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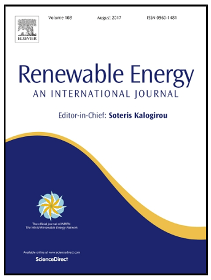

Seasonal effect of dust on the degradation of PV modules performance deployed in different climate areas

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Highlights:

- The effect of dust on PVs‘ performance varied with season
- Dust more dominant than non-dust related factors to degrade PV module performance
- More intense of cleaning should be applied for PV modules mounted at lower latitude and deployed in a tropical climate area

Seasonal effect of dust on the degradation of PV modules performance deployed in different climate areas

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Abstract

The aim of this study is to investigate the seasonal effect of dust on the degradation of PV modules deployed in two different climate areas, Perth, Western Australia, a temperate climate region and Nusa Tenggara Timur (NTT), Indonesia, a tropical climate region. Results revealed that PV performance varied with season. In Perth, the performance of PV modules which was maximal in the beginning of summer decreased significantly at the end of the season. The performance then increased back approaching the initial position at the end of autumn and reached a peak at the end of winter. Similar reduction to the summer's performance was accounted by the modules at the end of spring. Meanwhile, in NTT, the performance of PV modules was maximal in the beginning of wet season, dropped slightly at the end of the season and decreased significantly at the end of dry season. Degradation of all modules in the two sites was more affected by dust compared to the non-dust related factors. The degradation is important information for future PV design in both areas, especially in NTT which accounted greater values than the typical dust de-rating factors.

Keywords: seasonal dust, characteristic of dust, contribution of dust, PV performance

1. Introduction

Energy produced by a PV module deployed outdoors depends greatly on PV materials and solar insolation [1]. Over time, the electrical energy output will decrease, commonly due to humidity, thermal cycling, ultra-violet radiation and moisture ingress [2]. These causes lead to some permanent degradation, namely corrosion, discoloration, delamination and breakage and cracking cells [3]. Besides the internal factors, one environmental factor that significantly reduces the energy produced by a PV module temporarily is dust [1]. Even though PV performance could be recovered to its maximum capacity by cleaning activities, the effect of dust should not be underestimated [4].

Deposited dust on a PV module's cover glass diminishes the illumination by absorbing and scattering sun light received by solar cells [5]. In addition to morphology factors, the optical properties of dust are dependent on its density. The intensity of light reaching the modules tends to decline as the amount of dust deposited on module's surface increases [5-7]. Appels et al. [8] who examined the effect of different densities of dust reported that by spraying 20 g/m^2 of white sand onto the surface of a 100 W Sanyo PV module, the transmittance and power output reduced by 4.02% and 4.84% respectively. As the amount of dust increased to 40 and 60 g/m^2, the transmittance decreased as much as 9.18 and 15.03%, while power output dropped by 9.77% and 14.74%. An experiment featuring three different PV cell technologies such as mono-crystalline silicon (mc-Si), polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) performed by Jiang et al. [9] reported that efficiency of the modules decreased by up to 26% as dust deposition increased of from 0 to 22 g/m^2.

The amount of dust accumulated on a PV module's surface is affected by inclination angle of the module. Dust deposition decreases as the inclination angle of a PV module increases [5, 10]. Elminir et al. [5] in their experiments in Egypt reported that the difference of transmittance reduction for tilt angle of 0^o (dust accumulation maximum) and 90^o (dust accumulation minimum) is 21.3%. A work completed by Said and Walwil [11] in Dhahran noted that for 45 days of exposure, a 0^o glass sample was covered with about 6.5 g/m^2 of dust, while a 15^o, 60^o, 75^o and 90^o were coated with 5, 3.2, 2.2 and 0.9 g/m^2 respectively.

Dust deposition on PV modules is also driven by the material and surface texture of PV module's cover. Garg [12] who studied the effect of dust on two different materials exposed to outdoor conditions in India found that plastic collected more dust than glass. Similar result was revealed by Nahar and Gupta [13] in their work to observe optical properties of some PV covers. They reported that dust settled on glass cover was less than that impinged on acrylic and polyvinyl chloride (PVC). As a result the largest reduction of transmittance was accounted by PVC and followed by acrylic and glass.

In addition to the two factors, there are several elements of weather that also affect dust deposition on PV modules' surface including rain and wind. Rain has a dual role in terms of dust accumulation [14]. It can be a good cleaning agent when it occurs frequently and heavily as it would be able to wash away dust particles from PV module's surface. Conversely, light rain tends to drop the suspended particles from atmosphere and forms thin layers that worsen PV performance [7].

Wind contributes to dust accumulation on the surface of a PV module. Goossens et al. [15] reported that, in the morning, wind with speed of 0.57 m/s can attach 1334 $\mu g/cm^2$ of dust on PV surface with inclination of 29^o and direction of North 10^o East. Wind only can remove the dust from the PV surface at a very high velocity. Cuddihy [16] found that at a speed of 25 m/s and a relative humidity of 40%, wind can remove approximately 80% dust particles with a diameter of ≥ 50 µm, about 50% of 25 µm particles and $< 5\%$ of 10 µm particles.

The weather elements mentioned previously vary depending on the season. This affects the dust deposition on the PV modules. As a result PV performance degradation caused by dust is different seasonally. A study carried out by Kalogirou et al. [6] in Cyprus found that power output of PV modules was maximum during winter. The performance slightly decreased at a similar level during spring and autumn. A significant reduction was observed during the summer months. Seasons with less rainfall demonstrated more accumulation of dust that led to the more performance degradation. This is in line with a work by El-Nashar [17] in Abu Dhabi, UAE reported that the highest drop in glass covers' transmittance of solar desalination plant was recorded during summer. It is attributed to the greater accumulation of dust as a result of sand storms and lack of precipitation.

The present study went further by investigating the seasonal effect of dust on the degradation of PV modules deployed in two locations which have different seasons namely Perth, Western Australia and Nusa Tenggara Timur (NTT), Indonesia. This research also analyzed the contribution of dust and non-dust related factors to the degradation of PV modules at both locations over a one-year period. In addition to the factors affecting dust accumulation on PV module surface, morphology, chemical and optical properties of dust from Perth and NTT were investigated and compared as well.

2. Experimental methodology

2.1. PV performance experiment

The purpose of this study is to evaluate the effect of seasonal dust on the performance of PV modules with case studies in Perth and NTT. As a temperate climate area, Perth is situated between 31.95^o South latitude and 115.85^o East longitude. It has four seasons i.e. summer (December to February); autumn (March to May); winter (June to August); and spring (September to November). Meanwhile, NTT which is a tropical area exhibits two seasons including dry season (April to October) and wet season (November to March). It is located in the Eastern part of Indonesia with geographical situation of 10^o South latitude and 123^o East longitude.

Three PV modules featuring a-Si, pc-Si and mc-Si which represent technologies deployed in Perth were chosen randomly as samples for this research. The PV modules faced to North with an inclination angle of 32^{o} have been deployed for almost 20 years at the Renewable Energy Outdoor Testing Area (ROTA), Murdoch University. Two pc-Si and two mc-Si modules installed in 1997 at the State Polytechnic of Kupang (Politeknik Negeri Kupang (PNK)) were selected to represent PV modules in NTT, Indonesia. The modules pointed to North with inclination angle of 15^{o} were randomly selected from a PV power plant at PNK. Technical characteristics of the PV samples at the two sites provided by the manufacturers are given in Table 1.

To investigate the influence of dust on the PV modules' performance, experiments were carried out several times in accordance with the sampling sites' season. The same treatment was applied for all PV modules at both areas. To start with a clean condition, the PV samples were washed with clean water before measurements. An example of an "after cleaning" panel alongside a dusty panel at ROTA is shown in Figure 1. The PV modules were then left to be exposed to the environment without any cleaning procedures except for natural activities such as rain and wind. The PV's performance was recorded at the end of every season over the course of the study. In the last stage, PV performance was recorded in dusty and after cleaning conditions. Schedule of the measurement of PV module performance is shown in Table 2.

Methods commonly applied by researchers to monitor and assess a module's electrical performance are current voltage (I-V) and power voltage (P-V) curve scanning [18]. These curves represent the values of electrical parameters of a module such as maximum power output (P_{max}), maximum output current (I_{max}), maximum output voltage (V_{max}), open circuit voltage (V_{oc}) and short circuit current (I_{sc}).

A Prova 210 with 2% accuracy of current and voltage measurement [19] was used to analyse the I-V curve of the PV modules in the field. To get the best result, the module analyzer, which works on a range of solar insolation between 10 W/m^2 and 1000 W/m^2 and on a maximum voltage and current of 60V and 12A, respectively [19], was calibrated properly. Kipp&Zonen SP Lite 2 pyranometer positioned in the plane of the array was used to measure the solar irradiance. The instrument which has a response time of < 500 ns and working temperature from -40 ^{o}C to +80 ^{o}C [20], was equipped with a Meteon data logger with a measurement accuracy of < 0.1% [21]. In addition to the pyranometer, a digital thermometer was also deployed to measure the back side temperature of the modules. The thermometer is a T-type thermocouple with a typical percentage error of 0.75% [22].

Due to the I-V characteristic data recorded by the solar module analyser was under real operating condition (ROC), its results were transposed to standard test condition (STC) using IEC 60891 procedure 1 by deploying the following equations [23]:

$$I_2 = I_1 + I_{sc1}.\left(\frac{G_2}{G_1} - 1\right) + \alpha.(T_2 - T_1) \quad (1)$$

$$V_2 = V_1 - R_s.(I_2 - I_1) - \kappa.I_2.(T_2 - T_1) + \beta.(T_2 - T_1) \quad (2)$$

Based on the I-V curve produced by equation (1) and (2), P_{max} was obtained.

where, subscript 1 and 2: ROC and STC values respectively; I and V: current (A) and voltage (V), respectively of I-V characteristic data pairs; G: in-plane irradiance (W/m^2); T: module back side temperature (^{o}C); α: current temperature coefficient (A/^{o}C); β: voltage temperature coefficient (V/^{o}C); R_S: the internal series resistance of the test specimen (Ω); κ: curve correction factor (Ω/^{o}C); P_{max}: maximum power (W); I_{sc}: short circuit current (A); V_{oc}: open circuit voltage (V).

It is well known that I-V characteristic measurement in the field is dictated by the variation of the environmental factors such as temperature and solar irradiation. To achieve the accurate result, the performance of PV modules was recorded during daytime with irradiance from 800 to 1000 W/m^2 as measured by the Prova and stipulated in IEC 60891.

2.2. Dust density measurement

To find out the density of dust deposited on PV surfaces every season, glass samples were deployed at the sampling sites, in the beginning of November 2014 and December 2014, for PNK and ROTA sites respectively. The glass samples are 5x5 cm^2 in size and made of soda lime glass, which is a material commonly used to cover PV modules. As dust deposition is affected by the inclination angle of the PV module; the glass samples were mounted on the arms of a structure (Figure 2) which can be set to various angles to simulate the modules' inclination at ROTA (32^o) and PNK (15^o). The selected angles consist of 0^o, 30^o, 45^o and 60^o for ROTA, and 0^o, 15^o, 30^o and 60^o for PNK.

Before deploying in the field, the glass samples were weighed to obtain their clean weight (M_1 in mg). At the end of every season, glass sheets for each inclination angle were collected and taken to the laboratory. The collection task was undertaken in parallel with PV performance measurement, with schedules as explained in Table 2. The glasses were then weighed again to determine their weight in dusty conditions (M_2 in mg). Dust density (D in mg/cm^2) was calculated using formula:

$$D = \frac{M_2 - M_1}{A} \quad (3)$$

where, A= glass area (cm^2)

Each glass sample was then encapsulated with another glass sheet before performing transmittance measurements.

2.3. Dust characterization

2.3.1. Optical properties

A transmittance measurement was carried out to investigate to what extent dust particles block light. Encapsulated glass samples as described in section 2.2, representing dust density for a particular location, season (time exposure) and inclination angle, were taken to the laboratory and examined using an HP spectrophotometer.

2.3.2. Physical and chemical properties

Physical and compositional characteristics of dust from ROTA and PNK were examined in this research. A "JCM-6000 NeoScopeBenchtop" Scanning Electron Microscope (SEM) with X-ray analyser based on Energy-dispersive X-ray Spectroscopy (EDS) was used to investigate the morphology and elements of dust, respectively. Images captured by the SEM were analysed using image processing software to determine the grain size distribution of dust. In addition to EDS analysis, a X-ray diffraction (XRD) was performed to investigate the minerals composed of the elements that adhered to PV modules' surface.

For sample preparation, the surface of a stub type specimen holder was covered with an adhesive carbon tab to hold sprinkled dust. The carbon tab used in this experiment was chosen since it has significantly lower contaminant levels under the EDS process. The dust collected from the field was then deposited onto the surface of the storage container. The deposition of dust was performed by a free fall technical. The accumulated dust on the container was coated with carbon; a recommended material as it doesn't interfere with the characteristic X-ray peaks from the elements in the sample and prevents static charging of the dust before the SEM and EDS experiments were applied. Carbon coating was chosen as the focus of elemental composition tracing in this research to quantify elements in inorganic materials (materials lacking carbon) such as sand, cement and iron attached to PV module surfaces.

The research methodology of this study to investigate the effect of seasonal dust on the performance of PV modules with case studies in Perth and NTT can be summarized as shown in Figure 3.

2.4. Determining the contribution of dust and non-dust related factors

In this research, PV modules' losses commonly quantified by P_{max} [24] are classified into two types namely, losses caused by dust and non-dust related factors. The former expresses the difference of P_{max} value at the end of a period of study for a module in dusty conditions (no cleaning, dust particles still deposited on PV modules surface) and clean conditions (after dust particles are washed away). The latter indicates the difference of P_{max} value measured in clean conditions in the beginning and at the end of a period of study.

The contribution of dust (C_{dust}) and non-dust related factors ($C_{non\text{-}dust}$) on the degradation of PV modules performance over a one-year period of exposition at ROTA and PNK were calculated with the following formulas [4]:

$$C_{dust}(\%) = \left(\frac{P_{max}\ losses\ caused\ by\ dust}{total\ P_{max}\ losses}\right).100 \qquad (4)$$

$$C_{non-dust}(\%) = \left(\frac{P_{max}\ losses\ caused\ by\ non-dust\ factors}{total\ P_{max}\ losses}\right).100 \qquad (5)$$

Where total P_{max} losses is the summation of P_{max} losses caused by dust and P_{max} losses caused by non-dust related factors.

3. Results and discussion

3.1. Climatic condition of ROTA and PNK

As the existence of dust is dependent on weather elements, monthly climatic data of the two case studies locations during the study period was compiled and presented in Table 3. Climatic data of ROTA recorded every 10 minutes were accessed from the Murdoch University Weather Station [25]. It is shown that the average temperature at ROTA ranged from 13 to 25 °C with the maximum temperature reaching 44.98 °C in December. The driest month was also noted as December, whilst July was the wettest month with accumulate rainfall intensity of 146.7 mm. Similar to the rainfall pattern, the average relative humidity was high during winter season, which reached a peak at 78.75% in July. Average wind speed at ROTA at the PV modules' height (about 1.5 meters) ranged from 1.96 to 2.42 m/s. The values are the results of Synchrotac 706 series anemometer data mounted at the top of a 10 meters tower at ROTA, extrapolated down to 1.5 m using the power law formula as follows [26]:

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\alpha} \qquad (6)$$

where, V_1 and V_2 = measured and calculated wind speed (m/s), respectively; Z_1 and Z_2 = height at which the wind speed is measured and calculated, respectively (m); α = wind shear exponent (α = 0.15 as ROTA can be classified as an area with low crops, few trees and occasional bushes [27]).

During the period of study, NTT, as a tropical climate area, exhibited a steady trend in temperature (between 26 and 29.5 °C) and high relative humidity with (between 63 and 87%). The months without rainfall were June and during August to October whilst January was the wettest month with an accumulated rainfall of 659 mm. Climatic data recorded every 1 hour and provided by Bureau of Meteorology, Climatological and Geophysics of Kupang [28] also shows that temperature reached a maximum of 33.5 °C in November 2014. Wind speeds recorded at a height of 10 meters were converted to the modules' height of 1.5 meters using equation 6. Since the PNK site had similar terrain characteristics to ROTA, a roughness exponent of $\alpha = 0.15$ was again chosen and the average wind speed at PNK for the modules' height was calculated to range from 1.96 to 2.44 m/s.

3.2. Dust characterization

3.2.1. Chemical composition

Element analysis revealed that dust from ROTA consisted of O (34%) and Si (29.14%) as the major elements with some minor amounts of Ca, Al, Fe and K which account 13.21%, 9.26%, 8.83% and 5.56%, respectively. Dust from PNK was dominated by Ca (31.20%), O (26.68%), and Si (19.42) with smaller amounts of Fe, Al, K and P which are 9.03%, 7.28%, 4.08% and 2.31% of total element weight.

A mineralogical analysis was performed using X-ray diffraction to investigate minerals built of the elements. According to the result as shown in Figure 4, dust particles from ROTA were composed mostly of quartzite (SiO_2) followed by calcium oxide (CaO) and smaller amounts of some minerals from alkali feldspars group namely orthoclase and microcline ($KAlSi_3O_8$), meanwhile dust from PNK contained a large portion of calcium oxide (CaO) followed by quartzite (SiO_2) and some minor amounts of feldspars ($KAlSi_3O_8$) and berlinite ($AlPO_4$).

In addition to providing information about the type of dust, chemical composition analysis is to trace the source of dust adhered to PV modules' surface [5, 29]. This can provide useful information for dust mitigation policies and procedures. Considering Perth lies on a coastal plain dominated by acidic and sandy soils [30], erosion from the soils surrounding ROTA is likely to be the source of high portion of quartzite. Calcium oxide, which is the main component of limestone; and feldspar, which is the main component of some building materials were attributed to some building renovation works near ROTA. Calcareous soil, which is the dominant type of soil in NTT [31] is expected to be the main contributor to the higher composition of calcium oxide on PVs' surface at PNK. Quartz and berlinite could be from the erosion of sedimentary and metamorphic rocks around the site. The presence of orthoclase and microcline indicated a pollution of paint workshop located next to the plant.

3.2.2. Morphology

Figure 5 shows the SEM image of collected dust from ROTA and PNK sprinkled onto the surface of a stub type specimen storage. Referring to a standard nomenclature developed by the National Institute of Standard and Technology, USA [32], dust from ROTA (Figure 5(a)) can be classified as 'angular shape' because some particles exhibit sharp edges, while dust from PNK (Figure 5(b)) is identified as 'aggregate and porous shape' due to the dominance of porous particles.

To determine the size distribution of dust particles, SEM images representing dust from ROTA (magnification 450 times) and PNK (magnification 200 times) were analysed using image processing software and classified based on their diameter. The grain size analysis result of randomly sampled particles (Table 4) reveals that the percentage of clay and very fine silt of the dust from ROTA is higher than that from PNK. In other words, dust from ROTA is finer than dust from PNK. Consequently, it would have a greater potential to block light as it was distributed more uniformly on the module's surface so that areas of the voids between the particles through which light can pass were more minimal [7].

3.3. The effect of season and inclination angle on dust accumulation

By applying procedures as described in section 2.2, dust deposition data in both locations were obtained. Figure 6 shows that the amount of dust accumulated on a glass sample's surface varies with season. For ROTA, the highest dust density at each inclination angle was performed by glass samples collected at the end of summer followed by spring, autumn and winter as depicted in Figure 6(a). Meanwhile, the greater accumulation of dust at PNK was contributed by glass samples collected at the end of dry season as presented in Figure 6(b). Taking into account the climatic condition of both sites in Table 3, it can be stated that seasons with less rainfall demonstrated more accumulation of dust compared to those with greater rainfall.

Based on the inclination angle, the two areas show a similar pattern. Glass samples with 0° of inclination accounted highest density of dust, followed by 30°, 45° and 60° for ROTA, while 15°, 30° and 60° for PNK. As the tilt angle increased the dust deposition decreased.

To carry out further analysis, several assumptions were made. Firstly, the deposited dust on a glass sample's surface is similar to that impinged on a PV module's cover at the same location, season and tilt angle. Secondly, there is a linear relationship of dust density among the consecutive angles in a season so that dust density at an unidentified angle can be determined by performing a linear regression.

It is found that in some similar conditions, dust accumulation on PV modules' surfaces at ROTA is less than that at PNK. For the driest seasons, deposited dust on PV modules at ROTA with inclination angle of 32° was 0.17 mg/cm^2 recorded at the end of summer season, while modules at PNK with inclination angle of 15° were covered with 0.37 mg/cm^2 of dust at the end of dry season. For the wettest seasons, the accumulation of dust at ROTA and PNK was 0.038 and 0.168 mg/cm^2 noted at the end of winter and wet seasons respectively. The differences are attributed to the higher tilt angle of PV modules deployed at ROTA; as a result dust rolls off easily due to the gravitation effect or is cleaned off by natural cleaning agents. In addition, the shorter summer season at ROTA (3 months) caused less dust accumulated on PV modules' surface. Higher relative humidity in NTT is also a reason as it supports the cementation process of dust on PV surface [16].

3.4. The effect of season and inclination angle on transmittance

Transmittance results of the glass samples collected at the end of every season revealed that all spectras were fairly flat over the wavelength range from 400 to 1100 nm, although the curves approach zero transmittance for the ultraviolet (UV) end of the spectrum due to the glass absorbing the UV. In order to determine transmittance of dust only, the clean spectra was subtracted from the dusty glass transmission spectra. Their average results are presented in Figure 7.

The highest average transmittance of dust from ROTA at each inclination angle was contributed by glass samples collected at the end of winter followed by autumn, spring and summer as shown in Figure 7(a). For samples from PNK, the higher values of average transmittance were accounted by glass samples collected at the end of wet season as depicted in Figure 7(b). Greater rainfall seasons exhibited higher average transmittance. In addition to the season, average transmittance of dust is also affected by inclination angle. Glass samples deployed at ROTA with inclination of 60° performed the highest average transmittance of dust, followed by 45°, 30° and 0°. Similar trend was also shown by samples at PNK in which the highest value was recorded by samples with inclination of 60°, followed by 30°, 15° and 0°. As the tilt angle increases the average transmittance of dust increases.

The pattern of transmittance results in Figure 7 is in agreement with the trend of dust accumulation in Figure 6 where the greater the rainfall and the higher the tilt angle, the less accumulated dust on PV surface; as a result the higher the transmittance value.

By comparing Figure 7(a) and (b), it can be seen that there is a significant difference of average transmittance at both locations for the wettest seasons. At the end of winter, PV modules at ROTA with inclination angle of 32° which accounted 0.038 mg/cm^2 of dust (Figure 6(a)) exhibited average transmittance as much as 93.37%. Meanwhile, at the end of wet season, PV modules at PNK mounted at 15° tilt angle with 0.168 mg/cm^2 of dust (Figure 6(b)) performed 78.24% of average transmittance. A notable difference is also shown during the driest seasons. At the end of summer and dry seasons, dust from ROTA and PNK with density of 0.17 and 0.37 mg/cm^2 demonstrated 80.77 and 61.24% of average transmittance. These differences are attributed to the reasons as explained in section 3.3.

3.5. The effect of seasonal dust on PV performance degradation

P_{max} output of PV modules deployed at ROTA and PNK was recorded using a solar module analyser at the end of every season according to the schedule presented in Table 1. The performance results were then transposed to standard test conditions (STC) by applying equation 1 and 2. To compare the PV modules' performance, the transposed result of each PV module was normalized using its P_{max} ouput value in clean condition. The reference was measured at the initial stage of this study. Results are depicted in Figure 8 and 9. These figures show the uncertainties of all instruments (2.85%) deployed for PV performance experiment mentioned in section 2.1. The value is the sum of percentage uncertainty of the equipment combined [33].

Figure 8 indicates that normalised P_{max} output of PV modules at ROTA varies with season. Starting in a clean condition in the beginning of December 2014, P_{max} output of the modules was maximal. It then decreased after the modules being exposed to the elements for 3 months measured at the end of summer. This was caused by the accumulation of dust which blocked light that would be converted into electrical energy. From Figure 6(a), the calculation result revealed that PV modules at ROTA were covered by 0.17 mg/cm^2 of dust at the end of the season. The amount of dust reduced the average transmittance to 80.77% (Figure 7(a)). Table 3 indicates less rainfall occurred during this season. The meteorological data of Perth was retrieved from the Murdoch University Weather Station [25] revealed that, there were only 3 occasions of rain with an average intensity of 0.2 mm in the second and the third day of February 2015. These rains were expected to exacerbate dust concentration as it dropped suspended dust particles in the atmosphere and formed thin layers on modules' surface. Similar to the rain, wind with velocity ranged from 2.29 to 2.42 m/s (Table 3) was not able to remove dust accumulation on PVs' surface.

The performance of PV modules then increased back during autumn and reached a peak at the end of winter (August 2015). Great rainfalls as summarised in Table 3 were the major factor contributed to the improvement of PVs' performance as it could wash away dust from the PVs' surfaces. Dust concentration decreased from 0.16 mg/cm^2 at the end of summer to 0.057 and 0.038 mg/cm^2 at the end of autumn and winter respectively. Consequently, the average transmittance increased from 80.77% at the end of summer to 91.30 and 93.37% at the end of autumn and winter respectively. Greater rainfall in winter than that in autumn was the reason of the difference of dust density and transmittance results at the end of both seasons.

The PV modules' performance dropped again at the end of spring. The calculation result revealed that dust density increased from 0.038 mg/cm^2 at the end of winter to 0.108 mg/cm^2 at the end of spring. As a result transmittance decreased to about 15.5% (Figure 7(a)). Murdoch weather data [25] revealed less rainfall during November. There were six occasions of rain that occurred during November. It happened five times at the first and second day of the month and once on the eighteenth day with average intensity of 0.1 mm. Similar to the summer season, performing low intensity and frequency, the rainfall could not wash the dust away from PV surface. Conversely, it tends to drop dust from the atmosphere and accumulate it on the PV surface [7]. As a result, dust is continually sticking and worsening the performance of the modules.

Another point to be noted is that at the end of spring, P_{max} degradation of PV 1 (mc-Si) and PV 2 (pc-Si) was lower than that at the end of summer. The performance of the two modules is not in agreement with the dust density and the transmittance results during spring.

This is attributed to more dust covered the panels compared to glass samples used to measure dust density and PV 3 (a-Si). The location of the two PV modules is closer than the glass samples and PV 3 (a-Si) to the road used to access several buildings renovated during the season at ROTA.

By applying a manual cleaning procedure at the end of the study period (spring), the performance of PV modules was restored. The improvement values were lower than initials' performance recorded in the beginning of December 2014. This is attributed to the permanent degradation caused by non-dust related factors.

Similar to ROTA, the performance of PV modules deployed at PNK was different every season as shown in Figure 9. Normalised P_{max} output of the modules decreased slightly from maximum performance in the beginning of wet season (clean) to values between 0.96 and 0.98. These results were recorded after 5 months of exposure and measured at the end of wet season (March 2015). From Figure 6(b), it can be seen that the accumulation of dust on PV modules' surfaces at the end of wet season is 0.168 mg/cm^2 at 15^o inclination angle. As a result, the average transmittance decreased to 78.24% (Figure 7(b)). Table 3 shows great rainfalls occurred during wet season which reached a peak in January. However, the rains could not clean the PV modules perfectly. It is attributed to the lower tilt angle of modules at PNK (15^o) which decreased the movement of rain water to wash away dust. Also, rain only effectively removes bigger particles [8] so that the smaller particles of dust remained attached on PV surface.

The performance of PV modules continually decreased and reached its lowest point after exposing for 7 months over the dry season. The considerable reduction is in line with the large amount of dust impinged on PV surface i.e. about 0.4 mg/cm^2 recorded at the end of the season (Figure 6(b)). Due to the deposited dust, transmittance decreased to 61.24% as shown in Figure 7(b). Table 2 shows that there were almost 5 months passed without rain before the measurement of PV performance taking place. As a result dust continued to accumulate on PV modules' surface. The condition was aggravated by the higher humidity at the site i.e. between 63 and 79%. Consequently, dust lifted by wind and other activities in the environment would be cemented on PV surface easily.

By performing a manual cleaning procedure at the end of dry season, the performance of the PV modules was restored. Non-dust related factors caused the PVs' P_{max} output was lower than initial's performance values recorded in the beginning of summer in 2014.

3.6. Contribution of dust and non-dust related factors on PV performance degradation

Table 5 and Table 6 show the contribution of dust and non-dust related factors to the performance degradation of PV modules at ROTA and PNK over a one-year period of exposure calculated using equation 4 and 5.

According to the results, total P_{max} losses of the modules deployed at ROTA ranged from 6 to 8%, and from 16 to 19% for modules at PNK. These losses were mostly contributed by dust in which about 65 to 72% and 73 to 81% of the total power degradation of PV panels at ROTA and PNK respectively. Meanwhile, the contribution of non-dust related factor was from 28 to 35% and from 19 to 27% for ROTA and PNK respectively. These results are in contrast with our previous study on some PV modules deployed at ROTA for more than 18 years without any cleaning procedures [4]. The study revealed that power output losses of PV modules are mostly due to non-dust related factors which accounted about 71% to 84%. Thus, it is safe to say that dust seems to be more dominant than non-dust related factors to degrade PV module performance in a short term deployment.

Table 5 and Table 6 also present the percentage values of P_{max} losses caused by non-dust related factors at both locations after a one-year period. The degradation is from 2.09% to 2.64% for modules at ROTA and between 3.44% and 4.26% for modules at PNK.

The degradation values are very high compared to the calculation results of degradation rate per year of the modules, which is from 1.42% to 2.46% as presented in Table 7 and 8. In addition to the uncertainty of the applied instrument, this indicates a variation from the long term average where some years will be higher and some lower. It could be predicted that over the time of the measurements, the degradation is increasing due to the age of the modules. For a long time period (almost 20 years), parts of the modules experienced deterioration leading to permanent and significant power loss [2, 34] due to weathering and air pollution [34]. Lack of regular maintenance applied for the modules aggravated the performance degradation [35]. Various degradation effects including delamination, encapsulant browning, and corrosion of junction box connections were observed on the selected PV modules.

As mentioned above that the performance degradation of the modules is affected by their age, a further research which deploys new PV modules in the two areas is needed. By neglecting aging factor, the effect of seasonal dust on the degradation of PV modules can be assessed accurately. In addition, more frequent observations of dust deposition and PV performance can be performed through the seasons.

3.7. The impact of the study on solar PV application

A factor considered in PV system design is the dust de-rating factor. Typical value of power losses due to dust applied for a design is around 2 to 5% [36]. Table 5 and Table 6 show that P_{max} losses caused by dust are from 4.03 to 6.11% for modules at ROTA, and from 12.36 to 15.16% for ones at PNK. These results are very important information for future PV project design in the two sites. In particular in NTT the de-rating from the measured dust accounted larger losses than would conventionally be expected. An underestimated de-rating factor employed in a PV design will affect the reliability of the system to supply load.

The loss of power caused by dust is a serious problem for PV applications, mainly in a small scale project. A simple analysis allows us to assess the significant effect of dust. From Table 5 and 6, it can be seen that the most dust-affected PV module is PV C (pc-Si) deployed at PNK. The module lost 10.92 watts of its power output at the end of dry season. Considering that the site receives an average of 6.3 peak sun hours per day during the season (April – October) [37], then at least 69 Wh of electricity would be lost by the module every day. If this PV module was employed for a solar home system (SHS), the extra power from a cleaned panel could be used to supply basic lighting, such as a 5 watt light emitting diode lamp. It is equivalent to 300 lumen [38] - the minimum requirement lighting for a reading activity [39], for about 14 hours.

Based on the analysis above, some efforts including cleaning procedures are needed to keep PV modules at their best performance. Results show that PV modules in NTT, a tropical climate area, are more affected by dust compared to that in Perth, a temperate climate region. It is attributed to the lower tilt angle of PV modules, the longer summer season and higher relative humidity in NTT. From this study, it can be suggested that more intense of cleaning should be applied for PV modules mounted at lower latitude and deployed in a tropical climate area.

4. Conclusion

The results indicate that PVs' performance represented by normalised P_{max} output varied with season. In Perth, the performance of PV modules which was maximal in the beginning of summer decreased significantly at the end of the season. The performance then increased back approaching the initial position at the end of spring and reached a peak at the end of winter. Similar reduction to the summer's performance was accounted by the modules at the end of spring. Meanwhile, in NTT, the performance of PV modules was maximal in the beginning of wet season, dropped slightly at the end of the season and decreased significantly at the end of dry season. Rainfall was the main natural cleaning agent to reduce dust accumulation on PVs' surface deployed in the two sites. It was found that the degradation of all modules is more affected by dust compared to non-dust related factors for a short term period of study. P_{max} losses caused by dust ranged from 4 to 6% and 16 to 18% for PV modules in Perth and NTT respectively. The higher losses exhibited by modules in NTT are attributed to the lower tilt angle of the modules, the longer dry season and the higher relative humidity in the area. The losses results are important information for the future PV design in both areas, especially in NTT which accounted greater values than the typical dust de-rating factors. It can be suggested that more intense of cleaning should be applied for PV modules mounted at lower latitude and deployed in a tropical climate area.

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Figure 1. After cleaning and dusty PV panels

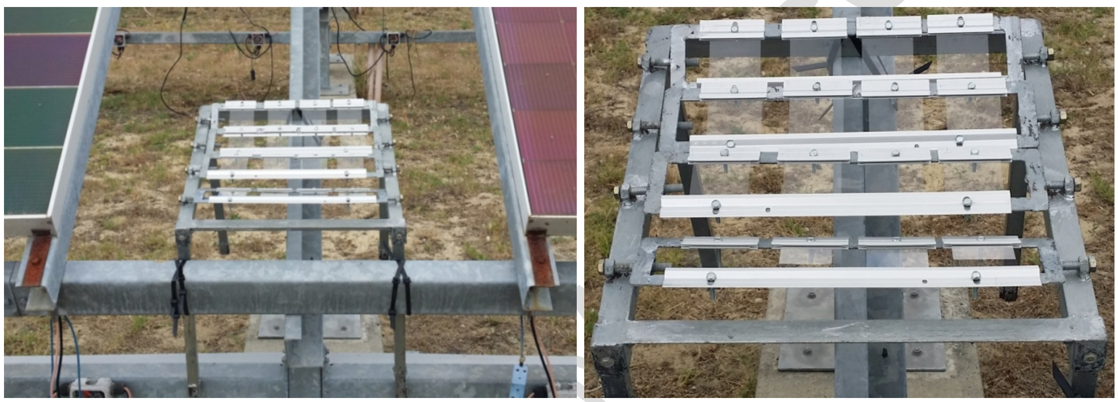


Figure 2. A structure and its close-up appearance that was used to hold glass samples at ROTA

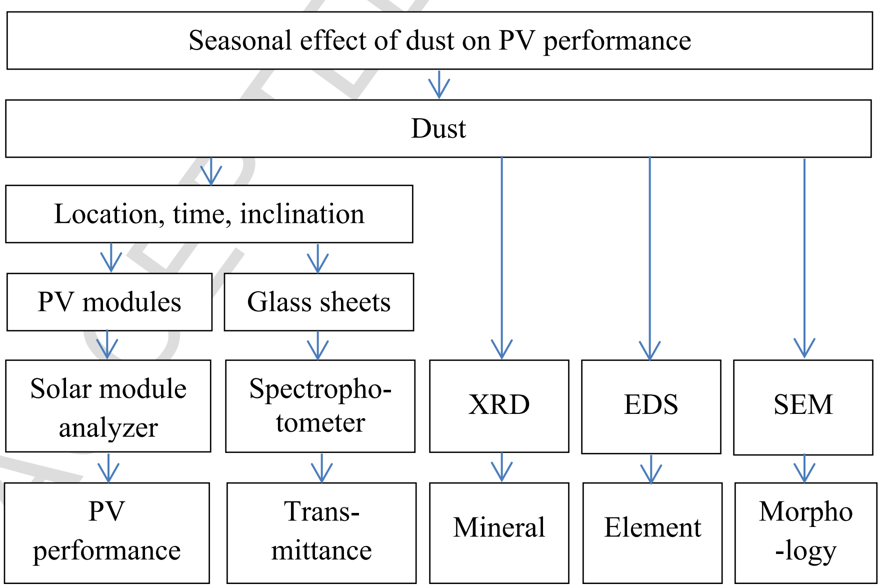


Figure 3. Methodology to study the effect of seasonal dust on the performance of PV modules

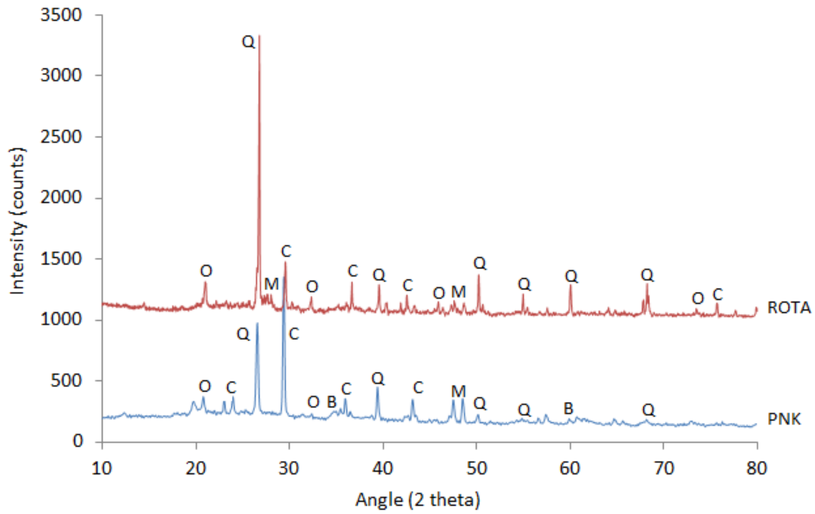
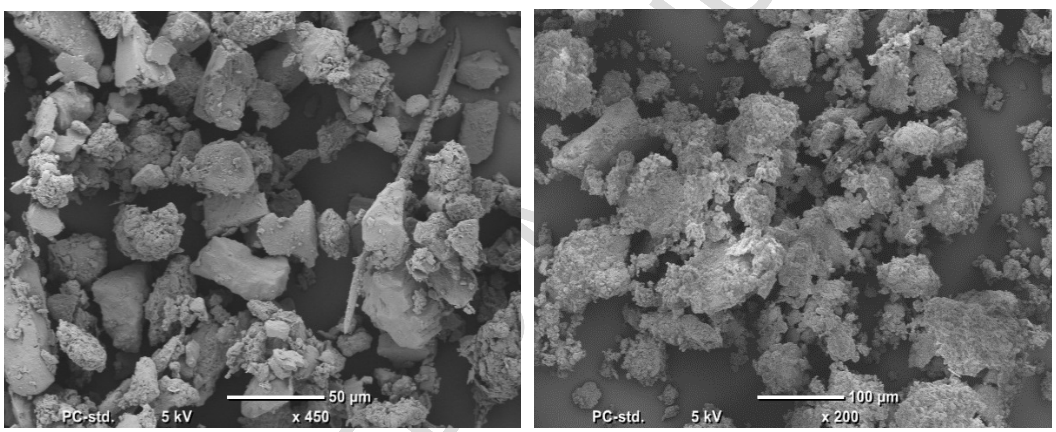
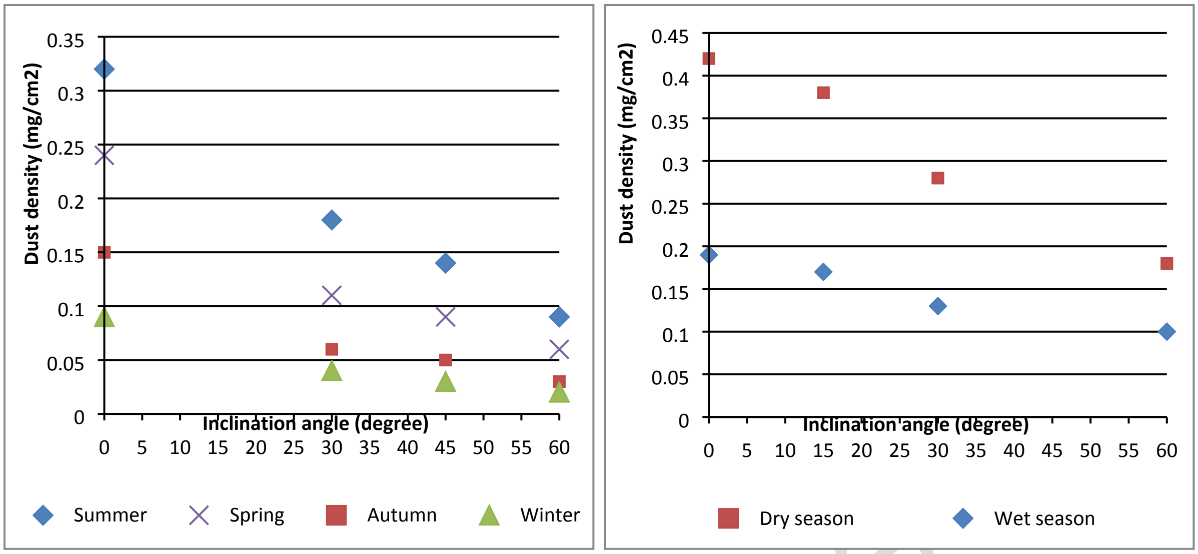


Figure 4. Analysis results of X-ray diffraction spectrum of minerals of dust from ROTA and PNK (Q: quartz, C: calcium oxide, M: microcline, O: orthoclase, B: berlinite)



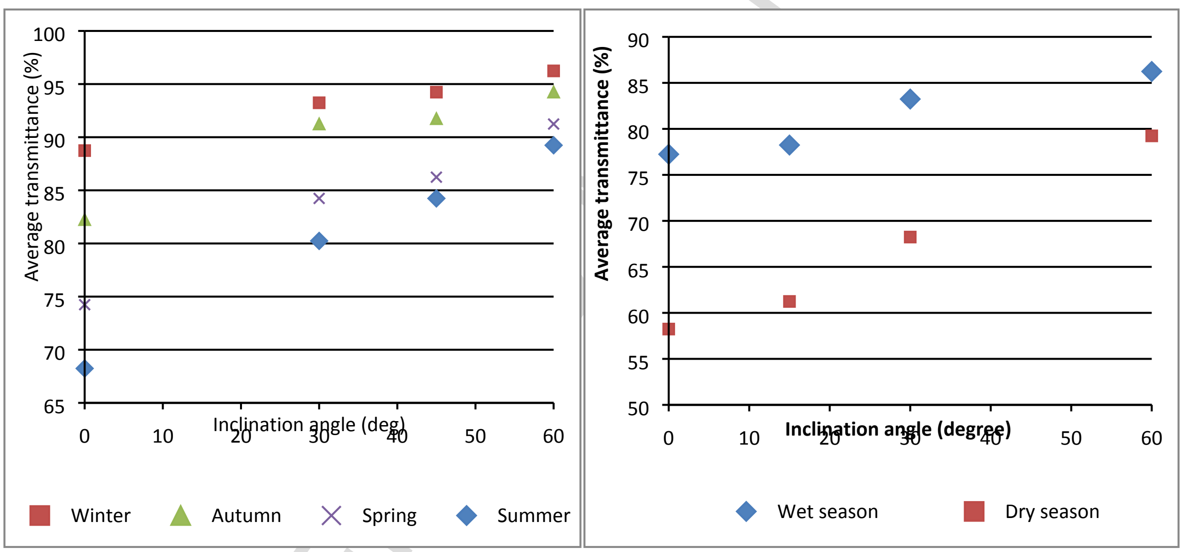
(a). ROTA (b). PNK

Figure 5. SEM images of dust



(a). ROTA (b). PNK

Figure 6. Deposited dust at different seasons and inclination angles



(a). ROTA (b). PNK

Figure 7. Average transmittance of dust at different seasons and inclination angles

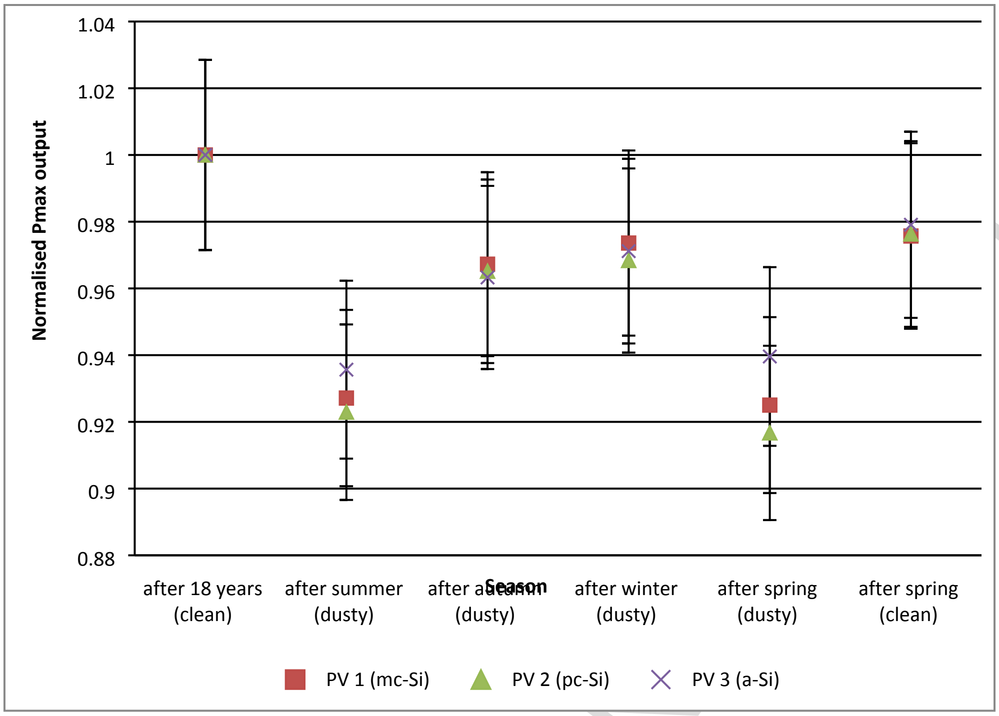


Figure 8. Performance of PV modules every season at ROTA

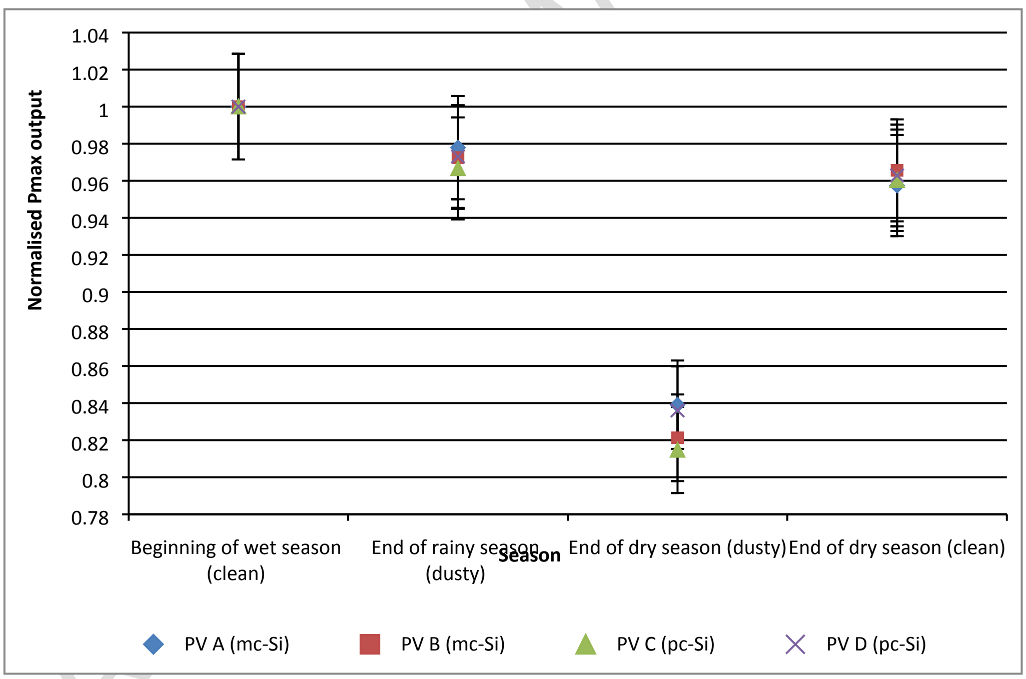


Figure 9. Performance of PV modules every season at PNK

Table 1. Technical specification of PV modules at ROTA and PNK

Location	PV module	Pmax (W)	Isc (A)	Voc (V)	Ipm	Vpm
ROTA	PV 1 (a-Si)	40	2.54	21.8	2.31	17.3
	PV 2 (pc-Si)	108.2	3.35	43	3.2	33.8
	PV 3 (mc-Si)	129	5.5	33	4.91	26.2
PNK	PV A & B (mc-Si)	100	5.78	22.5	5.35	18.7
	PV C & D (pc-Si)	100	5.58	22.68	5.26	19.01

Table 2. Schedule of PV performance measurement

Location	Time	PV condition
ROTA	Beginning of December 2014	Clean
	At the end of February 2015 (summer)	Dusty
	At the end of May 2015 (autumn)	Dusty
	At the end of August 2015 (winter)	Dusty
	At the end of November 2015 (spring)	Dusty and clean
PNK	Beginning of November 2014	Clean
	At the end of March 2015 (wet season)	Dusty
	At the end of October 2015 (dry season)	Dusty and clean

Table 3. Monthly climatic condition of ROTA and PNK over the period of study [25, 28]

Month	Average temperature (°C)		Maximum temperature (°C)		Accumulated rainfall (mm)		Rainy days		Average wind speed (m/s)		Average relative humidity (%)	
	ROTA	PNK	ROTA	PNK	ROTA	PNK	ROTA	PNK	ROTA	PNK	ROTA	PNK
Nov '14	19	28.6	38.32	33.5	13	20	7	4	2.27	2.39	60.91	78
Dec '14	21.27	29	44.98	32	1	201	1	14	2.39	2.44	51.82	82
Jan '15	24.58	27.9	38.99	30.8	2.5	659	1	23	2.42	2.29	44.96	84
Feb '15	24.36	27.3	35.76	31.2	23.2	112	3	17	2.29	2.29	57.29	85
Mar '15	22.15	27.2	29.89	31.4	16	339	5	16	2.29	2.38	55.46	87
Apr '15	19.1	28.1	26.07	33.3	44	61	8	4	2.38	2.02	58.07	79
May '15	14.77	27.3	25.33	32.9	72.5	13	6	2	2.02	2.15	67.24	74
Jun '15	14.83	26.8	22.63	32.5	62.5	0	9	-	2.15	1.96	73.42	71
Jul '15	13.45	26.2	27.72	31.9	117.5	4	17	1	1.96	2.12	78.75	70
Aug '15	14.01	26.1	32.06	32.1	70	0	13	-	2.12	2.21	74.11	67
Sep '15	15.39	26.7	33.74	32.3	33.8	0	6	-	2.21	2.08	62.13	69
Oct '15	18.97	27.8	39.6	32.6	47	0	6	-	2.08	2.28	65.09	63
Nov '15	20.84	29.5	38.32	33.3	16.7	17	6	3	2.28	2.39	58.98	76

Table 4. Grain size distribution of dust from ROTA and PNK

Diameter (µm)	Percentage of the total sample from ROTA	Percentage of the total sample from PNK	Grain type
< 4	67.34%	57.34%	Clay
4-8	22.24%	18.41%	Very fine silt
8-16	7.25%	12.53%	Fine silt
16-31	2.18%	8.27%	Medium silt
31-63	0.78%	2.28%	Coarse silt
63-125	0.21%	1.17%	Very fine grained

Table 5. Contribution of dust to PV performance degradation at ROTA over 1 year

PV module	P_{max} output (W)			P_{max} losses caused by				Total P_{max} losses		C_{dust}	$C_{non\text{-}dust}$
				dust		non-dust					
	i	ii	iii	W	%	W	%	W	%	%	%
PV 1 (a-Si)	25.33	23.8	24.8	1	4.03	0.53	2.09	1.53	6.12	65.36	34.64
PV 2 (pc-Si)	80.51	73.8	78.6	4.8	6.11	1.91	2.37	6.71	8.48	71.54	28.46
PV 3 (mc-Si)	94.7	87.6	92.2	4.6	4.99	2.5	2.64	7.1	7.63	64.79	35.21

Note: i: beginning of summer and clean (2014); ii: after spring and dusty (2015); iii: after spring and clean (2015); C_{dust}: contribution of dust factor; $C_{non\text{-}dust}$: contribution of non-dust related factor

Table 6. Contribution of dust to PV performance degradation at PNK over 1 year

PV module	P_{max} output (W)			P_{max} losses caused by				Total P_{max} losses		C_{dust}	$C_{non\text{-}dust}$
				dust		non-dust					
	i	ii	iii	W	%	W	%	W	%	%	%
PV A (mc-Si)	63.4	53.2	60.7	7.5	12.36	2.7	4.26	10.2	16.62	73.53	26.47
PV B (mc-Si)	58.2	47.8	56.2	8.4	14.95	2	3.44	10.4	18.39	80.77	19.23
PV C (pc-Si)	75	61.1	72.02	10.92	15.16	2.98	3.97	13.9	19.13	78.56	21.44
PV D (pc-Si)	78.1	65.3	75.2	9.9	13.16	2.9	3.71	12.8	16.87	77.34	22.66

Note: i: beginning of wet season and clean (2014); ii: after dry season and dusty (2015); iii: after dry season and clean (2015)

Table 7. Degradation rate of PV modules at ROTA

PV module	P_{max} (W)			Total degradation after 18 years (%)	Degradation rate per year (%)
	Initial (1996)	Beginning of summer (2014)	After Spring (2015)		
PV 1 (a-Si)	40	25.33	24.8	36.68	2.04
PV 2 (pc-Si)	108.2	80.51	78.6	25.59	1.42
PV 3 (mc-Si)	129	94.7	92.2	26.59	1.48

Table 8. Degradation rate of PV modules at PNK

PV module	P_{max} (W)			Total degradation after 17 years (%)	Degradation rate per year (%)
	Initial (1997)	Beginning of wet season (2014)	After dry season (2015)		
PV A (mc-Si)	100	63.4	60.7	36.6	2.15
PV B (mc-Si)	100	58.2	56.2	41.8	2.46
PV C (pc-Si)	100	75	72.02	25	1.47
PV D (pc-Si)	100	78.1	75.2	21.9	1.29