significantly influenced by

* Corresponding author: Anil Kumar Sisodia

environmental factors such as wind, temperature, humidity, dust, pollen, soot particles, and rainfall [1, 2]. PV installations are often located near industrial zones, including coal, lime, and cement factories, which release various pollutants into the atmosphere as shown in Fig. 1. In addition, pollutants from vehicular emissions and human activities, as well as the burning of fossil fuels, further contribute to the degradation of PV performance. Among the environmental factors, the accumulation of pollutants on the PV glass surface is considered one of the most detrimental, leading to a substantial decline in performance in localized regions [3]. In urban areas, one of the most common pollutants is limestone, which results from the precipitation of calcium carbonate ($CaCO_3$) and is primarily emitted through construction activities and vehicular emissions [4]. Given the significant impact of these pollutants, it is essential to establish an effective cleaning schedule to maintain optimal PV performance [5].

1.1. Effect of pollutants on PV performance

The significant amount of particulate matter (PM2.5, PM10) and smoke are to be emitted from industries and fossil fuels combustion. The PV performance loss due to deposition of small pollutants is referred to as soiling effect. The settled pollutants on PV module glass surface absorb and backscatter significant part of the incident sun radiation, thereby reducing the conversion of photo (optical transmittance) energy to electrical energy, subsequently in lower PV device efficiency. In "*JODHPUR*" zone, The concentration of multiple industries such as coal, cement, limestone, including ash, and bricks industries shows significant loss in PV power generation. The impacts of some common pollutants on PV module mentioned below as:

1.2. Cement

Cement is another major pollutant that poses a significant threat to the efficiency of solar power generation. Cement dust is a byproduct of the cement manufacturing process, which involves the grinding of raw materials and the use of high-temperature kilns. Cement plants, especially those located near PV installations, release large amounts of fine particulate matter into the air. This cement dust, when it settles on PV panels, forms a layer that obstructs sunlight and reduces the panel's ability to generate electricity [6]. Cement particles are often more chemically reactive than other types of dust, which can lead to the formation of a corrosive layer on the surface of the panels, further accelerating the degradation of their performance. In addition, cement dust can mix with moisture in the atmosphere to form a cement slurry, which can harden on the surface of the panels and make cleaning more difficult. This creates a long-term challenge for maintaining PV panel efficiency, especially in regions with high cement production or extensive construction activity.

1.3. Bricks Powder

Bricks powder is a common pollutant in urban and industrial areas where construction activities are prevalent. During construction, particularly in brick production and construction site activities, fine particles of brick dust are often released into the atmosphere. These particles settle on various surfaces, including PV panels, where they can accumulate and form a layer of dust. This dust can significantly reduce the amount of sunlight that reaches the surface of the solar panels, leading to a decrease in their energy output [7]. The fine particles in bricks powder are abrasive and can cause micro-scratches on the glass surface of PV panels, further compromising their performance. Moreover, these particles can create a sticky surface when combined with moisture from humidity or rain, leading to a harder-to-remove layer that reduces the overall transmittance of light. The cumulative effect of bricks powder on PV panels can be particularly detrimental in regions where construction activities are frequent, potentially leading to a significant loss of energy generation over time.

1.4. Limestone Powder

Limestone powder, which is produced through the weathering of calcium carbonate ($CaCO_3$), is another pollutant that significantly affects PV performance, particularly in urban areas with high construction and vehicular activity. Limestone powder is released into the air through the precipitation of calcium carbonate, which is common in areas where limestone is mined or used in construction activities. This fine powder can accumulate on the surface of solar panels, forming a layer that obstructs sunlight and reduces the energy conversion efficiency of the panels. Limestone particles are often smaller and finer than other types of dust, making them particularly effective at settling into the crevices and pores of the glass surface [8, 9]. This can further hinder the transmission of light through the panel, causing a decline in solar energy output. In addition, the calcium carbonate content in limestone powder can react with the surface of PV panels, potentially causing long-term damage through chemical weathering or etching of the glass surface. This issue is particularly significant in urban areas where construction activities, road traffic, and industrial emissions are common sources of limestone powder.

1.5. Carbon Emissions

Carbon emissions, primarily in the form of carbon dioxide (CO_2), are the most well-known form of pollution contributing to climate change. While carbon emissions do not directly interact with the surface of solar panels, they have an indirect effect on solar power generation by contributing to the overall pollution load in the atmosphere [10]. Carbon emissions from industrial activities, vehicles, and the burning of fossil fuels can lead to the formation of particulate matter, which can settle on the surface of PV panels. Furthermore, the increase in global temperatures resulting from the accumulation of carbon emissions can affect the efficiency of PV panels. Higher ambient temperatures can reduce the voltage output of solar panels, leading to a decrease in overall power generation. The combined effect of carbon emissions on both the environmental factors influencing solar energy production and the physical degradation of PV panels underscores the importance of addressing this pollutant in the context of solar power generation.

1.6. Ash emissions

The deposition of ash on photovoltaic (PV) module surfaces can have significant adverse effects on their performance and efficiency. The impact is primarily due to the obstruction of sunlight, thermal effects, and potential long-term degradation of module materials. Here are the key points of impact: This can lead to a substantial drop in energy output, with losses depending on the ash density, distribution, and type [11, 12].

2. Experimental methodology

The study was conducted in an indoor laboratory setting where solar PV modules were tested under controlled conditions. This setup allowed for precise measurement of the effects of different types of particulate matter such as cement, brick, lime stone, carbon, and ash powder (see Fig. 2) on panel performance. They were systematically applied to the PV panels to evaluate their ouput power and optical transmittance. Dust and pollutants block sunlight, reducing sunlight availability for the photovoltaic process. Particles with specific refractive indices scatter or reflect light away from the PV cells [13]. As result, Reduced $\mathbf{P_{max}}$, due to lower irradiance reaching the PV cells.

Figure 2 A group of pollutants: (a) cement, (b) brick, (c) lime stone, (d) carbon, and (e) ash powder used in the experiment

Note down the glass coupon (10cm×10cm) were polluted uniformly sieved particles of a particular diameter range (see Table 1).

Table 1 Different pollutant's diameter range

Pollutant	**Cement**	**Bricks**	**Limestone**	**Carbon**	**Ash**
Diameter (µm)	<38	<125	<45	<25	<25

2.1. Electrical analysis

The relationship between the maximum output power and dust deposition density (gm/m^2) was examined using various pollutants (i.e., cement, bricks, limestone, carbon, and ash powder samples). The reduction in output power was calculated by comparing the maximum power output of a clean PV module, P_{max} (clean) , with the maximum power output of the module covered with small pollutants, P_{max} (pollutant), utilizing the Solar Module Analyzer PROVA 210 [14] as shown in equation (1).

$$Power\ Loss\ (\%) = \frac{P_{max}(clean) - P_{max}(pollutant)}{P_{max}(clean)} \times 100 \ \ldots\ldots\ (1)$$

In experiment, measure the maximum output power Pmax (dust) of the dust-covered module using a Solar Module Analyzer (e.g., PROVA 210) and record the power output for each size category of pollutant particles. Experiments conducted under an artificial lighting source with an intensity of 650 W/m^2 revealed a significant reduction in output power as the grain size of pollutants decreased. The layer of pollutant effectively blocks a substantial portion of light from passing through the transparent glass cover of the module, leading to a considerable reduction in power output. The effect of different pollutants deposition on PV glass cover on their output power generation capacity can be seen in Fig. 3.

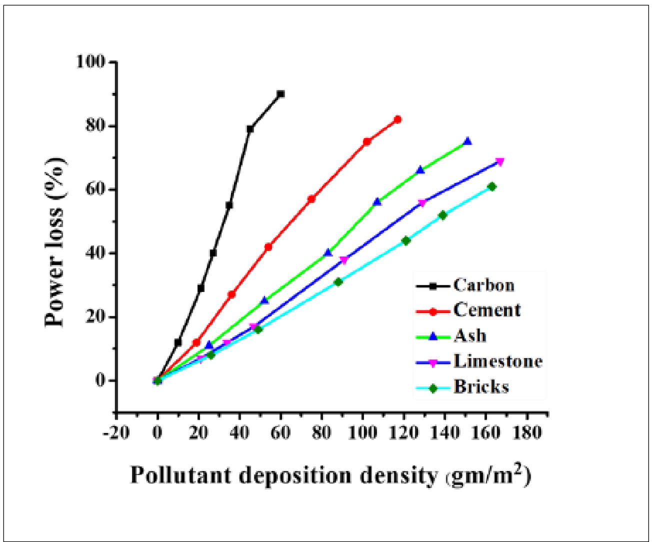

Figure 3 Effect of different pollutants deposition on Photovoltaic performance

2.2. Optical analysis

Similerly, This section describes an experiment to quantify the impact of particle (pollutant) size and deposition on the optical transmittance of a glass surface. Here's a, a glass coupon was coated with various sizes of dust particles through artificial deposition. Clean glass plates served as a baseline for comparison. The optical transmittance was assessed using a MECO solar power meter, measuring the intensity of transmitted light (in W/m^2). The transmittance loss (%) was calculated by comparing the measured transmittance through the soiled glass coupon against the clean glass plate as depicted in equation (2).

$$\Delta\tau(\%) = \frac{\tau_{max}(dust\ particles) - \tau_{max}(clean)}{\tau_{max}(clean)} \quad \ldots\ldots\ldots.\ (2)$$

As consequence, analysis of the resulting transmittance curve reveals a direct correlation between the loss in transmittance and the size of the dust particles as shown in Fig. 4. Additionally, as the rate of dust particle deposition increases, the transmittance loss also increases, but at a progressively slower rate, eventually reaching a saturation point. Beyond this limit, further dust accumulation has minimal impact on transmittance. Notably, the presence of smaller dust particles leads to a more rapid reduction in transmittance, highlighting their significant effect on optical performance.

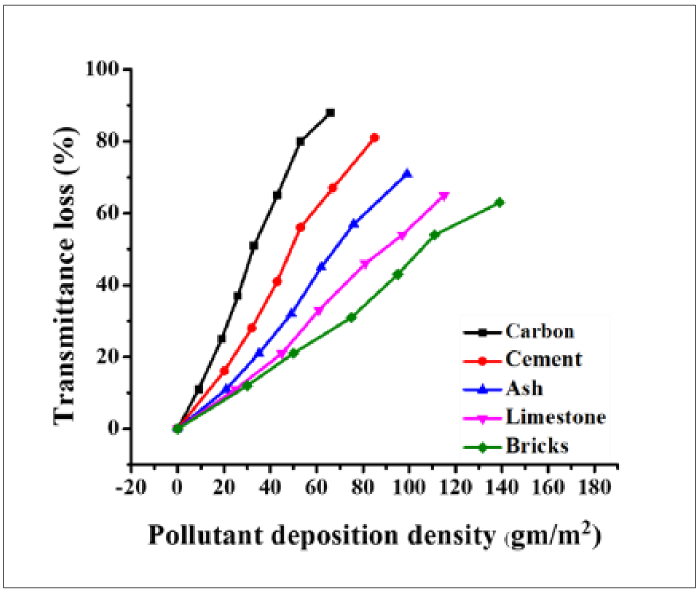

Figure 4 Effect of different pollutants deposition on optical performance of PV module.

3. Conclusion

Dust with fine particles (e.g., carbon, cement, and ash powder) results in higher efficiency drops than coarser materials like brick powder. Pollutants like cement, brick powder, limestone powder, carbon powder, and ash significantly reduce solar PV module performance, primarily by obstructing light and increasing thermal effects. Among these, carbon powder and fine particulates such as cement pose the greatest challenges. Effective cleaning and protective strategies are essential to mitigate these impacts and maintain long-term module efficiency. Furthermore, it is well-established that carbon pollutants exhibit a high capacity for absorbing solar radiation. This characteristic, combined with their physical properties, results in a significant deterioration in performance even with the deposition of a relatively small quantity of carbon particles.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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