Experimental study of dust impact on power output degradation of various photovoltaic technologies deployed in West Timor, Indonesia

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Abstract. Photovoltaic (PV) technology has been widely used as a source of electricity for household appliances, electrical vehicles, industrial and commercial systems. Energy yield by a PV panel installed in the field is dependent on the amount of photon reaching its solar cells. One environmental factor playing an important role to reduce PV power production is dust. Dust particles generated by human work and natural processes reflect, absorb and scatter solar radiation. This research examined dust effect on power degradation of several PV technologies commonly found in West Timor islands including mono-crystalline silicon (mc-Si), amorphous silicon (a-Si), and polycrystalline silicon (pc-Si) technology. Dust collected from a PV power plant in the island was coated artificially onto the front side of the PV samples. Furthermore, electrical parameters of the panels were examined using a SPIRE 5600SLP solar simulator. A HP spectrophotometer was applied to measure optical property of the dust. Results revealed that maximum power output value of all modules decreased as dust concentration increased. There is a linear relationship between PV output degradation and dust density <0.3 mg/cm². This is in line with the dust transmittance value which is linear within the density <0.3 mg/cm².

1. Introduction
A growing public awareness to address the global challenges of energy security and reduce environmental impact and dependence on fossil fuels has caused a dramatically growing demand for renewable energy sources in recent years. The International Energy Agency (IEA) data showed that renewable energy sources consisting of wind, geothermal, biomass, hydropower, and ocean shared about 983 million ton of energy (MTOE) of total primary energy supply in 2011. The value was predicted to increase and reach 2400 MTOE by 2025 [1].

Compared to other renewable energy sources, solar energy is the most abundant energy in the world that plays a significant role in energy generation mix. PV module is one of the fastest expanded technologies that have been developed to capture and convert the sun’s rays into electricity. This is indicated by the rapid increase of module installation capacity around the world. It grew from around 16 GW in 2008, crossing 227 GW by the end of 2015, and reaching 303 GW by the end of 2016 [2].

Performance of a solar panel installed in open areas is strongly affected by environmental factors including dust. PV panel performance commonly represented by its electrical parameters’ values tends
to decrease as dust covers its front side. The attached dust mitigates the illumination by absorbing, reflecting, and scattering photon to reach solar cells [3].

PV degradation caused by dust is temporary as its power output can be recovered to the maximum capacity through cleaning activities which can be performed naturally, automatically, and manually [4]. However, it should not be neglected as the negative impact caused by is relatively significant [5]. For instance, power production of PV modules in Tehran decreased by 8% after eight days of severe air pollution [6].

Since the distribution of dust impinged on a PV modules’ cover glass is far from uniform, it cells tend to work in a non-uniform condition. This, understandable, will result in a mismatch condition that causes a power degradation of the module. The entire cell of the module is forced to work following the most dust affected cell with the lowest current. If the module is a part of an array then the other modules’ power output tends to follow the affected module. Distributed maximum power point tracking [7] and reconfiguration of PV array architecture [8, 9] are the methods commonly applied to overcome the drawback effects of mismatching.

The intensity of sun light received by solar cells of a PV panel is dictated by the level of dust density. It tends to fall down as the amount of dust covers the front side of the module escarates. Kaldellis and Fragos [10], in their study reviewed power output of two pairs of identical PV modules in Greece. Results revealed that module’s efficiency went down by 1.5% when dust accumulation increased to a density of 0.4 mg/cm².

The literature revealed that response of different PV technologies on the impact of dust is different. Ferada et al. [11] who investigated the effect of natural dust on two PV technologies’ performances in Chile found that a-Si PV technology accounted higher performance degradation compared to mc-Si technology. Considering dust characteristic that dictates PV degradation is location dependent, dust effect investigation at each PV system location is strongly recommended. In addition to location, in the present study, we went further by examining the effect of dust on three PV technologies i.e. mc-Si, a-Si, and pc-Si commonly applied for PV power plants and solar home systems in West Timor, Indonesia. The study is expected to be a reference of PV modelling in the area.

2. Experimental methodology

2.1 I-V characteristic of PV modules

Three PV modules were deployed as samples of this research. The modules labelled with a-Si for amorphous silicon, pc-Si for polycrystalline and mc-Si for monocrystalline silicon had P_{max} outputs of 29.21 W, 76.04 W, and 119.35 W, respectively in clean and standard test condition (STC). Values of electrical parameters including current and voltage were recorded to assess the effect of dust on the modules. To characterize the parameters, a Spire 5600SLP sun simulator was applied. With pulse duration of 20-200 ms, the sun simulator can sweep an I-V curve within less than 1 second at STC [12].

I-V characteristic of PV module samples was initially scanned in clean condition. Afterwards, the modules were coated with a particular typical dust density before the same characterization was repeated. Levels of dust densities applied in this study i.e. 0.02, 0.04, 0.06, 0.08, 0.15 and 0.3 mg/cm². The quantities were within the range of variation of the deposited dust on PV covers at some sampling sites in the island measured before this experiment. To simulate dust deposition in the real condition, solution composed of water and dust from the field was sprayed onto the front sides of the PV modules inside a room to avoid the effect of wind. An example of a clean and a sprayed dusty panel is shown in figure 1.
To confirm its mass, the sprayed dust covering PV front side was re-collected and re-weighed after electrical performance measurement. Since the cotton under normal condition contained moisture so that it was dehumidified using a desiccator. The treated cotton was then weighed using an analytical balance to determine its clean mass ($M_{\text{clean cotton}}$ in mg). Subsequently, the cotton was wetted with water before using it to collect dust from PV cover. Collection procedure was repeated until the PV cover was clean indicating no more dust impinged on the surface. The cotton was then re-dehumidified and reweighted to determine its mass in dusty condition ($M_{\text{dusty cotton}}$ in mg). Sprayed dust density is given by [13]:

$$D_{\text{cotton}} = \frac{M_{\text{dusty cotton}} - M_{\text{clean cotton}}}{A_{\text{PV}}}$$  \hspace{1cm} (1)

where $A_{\text{PV}}$ = PV module area (cm$^2$)

2.2. Optical property of dust

In addition to the electrical characteristic of PV panels, the optical characteristic of the dust was also investigated in this experimental study. A "HP spectrophotometer" was used to measure the transmittance value of the dust. To simulate the actual condition, solution of water and dust was sprayed onto the surface of some 5x5 cm$^2$ soda lime glasses. The glasses were cleaned and weighed prior to their use to determine their clean mass ($M_{\text{clean glass}}$ in mg). Similar to the procedure applied to coat PVs’ front sides, the spraying process was performed in a room to avoid the influence of the wind. The glass samples containing dust were then weighed after coating ($M_{\text{dusty glass}}$ in mg). Mass of dust attached on glass surfaces was calculated by applying the following equation [13]:

$$D_{\text{glass}} = \frac{M_{\text{dusty glass}} - M_{\text{clean glass}}}{A_{\text{glass}}}$$  \hspace{1cm} (2)

where $A_{\text{glass}}$ = glass sample area (cm$^2$)

The glass sample containing dust was then encapsulated with another clean glass sheet to prevent dust being removed from the glass surface during the experimental process. Finally, the transmittance values of the dust were measured using a spectrophotometer.
3. Results and discussion

As described in Section 2, the effect of dust was assessed based on the degradation of the value of electrical parameters such as current and voltage. For the purpose, I-V and P-V characteristics of the three PV modules were recorded using a Spire 5600SLP sun simulator within dust level of 0 to 0.3 mg/cm$^2$. An example of the curve of the pc-Si module in clean and dusty conditions is shown in figure 2.

![Figure 2](image)

**Figure 2.** I-V and P-V curves of pc-Si module in dusty and clean conditions

The figure shows a significant degradation of PV performance characterized by a decrease of maximum power ($P_{\text{max}}$) output from 76.04 W to 70.20 W when it was subjected to dust of about 0.2 mg/cm$^2$. Furthermore, in order to compare the performance degradation of the various PV technologies due to dust, their $P_{\text{max}}$ output were compared as shown in figure 3. The figure depicts the normalization result of $P_{\text{max}}$ output of each sample using its clean condition value as a reference.
Figure 3. $P_{\text{max}}$ output degradation of PV panels affected by different levels of dust.

Figure 4. Transmittance of various densities of dust.
Figure 4 shows that as the dust concentration increases the transmittance decreases. Transmittance value and PV module power output will continue to go down along with the increasing of dust deposition on PV panel glass surface. The values will decrease progressively and reach their lowest point where the photon rays cannot pass through the dust particles. For further analysis, the average transmission along the wavelength (400-1100 nm) of each dust density is calculated and plotted in figure 5.

![Figure 5. Average transmittance for various densities of dust.](image)

In general, as described in figure 3, power output of all PV modules decreases as the dust density increases. There is a linear relationship of $P_{max}$ output of PV modules influenced by dust from the island for densities < 0.3 mg/cm². This relationship confirms that the more the dust deposits on a PV module’s glass cover, the greater it blocks light to reach PV cells. The results are in line with the transmittance values in figure 5 that demonstrate a linear relationship with the concentration of dust for densities < 0.3 mg/cm². Similar trends were also reported by Al- Hasan and Ghoneim [14], who found that deposition of sand dust in Kuwait for densities < 1.5 g/m² decreased normalized efficiency of PV modules proportionally. Klugmann-Radziemska also [15] noted that the efficiency of PV modules decreased linearly with the increasing of dust accumulation for thickness < 3µm in Poland.

Figure 3 also shows that the a-Si PV panel exhibits the largest performance degradation followed by pc-Si and mc-Si panels. This result is in line with the work completed by Ferrada et al. [11] who found that as dust impinged on its surface, a-Si PV technology accounted higher performance degradation compared to mc-Si technology. It might be attributed to the similar characteristics exhibited by the two types of dust. The characteristics could be grain size, colour, and mineral composition. Based on the explanation, this study can be expanded further by investigating the impact of various types of dust on PV panel performance.

From the trendline equation of test results in figure 2, the loss of power output of the PV samples was predicted. For the worst condition where dust can reach 0.3 mg/cm², $P_{max}$ output of the PV modules decrease by 9.2%, 7.6%, and 7.3% for a-Si, pc-Si, and mc-Si technology, respectively. These figures show significant losses that should be addressed. Further research, therefore, is needed to investigate economic losses caused by dust [16] and potential cleaning in the area [17]. Further research could also be performed to examine the effects of non-uniform dust deposition on a PV array focusing on the efforts to overcome the mismatch condition among the modules [7-9].

4. Conclusion
The impact of dust on the performance of various PV technologies was assessed in this study. It was found that the electrical parameter quantified by maximum power output (P_max output) of all PV panels decreased with the increasing of dust deposited on their front sides. There is a linear relationship of degradation of P_max output module with density < 0.3 mg/cm^2. This is in line with the optical value of the dust indicated by its transmittance value which is linear as well at density < 0.3 mg/cm^2. In addition, it was found that dust taken from a site in West Timor cause different performance degradation on the three PV technologies. According to the results, at the same mass of the attached dust, amorphous silicon (a-Si) PV module exhibited the largest maximum power output degradation followed by polycrystalline silicon (pc-Si) and monocrystalline silicon (mc-Si) technology. This result is in line with a previous work who found that as dust impinged on its surface, a-Si PV technology accounted higher performance degradation compared to mc-Si technology. It might be attributed to the similar characteristics exhibited by the two types of dust. The characteristics could be grain size, colour, and mineral composition.

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