The Effect of Dust on the Performance of Solar Photovoltaic Module: Case Studies in Nusa Tenggara Timur, Indonesia and Perth, Western Australia

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This thesis is presented for the degree of Doctor of Philosophy of Murdoch University 2018
Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary education institution.

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ABSTRACT

The performance of a PV module tends to decrease as dust impinges onto its cover surface. The attached dust diminishes the illumination by absorbing and scattering sunlight received by the solar module. Degradation caused by dust is temporary, but it should not be underestimated. Many studies investigated the influence of dust accumulation on optical properties and its impact on PV module performance. However, less attention was given to the effect of dust on small scale PV systems such as residential systems. Also, most of the preceding literature were not supported with an economic analysis which can inform maintenance activity scheduling. This study aims to identify the effect of dust on the performance of solar PV modules in varying environmental conditions and cost effective maintenance schedule for both solar home system and residential grid-connected system.

To study the effect of dust on PV performance in different climate areas, research was conducted in Nusa Tenggara Timur (NTT), Indonesia and Perth, Western Australia. A series of experiments in the laboratory was performed. A solar simulator was used to measure PV modules’ performance. A combination of a spectrophotometer, scanning electron microscope, electron dispersive spectroscope and an X-ray diffraction machine were used to examine properties of dust. In addition to the laboratory experiments, a field study was carried out to investigate the effect of dust accumulated naturally on PV performance degradation deployed in the two regions.
Characterization results revealed that dust in Perth exhibited angular shapes dominated by quartz, while porous particles with a large amount of calcium oxide were observed in dust from NTT. The grain size analysis showed that the percentage of clay and very fine silt of dust from Perth was higher than that from NTT. Therefore, at the same density, dust from Perth passed less light than that from NTT. Power output produced by PVs coated artificially with dust from Perth was lower than that from NTT although the difference was not statistically significant.

The performance degradation of PV modules deployed in the field varied with season. In Perth, power output of the modules which was maximal at the beginning of summer decreased significantly at the end of the season. The performance was then increased, approaching the initial position at the end of autumn and reached a peak at the end of winter. A similar decrease in the summer’s performance was observed in the modules at the end of spring. In NTT, the performance which was maximal at the beginning of wet season dropped slightly at the end of the season and had significantly decreased at the end of the dry season.

PV performance variations were in agreement with dust density deposited on the examined PV modules. Seasons with less rainfall demonstrated more accumulation of dust compared to those with greater rainfall. In addition, as the tilt angle increased dust deposition decreased; as a result, the average transmittance of dust increased. For a one year period, power loss of PV modules due to dust was 4 - 6% and 16 - 18% for Perth and NTT, respectively. The greater degradation in NTT is attributed to the lower tilt angle of the PV modules, the higher relative humidity, and the longer dry season in the region.
The effect of dust on PV performance for a long time period carried out in Perth revealed that the degradation of $P_{\text{max}}$ output of PV samples deployed for almost 18 years without any cleaning procedures were 8 - 12%. These losses are higher than that measured for the one year period and indicate that natural cleaning agents such as rain and wind could not remove dust particles attached on the surface of the PV modules perfectly. In addition to the power decrease, observation results in the field showed that the modules exhibited some permanent degradation indicated by corrosion, delamination, and discoloration. This may be attributed to hot spot phenomenon caused by dust for a long time period besides the age of the examined PV modules.

Economic analysis revealed that annual cost of production losses of residential PV systems in Perth and NTT with a degradation pattern as measured in the field was higher than the maintenance cost activities. Consequently, the system in Perth needs once cleaning in a year, meanwhile twice for the system in NTT. This thesis, therefore, suggested more intense cleaning should be applied for PV modules mounted at lower latitude and deployed in a tropical climate area.

Standard dust de-rating factor (5%) stipulated by Australian/New Zealand Standard 4509.2:2010 was appropriate for modelling a grid-connected PV system in Perth, but, the system required cleaning once per year. Conversely, the standard soiling loss factor of 5% was not suitable for solar home system modelling in NTT as the estimation of the impact of dust was underestimated. Thus, this thesis recommended that the soiling de-rating factor should vary between regions and with season. This will improve the accuracy and the reliability of PV system models.
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CHAPTER 1

GENERAL INTRODUCTION

1.1. Background

In order to address the global challenges of energy security and reduce the environmental impact of, and dependency on, fossil fuels, the demand for renewable energy sources consisting of solar, wind, geothermal, biomass, hydropower, and ocean has increased dramatically during the past few years. According to the International Energy Agency (IEA), the renewable energy sources share about 983 Mtoe (million tonnes of oil equivalent) in 2011 of the world total primary energy supply and it was predicted to increase to 2400 Mtoe in 2035, a rise of almost two-and-a-half times [1].

Compared to other renewable energy sources, solar energy could be used anywhere and could play a crucial role in the energy generation mix in the medium to long term [2]. A wide range of technologies have been developed to capture and convert the solar energy into its secondary forms. Based on their basic use, the solar energy technologies can be grouped into two categories:

- Passive solar energy technologies; systems that take advantages of heat and light of the sun directly without any mechanical devices for heating, cooling and lighting of living spaces. These methods are demonstrated by windows, roofs, walls and orientation design of living spaces.
Active solar energy technologies; systems applied to convert solar energy into thermal energy (well-known as solar thermal) and electricity by employing mechanical or electrical equipment. Besides producing hot water, a solar thermal system is utilized to generate electricity in areas featuring high solar intensity by deploying concentrators. In addition to the thermal energy, solar energy can be converted directly into electricity using PV modules.

Classification of the solar energy technologies is illustrated in Figure 1.

Among the active solar energy technologies, solar photovoltaic (PV) is the most advanced and developed technology [3]. The first application of solar PV, in the late 1950s and throughout the 1960s, was to generate electricity for earth-orbiting satellites [2-4]. The years immediately following oil-crisis in 1970s, applications of PV technology expanded and it started to be used for commercial use and providing electricity for residential such as solar home system [2-4].
Figure 1. Classifications of solar energy technologies

Adapted from Urmee and Kumar, 2018 [5]
PV technologies are considered a reliable technology to generate and supply short/mid-term electricity needs [6]. Consequently, the market for these systems is also expanding very rapidly. According to the literature, for the last two decades, there has been a dramatic increase in the cumulative installed PV capacity. It grew from about 9 GW in 2007 and attained 16 GW in 2008, crossed 100 GW and 227 GW by the end of 2012 and 2015, respectively, and reached 303 GW at the end of 2016 [7, 8]. Solar PV global capacity and annual additions is described in Figure 2.

![Solar PV global capacity and annual additions, 2005 – 2016](image)

Figure 2. Solar PV global capacity and annual additions, 2005 – 2016 [7, 8]

The rapid development of the PV market discussed previously is inseparable from government policies that promote PV utilization. For example, Renewable Energy Certificates (REC) program developed by the Australian government. Through this
scheme, the owners of PV systems with capacity 0-100 kWp received an up-front discount from retailers [9]. In addition to the up-front rebate program stipulated by the Federal Government, there is an on-going program set-up by the State Government called feed-in-tariff (FiT). Via this program, PV owners can receive extra income by selling the excess electricity produced by their systems to the grid [9]. These two support mechanisms were claimed to have significant contribution to the achievement of Australia as the country with the highest proportion of residential PV systems in the world (16.5%) [10].

Price reduction is also a factor supporting the spectacular growth of PV installations. At the time of commercialization in 1976, PV price was about $51/Wp. Due to the improved manufacturing and efficiency, the number decreased exponentially and reached almost $4.5/Wp in early 2000s [11]. The shortage of raw materials in mid-2000s led to an increase PV price. However, innovation in the raw material caused PV prices dropped sharply from 2010 onwards [12]. It was reported that, in 2010, the price of PV was about $4.1/Wp, subsequently it decreased to $2.1/Wp in 2012 and reached $0.3/Wp in mid-2017 [11].

With continuous technical advances, reduced prices, and supportive policies, PV power generation will certainly continue at a fast-growing pace and eventually become a key energy supplier in the world. It was predicted that PV will deliver about 5% of global power needs by 2030 and 11% by 2050 [6].

Energy produced by a PV module deployed in the field is dependent on environmental factors including dust. The sedimentation of the unavoidable particles
on the surface of the PV cover glass diminishes the amount of solar irradiation from reaching solar cells and therefore deteriorates the PV performance. The incoming light is scattered and absorbed by dust particles.

The presence of dust causes notable performance degradation on a PV system. The level of degradation is varied by its morphology and density. For an extreme case, a research in Tehran in 2001 revealed that power produced by a PV module decreased by 43% after 8 days of exposure during severe air pollution [13]. This, understandably, causes economic losses. Therefore, it is clear that the effect of dust on performance degradation of PV modules should not be underestimated.

1.2. Problem statement and research questions

The significant effect on the performance degradation caused by dust has attracted much attention by researchers during the last few decades. Studies conducted in this field which initially only investigated the effects of dust on the performance of PV modules [14-16] have developed to be multi-discipline projects which cover dust characteristics and their impacts on optical properties [17-20]. In addition, the studies were directed to explore mitigation procedures classified as restorative and preventive approaches [21-23].

One factor influences the optical properties of dust is morphology. Dust with different morphologies demonstrates different optical characteristics leading to different PV performance degradation. El-Shobokshy and Hussein [24] in their study found that at the same density, carbon (5µm) accounted a more significant effect on
the degradation of $P_{\text{max}}$ and $I_{\text{SC}}$ followed by cement (10µm) and limestone (60, 70 and 80µm). They concluded that finer dust particles play a greater role in decreasing power output than larger ones.

Besides grain size, the optical properties of dust are affected by shape and surface texture of dust particles [25, 26]. Literature reported that dust with different shapes posed dissimilar substantial deviations of phase function over a range of scattering angles [26-30]. In reference to the surface, rough surfaces have more potential to scatter light compared to smooth ones. Thus the greater the degree of surface roughness, the more the light is scattered [31].

Furthermore, as dust originates from various sources in the surrounding area and is influenced by environmental climate, its morphology varies from location to location. Ta et al. [32] who investigated the morphology of particulate matter in seven sites in China found various kinds of dust shapes such as spherical, irregular and sharp-edged shapes. Misrha et al. [26] in their research in six sampling sites in India grouped dust into six model shapes consisting of rectangular grain, rectangular plate, hexagon plate, ellipsoid, spheroid, and triangular plate. Looking at the studies mentioned previously it is known that there is still a lack of information on the effect of dust from different locations on PV performance accommodating all physical factors.

In addition to the morphology factors, solar intensity reaches PV cells is also affected by the density of dust driven by the tilt angle of the module. Dust accumulation decreases as the inclination angle of PV module increases [20, 33, 34].
The higher the tilt angles, the easier the dust to roll off due to the gravitation effect or to be cleaned off by natural cleaning agents. Elminir, et al. [34] in their experiments in Egypt reported that the difference of transmittance reduction for the tilt angle of 0° (dust accumulation maximum) and 90° (dust accumulation minimum) is 21.3%.

Weather elements including rain and the wind also influence dust deposition on PV modules’ surface. Rain has a dual role in terms of dust accumulation [35]. 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 [36]. Similar to the rain, at a higher velocity, wind also can be a means to sweep off dust from a PV surface [37]. At a lower velocity, on the other hand, the wind accumulates small dust particles on a PV module’s surface [38].

It is well known that the weather elements mentioned previously vary depending on the season. As a result PV performance degradation caused by dust is different seasonally. A study carried out by Kalogirou et al. [33] 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 [39] in Abu Dhabi, UAE reported that the highest drop of glass covers’ transmittance of a 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 previous studies were performed in a Mediterranean
and an arid region. The question then arises, “how is the degradation pattern of PV modules affected by seasonal dust in different climates?”

In very humid and light rain conditions, dust attached on PV module will be dissolved to form a thin layer. For a long time period the layer will stick perfectly, as a result it is hard to be removed as it is trapped by biological species [40]. Lorenzo et al. [41] reported that dust layer on PV surface could cause hot spot phenomenon which rise the temperature of the shaded cell of more than 20 degrees over the other cells in the same PV module. Over time, this is potential to lead to some destructive effects that degrade PV module performance. Referring to the exposure time period, it can be summarised that most of the previous studies were performed within 1 year [15, 42-45], but the longest one is 6 years [46]. Therefore, an investigation on the performance degradation of PV modules affected by dust for longer time period than that mentioned previously is needed. Question also arises, that, “is there any permanent degradation caused by a long term dust accumulation on PV surface“?

Performance degradation caused by dust leads to energy and economic losses. Kaldelis and Kokala [16] who investigated the effect of dust on PV modules in Athens found that by taking into account potential solar irradiation in the location, 1 g/m² of dust could cause annual income losses as much as 400 € for a 10 kWp PV system. Literature revealed that there is no study to investigate economic losses caused by dust on a small scale PV system.

One region in the world near the equator, where dust accumulation may be a problem for PV systems such as solar home system (SHS) in remote areas is in Nusa
Tenggara Timur (NTT) province, Indonesia. The area is blessed with significant amounts of sunlight - the average of the total intensity of radiation is 6.6 kWh/m² per year [47]. It was reported that PV systems had been applied to supply the electricity needs of local communities since 1980s [48]. By 2010, more than 1.7 MWp of PV systems have been installed in NTT [48] featuring SHS, stand-alone PV system, and hybrid systems.

Local climatic conditions are the primary factors of the building up of dust on PV module surfaces. According to Koppen-Geiger classification, the province is classified as savannah arid or tropical climate, which has only two seasons namely the dry season and the wet season [49]. Because the dry season (April to October) is more prolonged than the wet season (November to March), dust is present in addition to high temperature. If an installed PV system is exposed to such environment for long time period, then dust will continue to accumulate and affect the performance and safety of PV modules of the system.

Furthermore, the accumulation of dust on the PV surface is caused by the tilt angle of PV modules which are near to horizontal. As described in the previous section horizontal tilt angle strongly supports the build-up of dust precipitation because natural cleaners like rain and wind do not wash away the dust significantly. Retnanestri and Outhred [50] revealed that technical problems of PV system operation and maintenance in remote areas in Indonesia are highly related with the unavailability of the technician. Installation and maintenance of some renewable energy technologies including SHS are based solely on the knowledge of the technicians of the company involved the project.
Another factor is the lack of maintenance of the PV system. As revealed by Cuddihy [37] dirty layers on PV surfaces significantly promote dust accumulation. With the influence of gravity and the wind, dust in the atmosphere settles on the dirty layer of the PV surface. At high humidity or with light rain and heavy morning dews, a cementation process will happen to form a new layer that is more solid. In addition, a study done by Cabanillas and Munguía [51] found that some organic materials could provide a substance like glue that contributes to hold together dust particles on the surface of a PV module.

As mentioned previously, optical properties are dependent on the morphology and the density of dust. Thus, to study the effect of dust on a PV module performance comprehensively, research was conducted in two different locations featuring different climates, namely NTT, Indonesia and Perth, Western Australia. It is known that Perth region has a temperate climate with some characteristics such as lots of sunshine (5.87 kWh/m² per year [47]), moderate temperature and seasonal rain. In addition, it has four season, namely summer (December to February), autumn (March to May), winter (June to August) and spring (September to November).

Based on the above discussion, this study aims to answer the following research questions:

1. What are the factors affecting seasonal dust accumulation and transmittance on the surface of PV modules in varying climatic conditions?
2. What is the long-term effect of dust on PV modules and what are the impacts on the performance of PV in varying climatic conditions?

3. What are the energy and economic losses caused by dust or soiling when various cleaning practices are used?

The study accommodated all factors affecting dust accumulation on PV surface i.e. weather elements, location, exposure time, tilt angle. The effect of dust on various typical PV technologies performance in NTT and Perth influenced by morphology factors (shape, grain size and surface texture) were also studied. By adopting degradation pattern caused by seasonal dust from NTT and Perth, energy and economic losses of residential systems in the two areas were analysed; thereby the effective schedule of maintenance activity including cleaning procedures could be suggested.

1.3. Aim and objectives

The aim of this research is to identify the effect of dust on the performance of solar PV modules deployed in varying climatic conditions and to determine a cost effective maintenance schedule for residential PV systems in the regions. To achieve the aim as stated above, the objectives of this study are:

1. To measure the transmittance of dust exhibiting different size, shape, and surface texture.
2. To measure the density of dust affected by weather elements, exposure time, and tilt angle in varying climatic conditions.

3. To measure I-V curve of different PV technologies affected by dust deposition in varying climatic conditions.

4. To determine the energy and economic losses caused by dust on residential PV systems in different climates areas.

1.4. Theoretical concepts and literature review

1.4.1. Photovoltaic module

The photovoltaic (PV) module is a device used to convert incident light into electricity that exhibits a photovoltaic effect. A PV module typically consists of 36, 54, 72, or 96 solar cells connected in series. Power generated by a PV panel has been on increase, and it to date can come with 350 W (current and voltage output are about 9 A and 38 V, respectively) examined at standard test condition (STC) [52]. The solar cells, which are thin slices of semiconductor materials, are connected together in series and laminated into a module. Typically a solar cell generates about 0.5 to 1 volt when it is exposed to the sun [53]. In order to produce more power to meet the electricity needs of load, several PV modules are linked together to form an array. To obtain the desired voltage and current, the PV modules are connected in series and parallel [53].
Based on the material used, there are two popular PV technologies, namely crystalline silicon (c-Si) and thin films modules. Apart from the two technologies, the third PV generation has emerged including organic PV cells, hybrid PV cells and dye-sensitized. Tyagi, et al. [54] grouped solar cells based on their materials as shown in Figure 3.
Figure 3. Material-based solar cells chart

Adapted from Tyagi et al., 2013 [54]
Extensive research work in solar cell materials and sophisticated fabrication process has led to the following conclusions:

- Improvement of PV modules reliability: Typical power warranty given by manufacturers is 90% of initial maximum power ($P_{\text{max}}$) after 10 years and 80% after 25 years operation [55]. Research was done by Skoczek, et al. [55] to investigate the performance of 204 field-aged c-Si wafer based PV modules in Italy revealed that only 17.6% PV modules failed to meet the performance warranty.

- Improvement of PV modules’ efficiency: For wafer-based c-Si, the efficiency of mono-crystalline silicon (mc-Si) and polycrystalline silicon (pc-Si) has reached 14-20% and 13-15% respectively. Meanwhile, for thin film group, the efficiency of amorphous silicon (a-Si) accounted 6-9%, cadmium telluride (CdTe) and copper indium selenide/copper indium gallium selenide (CIS/CIGS) recorded 9-11% and 10-12% respectively [6, 54].

- Continual price reduction: The phenomenal downward trend in PV price due to manufacturing improvements was evident since 2010. It decreased from around $4.1/Wp at the time period to $2.1/Wp in 2012 and reached $0.3/Wp in mid-2017 [11].

As a consequence of these factors as well as government incentives, the demand for PV module has risen tremendously over the years. It has been used broadly to generate power in some areas such as residential systems, larger
industrial/commercial systems, utility-scale power plants, and some consumer goods [6].

1.4.1.1. Electrical characteristics of a PV module

As explained in section 1.4.1, a PV module comprised of a number of individual solar cells. As the solar cell behaves like a diode; its electrical characteristic can be modelled by a diode connected parallel with a current source as depicted in Figure 4. The current source and diode represent the solar radiation and P-N junction of a solar cell respectively.

![Figure 4. Equivalent circuit of an ideal PV cell](image)

Reproduced from Kumar and Kumar, 2017 [56]

From the equivalent circuit, the total current produced by a solar cell ($I$) is equal to the current generated by the photoelectric effect ($I_L$) minus the diode current ($I_D$), as expressed follows:
\[ I = I_L - I_D \] (1.1)

\[ I_D = I_0 \left( \exp \left( \frac{qV}{nKT} \right) - 1 \right) \] (1.2)

\( I_0 \) is known as reverse saturation current of diode (A), while \( n \) is the diode ideality factor (1 for an ideal diode). \( q \) is the elemental charge of an electron which is equal to \( 1.602 \times 10^{-19} \) Coulomb; \( K \) is the Boltzmann constant \( (1.38 \times 10^{-23} \text{ J/K}) \); \( T \) is the temperature of the device in Kelvin (K) and \( V \) is the voltage across the diode junction.

In practice, no solar cell is ideal due to ohmic losses in the front surface of the cell and diode leakage currents. Therefore, a series resistance \( (R_s) \) and a shunt resistance component \( (R_{\text{sh}}) \) are added to the model (Figure 4) to represent the former and the later losses as shown in Figure 5.

Figure 5. Equivalent circuit of a PV cell with \( R_s \) and \( R_{\text{sh}} \)

Reproduced from Kumar and Kumar, 2017 [56]
By adding $R_s$ and $R_{sh}$ to the ideal equivalent circuit, the total current produced by a solar cell is given by the following expressions:

$$I = I_L - I_D - I_{sh} \quad (1.3)$$

By substituting $I_D$ and $I_{sh}$, the total current is given by equation 1.4.

$$I = I_L - I_0 \left( \exp \left( \frac{qV}{n_kKT} \right) - 1 \right) - \frac{V + I_L R_s}{R_{sh}} \quad (1.4)$$

1.4.1.2. I-V and P-V curves

I-V and P-V curves are the basic performance descriptors which represent the ability of a PV module to produce current and voltage at a certain irradiance and temperature. In other words, these curves provide information on how much the maximum load capacity can be supplied by a PV module using its current and voltage generated at constant irradiance and cell temperature. An example of I-V and P-V curves of a mc-Si PV module is shown in Figure 6.
There are some important electrical parameters that can be extracted from the graph to analyse PV module performance, namely short-circuit current ($I_{sc}$), open-circuit voltage ($V_{oc}$), fill factor ($FF$), maximum power output ($P_{max}$) and efficiency ($\eta$) [57-59].

From Figure 6, it is clearly seen that short circuit current ($I_{sc}$) is the current delivered by a PV module when the voltage across its cells is zero and impedance is low. Similarly, open circuit voltage ($V_{oc}$) is also the maximum voltage yield by a module that occurs when there is no current passing through the cell. By assuming that the PV cells are ideal then $I_{sc}$ and $V_{oc}$ values are the maximum current and voltage can be produced in the solar cell by photon excitation.
Referring back to Figure 6, maximum power output \( P_{\text{max}} \) is a power point spotted near the knee of the I-V curve where the product of voltage \( V \) multiplied by current \( I \) is a maximum value. These notations then are called voltage at maximum power \( V_{\text{mp}} \) and current at maximum power \( I_{\text{mp}} \).

Ideally a PV module is expected to deliver current and voltage equal to their \( I_{\text{sc}} \) and \( V_{\text{oc}} \) respectively as it would produce a maximum power output. Due to parasitic losses, however, losses caused by the series and parallel resistances within the cell itself, the current is not constant and voltage is sloped. The degree of the ratio of a PV module actual’s power output versus its ideal power output indicates the quality of a PV module. It is known as fill factor \( (FF) \) as illustrated in Figure 7 and expressed by:

\[
FF = \frac{(V_{\text{mp}} \cdot I_{\text{mp}})}{(V_{\text{oc}} \cdot I_{\text{sc}})}
\]  

Typically commercial PV modules have fill factors varying from around 0.55 for a-Si up to around 0.8 for very high quality mc-Si [60].
The last electrical parameter for PV performance evaluation is efficiency. It is the ratio of the maximum electrical power produced by a module over the solar power input received by the device. The efficiency is quantified in per cent and commonly determined at Standard Test Conditions (STC) referring to the irradiance of 1000 W/m², air mass (AM) of 1.5, module temperature of 25 °C and incidence angle of 0°.

It is expressed by the following equation:

$$\eta = \left(\frac{V_{oc} \cdot I_{sc} \cdot FF}{A \cdot G}\right) \times 100$$  \hspace{1cm} (1.6)$$

where $G$ is the irradiance of the incident light measured in W/m², and $A$ is the surface area of the PV module (m²).
1.4.1.3. PV performance at various irradiances and temperatures

Power produced by a PV module varies with the changing intensity of incident light. The rate of electron production by photons striking the solar cell is directly proportional to the intensity of the light. That is, as the irradiance increases, the short circuit current and the open circuit voltage increase resulting in an increase in the overall power. Since the photocurrent produced by PV is directly proportional to the number of electrons, the increasing of the short circuit current is more significant than the open circuit voltage.

Similar to other semiconductor devices, the performance of PV modules is directly affected by the temperature. Increasing temperature reduces the effective band gap energy of the device so that lower energy is needed to break the bond. Consequently, more electrons will circulate for the same light intensity in the material which cause a slightly increase of short circuit current but a quite significant decrease of open circuit voltage. The combination of the temperature effect on the two parameters leads to a notable power loss.

1.4.2. Dust

Dust are small solid particles in the atmosphere with diameter less than 500 µm [36] generated by human, animals and natural activities [61]. Scanning electron microscope (SEM) images of dust collected from the Renewable Outdoor Testing Area (ROTA), Murdoch University, Perth are shown in Figure 8.
Dust originates from various sources in the surrounding area. There are some events contributing to lift dust to the atmosphere i.e. natural activities such as wind (aeolian dust) and volcanic eruptions; animal activities; and human activities (anthropogenic dust) [61]. Suspended dust in the atmosphere is known as atmospheric dust (aerosol).

Dust is one environmental factor that significantly reduces energy produced by a PV module temporarily [62]. Deposited dust on a PV module’s cover glass diminishes the illumination by absorbing and scattering sun light received by solar cells [18, 34, 63]. The PV performance could be recovered to its maximum capacity by cleaning activities performed manually, automatically and naturally [35].

1.4.2.1. Optical property of dust

When light impinges on a dust particle, it is reflected, transmitted and absorbed [64, 65] as illustrated in Figure 9.
The optical properties are defined as followings [65, 66]:

- Reflection of light is a phenomenon when an electromagnetic wave of light falls on and bounces away from a surface. Generally, only certain parts of the light falling on a surface will be reflected.

- Transmission is a process by which the part of electromagnetic radiation passes across a medium; consequently, the speed and wavelength of the light are changed.

- Scattering or diffusion is a phenomenon when a part of the electromagnetic radiation is deflected in many parts and direction.

- Absorption is a process to transform the electromagnetic energy of light into thermal energy. This energy can be retransmitted as thermal emission, or possibly fluorescence.
Reflection and transmission processes are dependent on the type of surface, the angle and the spectral composition of the incident wave. The combination effect of reflection, transmission and absorption are defined as extinction referring to the total energy loss of the incident wave.

Among the optical properties explained previously, transmission is the parameter frequently used by researchers to assess the effect of dust on PV performance. Literature reported that PV module’s performance decreases as the transmittance value decreases [18, 20, 63, 67, 68]. The reason is that dust attached on PV cover’s surface blocks the sun light to reach solar cells. Factors affecting transmittance that lead to the PV degradation are the density and morphology of dust.

1.4.2.1.1. Density of dust

PV module performance tends to degrade as the amount of dust impinged on its surface increases [33, 34, 36]. Appels, et al. [63] reported that by sprinkling 20 g/m² of white sand onto a clean PV module’s surface, the transmittance decreased by 4.03%, while the power output decreased by 4.5 to 5% for a 100 W PV module. Kaldellis and Fragos [69] in comparing the electrical parameters of two identical pairs of PV modules, found that a 1.5% reduction of efficiency was recorded by the accumulation of dust with a density of 0.4 mg/cm². Further, Jiang, et al. [70] in an experiment featuring three different PV cell technologies e.i. mc-Si, pc-Si and a-Si found that efficiency of the modules decreased from 0 to 26% as dust deposition increased of from 0 to 22 g/m². Although some of these results were not supported
by the transmittance investigation, but as explained above that the presence of dust reduces the value of transmittance resulting in PV performance degradation.

1.4.2.1.2. Morphology of dust

Dust is a kind of solid particle usually found in the atmosphere with irregular shapes and various sizes. The main purpose of morphology investigation is to provide information about size, surface and shape of dust particles which have significant effect to attenuating photon to reach solar cells. Dust can be divided into some types based on its diameter in micrometre as listed in Table 1.

Table 1. The grain type of dust based on its size [18]

<table>
<thead>
<tr>
<th>Diameter (µm)</th>
<th>Grain type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000-500</td>
<td>Coarse grained</td>
</tr>
<tr>
<td>500-250</td>
<td>Medium grained</td>
</tr>
<tr>
<td>250-125</td>
<td>Fine grained</td>
</tr>
<tr>
<td>125-63</td>
<td>Very fine grained</td>
</tr>
<tr>
<td>63-31</td>
<td>Coarse silt</td>
</tr>
<tr>
<td>31-16</td>
<td>Medium silt</td>
</tr>
<tr>
<td>16-8</td>
<td>Fine silt</td>
</tr>
<tr>
<td>8-4</td>
<td>Very fine silt</td>
</tr>
<tr>
<td>&lt; 4</td>
<td>Clay</td>
</tr>
</tbody>
</table>

El-Shobokshy and Hussein [24] concluded that finer dust particles play a more significant role in decreasing power output than larger ones. In their study, it was found that at the same level of density, carbon (5µm) had more significant effect on the degradation of \( P_{\text{max}} \) and \( I_{sc} \) of PV module followed by cement (10 µm) and limestone (60, 70 and 80µm). The reason is that finer dust distributed more
uniformly on PV surfaces than coarser dust particles; as a result, the voids between the particles through which light can pass are minimal [36].

On the other hand, coarser dust particles play a more significant role in the accumulation process of dust on a module’s surface. Coarser dust particles have higher adhesion force than finer ones [20]. The coarser the dust particle, the wider the contact area between the dust particle and the glass cover of the PV module; consequently, the cementation process of dust on the PV glass cover surface, as introduced by Cuddihy [37], is easier.

1.4.2.2. Chemical composition of dust

Due to dust originating from various sources in the environment, its constituents are specified by the geographic situation of the location. The aim of elemental and compound analysis is to trace the source of dust adhered to the PV modules’ surface [34, 71]. This provides useful information for dust mitigation policies and procedures. Table 2 shows elements of dust and their sources summarized from Elminir et al. [34] and Lax et al. [72].

Table 2. Elements emitted from various particle sources [34, 72]

<table>
<thead>
<tr>
<th>Emission sources</th>
<th>Elements emitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bush fires and cement works</td>
<td>Ca</td>
</tr>
<tr>
<td>Pollutant from fossil fuel power plants</td>
<td>S</td>
</tr>
<tr>
<td>Seaspray</td>
<td>Cl, Na</td>
</tr>
<tr>
<td>Combustion of petrol</td>
<td>Pb</td>
</tr>
<tr>
<td>Erosion from a desert land</td>
<td>Si</td>
</tr>
<tr>
<td>Pollutant from incinerators</td>
<td>Zn and K</td>
</tr>
<tr>
<td>Engine wear</td>
<td>Al and Fe</td>
</tr>
<tr>
<td>Motor vehicle emissions</td>
<td>Zn</td>
</tr>
</tbody>
</table>
1.4.2.3. Soiling mechanism

Before landing on PV surface, dust is suspended in the atmosphere due to human, animal and natural activities. Among the causes, the wind is the most dominant factor which blows the dust into the atmosphere [73]. The ability of the wind to transport the dust is dependent on the size of dust and the speed of the wind [74, 75]. Dust with particles of $<20 \, \mu m$ in size is suspended in the atmosphere by wind for a long term, while a short term for the size of 20-70 $\mu m$. Dust particles of $>70-500 \, \mu m$ in size will experience saltation, a term to represent jumping process of dust caused by the wind before falling back to the surface. Dust particles of $>500 \, \mu m$ in size will be moved along the surface called creep [76]. Transportation process of dust caused by the wind is shown in Figure 10.

![Figure 10. An illustration of creep, saltation and suspension of dust particles](image)

Adapted from Nickling and Neuman, 2009 [76]
To understand the mechanism of soil retention on a surface, Cuddihy [37] described it in a scheme as shown in Figure 11.

![Diagram of soil retention mechanism](image)

**Figure 11. A natural mechanism of soil retention**

*Adapted from Cuddihy, 1980 [37]*

It is known that the dust that lands on the surface of a PV module consists of soluble and insoluble compounds [36]. When light rains or heavy dews occur, the soluble particles would be dissolved and form thin layers on PV surface. The soluble solution also cements the insoluble particles when it dries. Consequently, the particles do not fall down easily due to gravity force or wind effect; or are not washed away easily by rain. The thin layer also allows new particles to stick more easily which eventually forms a thicker layer. As a result, PV performance degradation continually decreases.
1.4.2.4. Factors affecting dust accumulation

The following factors affected dust accumulation on PV panel:

a. Site characteristic
b. Tilt angle
c. Local weather
d. Characteristic of PV modules’ glass cover

1.4.2.4.1. Site characteristic

The accumulation of dust on a PV module’s surface is dependent on the site characteristics. Therefore, PV performance degradation caused by dust is not uniform for every region of the world. Desert areas that exhibit dry and windy weather suffer from dust more severely compared to regions with frequent precipitation. For just a few hours, a desert sandstorm can plaster solar panels with a thick layer of dust and reduce their efficiency by up to 70–80% [77]. Sarver, et al. [36] noted that a short period of PV modules’ exposure in dusty and windy regions such as the Middle East, North Africa, and Asia could cause the same reduction in PV performance observed over months in temperate and tropical climate areas.

1.4.2.4.2. Tilt angle

The tilt angle is the main factor that has a strong impact on dust deposition of PV modules’ surface. Dust accumulation decreases as the inclination angle of PV module increases [20, 33, 34]. The higher the tilt angles the easier the dust to roll off
due to the gravitation effect or to be cleaned off by natural cleaning agents. Elminir, et al. [34] in their experiments in Egypt reported that the difference of transmittance reduction for the tilt angle of 0° (dust accumulation maximum) and 90° (dust accumulation minimum) is 21.3%. An illustration of a PV module installed at the rooftop of a house in Perth is shown in Figure 12.

![Diagram of a rooftop PV system](image)

**Figure 12. A schematic diagram of a rooftop PV system**

### 1.4.2.4.3. Weather elements

One of the weather elements considered to have a significant effect on dust deposition is rain. It has a dual role in terms of dust deposition that affects PV module performance [35]. It can be a good cleaning agent when it occurs in heavy and frequent as it has the ability to wash away dust particles from PV surface [63]. In
contrast, light rain tends to drop the suspended particles in the atmosphere and forms residues that cause PV performance to degrade [36].

The wind also plays an important part of dust deposition on PV modules’ surface. Literatures revealed that the wind is one of the main contributors to lift dust to PV surface [59, 75]. The wind is expected to remove attached dust from PV surface at higher speed. Cuddihy [37] found that at a velocity of 50 m/s and relative humidity of 40%, the wind can remove approximately > 85%, 55% and 10% of dust particles with diameter ≥ 50 µm, 25 µm and 10 µm respectively, meanwhile at a speed of 65 m/s, the wind can remove about 5% of 3.5 µm dust particles.

In addition to rain and the wind, relative humidity is also an element which potential to increase dust deposition [35]. In a higher humidity condition, dust landing on a PV surface will be dissolved by water vapour and form a sticky thin layer as explained in section 2.8. The layer supports new dust particles to attach to the surface easily. For long term exposure, dust will be hard to remove as it is trapped by grown biological species [40].

1.4.2.4.4. Characteristics of PV modules’ cover glass

Dust deposition on PV modules is driven by the material and surface texture of PV module’s cover. Garg [78] who studied the effect of dust on two different materials exposed to outdoor conditions in India found that plastic collected more dust than glass. A similar result was revealed by Nahar and Gupta [79] 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. The difference is attributed to the smoother surface of glass than plastic and the polymers so that dust can be washed or wiped away by cleaning agents.

1.4.2.5. Dust mitigation

Serious performance degradation of PV modules caused by dust has provoked many efforts by stakeholders to mitigate the adverse impact. The actions can be classified into two parts, namely restoration and prevention action [36]. The former involves natural, manual, and automatic cleaning. Meanwhile the later comprises surface modification and electrodynamics screen (EDS) [35, 36]. The mitigation methods and their cleaning agents are illustrated in Figure 13.
1.4.2.5.1. Cleaning

Cleaning PV modules can be done by some natural events such as rain and wind. Great rainfall is considered as the most effective and least costly cleaning agent from the nature to restore a PV module performance affected by dust [35, 36]. Similar to rain, wind can be a cleaning agent but at a higher velocity range. Generally, at a typical speed range, it contributes to depositing dust on the surface of PV module.
The role of these natural cleanings to reduce dust accumulation has been discussed in sub section 1.4.2.4.3.

At lower velocity and intensity, wind and rain are not able to clean and maintain PV modules’ performance properly [35, 36]. In addition, the natural cleaning agents are not effective to remove the accumulation of bird droppings and some other air pollution and chemicals. For this situation, human intervention actions are needed to remove dust from PV surface. Typically the method is applied by washing PV surface using tap or distilled water followed by wiping the surface with a soft cloth. Ali Omar Mohamed et al., [80] in an experiment to rinse the dirt and debris build up on PVs’ surface in a desert region, Lybia, found that by performing a weekly periodic cleaning within February to May, the performance losses of the system can be maintained to be between 2–2.5%.

To get the best results, a chemical or detergent called surfactant is added to the cleaning water used to wash away dust. Literature revealed that the mixed water performed better cleaning on PV module’s than pure tap water and rain water [63]. Improved performance is indicated by the higher values of transmittance. Surfactants are often used to clean hard residues formed by a build-up of dust for long periods of time [81].

Besides surfactants employment, special tools are needed to clean certain kind of dust particles, for example, a soft brush. It is useful to remove fine particles adhered to the PV surface [35]. Pavan et al., [23] in a study employing two similar capacity PV plants (1 MWp) in Italy reported that the increasing of output power of the
system cleaned with brush (6.9%) was higher than that cleaned without brush (1.1%).

In order to minimize labour cost, automatic cleaning devices were developed [35]. Some of the technologies utilized gravitational force as a prime mover of bristled brushes mounted on an arm to clean PV surface [82]. Others using PLC and microcontroller to control the soft brushes to wipe dust away [83] or nozzles to spray water to wash PV modules [84]. Furthermore, a recent technology is using an automated cleaning robot [84].

1.4.2.5.2. Coating

Coating is a strategy to prevent dust to settle on a PV by covering its surface with hydrophobic (resistant to or avoiding water) or hydrophilic (have strong affinity to
water) materials. A coating material should meet several requirements such as safe to use, easy to apply (procedures), economical (cost), eco-friendly (environmental impact), can be applied in different climates zone (generality), and should be durable and reliable (performance) [36].

A comparison study of the coating application comprising metal-oxide nanoparticles and a binder of hybrid polymer on polycrystalline PV modules performance was done by Piliougine, et al. [22]. Results revealed that average daily soiling loss of coated PV modules for one year was 2.5%, while 3.3% for uncoated modules.

1.4.2.5.3. Electrodynamic Screens

PV modules contaminated by dust particles can cause significant losses of power output and reliability. In many cases, dry cleaning would be more efficient than a wet procedure. This is particularly interesting in areas where water is a scarce commodity, such as in arid regions.

One technology considered to be an effective method is electrostatic forces called electrodynamic screens (EDS). The principle of the technology is by utilizing electrical fields generated by electrodes. As depicted in Figure 14, the transparent electrodes are mounted on the surface of the PV module and connected with a voltage of 1 kV. When a dust particle deposited on the surface of the module, it will be charged by the electric field due to the different polarity of the electrodes. As a result, dust is lifted and flushed out of the surface of the PV. Mazumder, et al. [21]
found that the method was able to remove 90% of dust from a PV surface in less than 2 minutes.

Figure 15. Schematic view of an electrodynamic screen

Reproduced from Mazumder et al., 2011 [21]

1.5. Methodology

Laboratory and field experiments were performed to investigate the impact of dust on PV modules’ performance. A solar simulator was used to examine I-V and P-V characteristics of PV modules in the laboratory, while a portable solar module analyzer was used to assess electrical performance of PV modules in the field. A combination of a spectrophotometer, scanning electron microscope (SEM), electron dispersive spectroscopy (EDS) and X-ray diffraction (XRD) were applied to investigate the optical properties, morphology, elements and minerals of the dust accumulated on the PV modules' cover glass.
In addition to these tools, there are also some materials used as samples in the study including dust, PV modules and glass. For laboratory experiment purposes including morphology and chemicals characterization, dust was collected from the surface of non-sample PV modules installed in the study areas. It is to ensure that the results obtained represent a real condition in the field. In addition to dust, PV modules are the primary sample in this study. PV modules used were a-Si, pc-Si and mc-Si technologies representing PV module deployed in Perth and NTT. Other samples were glass. This material was used to simulate the optical property and the accumulation of dust on the cover of a PV module. To capture dust in the field, glass samples were mounted on a flexible arm structure. The glass was then collected and taken to the laboratory for testing. The glass sample is soda lime glass with an area of 5x5 cm². Details of the methodology will be discussed in each chapter according to the theme. A flow chart explaining the methodology of the research is shown in Figure 16.
Figure 16. Methodology to investigate the effect of dust on PV performance degradation
1.6. Structure of the thesis

According to Murdoch University Graduate Research Degrees Thesis Style Guideline, this thesis is classified as a thesis by publication. Structurally this thesis is divided into 6 chapters.

Chapter 1 explains general introduction including background, short basic theory and literature review, problem statement and research questions, aim and objectives, and methodology.

Chapter 2 is a manuscript discussing the property of dust from Perth and NTT. A series of laboratory experiments was conducted to characterize morphology, chemical and optical property of dust. The manuscript also presents the performance of PV modules examined in the laboratory featuring typical PV technologies in the two regions. The modules were coated with various density of dust artificially. The manuscript is being reviewed by Elsevier Sustainable Energy Technologies and Assessments journal.

Chapter 3 is a publication paper presenting comparison results of the short term effect of dust on PV performance deployed in Perth and NTT. A one-year period field study was carried out to investigate the effect of dust on PV modules. The study accommodated factors affecting dust deposition on PV surface namely, season, tilt angle and time exposure of PV modules. The paper is published at Elsevier Renewable Energy journal.
Chapter 4 is a publication paper detailing the impact of long term dust on the performance of PV modules in Perth. Seven PV modules consisting of a-Si, mc-Si and pc-Si were selected randomly as samples in the study. The modules had been deployed for almost 18 years at ROTA without any cleaning procedures. In addition, the chapter explains the contribution of dust and non-dust related factors to PV performance degradation. The paper is published at Elsevier Solar Energy journal.

Chapter 5 is a publication paper communicating the assessment results of energy and economic losses caused by dust on residential PV system in Perth and NTT. The losses were simulated by adopting degradation pattern found in the field as presented in Chapter 3. Economic analysis was applied to be a reference to suggest effective cleaning time. The paper is published at Elsevier Renewable Energy journal.

Chapter 6 is a general discussion and conclusion of results of this project. In addition, the need for future development based on results obtained is also briefly discussed.
CHAPTER 2

THE EFFECT OF DUST WITH DIFFERENT MORPHOLOGIES ON THE PERFORMANCE DEGRADATION OF PV MODULES

A note on content, formatting, and style

This chapter is a modified version of a submitted paper with details as follows:

Title: The effect of dust with different morphologies on the performance degradation of PV modules

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Journal: Elsevier Sustainable Energy Technologies and Assessments

Attribution

Julius Tanesab developed the concept, performed the experiment in the laboratory, interpreted the findings, and wrote the manuscript. David Parlevliet helped to design and to conduct the experiment in the laboratory. Jonathan Whale corrected the statistical analysis and edited the manuscript. Tania Urmee helped to design the experiment and edited the manuscript. All authors critically reviewed and approved the final version of the manuscript.
The effect of dust with different morphologies on the performance degradation of PV modules

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Abstract

This research investigated the effect of dust with different morphologies on the performance degradation of various PV technologies featuring mono-crystalline silicon (mc-Si), polycrystalline silicon (pc-Si), and amorphous silicon (a-Si). Dust collected from two different locations, Perth, Australia and Nusa Tenggara Timur (NTT), Indonesia, was coated artificially onto the surface of the PV modules. The analysis revealed that dust from one area not only exhibited physical characteristics with better optical property than dust from the other area, but also shared morphological factors that demonstrated adverse optical behaviour. As a result, transmittance values of the two types of dust tended to balance out. At an equivalent amount, the effect of dust from Perth and NTT on the performance degradation of each PV technology was similar. Furthermore, transmittance spectral curves of the two types of dust were fairly flat with respect to the wavelength range of a-Si, pc-Si and mc-Si technologies. Consequently, dust from either Perth or NTT performs similar effect on the three PV technologies. The similarities mean that the best practice maintenance of solar panels in Perth can inform the cleaning and maintenance of the solar home systems in remote areas of NTT.

Keywords: PV module performance, power degradation, dust, characteristics of dust

1. Introduction

Dust is small solid particles in the atmosphere with a diameter less than 500 µm [1] generated by human, animals and natural activities [2]. The presence of dust raises some negative impacts in many fields. Coughing and chest pain are common diseases suffered by someone who is exposed to some degree of dust [3]. In agriculture, deposited dust on leaf surfaces of a plant promotes unbalanced energy during the photosynthetic process that leads to productivity degradation [4, 5]. As a climate change agent, dust directly influences the intensity of sun light reaching the earth by absorbing and scattering the light causing temperature changes [6].

In addition to these adverse effects, dust also shares some disadvantages in the application of photovoltaic (PV) modules. The performance of a PV module generally quantified by the values of its electrical parameters tends to decrease as dust impinges onto its cover surface. The attached dust diminishes the illumination by absorbing and scattering sun light received by solar modules [7].

Degradation caused by dust is temporary as the PV performance can be recovered to its maximum capacity through cleaning activities which are performed manually, automatically and naturally [8]. However, it should not be underestimated as the losses caused by dust are relatively significant [9-18].

The intensity of sun light received by solar modules depends on dust density. It tends to decline as the amount of dust impinged on the PV glass surface increases [1,
In comparing the electrical parameters of two identical pairs of PV modules, Kaldellis and Fragos [20] found that a 1.5% reduction of efficiency was recorded by the accumulation of dust with a density of 0.4 mg/cm². An experiment featuring three different PV cell technologies such as mono-crystalline silicon (mc-Si), polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) reported that efficiency of the modules decreased up to 26% as dust deposition increased from 0 to 22 g/m² [21].

Dust with different morphologies demonstrates different effects on PV performance degradation. El-Shobokshy and Hussein [13] in their study found that at the same density, carbon (5µm) accounted a more significant effect on the degradation of Pmax and Isc followed by cement (10µm) and limestone (60, 70 and 80µm). They concluded that finer dust particles play a greater role in decreasing power output than larger ones. Work completed by Kaldellis et al. [22] has successfully examined the effect of different types of dust pollutants on the efficiency of PV modules, although it was not supported with an analysis of the dust properties that caused different performance of PV modules. The research, featuring three types of dust, found that the highest reduction was recorded by red soil followed by limestone and carbonaceous fly-ash particles. Khatib et al. [23] also investigated the effects of five types of dust on the performance of PV module. Results revealed that ash particles accounted for the highest voltage reduction followed by red soil, calcium carbonate, silica and sand.

In addition to the grain size distribution, the literature shows that the optical properties of dust are also driven by other morphology factors including shape and surface texture [24, 25]. There have been many studies investigating the optical properties of various shapes of dust. They revealed that dust with different shapes posed different substantial deviations of phase function over a range of scattering angles [24, 26-29]. Meanwhile, in reference to the surface, Li et al. [30] who investigated the impact of the surface on the optical characteristics of spherical shaped particles found that rough surfaces have more potential to scatter light compared to smooth ones. Thus the greater the degree of surface roughness, the more the light is scattered.

As dust originates from various sources in the surrounding area and is influenced by environmental climate, its morphology varies from location to location. Ta et al. [31] who investigated the morphology of particulate matter in seven sites in China found various kinds of dust shapes such as spherical, irregular and sharp-edged shapes. Misrha et al. [24] in their research in six sampling sites in India grouped dust in six model shapes consisting of rectangular grain, rectangular plate, hexagon plate, ellipsoid, spheroid, and triangular plate.

Due to the fact that the spectral response of a PV module depends on its technology, different types of module respond differently to the effects of dust. An analysis performed by Qasem et al. [17] to investigate the influence of dust from Kuwait on PV technologies concluded that dust had a more significant effect on the performance of PV modules with a wider spectral response like a-Si. This effect was indicated by a reduction in the spectral transmittance values of dust at lower wavelengths (300-570 µm).

In the present study, we examined the effect of dust collected from two areas: at the Renewable Outdoor Testing Area (ROTA), Murdoch University, Perth, Australia and at the PV power plant at Babuin, Nusa Tenggara Timur (NTT), Indonesia. The study investigated the performance of three PV technologies i.e. mc-Si, pc-Si and a-Si. These two regions are geographically different so it would be expected that the
dust have different morphology properties that lead to different performance degradation of PV modules.

2. Experimental methodology

2.1. Investigation of dust properties

In examining the morphology and the elements of dust from Perth and Babuin, a “JCM-6000 NeoScope Benchtop” Scanning Electron Microscope (SEM) with X-ray analyser based on Energy-dispersive X-ray Spectroscopy (EDS) was used. For sample preparation, dust collected from each site was coated artificially on the surface of stub type specimen storage containers using a free fall technical as performed by Qasem et al. [17]. To analyse the minerals of dust, an X-ray diffraction (XRD) was applied. Dust from the field was packed densely in a shallow well of a sample holder.

In addition to the physical and chemical investigation, an “HP spectrophotometer” was employed to investigate the optical properties of dust deposited on the PV modules. This experiment was initiated by weighing some 5 x 5 cm² soda lime glass plates, a material commonly used as a cover glass, to calculate their clean mass \((M_{\text{clean glass}} \text{ in mg})\) using an analytical balance. Afterwards, dust collected from the test-sites was mixed with water and sprayed uniformly onto the surface of the glass samples. During the coating process, enough time was given for the contaminant to evaporate. The glass samples were re-weighed to determine their mass after coating \((M_{\text{dusty glass}} \text{ in mg})\), which was then used to calculate dust density values \((D_{\text{glass}} \text{ in mg/cm}^2)\) by applying the following equation:

\[
D_{\text{glass}} = \frac{M_{\text{dusty glass}} - M_{\text{clean glass}}}{A_{\text{glass}}}
\]

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

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.

2.2. Electrical performance of PV modules

2.2.1. Dust density measurement

This section explains separate research which the authors have previously conducted to investigate dust deposition on PV module surfaces in Perth and Babuin referred by this study. The previous study was initiated by choosing a PV module randomly at each site. The modules had been exposed to the environment without any cleaning procedures for a year. Dust attached on the modules was collected using cotton treated before. It was started with inserting the prepared cotton into an envelope and loaded into a desiccator to remove contaminants with the water vapour into the atmosphere. Afterward, the envelope containing cotton was weighed using an analytical balance to determine their clean weight \((M_{\text{clean cotton}} \text{ in mg})\). The cotton was then wetted with clean water and used to remove dust on the PV surface. Dust was collected using wet cotton and the process was repeated until the wet cotton surface was clean after wiping. The clean cotton indicated that no dust was still attached on PV module’s surface.
The cotton containing dust was reinserted into the envelope and again was loaded into the desiccator to be dried. Finally, the envelope was weighed to determine the mass of dusty cotton \( M_{\text{dusty cotton}} \) in mg. Dust density values \( D_{\text{cotton}} \), mg/cm\(^2\), are given by:

\[
D_{\text{cotton}} = \frac{M_{\text{dusty cotton}} - M_{\text{clean cotton}}}{A_{\text{PV}}}
\]  

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

Results revealed that dust deposited on a PV surface over a one-year period measured at the end of summer and dry seasons was 0.21 and 0.28 mg/cm\(^2\) for Perth and Babuin, respectively. The authors took measurements at the end of the seasons with the assumption that these seasons received the lowest amount of rainfall and thus would provide the highest values of dust density.

2.2.2. PV performance measurement

A Spire 5600SLP sun simulator classified into class A\(^+\) with a superior repeatability of \( \leq 0.15\% \) was used to measure the I-V and P-V characteristics of PV modules. With pulse duration of 20-200 ms at 1000 W/m\(^2\), the sun simulator can sweep an I-V curve within less than 1 second [32]. Three PV modules featuring standard PV technologies at the two sites were deployed as samples of this research. The modules labelled with PV A (mc-Si), PV B (pc-Si) and PV C (a-Si) had \( P_{\text{max}} \) outputs of 76.04 W, 29.21 W, and 119.35 W, respectively in clean and standard test condition (STC). The results were affected by the accuracy of the I-V tracer by \( \pm 5\% \) [32].

PV performance measurements were initially carried out on clean PV modules and subsequently the modules were coated with a particular typical dust density before repeating the same measurement process. The study was performed using levels of dust densities i.e. 0.02, 0.04, 0.06, 0.08, 0.15 and 0.3 mg/cm\(^2\) that were within the range of variation of the deposited dust on PV modules at the two sampling sites mentioned in section 2.2.1.

Coating process was initiated by weigh the dust according to the required mass using an analytical balance. Total dust applied for a PV module equals to the required dust per cm\(^2\) multiplied by the area of the module to be coated. Subsequently, the dust was mixed with enough water. The solution was then sprayed on the PV surface using a manual sprayer. Spraying is done slowly in a room to avoid the influence of the wind. During the coating process, enough time was given for the contaminant to evaporate. An example of a clean panel alongside an artificially dusty panel is shown in Fig. 1.
Dust density measurement was performed after the I-V experiments. The process of collecting and weighing dust was undertaken using a similar methodology as explained in section 2.2.1. The research methodology of this study can be summarized as shown in Fig. 2.

Fig. 2. Methodology to examine the effect of different morphology of dust on PV modules performance degradation.

3. Results

3.1. Dust characterization

3.1.1. Chemical composition

Element analysis revealed that dust in Perth consisted of O (34%) and Si (29.14%) as the primary elements with some minor amounts of Ca, Al, Fe and K which contribute 13.21%, 9.26%, 8.83% and 5.56%, respectively, of total element weight. The dust from Babuin was dominated by Ca (32.42%), O (24.59%) and Fe (23.37%) with smaller amounts of Si, Al, Mg and K which are 9.03%, 5.28%, 3.16 and 2.15%, respectively.
A mineralogical analysis was done using X-ray diffraction to investigate minerals built of the elements. According to the result, dust particles from Perth were composed mostly of quartzite (SiO$_2$) followed by calcium oxide (CaO) and smaller amounts of some minerals from the alkali feldspars group, namely orthoclase and microcline (KAISi$_3$O$_8$). Meanwhile dust from Babuin contained a significant portion of calcium oxide (CaO) and some minor amounts of quartzite (SiO$_2$) and periclase (MgO) (Fig. 3).

Fig. 3. X-ray diffraction spectrum of minerals of dust from Perth and Babuin (Q: quartz, C: calcium oxide, M: microcline, O: orthoclase, P: periclase).

In addition to providing information about the type of dust, chemical composition analysis is used to trace the source of dust attached on the surface of PV modules [7, 33]. Considering Perth lies on a coastal plain dominated by acid and sandy soils [34], erosion from the soils surrounding ROTA was likely to be the source of a high portion of quartzite. Calcium oxide and feldspar were attributed to the works from a new hospital building being constructed near ROTA. Meanwhile, the presence of calcium oxide and quartz of dust from Babuin was from sedimentary and metamorphic rocks around the PV plant area. A smaller quantity of periclase was expected to come from marbles formed by the dissolution of dolomite. The results from Babuin are in agreement with research completed by Njurumana et al. [35] who found similar elements such as Ca and Mg in some areas near the sampling site.

3.1.2. Morphology

SEM images of collected dust from Perth and Babuin sprinkled onto the surface of a stub type specimen storage and recorded with secondary electron imaging (SEI) signal are shown in Fig. 4. Referring to standard nomenclature developed by National Institute of Standard and Technology, USA [36], dust from Perth can be classified as ‘angular shape’ because of its sharp edges, while dust from Babuin is identified as ‘porous shape’ due to the domination of porous particles.
The size distribution of the dust particles obtained from SEM images (randomly sampled particles) was analysed using image processing software and specified based on the diameter as shown in Table 1. The grain size analysis reveals that the percentage of clay and very fine silt of dust from Perth is higher than that from Babuin.

![SEM images of dust](image)

**Fig. 4. SEM images of dust.**

<table>
<thead>
<tr>
<th>Diameter (µm)</th>
<th>Percentage of the total sample from Perth</th>
<th>Percentage of the total sample from Babuin</th>
<th>Grain type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 4</td>
<td>67.34%</td>
<td>62.28%</td>
<td>Clay</td>
</tr>
<tr>
<td>4-8</td>
<td>22.24%</td>
<td>18.32%</td>
<td>Very fine silt</td>
</tr>
<tr>
<td>8-16</td>
<td>7.25%</td>
<td>10.98%</td>
<td>Fine silt</td>
</tr>
<tr>
<td>16-31</td>
<td>2.18%</td>
<td>4.72%</td>
<td>Medium silt</td>
</tr>
<tr>
<td>31-63</td>
<td>0.78%</td>
<td>3.08%</td>
<td>Coarse silt</td>
</tr>
<tr>
<td>63-125</td>
<td>0.21%</td>
<td>0.62%</td>
<td>Very fine grained</td>
</tr>
</tbody>
</table>

### 3.1.3. Transmittance

A spectrophotometer was applied to measure the transmission of light through glass samples containing dust collected from both locations. In this study, in addition to the range of dust deposited on the modules (0-0.3 mg/cm²), transmittance measurement was also applied for a larger range (0-0.8) that aimed to comparing the results with ones in the open literature. The results revealed that all curves were fairly flat over wavelength ranged from 400 to 1100 nm, although the spectras approach zero transmittance for the ultraviolet (UV) end of the spectrum due to the glass absorbing the UV. To show the transmission spectras of dust, the clean glass transmission spectras were subtracted from the results of dusty glass transmission for each level of dust density. The results are presented in Fig. 5.
The figures show that as the dust density increases the transmittance of dust from the two locations decreases. It can be predicted that the transmission of light and power output of PV modules decrease progressively with the increase of deposited dust until a point is reached where photons cannot pass through dust particles. To explore this further, the average of transmittance across the wavelengths (400-1100 nm) of each dust density was calculated and plotted in Fig. 6.
Fig. 6. Average transmittance for various densities of dust from Perth and Babuin.

The figure shows that at the same density, dust from Perth passed less light than that from Babuin. Also, it can be seen that the effect of dust accumulation on its average transmittance values is not linear for the densities > 0.3 mg/cm². Al-Hasan and Ghoneim [37] argued that at higher densities, deposited dust doesn’t spread to cover PV module, but tends to attach to other particles and builds up a layer.

3.2. The effect of dust from Perth and Babuin on PV performance

To quantify the effect of dust on performance degradation of the three PV modules, their P_max output values were assessed. Sun simulator test results of the modules with levels of dust densities ranging from 0 to 0.3 mg/cm² are plotted in Fig. 7. The figure shows the normalization results of P_max output of all PV modules using their values in clean conditions as a reference. It can be seen that the performance of the PV modules decreases progressively with the increasing of dust density. For the same technology, performance degradation caused by dust from Perth is higher than that of from Babuin, demonstrated by less P_max output produced. Moreover, for the same type of dust, a-Si PV module exhibits the largest performance degradation followed by pc-Si and mc-Si modules.

By deploying linear equations depicted in Fig. 7, P_max output of each PV module at dust densities of 0.02, 0.04, 0.06, 0.08, 0.15 and 0.3 mg/cm² can be determined. A two way analysis of variance (ANOVA) was applied to determine whether there are any significant differences in the values of P_max output affected by different types of dust and PV technologies, as shown in Fig. 7. Calculation result of the significance of the data (P_value) was 0.656 and 0.412 for type of dust and PV technology variables, respectively. The values are greater than the determined critical significance level (α) = 0.05, which means the null hypothesis (H₀) is accepted. In other words, at the same density, the effect of dust from Perth and Babuin on the performance degradation of each PV technology is similar. Also, there was no significant difference in the power degradation of the different PV technologies caused by each type of dust.
4. Discussion

Experiments of the performance of PVs affected by dust with different morphologies from different locations were carried out. In general, as presented in Fig. 7, the performance of all PV modules decreases as the dust density increases. There is a linear relationship of $P_{\text{max}}$ output degradation of PV modules influenced by dust from both locations for densities $< 0.3 \, \text{mg/cm}^2$. This relationship confirms that the more the dust impinges on a PV module, the greater it blocks light to reach PV cells. The results are in line with transmittance values in Fig. 6 that demonstrate a linear relationship with the concentration of dust for densities $< 0.3 \, \text{mg/cm}^2$. Similar trends were also reported by Al-Hasan and Ghoneim [37], who found that deposition of sand dust in Kuwait for densities $< 1.5 \, \text{g/m}^2$ decreased normalized efficiency of PV modules proportionally. Klugmann-Radziemska [14] noted that the efficiency losses of PV modules increased linearly with the increasing of dust accumulation for thickness $< 3 \mu\text{m}$ in Poland.

Performance comparison results in Fig. 7 reveal that dust from Babuin demonstrated less degradation of $P_{\text{max}}$ output of all PV modules than that from Perth although the difference in the power degradation was not significant. This result may be attributed to the similar light intensity received by solar cells at the same quantity of dust from both locations.

Due to the fact that the intensity of light affected by dust is driven by its morphology, an analysis was performed on physical factors of dust particles. SEM results in Fig. 4 show that dust from Perth exhibits an angular shape with some diagonals, while Babuin’s dust is dominated by porous particles with ellipsoidal and spheroid shapes. Mishra et al. [24], in their research, compared the optical properties...
of some shapes models of dust and found that single scattering albedo of hexagonal particles was higher than ellipsoidal and spheroid ones. Further, Kalashnikova and Sokolik [38] concluded in their work that non-spherical particles accounted for a higher phase function at forward scattering angles compared to the spherical ones. Therefore, regarding the shape factor, it can be predicted that dust from Perth would transfer greater intensity of light to reach solar cells than that from Babuin.

Referring to surface factor, however, Nirmal et al. [39] found that a porous layer transmitted more light than a smooth one, as demonstrated by an increase in transmittance that lead to a 30% higher PV current density. They modified the surface using zinc oxide (ZnO), a material used as an electron transport layer in organics PV. The research also concluded that porous structures promoted better scattering of light than the smooth ones. From Fig. 4, it can be seen that both types of dust exhibited porous surfaces although the dust from Babuin has a larger proportion of porous dust and that certainly contributed to better transmission of light.

Grain size distribution data in Table 1 shows that the percentage of clay from Perth is higher than that from Babuin. In other words, dust from Perth is finer than that from Babuin. Consequently, it would have a greater potential to block light as fine dust is distributed more uniformly on a PV’s surface, so that areas of the voids between the particles through which light can pass were reduced [1].

Previous analysis revealed that dust from one area not only exhibited physical characteristics with better transmission of light than that of from the other area, but also shared morphology factors that demonstrated adverse behaviour. As a result, the optical property of each dust tended to balance out indicated by the intensity of light transmitted by the two types of dust was similar. This is in agreement with a one way ANOVA analysis on the average transmittance values of the two types of dust (Fig. 6) with dust density ranging from 0 to 0.3 mg/cm². The analysis showed that P-value (0.236) > α (0.05), meaning Ho is accepted or there was no significant difference in the average transmittance of the two types of dust. Average transmittance values across the range of dust densities were calculated by applying the line of fit equations presented in Fig. 6.

In addition to the morphology effect, the difference in performance degradation among the PV modules due to the two types of dust was compared based on the PV technologies (Fig. 7). Results show that there was no significant difference of performance degradation between PV technologies contaminated by either type of dust. This is attributed to approximately flat spectral curves with respect to wavelength of light for both types of dust showed via the transmittance curves results as presented in Fig. 5. The result is in contrast with the spectral effect of dust in a Kuwait study, which showed more effect at lower wavelengths [17]. Therefore, wider band gap PV technologies such as a-Si and CdTe are more affected by dust deposition than c-Si and CIGS. As argued by Al-Hasan [37], the difference of color shared by dust examined in this study and dust from Kuwait might be the reason of the spectral response different.

5. Conclusion

The effect of dust with different morphologies from two geographically different locations on the performance of PV modules was examined. It was found that the performance of all PV modules decreased with increasing dust density. There was a linear relationship of $P_{\text{max}}$ output degradation of modules for the two types of dust for
densities < 0.3 mg/cm². Comparison results showed that at the same density, dust from Perth and Babuin did not have a significant difference in their impact on the performance degradation of each PV technology. The reason was that dust from one area not only exhibited physical characteristics with better transmission of light than dust from the other area, but also shared morphology factors that demonstrated adverse behaviour. As a result transmittance values of the two types of dust tended to balance out. Moreover, it was found that different PV technologies shared similar performance degradation affected by each type of dust. Flat spectral curve with respect to wavelength for both types of dust was a factor that led to the similar performance degradation of various PV technologies. Dust source tracing based on chemical analysis data revealed that the erosion from the soils surrounding ROTA, which located in Perth that lies on a coastal plain, dominated by acid and sandy soils, is likely to be the source of high portion of quartzite. Meanwhile, the presence of calcite, which is the main component of limestone, is derived from sedimentary and metamorphic rocks around the PV plant area at Babuin. The similarities of performance degradation of PV modules affected by different types of dust means that cleaning and maintenance suggestions applied for one location can be used in another. The best practice maintenance of solar panels in Perth can inform the cleaning and maintenance of the solar home systems in remote areas of NTT.

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References


Summary and link to next chapter

Chapter 2 presents a study about the effect of dust with different morphologies on the performance of PV modules. Dust samples were collected from The Renewable Outdoor Testing Area (ROTA), Perth, Australia, a temperate climate area and Babuin, Nusa Tenggara Timur (NTT), Indonesia, a tropical climate region. Performance degradation of three PV modules featuring a-Si, pc-Si, and mc-Si technology was examined in the research.

The study which was initiated with dust characterization found that the type of the dust was different in different climates. Chemical analysis showed that dust at ROTA was dominated by quartzite (SiO₂), meanwhile calcium oxide (CaO) was the main component of one from Babuin. Erosion from acid and sandy soils at ROTA and sedimentary and metamorphic rocks around the PV plant at Babuin were the sources of the dust.

The two types of dust shared similar optical property although they were different chemically. This is because dust from one area not only exhibited particles with physical properties that led to better transmission of light than the other, but also shared morphological factors that demonstrated adverse optical behaviour. As a consequence, performance of each PV module coated artificially with the same amount but different types of dust was similar.

In addition, it was found that dust from either ROTA or Babuin caused similar degradation on a-Si, pc-Si and mc-Si technologies. It is attributed to the spectral
curves of the two types of dust which fairly flat with respect to the wavelength range of the three PV technologies.

The similarity of the performance degradation of various PV technologies affected by different types of dust means that cleaning and maintenance suggestions applied for one location can be used in another. The significance of this study is that best practice maintenance of solar panels in Perth can inform the cleaning and maintenance of the solar home systems in remote areas in NTT.

Laboratory experiments conducted with coating the dust artificially as explained in Chapter 2 was feasible to assess the effects of different types of dust on PV performance. However, the results did not represent the real dust density in the field for a certain period of time. The reason is that dust deposition is influenced by many factors including weather elements, tilt angle, and other activities surrounding the site.

It is known that the performance degradation of a PV module deployed outdoors over time is not only affected by dust, but also non-dust related factors which caused permanent degradation. The non-dust factors consist of corrosion, discoloration, delamination and breakage and cracking cells.

To address the limitation of the study mentioned previously, a further research was carried out as reported in Chapter 3. It investigated the effect of dust accumulated naturally on PV module performance in the field for a one year time period without
any cleaning procedure. The research also compared the contribution of dust and non-dust related factors to degrade PV performance.
CHAPTER 3

SEASONAL EFFECT OF DUST ON THE DEGRADATION OF PV MODULES PERFORMANCE DEPLOYED IN DIFFERENT CLIMATE AREAS

A note on content, formatting, and style

This chapter is a published paper with details as follows:
Title: Seasonal effect of dust on the degradation of PV modules performance deployed in different climate areas
Authors: Julius Tanesab\textsuperscript{a, b, *}, David Parlevliet\textsuperscript{a}, Jonathan Whale\textsuperscript{a}, and Tania Urmee\textsuperscript{a}
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Attribution

Julius Tanesab developed the concept, performed the experiment in the laboratory and in the field, collected the data, and wrote the manuscript. David Parlevliet contributed to the laboratory experiment and revised the manuscript. Jonathan Whale helped to develop the concept and corrected the climatological data. Tania Urmee contributed to deploy samples in Perth and to interpret the findings. All authors critically reviewed and approved the final version of the manuscript.
Amendments of Chapter 3

1. The word “weight” written in page 66, Section 2.2, paragraph 2, line 2 and 7 should be changed with “mass”.

2. In section 2.1, paragraph 4, it is mentioned that Prova 210 module analyser works on a range of solar insolation between 10 W/m$^2$ and 1000 W/m$^2$. To ensure that I-V curve of the PV modules was recorded in the desired range of solar intensities of the I-V tracer, measurements were conducted in the morning and before afternoon on clear-sky days. To explain this, the information should be included in paragraph 4, line 7.

3. The word “avoidable” mentioned in Section 1, paragraph 2, line 4 should be written as “unavoidable”.
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.

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1. Introduction

Nowadays, PV module has been the fastest growing renewable energy technology used to convert solar energy into electricity [1]. The rapid development is attributed to a rising level of public awareness to diminish greenhouse gas emissions, a continuing PV price reduction, and an improvement of PV efficiency and reliability. The total capacity of installed PV systems globally grew slowly from 5.1 GW in 2005 to 23 GW in 2009 [2]. With an annual addition capacity between 30 and 50 GW, the number increased dramatically since 2010 and reached more than 227 GW at the end of 2015 [2].

Among the environmental factors including ambient temperature and humidity, rainfall, and wind movements, the performance of a PV module deployed outdoor is dependent on the amount of solar irradiation [3]. The performance increases proportionally with the increasing of the light intensity. Avoidable particles in the atmosphere contribute to decrease the amount of sun light received by a PV module is dust. The presence of dust on the cover glass of a PV module absorbs and scatters the solar irradiation; as a result PV performance decreases. Even though the degradation could be recovered by a cleaning activity, the effect of dust should not be underestimated [4].

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 monocrystalline 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 comprehensive experiments in Egypt
reported a 71% dust density reduction for tilt angles of 0° and 90°. A work completed by Said and Walwil [11] in Dhahran noted that for 45 days of exposure, a 0° glass sample was covered with about 6.5 g/m² of dust, while a 15°, 60°, 75° and 90° were coated with 5.3, 2.2 and 0.9 g/m² 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.

Besides the two factors mentioned above, weather elements such as rain and the wind also dictate the density of dust on PV surface. Rain can remove dust from PV surface when it occurs heavily and frequently. In contrast, light rain contributes to accumulate dust and aggravate PV performance [14]. The reason is that the rain tends to drop dust in the atmosphere and land it on PV cover glass [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 m² of dust on PV surface with inclination of 29° and direction of North 10° 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.

It is well known that rain intensity and wind velocity vary with season. The phenomenon influences the amount of dust attached on a PV module. Consequently, performance degradation of a module affected by dust is not uniform every season. Literature reveals that performance degradation of a module caused by dust is increasing during the driest seasons and conversely decreasing during the wetter seasons. 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. Another work carried out by El-Nashar [17] in Abu Dhabi, UAE showed that transmittance value of a glass cover of a solar desalination recorded during wetter seasons were higher compared to that during driest months.

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 analysed 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° South latitude and 115.85° 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° South latitude and 123° 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° 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° 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 Fig. 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.

A method commonly applied by researchers to assess the electrical performance of a module is current voltage (I-V) curve tracing [18]. 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 analyser, which works on a range of solar insolation between 10 W/m² and 1000 W/m² and on a maximum voltage and current of 60 V and 12 A 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 °C to +80 °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]:

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

Table 1

<table>
<thead>
<tr>
<th>Location</th>
<th>PV module</th>
<th>P(peak) [W]</th>
<th>Isc [A]</th>
<th>Voc [V]</th>
<th>Ip [mA]</th>
<th>Vjp [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROTA</td>
<td>PV 1 (a-Si)</td>
<td>40</td>
<td>2.54</td>
<td>21.8</td>
<td>2.31</td>
<td>17.3</td>
</tr>
<tr>
<td></td>
<td>PV 2 (pc-Si)</td>
<td>108.2</td>
<td>5.33</td>
<td>43</td>
<td>3.2</td>
<td>33.8</td>
</tr>
<tr>
<td></td>
<td>PV 3 (nc-Si)</td>
<td>125</td>
<td>5.5</td>
<td>33</td>
<td>4.91</td>
<td>26.2</td>
</tr>
<tr>
<td>PNK</td>
<td>PV A &amp; B (mc-Si)</td>
<td>100</td>
<td>5.78</td>
<td>22.5</td>
<td>5.35</td>
<td>18.7</td>
</tr>
<tr>
<td></td>
<td>PV C &amp; D (pc-Si)</td>
<td>100</td>
<td>5.58</td>
<td>22.68</td>
<td>5.26</td>
<td>19.01</td>
</tr>
</tbody>
</table>
2.2. Dust density measurement

Stipulated in IEC 60891. The open circuit voltage (V).

Based on the I-V curve produced by equations (1) and (2), the maximum power (W); I_{sc}: short circuit current (A); V_{oc}: open circuit voltage (V).

Based on the I-V curve produced by equations (1) and (2), P_{max} was obtained. Where, subscript 1 and 2: ROC and STC values respectively; I \text{ and } V: \text{current (A) and voltage (V), respectively of I-V characteristic data pairs; G: in-plane irradiance (W/m}^2); T: \text{module back side temperature (°C); } \alpha: \text{current temperature coefficient (A/°C)}; \beta: \text{voltage temperature coefficient (V/°C)}; R_s: \text{the internal series resistance of the test specimen (Ω)}; k: \text{curve correction factor (Ω/°C)}; P_{max}: \text{maximum power (W)}; I_{sc}: \text{short circuit current (A); V_{oc}: open circuit voltage (V).}

\[ V_2 = V_1 - R_s(I_2 - I_1) - \kappa J_2(T_2 - T_1) + \beta(T_2 - T_1) \]  

(2)

Table 2

<table>
<thead>
<tr>
<th>Location</th>
<th>Time</th>
<th>PV condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROTA</td>
<td>Beginning of November 2014</td>
<td>Clean</td>
</tr>
<tr>
<td></td>
<td>At the end of February 2015 (summer)</td>
<td>Dusty</td>
</tr>
<tr>
<td></td>
<td>At the end of May 2015 (autumn)</td>
<td>Dusty</td>
</tr>
<tr>
<td></td>
<td>At the end of August 2015 (winter)</td>
<td>Dusty</td>
</tr>
<tr>
<td></td>
<td>At the end of November 2015 (spring)</td>
<td>Dusty and clean</td>
</tr>
<tr>
<td></td>
<td>At the end of March 2015 (wet season)</td>
<td>Dusty</td>
</tr>
<tr>
<td></td>
<td>At the end of October 2015 (dry season)</td>
<td>Dusty and clean</td>
</tr>
<tr>
<td>PNK</td>
<td>Beginning of November 2014</td>
<td>Clean</td>
</tr>
<tr>
<td></td>
<td>At the end of December 2014</td>
<td>Clean</td>
</tr>
<tr>
<td></td>
<td>At the end of March 2015</td>
<td>Dusty</td>
</tr>
<tr>
<td></td>
<td>At the end of June 2015</td>
<td>Dusty</td>
</tr>
<tr>
<td></td>
<td>At the end of September 2015</td>
<td>Dusty</td>
</tr>
</tbody>
</table>

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

To analyse morphology of dust from ROTA and PNK, a "JCM-6000 NeoScopeBenchtop" Scanning Electron Microscope (SEM) was applied. Dust collected from the two sites was sprinkled on a stub type specimen storage container with a free fall technical. The accumulated dust on the container was then coated with carbon to minimize static charging effect. SEM images of dust were analysed using image processing software to determine grain size, surface texture, and shape of dust. An Electron Dispersive Spectroscopy (EDS) embedded to the SEM was used to investigate the element of dust. To identify chemical composition of dust, a PANalytical X-ray diffraction (XRD) was deployed.

The research methodology of this study to investigate the effect of seasonal dust on the performance of PV modules with case 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 5 × 5 cm² 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 (Fig. 2) which can be set to various angles to simulate the modules’ inclination at ROTA (32°) and PNK (15°). The selected angles consist of 0°, 30°, 45° and 60° for ROTA, and 0°, 15°, 30° and 60° for PNK.

Before deploying in the field, the glass samples were weighed to obtain their clean weight (M₁ 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 (M₂ in mg). Dust density (D in mg/cm²) was calculated using formula:

\[ D = \frac{M_2 - M_1}{A} \]  

(3)

where, A = glass area (cm²)

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

66
studies in Perth and NTT can be summarized as shown in Fig. 3.

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

\( P_{\text{max}} \) output is an important electrical parameter used to assess performance of a PV module [24]. In this research, \( P_{\text{max}} \) losses caused by dust were calculated by subtracting \( P_{\text{max}} \) values of a module in dusty conditions (no cleaning, dust particles still deposited on PV modules surface) from \( P_{\text{max}} \) values in clean conditions (after dust particles are washed away) measured at the end of a period of study. \( P_{\text{max}} \) losses caused by non-dust related factors were determined by subtracting \( P_{\text{max}} \) values in clean conditions at the end of a period of study from \( P_{\text{max}} \) values in clean conditions in the beginning of the study.

Referring to a work completed by Tanesab et al. [4], the contribution of dust (\( C_{\text{dust}} \)) and non-dust related factors (\( C_{\text{non-dust}} \)) on the degradation of PV modules’ performance over a one-year period of exposition at ROTA and PNK were calculated with the following formulas:

\[
C_{\text{dust}}(\%) = \left( \frac{P_{\text{max}} \text{ losses caused by dust}}{\text{total } P_{\text{max}} \text{ losses}} \right) \times 100 \tag{4}
\]

\[
C_{\text{non-dust}}(\%) = \left( \frac{P_{\text{max}} \text{ losses caused by non-dust factors}}{\text{total } P_{\text{max}} \text{ losses}} \right) \times 100 \tag{5}
\]

where total \( P_{\text{max}} \) losses is the summation of \( P_{\text{max}} \) losses caused by dust and \( P_{\text{max}} \) 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 min 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

<table>
<thead>
<tr>
<th>Month</th>
<th>Average temperature (°C)</th>
<th>Maximum temperature (°C)</th>
<th>Accumulated rainfall (mm)</th>
<th>Rainy days</th>
<th>Average wind speed (m/s)</th>
<th>Average relative humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov ‘14</td>
<td>19 28.6</td>
<td>38.32 33.5</td>
<td>13 20</td>
<td>7 4</td>
<td>2.27 2.39</td>
<td>69.11 78</td>
</tr>
<tr>
<td>Dec ‘14</td>
<td>21.27 29</td>
<td>44.98 32</td>
<td>1 201</td>
<td>1 14</td>
<td>2.39 2.44</td>
<td>51.82 82</td>
</tr>
<tr>
<td>Jan ‘15</td>
<td>24.58 27.9</td>
<td>38.99 30.8</td>
<td>2.5 659</td>
<td>1 23</td>
<td>2.42 2.29</td>
<td>44.96 84</td>
</tr>
<tr>
<td>Feb ‘15</td>
<td>24.36 27.3</td>
<td>35.76 31.2</td>
<td>23.2 112</td>
<td>3 17</td>
<td>2.29 2.29</td>
<td>57.29 83</td>
</tr>
<tr>
<td>Mar ‘15</td>
<td>22.15 27.2</td>
<td>29.89 31.4</td>
<td>16 339</td>
<td>5 16</td>
<td>2.29 2.38</td>
<td>55.46 87</td>
</tr>
<tr>
<td>Apr ‘15</td>
<td>19.1 28.1</td>
<td>26.07 33.3</td>
<td>44 61</td>
<td>8 4</td>
<td>2.38 2.02</td>
<td>58.07 79</td>
</tr>
<tr>
<td>May ‘15</td>
<td>14.77 27.3</td>
<td>25.33 32.9</td>
<td>72.5 13</td>
<td>6 2</td>
<td>2.02 2.15</td>
<td>67.24 74</td>
</tr>
<tr>
<td>Jun ‘15</td>
<td>14.83 26.8</td>
<td>22.63 32.5</td>
<td>62.5 0</td>
<td>9 –</td>
<td>2.15 1.96</td>
<td>73.42 71</td>
</tr>
<tr>
<td>Jul ‘15</td>
<td>13.45 26.2</td>
<td>27.72 31.9</td>
<td>117.5 4</td>
<td>17 1</td>
<td>1.96 2.12</td>
<td>78.75 70</td>
</tr>
<tr>
<td>Aug ‘15</td>
<td>14.01 26.1</td>
<td>32.06 32.1</td>
<td>70 0</td>
<td>13 –</td>
<td>2.12 2.21</td>
<td>74.11 67</td>
</tr>
<tr>
<td>Sep ‘15</td>
<td>15.39 26.7</td>
<td>33.74 32.3</td>
<td>33.8 0</td>
<td>6 –</td>
<td>2.21 2.08</td>
<td>62.13 69</td>
</tr>
<tr>
<td>Oct ‘15</td>
<td>18.97 27.8</td>
<td>39.6 32.6</td>
<td>47 0</td>
<td>6 –</td>
<td>2.08 2.28</td>
<td>65.09 63</td>
</tr>
<tr>
<td>Nov ‘15</td>
<td>20.84 29.5</td>
<td>38.32 33.3</td>
<td>16.7 17</td>
<td>6 3</td>
<td>2.28 2.39</td>
<td>58.98 76</td>
</tr>
</tbody>
</table>
at ROTA at the PV modules’ height (about 1.5 m) 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 m tower at ROTA, extrapolated down to 1.5 m using the power law formula as follows \[ (6) \]

\[
\frac{V_2}{V_1} = \left( \frac{Z_1}{Z_2} \right)^a
\]

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); \( a = \) wind shear exponent (\( a = 0.15 \) 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 h 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 m were converted to the modules’ height of 1.5 m using equation (6). Since the PNK site had similar terrain characteristics to ROTA, a roughness exponent of \( a = 0.15 \) 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 Fig. 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 (KAISi\(_3\)O\(_8\)), meanwhile dust from PNK contained a large portion of calcium oxide (CaO) followed by quartzite (SiO\(_2\)) and some minor amounts of feldspars (KAISi\(_3\)O\(_8\)) 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

Fig. 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 (Fig. 5(a)) can be classified as ‘angular shape’ because some particles exhibit sharp edges, while dust from PNK (Fig. 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. Fig. 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 Fig. 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 Fig. 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 impinging 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/cm² recorded at the end of summer season, while modules at PNK with inclination angle of 15° were covered with 0.37 mg/cm² 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/cm² 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 spectra 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 Fig. 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 Fig. 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 Fig. 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°.

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

<table>
<thead>
<tr>
<th>Diameter (μm)</th>
<th>Percentage of the total sample from ROTA</th>
<th>Percentage of the total sample from PNK</th>
<th>Grain type</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;4</td>
<td>67.34%</td>
<td>57.34%</td>
<td>Clay</td>
</tr>
<tr>
<td>4–8</td>
<td>22.24%</td>
<td>18.41%</td>
<td>Very fine silt</td>
</tr>
<tr>
<td>8–16</td>
<td>7.25%</td>
<td>12.53%</td>
<td>Fine silt</td>
</tr>
<tr>
<td>16–31</td>
<td>2.18%</td>
<td>8.27%</td>
<td>Medium silt</td>
</tr>
<tr>
<td>31–63</td>
<td>0.78%</td>
<td>2.28%</td>
<td>Coarse silt</td>
</tr>
<tr>
<td>63–125</td>
<td>0.21%</td>
<td>1.17%</td>
<td>Very fine grained</td>
</tr>
</tbody>
</table>

Fig. 6. Deposited dust at different seasons and inclination angles.
followed by 30°, 15° and 0°. As the tilt angle increases the average transmittance of dust increases.

The pattern of transmittance results in Fig. 7 is in agreement with the trend of dust accumulation in Fig. 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 Fig. 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/cm² of dust (Fig. 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/cm² of dust (Fig. 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/cm² 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

$P_{\text{max}}$ 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 equations (1) and (2). To compare the PV modules’ performance, the transposed result of each PV module was normalised using its $P_{\text{max}}$ output value in clean condition. The reference was measured at the initial stage of this study. Results are depicted in Figs. 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].

Fig. 8 indicates that normalised $P_{\text{max}}$ output of PV modules at
ROTA varies with season. Starting in a clean condition in the beginning of December 2014, $P_{\text{max}}$ 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 Fig. 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% (Fig. 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 summarized 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% (Fig. 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, $P_{\text{max}}$ 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 Fig. 9. Normalised $P_{\text{max}}$ 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 Fig. 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° inclination angle. As a result, the average transmittance decreased to 78.24% (Fig. 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°) 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 (Fig. 6(b)). Due to the deposited dust, transmittance decreased to 61.24% as shown in Fig. 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

![Fig. 9. Performance of PV modules every season at PNK.](image-url)
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

Tables 5 and 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 equations (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 65–72% and 73–81% 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%–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.

Tables 5 and 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 Tables 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

### Table 5

<table>
<thead>
<tr>
<th>PV module</th>
<th>$P_{max}$ output (W)</th>
<th>$P_{max}$ losses caused by</th>
<th>Total $P_{max}$ losses</th>
<th>$C_{dust}$</th>
<th>$C_{non-dust}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>i</td>
<td>ii</td>
<td>iii</td>
<td>dust</td>
<td>non-dust</td>
</tr>
<tr>
<td>PV 1 (a-Si)</td>
<td>25.33</td>
<td>23.8</td>
<td>24.8</td>
<td>1</td>
<td>4.03</td>
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<tr>
<td>PV 2 (pc-Si)</td>
<td>80.51</td>
<td>73.8</td>
<td>78.6</td>
<td>4.8</td>
<td>6.11</td>
</tr>
<tr>
<td>PV 3 (mc-Si)</td>
<td>94.7</td>
<td>87.6</td>
<td>92.2</td>
<td>4.6</td>
<td>4.99</td>
</tr>
</tbody>
</table>

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; $C_{non-dust}$: contribution of non-dust related factor.

### Table 6

<table>
<thead>
<tr>
<th>PV module</th>
<th>$P_{max}$ output (W)</th>
<th>$P_{max}$ losses caused by</th>
<th>Total $P_{max}$ losses</th>
<th>$C_{dust}$</th>
<th>$C_{non-dust}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>i</td>
<td>ii</td>
<td>iii</td>
<td>dust</td>
<td>non-dust</td>
</tr>
<tr>
<td>PV A (mc-Si)</td>
<td>63.4</td>
<td>53.2</td>
<td>60.7</td>
<td>7.5</td>
<td>12.36</td>
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<tr>
<td>PV B (mc-Si)</td>
<td>58.2</td>
<td>47.8</td>
<td>56.2</td>
<td>8.4</td>
<td>14.95</td>
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<tr>
<td>PV C (pc-Si)</td>
<td>75</td>
<td>61.1</td>
<td>72.02</td>
<td>10.92</td>
<td>15.16</td>
</tr>
<tr>
<td>PV D (pc-Si)</td>
<td>78.1</td>
<td>65.3</td>
<td>75.2</td>
<td>9.9</td>
<td>13.16</td>
</tr>
</tbody>
</table>

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.

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

### Table 8

Degradation rate of PV modules at PNK.

<table>
<thead>
<tr>
<th>PV module</th>
<th>$P_{max}$ (W)</th>
<th>Initial (1997)</th>
<th>Beginning of wet season (2014)</th>
<th>After dry season (2015)</th>
<th>Total degradation after 17 years (%)</th>
<th>Degradation rate per year (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV A (mc-Si)</td>
<td>100</td>
<td>63.4</td>
<td>60.7</td>
<td>36.68</td>
<td>2.15</td>
<td></td>
</tr>
<tr>
<td>PV B (mc-Si)</td>
<td>100</td>
<td>58.2</td>
<td>56.2</td>
<td>41.8</td>
<td>2.46</td>
<td></td>
</tr>
<tr>
<td>PV C (pc-Si)</td>
<td>100</td>
<td>75</td>
<td>72.02</td>
<td>25</td>
<td>1.47</td>
<td></td>
</tr>
<tr>
<td>PV D (pc-Si)</td>
<td>100</td>
<td>78.1</td>
<td>75.2</td>
<td>21.9</td>
<td>1.29</td>
<td></td>
</tr>
</tbody>
</table>
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 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 2–5% [36]. Tables 5 and 6 show that $P_{\text{max}}$ 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 Tables 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 W 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 W light emitting diode lamp. It is equivalent to 300 lumen [38] - the minimum requirement lighting for a reading activity [39], for about 14 h.

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 normalized $P_{\text{max}}$ 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. $P_{\text{max}}$ losses caused by dust ranged from 4 to 6% and 16–18% 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.

Acknowledgements

The authors would like to acknowledge Mr. Marc Hampton and Mr. Andrew Foreman for their technical assistances. Julius Tanesab gratefully acknowledges the Indonesian Government (DIKTI) (620/ E4.4/IK/2012) for providing a PhD scholarship.

References

Chapter 3 communicates the seasonal effect of dust on the performance degradation of PV modules deployed in two different climate areas, Perth, Australia, a temperate climate region and Nusa Tenggara Timur (NTT), Indonesia, a tropical climate area. A laboratory experiment was carried out to assess the chemical, morphology, and optical properties of dust. A field experiment was conducted to measure dust density affected by weather elements, exposure time, and tilt angle. In addition to the dust deposition measurement, the performance of selected PV modules in the field study areas was recorded at the end of every season.

Chemical and morphological analysis results informed that dust collected from the Renewable Outdoor Testing Area (ROTA), Perth was dominated by quartzite (SiO$_2$) with an angular shape, while a large portion of calcium oxide (CaO) with aggregate and porous shape was found in dust collected from a PV plant at Politeknik Negeri Kupang (PNK), NTT. The grain size analysis revealed that dust particles from Perth were finer than that from NTT.

Optical property analysis of dust showed that transmittance was changed with the density of dust affected by season, exposure time, and tilt angle of PV module. The highest transmittance values were exhibited by the highest tilt angle samples collected at the end of the greatest rainfall seasons. In Perth, the highest transmittance was recorded at a tilt angle of 60° at the end of summer followed by spring, autumn, and winter. Meanwhile in the NTT, the higher value was noted at a tilt angle of 60° at the end of dry season.
The performance degradation of the PV modules varied with season as well. In Perth, the performance of PV modules at tilt angle of 32° 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 with tilt angle of 15° 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.

In similar conditions, for the wettest and driest seasons, performance degradation of PV modules in NTT was greater than that of Perth. The higher losses were attributed to the lower tilt angle of the modules, the longer dry season and the higher relative humidity in the area.

Contribution of dust analysis showed that, for a one-year period of study, the degradation of all modules was more affected by dust compared to the non-dust related factors. $P_{\text{max}}$ losses caused by dust ranged from 4 to 6% and 16 to 18% for PV modules in Perth and NTT, respectively.

The results of losses in PV power generation are important information for future PV design in both areas, especially in NTT which accounted greater values than the typical dust de-rating factors (2 to 5%). 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.
Dust attached on a PV module surface tends to form a thin layer that cause hot spot phenomenon. It rise the temperature of the shaded cell of more than 20 degrees over the other cells in the same PV module. Over time, this is potential to lead to some destructive effects that degrade PV module performance. Therefore, an investigation on the performance degradation of PV modules affected by dust for a longer time period than that mentioned previously is needed. The question needs to ask now, “is there any permanent degradation caused by a long term dust accumulation on PV surface”?

Referring to the limitation of this study mentioned above, a further research was carried out as reported in Chapter 4. It investigated the effect of dust accumulated naturally on PV module performance in the field for a long time period without any cleaning procedure. The research also compared the contribution of dust and non-dust related factors to degrade PV performance for a long time period.
CHAPTER 4

THE CONTRIBUTION OF DUST TO PERFORMANCE DEGRADATION OF PV MODULES IN A TEMPERATE CLIMATE ZONE

A note on content, formatting, and style

This chapter is a published paper with details as follows:
Title: The contribution of dust to performance degradation of PV modules in a temperate climate zone
Authors: Julius Tanesab*, David Parlevliet, Jonathan Whale, and Tania Urmee
Affiliation: School of Engineering and Information Technology, Murdoch University, WA, Australia
DOI: http://dx.doi.org/10.1016/j.solener.2015.06.052.
Impact factor: 4.01

Attribution

Julius Tanesab developed the concept, performed the experiment in the laboratory and in the field, collected data, interpreted the findings, and wrote the manuscript. David Parlevliet helped and supervised the experiment in the laboratory. Jonathan Whale developed the theme of the paper, supervised the experiment in the field, and edited the manuscript. Tania Urmee designed the experiment and collected PV modules specification data. Trevor Pryor contributed in developing the concept and providing specification data of PV modules. All authors critically reviewed and approved the final version of the manuscript.
Amendment of Chapter 4

Table 3, Column 2 (page 86) shows initial $P_{\text{max}}$ of six PV modules (PV A to PV G) measured 18 years ago before exposing to the field. The data recorded by a solar simulator class A+, SPIRE 460 (Carr et al., 2003) were affected by the typical measurement accuracy of the device of ±5% (Emery et al., 1988). This information should be added as a new paragraph (paragraph 2) in section 3.2, page 85 to clarify the source of the data.

Due to the revision, a new bibliography should be added in the References as follows:

The contribution of dust to performance degradation of PV modules in a temperate climate zone

Julius Tanesab *, David Parlevliet, Jonathan Whale, Tania Urmee, Trevor Pryor

School of Engineering and Information Technology, Murdoch University, Murdoch, WA 6150, Australia

Received 2 April 2015; received in revised form 13 June 2015; accepted 29 June 2015

Abstract

This research investigates the contribution of dust to the long-term performance degradation of various photovoltaic (PV) modules that have been operating for almost eighteen years without any cleaning procedures at the Renewable Energy Outdoor Testing Area (ROTA), Murdoch University, Perth, Australia. A solar module analyser was used to assess the PVs’ electrical performance, while a combination of spectrophotometer, scanning electron microscope, electron dispersive spectroscope and X-ray diffraction were used to examine the properties of the dust on the panels. The study found that the degradation of the PV modules’ power output, ranged from 19% to 33%. The degradation is mostly due to non-dust related factors such as corrosion, delamination, and discoloration, which account about 71–84%, although the contribution of dust is still significant at 16–29%. Anova analysis shows that the dust has a fairly uniform impact on the performance degradation of all PV technologies at ROTA. This is in line with the results of spectral transmittance curves for different dust density samples that essentially flat over the wavelength range of the PV modules. An investigation of the properties of dust revealed that dust particles deposited on PV modules’ surface at ROTA were dominated by fine particles built of large amounts of quartz (SiO2), followed by calcium oxide (CaO) and some minors of feldspars minerals (KAlSi3O8), which are the main factors in transmittance losses that affect PV module performance.

1. Introduction

Due to a continuing price reduction, government subsidies and an improvement in reliability and efficiency, the demand for photovoltaic (PV) modules has increased tremendously over the last ten years (Tyagi et al., 2013). An analysis completed by the International Energy Agency (IEA) indicated that the capacity of new systems installed was at a rate of 100 MW per day in 2013, as a result the electricity yielded by solar PV globally reached 150 GW in early 2014 (IEA, 2014).

Energy produced by a PV module deployed outdoors depends greatly on PV materials and solar insolation (Mani and Pillai, 2010). Over time, the electrical energy output will decrease, commonly due to causes such as humidity, thermal cycling, ultra-violet radiation, and moisture ingress (Quintana et al., 2002) that lead to some permanent degradation, namely corrosion, discoloration, delamination, and breakage and cracking cells (Munoz et al., 2011). Besides these internal factors, one environmental factor that significantly reduces the energy produced by a PV module temporarily is dust (Mani and Pillai, 2010). The PV performance could be recovered to its maximum capacity by cleaning activities performed manually, automatically and naturally (Sayyah et al., 2014).

Keywords: PV module performance; I–V and P–V curves; Power degradation; Dust; Soiling

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Deposited dust on a PV module’s cover glass diminishes the illumination by absorbing and scattering sun light received by the solar cells (Elminir et al., 2006; Qasem et al., 2012; Appels et al., 2013). The accumulation of dust on a PV module’s surface is different from location to location and depends on the environmental conditions of ambient temperature and humidity, rainfall and wind velocity (Sarver et al., 2013). Therefore, PV performance degradation caused by dust is not uniform for every region of the world. Adinoyi and Said (2013) found that dust reduces the power output of PV modules by 50% for panels exposed for approximately six months without cleaning in the eastern part of Saudi Arabia. Kalogirou et al. (2013) revealed a 6–13% reduction in power output due to dust recorded in three seasons (spring, winter and summer) in Cyprus. Zorrilla-Casanova et al. (2011) reported that daily energy losses caused by dust in the south of Spain averaged around 4.4% for a year and could increase to more than 20% in dry conditions. Elminir et al. (2006) in their intensive experiments in Egypt found that the energy yield of a PV module decreased about 17.4% per month for south-facing panels at a tilt angle of 45°.

In addition to location, dust accumulation is affected by the PV’s tilt angle (Mani and Pillai, 2010; Qasem et al., 2012; Sarver et al., 2013). Elminir et al. (2006) in their experiments in Egypt reported that the difference of transmittance reduction for tilt angle of 0° (dust accumulation maximum) and 90° (dust accumulation minimum) is 21.3%.

PV module performance tends to degrade as the amount of dust impinged on its surface increases (Elminir et al., 2006; Kalogirou et al., 2013; Sarver et al., 2013). Kaldellis and Fragos (2011), in comparing the electrical parameters of two identical pairs of PV modules, found that a 1.5% reduction of efficiency was recorded by the accumulation of dust with a density of 0.4 mg/cm². Jiang et al. (2011) in an experiment featuring three different PV cell technologies such as monocrystalline silicon (mc-Si), polycrystalline silicon (pc-Si) and amorphous silicon (a-Si) observed the efficiency of the modules decrease from 0% to 26% as dust deposition increased of from 0 to 22 g/m².

In addition to dust density, PV performance is also dictated by the properties of dust. Kaldellis et al. (2011) examined the effect of pollutants comprising red soil, limestone and carbonaceous fly-ash particles on module performance. The study revealed that red soil particles contributed the highest reduction followed by limestone and carbon-base ash. Furthermore, Appels et al. (2013) reported that finer dust particles play a more significant role in decreasing power output than larger particles.

Different PV technologies respond differently to the adverse effect caused by dust. Ndiaye et al. (2013) compared the electrical output parameters of crystalline PV modules that had been exposed without cleaning for a year in Senegal. The result revealed a more severe power reduction for mc-Si modules (77.75%) than pc-Si modules (18.02%). Moreover, a spectral analysis performed by Qasem et al. (2012) to investigate the effect of dust on PV technologies concluded that dust has a more significant effect on the performance of those PV modules that have a wider spectral response e.g. a-Si.

Very little seems to be known about the effect of dust on performance in a long-term study. The longest study appears to be the one year Senegal study by Ndiaye et al. (2013). Yet it is not uncommon for PV arrays to be installed and have very little cleaning over their lifetime, particularly in renewable energy projects in remote areas such as solar home system (SHS) projects. The reasons for a lack of cleaning in these types of projects are that the PV modules are not accessible to the villagers and there is no formal maintenance program (Ismail et al., 2012). Kaldellis and Kokala (2010) estimate the income loss to dust accumulation minimum (dust accumulation maximum) is 21.3%.
associated with not cleaning panels to be almost 40 €/kWp (US$ 42.44) on an annual basis. Solar farm owners pay a maintenance cost for cleaning panels in order to prevent the losses due to power degradation and maximise income. The cost benefit analysis of cleaning then depends on the amount of income gains compared to the maintenance costs. Over a short period of exposure (5 weeks), Appels et al. (2013) suggest that power losses due to dust converge over time to around 3–4% thus limiting income losses and indicating that regular cleaning of modules may be unnecessary. They, however, note that the results do not reflect losses that may occur over longer periods. In particular there would be non-dust related factors that would degrade the performance of modules over a long period as noted by Quintana et al. (2002) and make the cost benefit analysis of cleaning more complex.

This paper addresses the research questions surrounding the long-term degradation of PV modules over long periods of exposure without maintenance. In particular:

1. What are the power losses from different PV technologies over long periods of exposure without cleaning?
2. What is the contribution of dust to the long-term degradation of the PV modules performance?

The research focusses on various photovoltaic (PV) modules that have been operating for almost eighteen years without any cleaning procedures at the Renewable Energy Outdoor Testing Area (ROTA), Murdoch University, Perth, Australia. The contribution of this work is to place modules that have been operating for almost eighteen years without any cleaning procedures at the Renewable Energy Outdoor Testing Area (ROTA), Murdoch University, Perth, Australia. The contribution of this work is to place

<table>
<thead>
<tr>
<th>Month</th>
<th>Hbar (MJ/m²/day)</th>
<th>Hbar( tilt = lat) (MJ/m²/day)</th>
<th>KTbar</th>
<th>Temperature (°C)</th>
<th>Average rainfall (mm)</th>
<th>Aver. Wind speed (m/s)</th>
<th>Average RH (%)</th>
</tr>
</thead>
<tbody>
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<td>27.68</td>
<td>24.59</td>
<td>0.71</td>
<td>25.50 31.50</td>
<td>19.20</td>
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<td>5.89</td>
</tr>
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<td>23.76</td>
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</table>

Table 1

2. What is the contribution of dust to the long-term degradation of the PV modules performance?

The research focusses on various photovoltaic (PV) modules that have been operating for almost eighteen years without any cleaning procedures at the Renewable Energy Outdoor Testing Area (ROTA), Murdoch University, Perth, Australia. The contribution of this work is to place

1.1. Meteorological conditions in Perth

Perth, Western Australia is situated in between 31.95° South latitude and 115.85° East longitude. As a temperate climate area, it has four seasons that similar to areas in the southern hemisphere in which December to February is summer; March to May is autumn; June to August is winter; and September to November is spring. According to meteorological data, the average maximum temperature is 31.7 °C in February (summer) while the average minimum is 7.6 °C (winter) in July. Perth, which has more sunny days annually than any other areas in Australia, has average amount of solar irradiation annually 13.284 MJ/m²/day on a horizontal surface and increases to 14.112 MJ/m²/day when the surface tilted on latitude position and pointing to equator. The months with little rainfall was recorded in December, January, and February whilst July was the wettest month with 146.7 mm rain falling. Similar to the rainfall pattern, average relative humidity was relatively high in winter season. The details of these data are shown in Table 1.

2. Experimental procedures and methodology

2.1. Electrical performance measurement

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 (Carr and Pryor, 2004; Gxasheka et al., 2005; Ndiaye et al., 2014). 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).

The Renewable Outdoor Testing Area (ROTA) is a facility for field testing renewable energy systems at Murdoch University. Seven PV modules at ROTA, comprising two mc-Si, three pc-Si and two a-Si, were used in this research. The modules, which are mounted on north-facing racks tilted at Perth’s latitude of 32° (Carr and Pryor, 2004), have been in operation since November 1996 without any cleaning procedures.

I–V and P–V curves of the PV modules were recorded using a “Prova” solar module analyzer under dusty and...
clean conditions. In parallel with this, module backside temperature and global radiation on the tilted surface were measured with a digital thermometer and a “Kipp and Zonnen” pyranometer, respectively. Measurements were initially carried out on dusty PV modules and subsequently the dusty PV modules were cleaned before repeating the same measurement process. Manual cleaning method was performed by spraying PV modules’ cover glass surface with clean water and scraping it with soft foam. A soft wiper blade for windowpane cleaning then was used to dry the surface (Sayyah et al., 2014). It was observed that this method managed to get all the soil off from the surface of PV modules (no residue). An example of a cleaned panel alongside a dusty panel is shown in Fig. 1.

The experiment was conducted during summer as in Perth in this period there is little rain fall and several months would have passed since the last significant rain. The $I–V$ and $P-V$ curves measurements were performed under real operating conditions (ROC) with varying solar irradiation and temperature. To compare the effect of dust on each PV module’s performance, the electrical parameters’ values were first transposed to their equivalent values in standard test conditions (STC), referring to a radiation of 1000 W/m$^2$, temperature 25 °C and air mass 1.5. In this research, procedure 1 of the IEC 60891 method (IEC 60891, 2009) was used to transpose between ROC and STC for the crystalline and amorphous PV technologies used in the experiment. The key equations employed in this method are as follows:

$$ I = I_1 + I_{sel} \cdot \left( \frac{G}{G_1} - 1 \right) + \alpha \cdot (T - T_1) \quad (1) $$

$$ V = V_1 - R_s \cdot (I - I_1) - \kappa \cdot I \cdot (T - T_1) + \beta \cdot (T - T_1) \quad (2) $$

Based on the $I–V$ curve produced by Eqs. (1) and (2), $P_{max}$, $V_{oc}$, and $I_{sc}$ were scanned and then applied to calculate fill factor ($FF$) by the following equation:

$$ FF = \frac{P_{max}}{V_{oc} \cdot I_{sc}} \quad (3) $$

2.2. Investigation of dust properties

When light impinges on a dust particle on a solar cell, it is either scattered or absorbed (Mann et al., 2007), as a result the amount of light received by the solar cell is decreased. To investigate this phenomenon on the dust deposited on the PV modules at ROTA, a transmittance measurement was performed. Dust was collected from ROTA, mixed with water and sprayed uniformly onto the surface of some 5 $\times$ 5 cm$^2$ soda lime glass plates, a material commonly used as a cover glass for PV modules. During the coating process, enough time was given for the water to evaporate. The transmittance values of the dust accumulated on the glass samples were measured using a “HP” spectrophotometer and afterwards, the samples were weighted using an analytical balance with a 0.1 mg accuracy to determine the mass of the deposited dust.

In addition to the optical properties, the physical characteristics of the dust at ROTA were examined in this research. A “JCM-6000 NeoScope Benchtop” 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. For sample preparation, the surface of a stub type specimen storage container 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 artificial dust collected from ROTA was then deposited onto the surface of the storage container. The deposition of dust was performed by free fall technical using a cylindrical tube to minimize the influence of wind flow as performed by Qasem et al. (2012). 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 adhered to PV module surfaces. In addition to elemental analysis, X-ray diffraction (XRD) was performed to investigate the minerals built of the elements that adhered on PV module surface.

2.3. Determining the contribution of dust

As mentioned previously, the performance degradation of PV modules is temporary as a result of dust deposition on the module’s glass cover (Mani and Pillai, 2010) and permanent caused by non-dust related factors such as yellowing, delamination, bubbles, cracks in the cells, defects in the anti-reflective coating and burnt cells.

Fig. 1. Clean and dusty PV modules installed at ROTA.
Therefore, in this research, the losses are classified into 2 groups that represent the two kinds of performance degradation. Losses caused by dust expresses the difference of electrical parameters output values of PV modules in clean conditions (after dust particles are washed away) and dusty conditions (no cleaning, dust particles still deposited on PV modules surface), whereas the losses caused by non-dust related factors indicates the difference of electrical parameters output values of PV modules from their initial condition (first deployment of PV modules) to their present condition in clean conditions.

\[
C_{\text{dust}}(\%) = \left( \frac{P_{\text{max}} \text{ losses caused by dust}}{\text{total } P_{\text{max}} \text{ losses}} \right) \cdot 100
\]

Meanwhile the contribution of non-dust related factors \( (C_{\text{non-dust}}) \) is expressed by:

\[
C_{\text{non-dust}}(\%) = \left( \frac{P_{\text{max}} \text{ losses caused by non-dust factors}}{\text{total } P_{\text{max}} \text{ losses}} \right) \cdot 100
\]

where total \( P_{\text{max}} \) losses is the summation of \( P_{\text{max}} \) losses caused by dust and \( P_{\text{max}} \) losses caused by non-dust related factors.

The research methodology of this study to investigate the properties of dust and its contribution to performance degradation of PV modules can be summarized as shown in Fig. 2.

### 3. Results and discussion

#### 3.1. The influence of dust on PV module performance

Fig. 3 shows the transposed \( I-V \) and \( P-V \) curves of seven PV module samples, consisting of two mc-Si (label A and B), three pc-Si (label C, D and E) and two a-Si (label F and G), recorded under dusty and clean conditions.

Generally, the results depict lower values for both \( I-V \) and \( P-V \) curves of all PV modules in dusty conditions compared to clean conditions. The mismatch in the curves indicates a degradation caused by dust deposition on each PV module’s surface that blocks solar irradiation received by the solar cells. The discrepancy between these curves is expected to increase with the increase of dust accumulated on the module’s surface (Elminir et al., 2006).

The effect of dust on the characteristic of electrical parameters of PV modules is shown in Table 2. \( I_{SC} \) and \( P_{\text{max}} \) are parameters significantly affected by dust deposition with decreasing output ranging from approximately 5% up to 10% and 8% to 12%, respectively. In contrast \( V_{OC} \) output and \( FF \) are less sensitive to dust and drop by 3% at most compared to values recorded in clean conditions. These results confirm previous research done by Ndiaye et al. (2013) that found a similar trend, in which the \( I_{SC} \) and \( P_{\text{max}} \) outputs of a mc-Si and a pc-Si module significantly decreased due to dust deposition after a year exposure, while the change in \( V_{OC} \) and \( FF \) values of the modules were negligible.
3.2. Dust contribution

Table 3 shows the contribution of dust and non-dust related factors to the degradation in performance (quantified by $P_{\text{max}}$ losses) of PV modules which have been deployed at ROTA for almost 18 years without any cleaning procedures.

According to the result, the degradation of power output of the PV modules ranged from 19% to 33%. The degradation is mostly due to non-dust related factors which account about 71–84%, although the contribution of dust is still significant at 16–29%. Based on the observation in the field the permanent factors consisted of corrosion, delamination and discoloration as shown in Fig. 4.

The percentage of power output reduction caused by dust differs for each PV technology ranged from 8% to 12%. To determine whether there are any significant statistical differences between the means of these data, a one-way analysis of variance (ANOVA) was performed. A critical significance level ($\alpha = 0.05$), yields $F_{\text{ratio}} (0.48) < F_{\text{critical}} (9.55)$ that means null hypothesis ($H_0$) is accepted. In other words, the effect of dust on the
performance of all PV technologies at ROTA, Perth appears to be fairly uniform. In the case of the mc-Si modules, the difference in power output of module A (11.19%) and module B (8.33%) may possibly be attributed to their location close to a veterinary farm and some trees, as they are more likely to be exposed to dust and soiling caused by horse feeding vehicle activities and bird droppings.

Table 3 estimates the minimum power expected to be produced by the PV modules after around 20 years. This is based on the work of Vázquez and Rey-Stolle (2008) who suggest that the minimum output power of a PV module at a certain time period of employment can be determined by: (a) taking into account minimum power output guaranteed by the manufacturer (at least 90% of its initial nominal power for after the first 10–12 years and at least 80% after 20–25 years employment), (b) manufacturing tolerance in module power (5%), and (c) measurement uncertainty (3%). Based on the results in Table 3, there are 2 of 7 PV modules (B and F) that produced less power than the predicted ones. This may be attributed to the adverse effect of dust besides some permanent degradation mentioned previously. Lorenzo et al. (2013) found that dust accumulation on a PV module surface can cause hot spot phenomena which rise the temperature of the shaded cell of more than 20 degrees over the other cells in the same PV module, leading to some destructive effects that degrade PV module performance (Molenbroek et al., 1991).

### 3.3. Dust characterization

#### 3.3.1. Transmittance

The transmission of light through glass samples containing dust collected from ROTA is shown in Fig. 5 for light wavelengths from 300 nm to 1100 nm. Note that all curves approach zero transmittance for the ultraviolet (UV) end of the spectrum due to the glass absorbing the UV.

Fig. 5 shows that as the dust density increases the transmittance decreases. To explore this further the average of transmittance (across the wavelengths > 350–1100 nm) of each glass sample was calculated and normalised to the clean sample average transmittance, and the results are shown in Fig. 6. For example, the increasing dust densities from 0 mg/cm² to 0.04 mg/cm² decreases the transmittance by 18.34%.

Appels et al. (2013) investigated the effect of dust accumulation on the transmittance and power losses of PV modules and reported that by sprinkling 20 g/m² of white sand onto a clean PV module’s surface the transmittance decreased by 4.03%, while the power output decreased by 4.5–5% for a 100 W PV module. Furthermore, for 60 g/m², the transmittance was reduced by 15.03%, while the power output decreased by 13–15%. It may be predicted that the transmittance of light and power output of PV modules decrease progressively with the increase of deposited dust until a point is reached where photons cannot pass through dust particles.
Fig. 5 shows that the spectral transmittance curves for different dust density samples are fairly uniform over the wavelength range of the PV modules. It can be postulated that the soiling at ROTA has an equal impact on the performance between the technology types. On the contrary, Qasem et al. (2012) in Kuwait found that the transmittance...
is affected more by dust at lower wavelengths. Therefore, wider band gap PV technologies such as a-Si and CdTe are more affected by dust deposition than c-Si and CIGS. This contributes to different localities having different soil composition which will affect the transmission of light to a different extent.

3.3.2. Morphology

Fig. 7 shows the SEM image of collected dust from ROTA sprinkled onto the surface of a stub type specimen storage. To determine the size distribution of dust particles, a SEM image (randomly sampled particles) was analysed and specified based on the diameter (Qasem et al., 2012). The results are shown in Table 4.

The results of image processing analysis reveals that dust particles from ROTA were dominated by clay, very fine and fine silt particles. Appels et al. (2013) in their research concluded that finer dust deposition (2–10 μm) on the surface has a more significant effect in decreasing the solar intensity received by solar cells compared to coarser particles. This is because finer dust is distributed more uniformly on PV surfaces than coarser dust particles, thus minimizing the voids between the particles through which light can pass (Sarver et al., 2013). Due to the dependence of the power output of a PV module is on solar intensity, it can be confirmed that the fine dust particle is the major factor in transmittance losses that caused the degradation of PV modules performance at ROTA.

On the other hand, coarser dust particles play a more significant role in the accumulation process of dust on a module’s surface. Based on their research on dust-resembling silica particles, Said and Walwil (2014) concluded that coarser dust particles have higher adhesion force than finer ones. The coarser the dust particle, the wider the contact area between the dust particle and the glass cover of the PV module, as a result the cementation process of dust on the PV glass cover surface, as introduced by Cuddihy (1980), is easier.

3.3.3. Chemical composition

The most important reason to analyze the elements and compounds of dust is to trace the source of dust adhered on the PV modules’ surface (Lax et al., 1986; Elminir et al., 2006) that can provide useful information for dust mitigation policies and procedures.

Elements analysis revealed that there are 6 main elements from the collected dust samples at ROTA. It is noted that the amount of carbon (C) in the results was ignored for reasons explained in Section 2.2. The major elements of the dust samples are oxygen (O) and silicon (Si) which accounts for 34% and 29.14% by weight. In addition, calcium (Ca) and aluminium (Al) are other elements that contribute by 13.21% and 9.26%, respectively. Some minor amounts of iron (Fe) and potassium (K) also were found in dust samples from ROTA which are 8.83% and 5.56% of total element weight.

In addition to the elemental analysis, a mineralogical analysis was done using X-ray diffraction to investigate minerals built of elements above. According to the result as shown in Fig. 8, the dust particles 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 (KAISi$_3$O$_8$).

Quartz and feldspar are the most common minerals found in sandstone. Considering Perth is a desert land and dominated by acid and sandy soils (Waddel et al., 2002), the erosion from the sandstone in the land surrounding ROTA is likely to be the source of high portion of quartzite and some minors of feldspars. Quartz could be found in igneous, sedimentary and metamorphic rocks, meanwhile the feldspar is found in granite and pegmatite bodies. Meanwhile, the presence of calcium oxide, a substance generally from calcium carbonate or limestone, is attributed to cement works in the local environment. The cement works from a new hospital building being constructed near ROTA could be one source of the dust. The materials in which these minerals can be found have been lifted up to PV module surface by wind, and human, or animal activities surrounding the site (Elminir et al., 2006).

4. Discussion on the value of cleaning solar modules

According to the results in Sections 3.1–3.3, it is apparent that besides ageing factors, the decreasing energy yield

### Table 4

<table>
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<td>16–31</td>
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<td>Coarse silt</td>
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<td>63–125</td>
<td>0.21</td>
<td>Very fine grained</td>
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</table>
by PV modules at ROTA is also as a consequence of dust deposition on their surface. A simple analysis was done in order to assess the effect of dust on power produced by a PV module and thus the value of cleaning of the module. From Section 3.2 it can be seen that the most dust-affected module is the mc-Si module (labelled A, as shown in Table 3). The power output loss of that module due to dust was 12.18%, or 11.65 W. Considering that Perth, Western Australia receives an annual average of 5.3 peak sun hours per day (Stapleton et al., 2013), then at least 60 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 W compact fluorescent lamp (CFL) (Khan and Abas, 2011) equivalent to 300 lumen - the minimum requirement lighting for a reading activity (Practical Action, 2012), for about 12 h.

Based on explanation above, dust is an important factor that contributes to the reduction of power from solar PV modules and regular cleaning activities are recommended for small scale long term projects such as SHS. Nevertheless, one aspect that needs to be considered in cleaning activities is a study to investigate the best time to undertake the cleaning activities since dust deposition depends on environmental conditions such as rainfall, wind, relative humidity and temperature (Elminir et al., 2006; Mani and Pillai, 2010; Sarver et al., 2013). In addition further work is needed on designing SHS that are accessible for cleaning while being safe from vandalism as well as training villagers on conducting regular maintenance. For large arrays operating over long lifetimes, there may come a time when the cost of cleaning the panels is not worth the improvement in performance achieved due to the non-dust related factors that are the main cause of performance degradation that, unlike the dust cannot be simply washed away. Further research would involve a cost-benefit analysis of cleaning in the later years of large PV arrays.

The study assessed the contribution of dust to performance degradation of PV modules that have been deployed for 18 years at ROTA, Perth. This was a short-term study, performed during one summer season, and as such is limited in estimating the annual soiling effect. Estimating annual soiling effect would be very useful but this would require a longer term study of repeated rain periods and soiling over at least one year. Such a study might involve deploying identical PV module pairs and comparing their performance in clean and dusty conditions to produce a model of changes in dust density on the panels over the whole year.

5. Conclusion

The contribution of dust to the long-term performance degradation of seven PV modules deployed at ROTA for almost 18 years without any cleaning procedure was investigated. The results depict lower values for both $I-V$ and $P-V$ curves of all PV modules in dusty conditions compared to clean conditions. This indicates a degradation caused by dust deposition on the surface of the PV modules that blocks solar irradiation received by solar cells. Degradation analysis shows that the performance degradation of PV modules quantified by power output losses is mostly due to non-dust related factors such as corrosion, discoloration and delamination which account about 71–84%, although the contribution of dust is still significant by 16–29%. Anova analysis shows that the dust has a fairly uniform impact on the performance degradation of all PV technologies at ROTA confirmed by its $F_{\text{max}}$ result (0.48) of difference of power output reduction ranged from 8% to 12% is less than $F_{\text{critical}}$ value (9.55). This is in line with the results of spectral transmittance curves for different dust density samples that essentially flat over the wavelength range of the PV modules. An investigation of the properties of dust revealed that dust particles deposited on PV modules’ surface at ROTA were dominated by fine particles built of large amounts of quartz ($\text{SiO}_2$), followed by calcium oxide ($\text{CaO}$) and some minors of feldspars minerals (KAlSi$_3$O$_8$), which are the main factors in transmittance losses that affect PV module performance.

Acknowledgements

The authors would like to acknowledge Mr. Marc Hampton, Mr. Ken Seymour and Mr. Andrew Foreman for their technical assistances.

References


Chapter 4 presents an investigation of the impact of a long term exposure to the environment on the performance degradation of PV modules in Perth. The chapter also reports the comparison results of the contribution of dust and non-dust related factors to the performance degradation. Besides the field study, laboratory experiment was also carried out to investigate morphology, optical, and chemical properties of dust.

Chemical analysis indicated that dust collected from The Renewable Outdoor Testing Area (ROTA), Perth were dominated by fine particles built of large amounts of quartz (SiO$_2$), followed by calcium oxide (CaO) and some minors of feldspars minerals (KAlSi$_3$O$_8$).

Maximum output power ($P_{\text{max}}$) was the parameter significantly affected by dust deposition with decreasing output ranging from approximately 8% to 12%. These losses were mostly contributed by dust in which about 16% to 29% of the total power degradation. Meanwhile, the contribution of non-dust related factors such as corrosion, discoloration and delamination was from 84% to 71%.

Statistical analysis showed that dust in Perth had a fairly uniform impact on the performance degradation of all PV technologies. The results were confirmed by the spectral transmittance curves of dust that essentially flat over the wavelength range of the modules.
It is well known that dust causes degradation on the performance of PV module leading to the economic losses. One of the ways to diminish the losses is by performing a cleaning procedure. Literature revealed that cleaning of PV system is worth when cost of production losses due to dust is greater than cost of maintenance activity. Referring to this issue, a further research was needed to determine whether the PV systems in Perth and NTT need a cleaning or not and when is the effective time to perform the cleaning.

To answer the questions a study was carried out as presented in Chapter 5. The analysis was performed by adopting degradation pattern of the most affected PV modules in Perth and NTT as reported in Chapter 3. The analysis results were expected to be useful information for PV users in both Perth and NTT.
CHAPTER 5

ENERGY AND ECONOMIC LOSSES CAUSED BY DUST ON RESIDENTIAL PHOTOVOLTAIC (PV) SYSTEMS DEPLOYED IN DIFFERENT CLIMATE AREAS

A note on content, formatting, and style

This chapter is a published paper with details as follows:
Title: Energy and economic losses caused by dust on residential photovoltaic (PV) systems deployed in different climate areas
Authors: Julius Tanesab\textsuperscript{a, b, *}, David Parlevliet\textsuperscript{a}, Jonathan Whale\textsuperscript{a}, and Tania Urmee\textsuperscript{a}
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Journal: Renewable Energy, Volume 120 (2018), Pages 401- 412
DOI: \url{https://doi.org/10.1016/j.renene.2017.12.076}
Impact factor: 4.35

Attribution

Julius Tanesab designed the concept, interpreted the findings, and wrote the manuscript. David Parlevliet edited the literature review and corrected the manuscript. Jonathan Whale helped to develop the concept by suggesting three scenarios of the effect of dust on the PV systems, edited economic analysis equations and the manuscript. Tania Urmee interpreted the findings especially in the discussion section and edited the manuscript. All authors critically reviewed and approved the final version of the manuscript.
Amendment of Chapter 5

As explained in section 5, page 99 that the presence of dust reduces the amount of power from the system and, in the worst case scenario, increases the shortfall so that the owner has to provide electricity from other sources. The shortfall simply can be addressed by the application of an oversize dust de-rating factor. This approach, however, would cause a larger PV capacity than the standard modelling. Therefore, dust de-rating factor determination should be based on the result of dust impact research at the location. This information could be added as a last paragraph in section 5, page 99.
Energy and economic losses caused by dust on residential photovoltaic (PV) systems deployed in different climate areas

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ABSTRACT

Results of the study revealed that when dust impinged on the surface of the PV modules, monthly maximum power output of a 1.5 kWp system in Perth, Australia and a 50 Wp system in Nusa Tenggara Timur (NTT), Indonesia decreased, on average, by about 4.5% and 8%, respectively. Economic modelling showed that, the cost of production per kWh lost due to dust exhibited by these systems were A$ 0.26/kWh and A$ 0.15/kWh, respectively. Comparison of the cost of energy losses and maintenance revealed that, the Perth system would require manual cleaning in October while the system in NTT would require cleaning in August and October. Although the saving in production losses is not economically significant, this cleaning schedule was recommended, particularly for small systems in NTT since the extra output can have a significant effect on the quality of life in remote villages. The key finding was that higher dust de-rating factors and more cleaning activity may be more appropriate for PV systems deployed in tropical climate areas than that in temperate climate regions. It is recommended that PV system Standards that use the 5% performance de-rating factor due to soiling are reviewed and consideration given to climate-dependent de-rating factors.

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1. Introduction

Performance of a PV module deployed in the field declines as the amount of solar radiation decreases. One factor contributes to diminish the photon to reach solar cells is the incidence of shading [1,2]. With a good design of installation, the effect of shading due to trees, buildings and other high objects can be evaded. However, the presence of dust to cover the surface of the PV module cannot be avoided. The small particles generated by natural and human activities in the environment [3] scatter and absorb the incoming light [4].

PV performance degradation from dust varies with exposure time and location. Adinoyi and Said [5] found that dust reduces the power output of PV modules by 50% when they were exposed for approximately six months without cleaning in the eastern part of Saudi Arabia. Zorrilla-Casanova et al. [6] noted that daily energy losses caused by dust in the south of Spain averaged around 4.4% for a year and could increase to more than 20% during dry conditions. Elminir et al. [7], in their intensive experiments in Egypt, revealed that the energy yield of a PV module decreased about 17.4% per month for south-facing panels at a tilt angle of 45°. Tanesab et al. [8] reported that the degradation of power output of various PV technologies exposed to the elements for almost 18 years without any cleaning procedures in Perth, Australia ranged from 8% to 12%.

Besides the two factors mentioned previously, the effect of dust on the performance degradation of a PV module is dependent on the season. A study carried out by Kalogirou et al. [9] in Cyprus found that the power output of PV modules reached a maximum during winter. The performance slightly decreased during spring and autumn (by a similar amount). A significant reduction was observed during the summer months. In summary, seasons with less rainfall demonstrated more accumulation of dust leading to more performance degradation. This is in line with work by El-Nashar [10] in Abu Dhabi, UAE who reported that the highest drop of the glass covers’ transmittance of a solar desalination plant was recorded during the summer season and was attributed to the increased accumulation of dust as a result of sand storms and lack of precipitation.

on PV modules in Athens found that, taking into account the potential solar irradiation in the region, 1 g/m² of dust could cause annual income losses as much as $400 for a 10 kWp PV system.

Besides natural cleaning, many efforts have been performed by stake holders to mitigate the impact of dust. The actions can be classified into two approaches - restoration and prevention. The former involves manual and automatic cleaning, while the latter comprises surface modification and electrodynamic screening [12,13].

A cleaning procedure should be performed when the cost of production losses ($C_{PL}$) caused by dust is higher than the maintenance cost activity ($C_{MA}$), which is influenced by the cost of materials applied to clean PV modules and the cost of labour [14,15]. Cristaldi et al. [14], who investigated the economic losses of a 20 kWp system installed on the roof of a building in Milan, reported that assuming the system was cleaned in January, the next effective cleaning would be after 5 months.

In a grid connected system, $C_{PL}$ is affected by: (1) the energy losses of the system ($E_{L}$); (2) the saving value ($R_{S}$) i.e. the amount of income saved by electricity needs being supplied by PV modules instead of purchasing grid electricity; and (3) the incentive value ($R_{INC}$) i.e. the amount of income received from excess electricity exported to the grid [15]. An expression for the cost of production losses due to dust has been formulated by Faifer et al. [15] as

$$C_{PL} = E_{L} \times (R_{INC} + R_{S})$$

and applied to a case study of a 20 kW system. However, the term represents only one situation of the effect of dust on energy losses in the field and appears to overestimate the economic losses.

A comprehensive search of the literature has revealed that there are no previous studies that investigate the economic losses caused by dust on small scale residential PV systems and quantify whether its effect is significant. A simple analysis conducted by Tanesab et al. [8] in Perth, Australia, argued that by performing manual cleaning with water, annual power losses of 12.18% due to a dust-affected module could be restored. The power could be used to supply a 5 W light emitting diode lamp, a typical load of a solar home system (SHS), which is suitable to sustain reading activity for about 12 h.

This study was carried out to investigate energy and economic losses caused by dust on typical residential PV systems deployed in the two different climate areas of Perth, Australia and Nusa Tenggara Timur (NTT), Indonesia and identify the cost effectiveness of cleaning as part of regular maintenance. The study aims to expand the work of Faifer et al. and develop an economic model that covers different situations of dust-affected PV output in relation to realistic load profiles.

The following research questions will be answered in this paper:

- What are the energy and economic losses caused by dust on a typical grid-connected PV system in Perth and an off-grid SHS deployed in NTT?
- Does the cost of energy production losses of the systems warrant cleaning of the modules and if so, what is the optimal schedule for cleaning?

2. PV performance degradation caused by dust

The seasonal effect of dust on the performance of PV modules in Perth and NTT had been studied in previous research by the authors. As a temperate climate area, Perth is situated at 31.95° South latitude and 115.85° East longitude. It has four seasons comprising of 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, namely, the dry season (April to October) and the wet season (November to March). NTT is located in the Eastern part of Indonesia with a geographical location of 10° South latitude and 123° East longitude.

PV performance measurements in Perth were conducted from the beginning of December 2014 to the end of November 2015 on
three PV modules deployed at the Renewable Outdoor Testing Area (ROTA), Murdoch University. The modules pointed to North with an inclination angle of 32° were typical of PV technologies used in the region e.g. amorphous silicon (a-Si), polycrystalline silicon (pc-Si), and mono-crystalline silicon (mc-Si). Meanwhile, performance measurements on PV modules in NTT were initiated in the beginning of November 2014 and ran to the end of October 2015. Four PV modules (two pc-Si and two mc-Si), installed at Kupang State Polytechnic (PNK - Politeknik Negeri Kupang) and facing North with an inclination angle of 10°, were chosen to represent PV modules in NTT. All PV modules were washed with clean water so that they started in a clean condition at the beginning of the study. At both sites, measurements were performed at the end of every season in order to capture a worst case soiling scenario e.g. PV modules being left all summer (or dry season) to collect dust. Weather and environmental conditions during the study period were recorded and then used to analyse the experimental results in relation to the impact of dust.

The maximum power output ($P_{\text{max}}$) of the PV modules deployed at ROTA and PNK was recorded using a solar module analyser. The performance results were then transposed to standard test conditions (STC), referring to solar intensity 1000 W/m², temperature 25°C, and air mass 1.5, by applying procedure 1 of the IEC 60891 standard [16]. To compare the PV modules' performance, the transposed result of each PV module was normalised by using, as a reference point, its $P_{\text{max}}$ output value in a clean condition, measured at the initial stage of the study. The results are depicted in Figs. 1 and 2.

The figures show that initially clean PV modules produced their maximum power output, which then decreased with certain site-dependent patterns after exposure to the elements. Variation in performance degradation indicates that the amount of dust accumulated on the modules' surfaces was different over the seasons of the study period. The amount of dust that attaches to the modules was strongly influenced by weather and environmental conditions. The greatest drop in performance was noted during the seasons with less rainfall, i.e. at the end of summer in Perth and at the end of dry season in NTT. These results are supported by the climatological data in Table 1 that reveals there were only 5 rainy days at ROTA during the summer season (December–February). Three occasions of rain occurred in the second and the third day of February 2015 [17]. The less rainfall, understandably, could not wash away all the dust from the PV surfaces. In contrast, raindrops can gather dust particles in the atmosphere as they fall and this dust can then get deposited on the PV surface, exacerbating PV performance degradation [12]. It was also recorded that there were several buildings being renovated at ROTA in the end of spring. Vehicles and worker activities can cause more accumulation of dust in the atmosphere and subsequently more dust on the surface of the PV modules. This may explain why, in Fig. 1, the $P_{\text{max}}$ degradation of PV 1 (mc-Si) and PV 2 (pc-Si) at the end of spring was lower than that at the end of summer. PV 3 (a-Si), however, does not follow this trend and it may be that it was not affected by the activities as its location was far away from the road used to access the buildings. As a tropical climate region, NTT exhibits a longer period of dry season (April to October) than Perth. Table 1 shows there was only one rainy day in July for the last five months of the dry season in NTT. The long dry season caused more dust to build up on PV surfaces leading to its significant degradation. Improvements in performance (without cleaning) were noticeable in seasons with more rainy days such as winter and wet seasons in Perth and NTT, respectively. Table 1 shows that there were 39 rainy days in Perth during winter (June–August) and 74 days in NTT during wet season (November–March). These greater rainfalls were able to clean away significant amounts of dust concentrated on PV surfaces.

Comparing the two sites, it was found that over the examined periods (one year), the performance degradation of PV modules in NTT (12–15%) was higher than that in Perth (4–6%). This indicates that the quantity of dust on PV surface in NTT was greater compared to that in Perth. There are a number of possible reasons for this; the long dry season that caused dust build-up, lower PV inclination angles that made the cleaning processes performed by rain and gravitation more difficult, and higher relative humidity that supported the cementation of dust on the PV cover glass.

### 3. A brief review of residential PV systems in Perth and NTT

The application of PV systems to produce electricity is growing very rapidly in Australia. The Australian Photovoltaic Institute noted that Australia has the highest proportion of residential PV systems in the world (16.5%) and the majority of PV systems are small-scale household rooftop systems with now around 5 GW of installed PV in systems less than 10 kW in rated power [19]. This success has been driven by the significant reduction in cost of PV
module as well as government support by providing a variety of programs to attract the community to install PV systems. One key support mechanism has been the generation of Renewable Energy Certificates (REC) as part of the Renewable Energy Target (RET). Through this scheme, the owners of small scale PV systems (0–100 kW) receive an up-front discount from retailers that reduces the total installed cost of the system. During the period 2009–2012, customers were eligible to receive up to 5 times the amount of RECs on systems that were less than 1.5 kWp in capacity [20].

In addition to REC schemes stipulated by the Federal Government, there have also been some feed-in-tariff (FiT) programs set-up by State Governments in the past seven years. Via this type of program, PV owners receive extra income by selling the excess electricity produced by their systems to the grid.

In Perth, one in every five households has a rooftop PV system and combined capacity has now reached 500 MW [21]. The systems are applied in parallel with the grid to supply the energy needs of the household and popular system sizes are 1.5; 2; 3; 4; 5 and 10 kW [22].

For the purpose of rural electrification, PV modules are also deployed in some remote areas in NTT. Most PV systems in the region are small-scale off-grid systems commonly known as solar home system (SHS). A typical system in NTT features a 50 Wp PV module, a lead acid battery with capacity 70 Ah, a 12 V and 10 Amps solar charge controller, three light emitting diode/LED (6–10 Watts each) and one DC outlet socket for low power consuming appliances such as a television (20 W) and a radio/cassette player (6 W) [23].

The government has encouraged the community to use SHSs through financial incentives such as the credit schemes applied in NTT to increase the affordability of the systems to the users. The scheme allows householders to deposit a down payment of 20% of the cost of the system and pay the rest by instalments over a period of 2–3 years [24].

### Energy produced by a PV system

The average energy produced by a PV system per day \( (E_{PV}) \) is expressed by [25,26]:

\[
E_{PV} = P_{mod} \times H_{tilt} \times N
\]

where

\[
E_{PV} = P_{mod} \times f_{man} \times f_{temp} \times f_{dirt} \times \eta_{inv-int} \times \eta_{inv-sb}
\]

For a grid-connected PV system [26]:

For an off-grid PV system such as a solar home system designed to operate independently, a battery bank is required to back up

### Table 1

Monthly climatic condition of ROTA and PNK over the period of study [17], [18].

<table>
<thead>
<tr>
<th>Month</th>
<th>Average temperature (^\circ)C</th>
<th>Maximum temperature (^\circ)C</th>
<th>Accumulated rainfall (mm)</th>
<th>Rainy days</th>
<th>Average wind speed (m/s)</th>
<th>Average relative humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ROTA</td>
<td>PNK</td>
<td>ROTA</td>
<td>PNK</td>
<td>ROTA</td>
<td>PNK</td>
</tr>
<tr>
<td>Nov '14</td>
<td>19</td>
<td>28.6</td>
<td>38.32</td>
<td>33.5</td>
<td>13</td>
<td>20</td>
</tr>
<tr>
<td>Dec '14</td>
<td>21.27</td>
<td>29</td>
<td>44.98</td>
<td>32</td>
<td>1</td>
<td>201</td>
</tr>
<tr>
<td>Jan '15</td>
<td>24.58</td>
<td>27.9</td>
<td>38.99</td>
<td>30.8</td>
<td>2.5</td>
<td>659</td>
</tr>
<tr>
<td>Feb '15</td>
<td>24.36</td>
<td>27.3</td>
<td>35.76</td>
<td>31.2</td>
<td>23.2</td>
<td>112</td>
</tr>
<tr>
<td>Mar '15</td>
<td>22.15</td>
<td>27.2</td>
<td>29.89</td>
<td>31.4</td>
<td>16</td>
<td>339</td>
</tr>
<tr>
<td>Apr '15</td>
<td>19.1</td>
<td>28.1</td>
<td>26.07</td>
<td>33.3</td>
<td>44</td>
<td>61</td>
</tr>
<tr>
<td>May '15</td>
<td>14.77</td>
<td>27.3</td>
<td>25.33</td>
<td>32.9</td>
<td>72.5</td>
<td>13</td>
</tr>
<tr>
<td>Jun '15</td>
<td>14.83</td>
<td>26.8</td>
<td>22.63</td>
<td>32.5</td>
<td>62.5</td>
<td>0</td>
</tr>
<tr>
<td>Jul '15</td>
<td>13.45</td>
<td>26.2</td>
<td>27.72</td>
<td>31.9</td>
<td>117.5</td>
<td>4</td>
</tr>
<tr>
<td>Aug '15</td>
<td>14.01</td>
<td>26.1</td>
<td>32.06</td>
<td>32.1</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Sep '15</td>
<td>15.39</td>
<td>26.7</td>
<td>33.74</td>
<td>32.3</td>
<td>33.8</td>
<td>0</td>
</tr>
<tr>
<td>Oct '15</td>
<td>18.97</td>
<td>27.8</td>
<td>39.6</td>
<td>32.6</td>
<td>47</td>
<td>0</td>
</tr>
<tr>
<td>Nov '15</td>
<td>20.84</td>
<td>29.5</td>
<td>38.32</td>
<td>33.3</td>
<td>16.7</td>
<td>17</td>
</tr>
</tbody>
</table>

### Fig. 2. PV modules’ performance every season at PNK.
electricity needs during the night or cloudy periods. Thus, \( P_{\text{mod}} \) of an off-grid system is determined by equation [26]:

\[
P_{\text{mod}} = P_{\text{STC}} \times f_{\text{man}} \times f_{\text{temp}} \times f_{\text{dirt}} \times f_{\text{cable}} \times \eta_{\text{coul}} \times \eta_{\text{charge}}
\]  

(3)

Furthermore, correction factor of temperature \( f_{\text{temp}} \) is given as [26]:

\[
f_{\text{temp}} = 1 + \left( \gamma \cdot (T_{\text{cell eff}} - T_{\text{STC}}) \right)
\]  

(4)

\[
T_{\text{cell eff}} = T_a + T_f
\]  

(5)

5. Economic losses caused by dust

Cost of production losses (\( C_{PL} \)) is dependent on energy losses caused by dust, \( E_L \) (in Wh), which is the difference in energy produced by the PV system in a clean condition (\( E_{PV,\text{c}} \)) compared to a dusty condition (\( E_{PV,d} \)):

\[
E_L = E_{PV,\text{c}} - E_{PV,d}
\]  

(6)

In grid-connected systems, any excess energy produced by the PV array is exported to the grid while any shortfall is met by importing electricity from the grid, where:

\[
\text{Excess generation, } X = E_{PV} - L_T, \text{ and}
\]  

(7)

\[
\text{Shortfall, } Y = L_T - E_{PV}
\]  

(8)

Three possible situations were formulated for grid-connected systems with regards to the impact of dust on the cost of production losses:

- The energy losses caused by dust reduce the amount of excess energy exported to the grid without leading to shortfall, and the cost of production losses is given by:

\[
C_{PL} = E_L \cdot \eta_{\text{selling}}
\]  

(9)

- The energy losses caused by dust increase the existing shortfall, and the cost of production losses is given by:

\[
C_{PL} = E_L \cdot \eta_{\text{purchasing}}
\]  

(10)

- The energy losses caused by dust decrease excess output exported to the grid, but also reduce energy for self-consumption so that electricity must be imported from the grid to make up the shortfall. In this case the cost of production losses can be shown to be:

\[
C_{PL} = E_L \left( R_{\text{selling}} + R_{\text{purchasing}} \right) - X_{\text{clean}} \cdot \eta_{\text{selling}} - Y_{\text{dusty}} \cdot \eta_{\text{purchasing}}
\]  

(11)

For SHSs that are off-grid systems the energy produced is commonly used for self-consumption only. The presence of dust reduces the amount of power from the system and, in the worst case scenario, increases the shortfall so that the owner has to provide electricity from other sources such as diesel or petrol generator to meet the needs of the household. Accordingly, the \( C_{PL} \) can be calculated by:

\[
C_{PL} = E_L \cdot \eta_{\text{O}}
\]  

(12)

Further, as stated in [14]; [15], maintenance activity cost (\( C_{MA} \)) is expressed by:

\[
C_{MA} = C_M + C_{WF}
\]  

(13)

A cleaning procedure should be performed when

\[
C_{PL} \geq C_{MA}
\]  

(14)

6. Methodology

Simulation of the effects of dust was performed in three scenarios as explained below:

- In scenario 1, it was assumed that the PV modules were cleaned every day so that the loss caused by dust was 0%.
- In scenario 2, it was assumed that the effect of dust was a constant 5% power degradation over the study period, as per the losses recommended by AS/NZS 4509-2:2010 [25].
- In scenario 3, it was assumed the effect of dust was that observed in the field at the end of every season as shown in Figs. 1 and 2, with a further assumption that the effect is linear between the consecutive seasons. For this scenario, the PV modules with the worst performance were chosen to provide an overview of the worst impact of dust on the economic losses in both areas. The modules are PV 2 (pc-Si) and PV C (pc-Si) for Perth and NTT, respectively, with a degradation pattern over the months shown as the dashed lines in Figs. 1 and 2. To adopt the degradation pattern for the residential PV systems in Perth and NTT, the monthly \( P_{\text{max}} \) output of modules proposed for the systems was multiplied by monthly dust correction factors (\( DCF \)) for each region, calculated from the chosen PVs i.e. PV 2 (pc-Si) and PV C (pc-Si). The \( DCF \) for a certain month (see Fig. 3) is the average of daily \( P_{\text{max}} \) output over a month normalised by \( P_{\text{max}} \) reference, which is \( P_{\text{max}} \) recorded in clean conditions at the beginning of the study.

For the selected residential PV systems in both locations, energy produced by the systems was calculated by deploying the equations in section 4. PV module performance data for each of scenarios 1 to 3 were then applied to calculate the energy and economic losses using the formulas in section 5. In addition, the cost of materials and labour for cleaning the system was estimated to determine maintenance cost activities. A decision of maintenance procedures was then made by considering the economic result and cost of maintenance activities. The summary of the methodology is shown in Fig. 4.

![Fig. 3. Monthly dust correction factor (DCF) of Perth and NTT.](image-url)
7. Supporting data for typical small-scale PV systems in Perth and NTT

During 2009–2012, a 1.5 kWp grid-connected PV system was the most common system installed in Perth due to the terms of the Solar Credits Scheme [20]. Many of these systems exist in Perth today and therefore, a 1.5 kWp system was selected for simulation in this study. The Australian Government’s ‘Energy Made Easy’ electricity usage calculator [27] was used to calculate the average household electricity usage based on a 2014 survey of 4000 households. The calculator shows the average electricity consumption in each season for a typical house in your localised zone with the same number of occupants as in your house. For this research the calculator was used to estimate the monthly average daily energy consumption for a 4-person household in the suburb of Kardinya in the Perth metropolitan area (see Fig. 5). This estimated has assumed that the average daily energy consumption does not vary significantly between months for each season.

Based on the explanation in section 3, it was assumed that a SHS in NTT contains typical loads with characteristics as shown in Table 2. It is noted that an element of customer demand management is important for a SHS. It was assumed the lights were supplied by battery during the night, and the other loads were during the day time so that the system could handle the loads without interruption.

To calculate the energy produced by the residential PV systems, all de-rating factors were sourced from [25], [26] and are summarised in Table 3. Ten 150 Wp mc-Si PV modules, mounted parallel with the roof, were assumed for the typical 1.5 kWp system in Perth. Meanwhile, for a SHS in NTT, a 50 Wp mc-Si PV module mounted on a free standing frame on the roof was considered. As well as the selected typical PV systems and load characteristics, monthly solar irradiation and ambient temperature of the case studies areas were compiled as depicted in Table 4.

8. Results

8.1. Grid connected PV system in Perth

By deploying equations (1)–(5) supported with all data

![Fig. 4. Methodology to determine energy and economic losses caused by dust.](image)

![Fig. 5. Typical daily electricity consumption of a 4-person household in Perth.](image)

<table>
<thead>
<tr>
<th>Description</th>
<th>Base case load</th>
<th>Hours of use per day</th>
<th>Days of use per week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lights (2 x 8 W)</td>
<td>16</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Light (1 x 5 W)</td>
<td>5</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Radio/cassette player</td>
<td>6</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Mobile charger</td>
<td>3</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>TV</td>
<td>15</td>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

Table 2

Assumed load characteristic of PV system in NTT.
mentioned in section 7, the monthly energy produced by the 1.5 kWp system in Perth was obtained for each scenario (Fig. 6). To determine the total load capacity it was assumed that people are at work and the greatest loads are in the morning when the solar radiation is weak and in the evenings when the sun has already set. Data Analysis Australia (DAA), an organisation that provides services for survey and data analysis, analysed half-hourly electricity consumption data, collected as part of the Perth Solar City Program, for thousands of metropolitan residential customers in order to characterise the load profiles of different consumer groups [32].

Based on the load profiles presented by the DAA, it can be estimated that the amount of energy consumption in daylight hours (6am to 6pm) is roughly 40% of the total daily energy consumption. Given the daily energy consumption values depicted in Fig. 5, the total load capacity over daylight hours can be calculated for each month and is contrasted with the energy produced by the PV system in those hours as presented in Fig. 6.

Fig. 6 shows that, due to its small capacity, the energy produced by the 1.5 kW system, in most cases, did not meet the electricity consumption of a 4-person household in Perth and surplus energy from the solar modules only existed during January. In addition, it can be seen that, starting in December, energy produced by the 1.5 kW system decreased progressively to the lowest point at the end of June, but then increased again and reached a peak at the end of the measurement period in November. The trend is in line with monthly solar irradiation data presented in Table 4.

Fig. 6 also shows that the presence of dust caused a decrease of energy generation under scenarios 2 and 3, compared to scenario 1. Applying equation (6), monthly energy losses were obtained as depicted in Fig. 7. Note that under scenario 1, the modules are cleaned every day, assumed to be in a constant clean condition and hence monthly energy losses are zero. Since the energy losses under scenario 2 were constant (5% per month), its monthly energy production will be 95% of the values in scenario 1. Scenario 3, however exhibited variation in losses; energy losses in February (the end of summer) and November (the end of spring) were greater than the other months. This indicates that the amount of dust attached on the PV cover glass over these two months was higher than the other months, as shown by the lower dust correction factors in Fig. 3. As mentioned in section 2, higher dust levels are attributed to lower rainfall occurring during the late spring/summer seasons as presented in Table 1. In addition, building renovation at the PV site at the end of spring also contributed to the greater energy losses. Calculation results reveal that totals of 109.58 kWh/year and 113.54 kWh/year of energy are lost by the system under scenario 2 and scenario 3, respectively.

Referring back to Fig. 6, the presence of dust increases the existing shortfall for all months apart from January. In January, the dust initially decreases the excess energy exported to the grid until there is no excess, and then reduces energy for self-consumption so that electricity must be imported from the grid. Based on these dust impact situations the cost of production losses ($C_{PL}$) was

---

### Table 3
De-rating factors of PV system in Perth and NTT.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Grid-connected PV in Perth</th>
<th>SHS in NTT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{	ext{man}}$ (%)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>$r$ (%/°C)</td>
<td>$-4.5$</td>
<td>$-4.5$</td>
</tr>
<tr>
<td>$T_{	ext{EFC}}$ (°C)</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>$T_{r}$ (°C)</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>$\eta_{	ext{inv}}$ (%)</td>
<td>95</td>
<td>–</td>
</tr>
<tr>
<td>$\eta_{	ext{inv,sc}}$ (%)</td>
<td>3</td>
<td>–</td>
</tr>
<tr>
<td>$\eta_{	ext{site}}$ (%)</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td>$\eta_{	ext{loss}}$ (%)</td>
<td>–</td>
<td>95</td>
</tr>
<tr>
<td>$\eta_{	ext{charge}}$ (%)</td>
<td>95</td>
<td>95</td>
</tr>
<tr>
<td>$f_{	ext{cable}}$ (%)</td>
<td>–</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 4
Monthly solar irradiation and temperature of Perth and NTT [28].

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar irradiation (kWh/m²)</th>
<th>Average temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perth</td>
<td>NTT</td>
</tr>
<tr>
<td>Jan</td>
<td>7.46</td>
<td>5.83</td>
</tr>
<tr>
<td>Feb</td>
<td>7.28</td>
<td>5.57</td>
</tr>
<tr>
<td>Mar</td>
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<tr>
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![Fig. 6. Energy produced by a 1.5 kWp system in Perth.](image-url)
determined by deploying equations (10) and (11). Taking into account the feed-in-tariff value in Perth is 7.13 cents/kWh [33] and energy charge on flat rate tariff is 26.50 cents/kWh [34] the annual C<sub>PL</sub> of the system due to dust with degradation patterns of scenario 2 and scenario 3 is A$ 28.44 and A$ 29.50, respectively. This result reveals that the C<sub>PL</sub> values are greater than the maintenance activity cost (C<sub>MA</sub>) value (A$ 23 for one time cleaning of 10 PV modules) and indicates that it is economically viable for the PV system to undergo a cleaning procedure. Fig. 8 shows the C<sub>MA</sub> and cumulative C<sub>PL</sub> values and indicates that manual cleaning should be performed at the end of September for scenario 2 and in the middle of October for scenario 3 as marked with vertical dashed lines. After the cleaning, dust started to build up again on the surface of the PV modules and consequently it increased the C<sub>PL</sub> although further cleaning was not required for the two scenarios. A different result was exhibited by scenario 1 where the PV modules are washed every day; the annual C<sub>PL</sub> of the system was A$ 0, while the C<sub>MA</sub> was A$ 8395. The cost of cleaning the modules is much higher compared to the production loss costs avoided (about A$ 28.44 and A$ 29.50 for scenarios 2 and 3 respectively) and suggests that the owner of the PV system could afford to reduce the frequency of cleaning.

In addition to the method explained previously, optimal cleaning can be recommended based on the value of power loss of the PV system in the month when C<sub>PL</sub> > C<sub>MA</sub>. The power loss is the difference between power produced by the PV system in clean condition (at the beginning of the study i.e. December) and dusty condition (after exposure to the elements for a certain period). Referring to the assumption in section 2 that the effect of dust per day is similar over a month then the generated power in a dusty month can be determined by multiplying the system’s power output in clean condition by its monthly dust correction factor (DCF) from Fig. 3. From Fig. 8, it is known that power loss values in September for scenarios 2 and October for scenario 3 determined the cleaning schedule in Perth. Calculation results suggest that PV owners in Perth should then clean their PV systems when power losses reach 0.05 kW and 0.07 kW for scenarios 2 and 3 respectively. In practice the PV owners can calculate the monthly power losses by deploying the data of power provided by their inverter. It is important to note that the power values should be recorded during clear days to avoid the effect of variation in irradiation.

8.2. Off-grid PV system in NTT

Similar to the system in Perth, by utilizing the solar irradiation, temperature data and de-rating factors, the monthly energy produced by a 50 Wp SHS in NTT was determined for each scenario (Fig. 9). As stated in the explanation of Table 2, it was assumed that the users employed demand management for this system. Energy produced by the PV system over daylight hours was used to charge a battery and to run a mobile charger, a TV, and a radio. The lights operated during the night time were supplied by the battery. From Table 2, it can be calculated that the lights consumed 21 W of power and 7 Ah of current for 4 h per day. Considering the specification of the solar charge controller (12 V, 10 A, efficiency 5% (Table 3)), the time to recharge the battery is about 0.73 h per day.

Fig. 9 shows that the system could handle the load without interruption and there was excess energy. However, the presence of dust reduced the energy generation of the system. Monthly energy losses due to dust were determined via equation (6) and are shown in Fig. 10. Calculations revealed that the system lost about 4.43 kWh/year and 7.11 kWh/year of energy for scenarios 2 and 3, respectively.

Fig. 9 also shows that dust only reduces the excess energy of the system commonly used by the PV owners to charge additional batteries and other appliances. In the past, before using SHS, the owners used to charge the appliances at neighbouring villagers who are connected to the grid. To determine C<sub>PL</sub> of the system, it was assumed that: (1) decreasing the excess energy meant that some of the extra appliances required charging at neighbouring villagers, with the amount of energy needed was indicated by the energy losses of scenarios 2 and 3; (2) the cost of electricity for asked by the neighbour for charging the appliances was 15.12 cent/kWh, which is the electricity tariff for a small load capacity household [35]. The result of calculations reveals that the C<sub>PL</sub> caused by dust on SHS in NTT was A$ 0.68 and A$ 1.10 for scenarios 2 and 3, respectively. The values are higher than the C<sub>MA</sub> value, which is estimated to be about A$ 0.5 per one time cleaning of a 50 Wp module. From Fig. 11, it can be seen that a manual cleaning should be performed at the beginning of August for the two scenarios as indicated by vertical dashed lines. Since dust re-accumulated on PV surface after the cleaning, C<sub>PL</sub> increased again as shown in the figure. The rate of increase of C<sub>PL</sub> under scenario 3 was greater than scenario 2; as a result for scenario 3, a manual
cleaning needs to be performed again in the end of October. Assuming the PV module was washed every day (scenario 1), the annual $C_{PL}$ of the system was A$ 0, while the annual $C_{MA}$ of the system was A$ 182.5. This scenario exhibits a much higher cleaning cost than the benefit received.

Similar to the discussion in section 8.1, optimal cleaning of PV systems in NTT can be suggested by referring to the power loss values in the months when $C_{PL} > C_{MA}$, i.e. August for scenario 2, and August and October for scenario 3. It is found that a manual cleaning procedure should be conducted when power loss of the system reaches 1.84 W under scenario 2, and 5.17 W and 6.70 W for the first and second time respectively under scenario 3. A PV operator in NTT can deploy a multimeter to measure power generated by the PV system in clean and dusty conditions. The power values should be recorded during clear days to avoid the effect of variation in irradiation.

9. Discussion

Results revealed that when dust impinged on the surface of the examined PV modules, their monthly $P_{max}$ output decreased, on average, around 4.5% and 8% for the systems in Perth and NTT respectively. Analysis of the dust impact based on real degradation in the field, represented by scenario 3, revealed that a total of
113.54 kWh/year (about 300 Wh/day) and 7.11 kWh/year (about 19.5 Wh/day) of energy was lost by the PV systems in Perth and NTT, respectively. The energy losses caused economic losses of A$ 29.50 and A$ 1.10 for the systems in Perth and NTT, respectively. In terms of the costs involved for each kWh of energy lost due to soiling under scenario 3, the Perth system has the largest cost at 25.98 c/kWh compared to the NTT system at 15.47 c/kWh. In the case of the Perth system, the majority of the cost of production losses is due to energy losses increasing the existing shortfall (Equation (10)) and hence the cost for each kWh lost is close to the cost of purchasing electricity, which was 26.5 c/kWh. For the NTT system, the only costs related to energy losses are if users go to neighbours to charge additional batteries and hence the cost for each kWh lost is close to the price of charging at a neighbour’s house, which was assumed to be 15.12 kWh.

By performing a manual cleaning, the most appropriate cleaning method for systems [29], as per the recommended schedule for real dust-affected energy degradation in the field, a PV owner in Perth and an owner in NTT can save about A$ 6.50 and A$ 0.10, respectively. The values are the difference between the total cost of production losses and the cost of maintenance activities. The findings of this study suggest that the impact of cleaning is not economically significant. However, the accumulation of dust on a PV cover does cause a degradation of energy produced by the systems. The cumulative effect of these losses would be significant if it was a very large PV system, such as a solar farm. Further, even a small loss in output would be a serious problem for PV applications, like the small scale PV system in NTT. If a cleaning procedure is applied to the SHS in NTT, the extra power from the cleaned panel can be used to supply basic needs for the villagers. For example, the

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**Fig. 10.** Energy losses caused by dust on a 50 Wp SHS in NTT.

![Energy losses caused by dust on a 50 Wp SHS in NTT.](image)

**Fig. 11.** CPL and CMA of a 50 Wp SHS in NTT.

![CPL and CMA of a 50 Wp SHS in NTT.](image)
19.5 Wh/day of energy calculated as the loss of the PV system in NTT due to dust, could be used to run a 5 W light emitting diode (LED) lamp for about 4 h. The light intensity of these LED lamps is equivalent to 300 lumen [36], the minimum requirement lighting for a reading activity [37]. The electricity can also be utilized for charging phones and running low power entertainment appliances.

In addition to these life quality improvements, cleaning is also to prevent hot spot phenomena. In light rain or high humidity conditions, dust landing on a PV surface will be dissolved by water vapour and form a thin layer [38]. This layer can stick to the PV glass cover for a long time period; the layer may get trapped by biological species including moss and lichen and become hard to remove [39]. Lorenzo et al. [40] reported that the layer can rise the temperature of the shaded cell by more than 20°C over the other cells in the same PV module, leading to some destructive effects that degrade PV module performance permanently.

The difference of the impact of dust on energy and economic losses simulated with the dust-affected degradation patterns of scenarios 2 and 3 for the grid-connected system in Perth is not much as indicated by their C9 values plotted in Figs. 7 and 8. This means that the standard soiling losses of 5% is fairly accurate and can be applied for modelling dust on a PV system in Perth. However, it should be noted that the system needs one time of cleaning per year. A different result was shown by the system in NTT. When the dust-affected losses modelled the real degradation in the field (scenario 3), a SHS in NTT needs two times of cleaning activity, slightly higher compared to modelling standard 5% soiling losses result (scenario 2), which suggests once a year. Therefore, the standard dust de-rating factor should not be applied for a SHS in NTT as it underestimates the dust effect that reduces the reliability of the system. From the previous explanation, it is concluded that a higher dust de-rating factor should be applied in NTT than in Perth. As mentioned in section 2, the decrease in output was caused by the greater amount of dust attached to the PV surface in NTT, confirmed by higher P_{max} degradation in NTT (12–15%) than in Perth (4–6%). The greater concentration of dust in NTT was attributed to the longer dry season, the lower tilt angle of PV module, and higher relative humidity in the location. Furthermore, the C9 of the two systems simulated with scenario 1 was, understandably, A$ 0, but about A$ 8395 and A$ 182.5 was paid to perform manual cleaning every day for the systems in Perth and NTT, respectively. Scenario 1 is clearly not cost effective and daily cleaning would not be recommended for these small-scale systems.

The accumulation of dust over a one year period caused a decrease of P_{max} output by about 4–6% for the system in Perth (moderate climate) and 12–15% for the systems in NTT (tropical climate). The literature suggests that PVs installed in areas with lower precipitation that the two regions studied here may account for greater performance degradation over an even shorter period. For example, a study carried out in Dhahran (desert climate) reported that there was a P_{max} output loss of more than 50% experienced by PV modules exposed for about 6 months [3]. The loss, of course, leads to greater energy and economic losses. Therefore, in addition to sizing with a higher de-rating factor, more intensive dust prevention and performance restoration activities are needed for PV system in low precipitation areas.

It is important to note that the daily load capacity data in Perth used in this research was a simplification based on a typical group of consumers in Perth. Further studies can be done to improve the modelling of energy and economic losses caused by dust by investigating different percentages of electricity consumption during daylight hours for a household, different system sizes and varying costs and tariffs.

The study is limited to the effect of dust on the performance of PV modules at the end of each season over a one year period in 2015. Since monthly performance degradation due to dust would vary from year to year, the C9 data provided in this paper could not be used for modelling the optimal cleaning schedule for several years of PV system operation in Perth and NTT. Further research is needed with more frequent measurement and longer time periods to obtain a clear figure of PV degradation dictated by dust and environmental conditions.

10. Conclusion

This research investigated the energy and economic losses caused by dust on residential PV systems deployed in Perth, Australia, a temperate climate region, and Nusa Tenggara Timur (NTT), Indonesia, a tropical climate area. Energy losses of a 1.5 kWp grid-connected PV system in Perth and a 50 Wp solar home system (SHS) in NTT due to dust, with a degradation pattern as measured in the field at the end of every season, was 113.54 kWh/year (about 300 Wh/day) and 7.11 kWh/year (about 19.5 Wh/day) respectively. Economic modelling showed that, the cost of production per kWh lost due to dust exhibited by these systems were A$ 0.25/kWh and A$ 0.15/kWh, respectively. The cost per kWh lost is a useful metric with which to compare different systems and is influenced by the local situation in terms of excess or shortfall between PV output and load, the possibility of selling excess power and the costs of making up the shortfall. The optimal time to perform a manual cleaning procedure was in the middle of October (P_{max} loss by 0.07 kW) for the system in Perth, while at the beginning of August (P_{max} loss by 5.17 W) and in the end of October (P_{max} loss by 6.70 W) for the system in NTT. By doing a cleaning activity as per the suggested time in the real dust degradation scenario, a PV owner in Perth and NTT can save about A$ 6.50/year and A$ 0.10/year, respectively. Although the cost of production losses is not economically significant for these small-scale systems, cleaning PV modules is recommended as it prevents hot spot phenomenon leading to a permanent performance degradation. Further, the excess energy from the module improves the renewable energy fraction from the system and, particularly in NTT, improves the quality of life. The insignificant economic impact of cleaning, however, signals that dust mitigation procedures on small scale PV systems, including surface technology modification such as coating, may not be appropriate as it, will increase system costs over and above whatever savings could be gained in performance. The standard dust de-rating factor (5%) is appropriate for modelling a grid-connected PV system in Perth, but, the system requires cleaning once per year. Conversely, the standard soiling loss factor of 5% is not suitable for SHS modelling in NTT as the estimation of the impact of dust is underestimated. Therefore, higher dust de-rating factors and more cleaning activity may be more appropriate for PV systems deployed in tropical climate areas compared to that in temperate climate regions. Further, comparing the two regions, much higher de-rating factors and more intensive prevention and performance restoration procedures should be applied for systems installed in regions of the world with low precipitation such as deserts. It is recommended that PV system Standards that use the 5% performance de-rating factor due to soiling, such as AS4509.2 [25], are reviewed and consideration given to climate-dependent de-rating factors.

Acknowledgements

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Summary

The study investigated energy and economic losses caused by dust on residential PV systems deployed in Perth, Australia, a temperate climate region and Nusa Tenggara Timur (NTT), Indonesia, a tropical climate region.

The effect of dust on a 1.5 kWp grid connected PV system in Perth and a 50 Wp solar home system (SHS) in NTT was simulated in three scenarios: (1) it was assumed that performance degradation of the systems caused by dust was 0% as they were cleaned every month; (2) it was assumed that energy loss caused by dust was 5% every month as recommended by Australian/New Zealand Standard 4509-2:2010; (3) it was assumed that the effect of dust was that observed in the field at the end of every season.

Simulation results showed that energy loss of the PV systems with a degradation pattern as measured in the field (scenario 3) caused higher cost of production losses than cost of maintenance activity. Therefore, a manual cleaning procedure should be performed in the middle of October for the system in Perth, while at the beginning of August and in the end of October for the system in NTT. Similar to the results of scenario 3, the simulation results of the effect of dust represented by scenario 2 revealed that the residential PV systems in Perth and NTT needed a manual cleaning at the end of September and at the beginning of August, respectively.

Equivalent economic losses accounted by the system in Perth with dust-affected degradation patterns of scenario 2 and scenario 3 means that the standard dust de-
rating factor (5%) can be applied for dust modelling of a grid-connected PV system in the area, but, it needs one time of cleaning per year. A different result was shown by the system in NTT where the loss value under scenario 3 was greater than scenario 2. Thus, it is safe to say that the standard is not suitable for dust modelling in NTT as it underestimates the effect of dust that potential to reduce the reliability of the system.

When a PV system was cleaned every month as indicated by scenario 1, it was found that the total of economic loss could be neglected. However, this scenario exhibited a much higher cleaning cost than the benefit received. Thus, the scenario is not suggested for the two residential PV systems.

Although it is not economically significant, cleaning PV modules is strongly recommended for the PV systems as it sustains the quality of system and support the improvement of the quality of life. Also, higher dust de-rating factor and more cleaning activity should be applied for PV systems deployed in the tropical climate areas compared to that in the climate regions.
CHAPTER 6

GENERAL DISCUSSION, CONCLUSIONS, AND FURTHER WORK

6.1. General discussion

In addition to some adverse effects on agriculture [85, 86], climate [87], transportation [88], and human health [89], dust also has some disadvantages on the application of photovoltaic (PV) modules. Performance of a PV module tends to decrease as dust impinges onto its cover surface [14, 24, 34, 63, 70, 90]. The attached dust diminishes the illumination by absorbing and scattering sunlight received by solar cells [34, 64, 65].

Many studies have investigated the influence of dust accumulation on the optical properties of solar modules and the impact on the modules’ performance. Some papers reported the effect of dust on the degradation of power [14], energy [45], and efficiency of PV modules [13, 14]. Others not only reported the effect of dust on the electrical parameters’ performance degradation, but also suggested effective remedies. The actions consist of casual cleaning [80], static devices [21], optimization for tilt angle according to the dust information in the region [34], and special glass coatings using hydrophilic and hydrophobic materials that promote self-cleaning [22, 91]. Nevertheless, there are still some knowledge gaps that need to be addressed. It was found that most of the previous studies investigated factors
influencing dust transmittance and accumulation partially. Less attention was given to the long term effect of dust and its impact on PV performance. Furthermore, there is not much information in the literature on research that accommodates the economic losses particularly in regards to small scale systems.

This study aimed to identify the effect of dust on the performance of PV modules in Nusa Tenggara Timur (NTT), Indonesia and Perth, Australia which exhibit different climatic conditions and to determine cost effective maintenance schedules for both solar home system and residential grid connected systems deployed in the regions. To achieve this purpose, the study was focused on several issues:

- Characteristic of dust in NTT and Perth comprising optical, chemical and physical properties.

- The effect of weather elements, site characteristics, tilt angle, and exposure time on dust accumulation on the surface of PV modules in NTT and Perth.

- The effect of dust on the performance degradation of various PV technologies in NTT and Perth.

- The energy and economic impacts of dust on SHS and grid connected PV system in NTT and Perth.

Characterization of dust collected from the field revealed that dust attached to the cover glass of PV modules in Perth was dominated by quartz (SiO$_2$), while calcium
oxide (CaO) was the largest amount of mineral found in dust from NTT. Erosion from soils, sedimentary rocks, and other objects around the PVs’ site were the source of the dust. In addition to the wind, these minerals were lifted up to the surface of the modules by human or animal activities.

For a better understanding of the effect of the different types of dust collected from the different climate areas on the performance of PV modules, a laboratory experiment was performed. The results as presented in Chapter 2 showed that, at an equivalent amount of the dust and on the same PV technology, performance degradation of the modules coated artificially with dust from Perth was greater than that coated with dust from NTT although the differences were not statistically significant. This similarity is attributed to the equivalent amount of solar radiation passed by the two types of dust which achieved solar cells of the modules.

Performance of the examined PV modules is in line with optical results of the dust. It was found that dust from NTT and Perth had similar average transmittance values. The reason is that dust from one area not only exhibited particles with physical properties that led to better transmission of light than the other, but also shared morphological factors that demonstrated adverse optical behaviour. Consequently, the transmittance values of the two types of dust tended to balance out.

The impact of each type of dust on various PV technologies was also investigated in Chapter 2. Results revealed that the dust from each location shared equivalent impact on the performance degradation of the tested modules comprising a-Si, p-Si, and mc-Si technologies. This is attributed to the spectral transmittance curves of the dust that
essentially flat over the wavelength range of the PV technologies. The flat spectral pattern is similar to that reported by Al-Hasan [17] in Kuwait and Al Shehri et al. [92] in Saudi Arabia. However, the findings in this study are in contrast with the results of Qasem et al. [18] in Kuwait who found that the transmittance was affected more by dust at lower wavelengths. As a result, wider band gap PV technologies such as a-Si and CdTe are more affected by dust deposition than c-Si and CIGS. The differences in the colour of dust from the two sites as argued by Al-Hasan [17] might be responsible for the different transmittance curves found in both studies.

In addition to the morphological factors, the performance of a PV module tends to decrease as the amount of dust impinged on its surface increases [34, 63]. It was found that the accumulation of dust on PV cover glass is influenced by weather elements including rain and wind which vary with season. Field study results for a one year period are presented in Chapter 3. In Perth, dust deposition which was maximal at the end of summer decreased significantly at the end of autumn and reached a peak at the end of winter. The dust deposition then increased back approaching the summer’s density at the end of spring. Meanwhile, in NTT, the attached dust which was maximal at the end of dry season exhibited a notable drop at the end of wet season. These results indicated that during the wetter seasons, the greater and more frequent rainfalls were able to wash away dust. But, dust accumulated back on the glass cover of PV samples during the drier seasons as no rain or just light rain occurred. Similar phenomenon to the light rain, wind was considered to be not able to remove dust from the glass surfaces. To sweep away dust from PV surface, an extremely high velocity of wind is needed as found by Cuddihy [37]. Referring to the study of Goossens et al. [38], wind in the two sites
with average speed between 2 and 2.5 m/s [93, 94] was predicted to worsen dust accumulation on PV surface. This study confirmed the work reported by Kalogirou et al. in Cyprus [33]. The authors found that power output of PV modules was maximum during winter. The performance then slightly decreased at a similar level during spring and autumn. A significant reduction was observed during the summer months.

It was found that tilt angle affected dust deposition besides the weather elements. The effect of various tilt angles (0° to 60°) on dust accumulation showed a similar pattern as discussed in Chapter 3. As the tilt angle increased, the accumulation of dust on the PV surface deployed in Perth and NTT decreased. At the same inclination angle, the greatest amount of dust was recorded at the end of the driest seasons (summer and dry season for Perth and NTT, respectively) whereas the lowest level was observed at the end of the wettest seasons (winter and wet season for Perth and NTT, respectively). The higher the tilt angle, the easier the gravitation and natural cleaning agents remove the dust. The results are in agreement with a study done by Elminir et al. [34] in Egypt who found that the amount of dust on a glass surface decreased by 11.36 g/m² from 15.84 g/m² at an inclination angle of 0° when the tilt angle of the module increased by 90°. Similar pattern was also reported by Said and Walwil [20] and Hegazy [68].

To examine the optical value of dust which deposited naturally on PV modules in NTT and Perth, transmittance measurements were performed at the end of every season. Results of dust transmittance revealed a contrast pattern with its density characteristic mentioned previously. The more the dust impinged on the PV surface
the lower the transmittance value. This is caused by minimum voids occurred between dust particles so that less light can pass through [36]. The optical characteristic results are in line with experiments done by Said and Walwil [20] who examined the impact of various densities of dust on transmittance. It was reported that transmittance values of a 30° clean glass sample decreased by 0.03, 0.08, and 0.17% with the increasing of dust by 0.25, 3.5, and 4.6 g/m².

The performance degradation of the chosen PV modules for a one-year period follows the transmittance pattern dictated by dust accumulation which varied with season. In some similar weather conditions, for the wettest and driest months, performance degradation of PV modules in NTT was greater than that in Perth. The higher degradation is attributed to the lower tilt angle of PV modules in NTT (15°) compared to that in Perth (32°); as a result dust was not easily removed by the gravitational effect and not cleaned off perfectly by natural cleaning agents. In addition, the longer dry season in the region (7 months) which caused more dust accumulation on the PV modules’ surface. Higher relative humidity is also a reason for the higher degradation as it support the cementation process [37] of dust on PV surface.

It was found that for the one-year period, \( P_{\text{max}} \) output losses of PV modules deployed in Perth ranged from 4 - 6%, and from 16 - 18% for modules in NTT. For an equivalent period of time, a study by Al-Busairi and Al-Kandari [95] in Kuwait which is a desert climate area reported that dust degraded PV performance exposed to the environment for 14 months by up to 55%. The differences show that the effect of dust is dependent on the site characteristic. PV modules installed in the lower
precipitation regions and tilt angles accounted for more accumulation of dust compared to that exposed in the higher rainfall areas and tilt angles.

In addition to the short-term studies, the effect of dust on PV performance degradation for a long term period was investigated. Result of the field study carried out in Perth is presented in Chapter 4. It was found that the degradation of $P_{\text{max}}$ output of PV samples caused by dust for almost 18 years without any specific manual cleaning procedures were 8 - 12%.

By comparing the degradation results caused by dust on PV modules deployed in Perth for the different periods of time, it is known that their level of degradation increased over time. This indicates that natural cleaning agents such as rain and wind could not remove dust particles perfectly; as a result the amount of dust tends to accumulate continually on PV surface. This obviously deteriorated the PV modules’ performance as the attached dust has the potential to cause a hot spot phenomenon which raises the temperature of the shaded cell by more than 20 degrees over the other cells in the same PV module. Consequently, some destructive effects which degraded the PV module performance permanently occurred [41]. Based on the observation in the field the modules in Perth exhibited some permanent degradation indicated by corrosion, delamination, and discoloration.

The effect of natural dust on the performance of various PV technologies deployed in Perth for almost 18 years was assessed in Chapter 4 also. Statistical analysis showed that the difference of performance degradation of three PV technologies comprising a-Si, pc-Si, and mc-Si was not significant. The similar performance is
attributed to the flat spectral of transmittance exhibited by the dust over the wavelength ranges of the PV technologies. These results confirm PV performance measurement results affected by artificial dust examined in the laboratory as discussed in Chapter 2.

Dust decreases energy production of a PV module leading to economic losses [16, 23, 96]. Chapter 5 reported a simulation result carried out on typical residential PV systems in Perth and NTT. It was found that energy losses of a 1.5 kWp grid-connected PV system in Perth and a 50 Wp solar home system (SHS) in NTT caused by dust were 113.54 kWh/year and 7.11 kWh/year, respectively. Cost of production losses (C_{PL}) caused by the energy losses were A$ 29.50/year and A$ 1.10/year, for Perth and NTT, respectively.

Economic analysis showed that the two systems need a cleaning procedure. By performing a manual cleaning as per the suggested time, in October for system in Perth and in August and October for system in NTT, a PV owner can save about A$ 6.50 and A$ 0.10 per year. The impact of cleaning is not economically significant. However, the extra power from a cleaned panel can be used to supply basic needs especially for small system such as in solar home system in NTT. Besides the life quality improvement, some permanent effects suffered by a PV module as a result of a hot spot phenomenon for a long term period as mentioned previously can be minimized by a cleaning activity which obviously sustains the life time of PV modules [41].
In addition to the real degradation, the effect of 5% soiling every month as stipulated by AS-NZ 4509-2:2010 [97] on the two PV systems was simulated. Results showed that energy and economic losses exhibited by the system in Perth were similar to the result of the real degradation scenario. As a consequence, an equivalent frequency of cleaning was recommended for the system which should be performed once a year (in September). Meanwhile, lower energy and economic losses were shown by the system in NTT. With the standard de-rating factor scenario, only one instance of manual cleaning (in August) was needed by the system in NTT.

An interesting point to note is that by comparing the results of the real degradation and standard de-rating scenarios simulated on the two systems; it is known that PV systems in NTT need more frequent cleaning than the systems in Perth. This is attributed to the larger amount of dust accumulated on the surface of the modules in NTT. As a consequence the systems require shorter intervals between cleaning activities. High concentration of dust is caused by the lower tilt angle, higher relative humidity, and the longer dry season in NTT as mentioned in Chapter 3.

6.2. Conclusion

This thesis highlighted that the type of dust impinged on the surface of PV modules in Perth, Australia, a temperate climate area and Nusa Tenggara Timur (NTT), Indonesia, a tropical climate region was different. A large portion of quartzite (SiO$_2$) was the main component of dust in Perth, while calcium oxide (CaO) dominated the composition of minerals of one in NTT. Erosion from acid and sandy soils in Perth
and sedimentary and metamorphic rocks around the PV plant in NTT were the source of the dust.

Dust accumulation on the surface of PV modules in the field was affected by season and tilt angle. Seasons with greater rainfall demonstrated less accumulation of dust compared to those with less rainfall. As the tilt angle increased the dust deposition on glass samples deployed in NTT and Perth decreased. Transmittance results of dust in NTT and Perth revealed a contrasting pattern with the dust accumulation characteristics. The higher the tilt angles and the wetter the seasons, the lower the transmittance values.

Similar to the transmittance, performance degradation caused by dust on fixed PV modules was influenced by the density of dust which varied with season. In Perth, the performance of PV modules decreased significantly at the end of summer. The performance then increased back at the end of autumn and reached a peak at the end of winter. Similar reduction to the summer’s performance was demonstrated 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. In some comparable weather conditions, PV modules in NTT experienced greater performance reduction than that of in Perth. Lower tilt angle of PV modules, higher relative humidity, and longer dry season in NTT are the factors contributed to more degradation.

The performance degradation caused by dust increased over time. The results showed that natural cleaning agents such as rain and wind could not remove dust
particles perfectly; as a result the amount of dust tend to accumulate continually on PV surface in the field. The attached dust potentially caused a hot spot phenomenon which escalated the temperature of the shaded cell in the same PV module. As a result some destructive effects such as delamination and discoloration that degrade PV module performance permanently were observed.

Dust attached on PV surface caused high energy loss especially in NTT. Economic analysis suggested one cleaning of modules per year in Perth and twice in NTT. The impact of cleaning is not economically significant, but it has a great effect on energy which is very important for renewable energy mainly for a small PV system such as a solar home system in NTT. In addition to increase the quality of life by utilising the energy obtained from cleaning modules for basic needs, cleaning PV module helps to sustain the life time of the systems. This thesis, therefore, suggests more cleaning activity on PV modules deployed in a tropical climate region and near the equator than that in a temperate climate zone. It should be noted that it is valid if tilt angle of PV module and dust characteristics investigated are similar to the ones examined in this study.

Unlike the system in NTT, the effect of dust on the performance degradation of PV modules in Perth can be presented by 5% standard de-rating factor stipulated by Australian/New Zealand Standard 4509.2:2010 with one cleaning per year. Thus, this thesis recommends higher seasonally or monthly variable dust de-rating factor than the standard value should be used for modelling PV system in a tropical climate area. In a broader sense, the soiling de-rating factor should vary between regions. This will improve the accuracy and the reliability of PV system models.
6.3. Further work

This thesis accommodated optical property of dust influenced by morphology factors including shape, surface texture, and grain size. However, literature revealed that one characteristic of dust that affects optical property is the colour of the dust element. Different colours indicated different optical properties. For example, dust with large amount of iron oxides causes significant performance on PV module as it has a strong light absorbance characteristic. Red colour dust tends absorb the smaller wavelengths and reflect the longer ones. A further study can be done by characterizing dust element and investigating the colour of the dust in relation to the optical properties such as transmittance, absorbance, and reflectance.

The study accommodated the effect of dust and its economic analysis on PV performance in NTT and Perth calculated at the end of every season over a one year period. The effect of dust was determined at the end of every season in the two regions. In other words, the degradation of PV modules for several months was based on assumption values. Future research is needed to measure the effect of dust in the field at a higher sampling rate. As a result the variable dust correction factor in both areas can be determined precisely. The study can be initiated with choosing typical PV modules and deploying glass samples in the field. PV performance is measured at the end of every month. In parallel with that, glass samples can be collected to measure dust density in the laboratory.
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