Effects of Coal and Fly Ash Dust Deposition of Photovoltaic Panel Performance: A Photovoltaic System at Coal-Fired Power Plant Case Study

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Abstract. Malaysia is aiming to increase its renewable energy generation capacity from 2\% to 20\% by 2030. Solar photovoltaic (PV) system will play a huge role in getting this target achieve as it is considered a maturing technology in Malaysia and the nation is blessed with ample amount of solar irradiation throughout the year. However, in Malaysia, this technology faces various implementation challenges such as the PV performance degradation due to dust deposition on the PV panels. Generally, coal-fired power plants have an abundant area of coal ash pond that is suitable for installing floating PV systems. However, this area is prone to dust deposition resulting from pulverized coal particles and fly ashes. This paper aims to evaluate the effects of dust deposition on PV panels’ performance, specifically for PV systems that will be installed near coal-fired power plants in Malaysia. In this study, PV panels were exposed to four different types of dust deposit conditions, which are coal particles, fly ashes, normal environmental dust as well as control PV panel that was clean on daily basis. The tests were carried out outdoor under natural sunlight. Performance of the PV panels were measured based on the power generated by the panels. The average power drop based on the types of dust deposition on PV panels are; natural dust (2.72\%), fly ash (13.16 \%) and coal ash (15.82 \%).

Key words: Photovoltaic panel, solar energy, dust deposition, coal ash, PV performance

1. Introduction
As Malaysia is ready for new targets to have 20\% energy from renewable energy (RE) by 2030 [1], many professionals view that solar energy will be the largest source of RE to achieve the target. Despite the fact that solar energy being viewed as the best RE source in Malaysia, there are still a lot of challenges that yet to be explored in various areas of solar energy, including system design, products suitability, operation and maintenance (O&M) and reliability. From the O&M point of view, dust accumulation on PV panels can be a hassle.

Many studies on dust accumulation on PV panels have been carried out in various physical environments and geographical locations throughout the world. For example Tanesab studied for two southern hemisphere sites; Indonesia and Australia [2], Javed [3] and Fountoukis [4] studied the effects of desert environment to the dust accumulation on PV panels in Qatar, Menoufi performed a case study of PV panel dust accumulation in Egypt [5], and Sulaiman studied the tropical-urban environment, 200 km north of Kuala Lumpur, Malaysia [6]. On the other hand, researchers have also...
explored the effects of different types of dust accumulation. This includes ash, salt and soil types of dust accumulation which has been studied by Abderrezek and Fathi [7]. A review performed by Mohd Zaihidee has shown that the energy generated by the PV dropped linearly with the density of dust accumulation and also types of dust [8]. Sulaiman has conducted an experiment to study the effects of different types of dust accumulation on PV panels; mud dust and talcum [9]. Sulaiman performed another study on the effects of talcum, dust, sand and moss on the performance of PV panel [10]. A review on research status of PV panel dust accumulation study prepared by Ahmed has suggested for further study to be done on effects of dust particle size, on the performance of PV panel [11].

This paper presents a study on different particle sizes of dust accumulated on PV panels and how this relates to the performance of the PV panels. In addition, the particle sizes are governed by the types of dust accumulated to the panels, and these are obtained from dust that is typically available within coal-fired power plant environment. This is performed as part of a case study to install a PV system within that environment.

2. Materials and methods

The experiments were performed outdoor and two panels were exposed to two types of dust deposition that imitate the condition in the coal-fired power plant. Another panel was exposed to the environment where the experiment was carried out to eliminate the effect of power plant environment. Performance of PV panel that was cleaned on daily basis was used as control. Coal ash and fly ash were obtained from active coal-fired power plants. Coal ash used in this study was sifted down to 70 µm. Fly ash, on the other hand, was obtained from flue gas deposition its size is about 10 µm. Coal ash and fly ash used in the experiments are as depicted in Figure 1 and Figure 2 respectively.

![Figure 1. Coal Ash.](image1)

![Figure 2. Fly Ash.](image2)

The equipment and instrument used in the study are described in Table 1. The main equipment, which is the PV panel, has maximum power output of 250 Wp per panel and the PV system is grid-connected. Each PV panel has its own micro-inverter, a device to invert the direct current (DC) generated by the PV panel to alternate current (AC) which is the mode of current of the grid. Monitoring system was also installed, this includes the data acquisition system and its software, and other manually operated devices which are the probe thermometer and the solar irradiance meter.
Table 1. Equipment and instrument used in the experiment.

| Equipment / Instrument       | Purpose                                                                 |
|------------------------------|-------------------------------------------------------------------------|
| Polycrystalline PV Panel     | Converts solar energy to electrical energy                             |
| Micro-inverter               | Converts direct current (DC) generated by PV panel to alternate current (AC) |
| Data Transmission Unit       | Data acquisition system                                                |
| WiFi Router                  | Transfers data from DTU to a computer                                  |
| Probe Thermometer            | Measures the temperature at the bottom of the PV panel                |
| Solar Pyranometer            | Measures the solar irradiance                                          |

There were four PV panels set for the PV system in the study. The four PV panels were configured for the followings; Panel 1 – cleaned every day and set as the control for the experiment, Panel 2 – natural deposition of dust from the ambient, Panel 3 – deposited with fly ash, Panel 4 – deposited with coal ash.

Preliminary experiments were carried out to determine the adequate amount of dust that can cover the whole PV panel surface. From the preliminary experiments, it was found that minimum of 10 grams of dust were covering the whole PV panel surface. Therefore, this value is chosen as the baseline for the dust deposition. For conservatism, additional experiment setups were added; 15 grams and 20 grams dust deposition.

The experiments were performed for three weeks. The panels were cleaned prior to the deposition of dust at the beginning of each week. The weight for both fly ash and coal ash dust deposited on the respective PV panels was fixed for a week. The weight of the ashes was varied in the next following weeks. The experimental setup is described in Table 2.

Table 2. Configuration of each PV panel.

| Week | Panel 1     | Panel 2         | Panel 3                          | Panel 4                          |
|------|-------------|-----------------|----------------------------------|----------------------------------|
| 1    | Clean everyday | Naturally deposited | Deposited by 10 grams of fly ash | Deposited by 10 grams of coal ash |
| 2    | Clean everyday | Naturally deposited | Deposited by 15 grams of fly ash | Deposited by 15 grams of coal ash |
| 3    | Clean everyday | Naturally deposited | Deposited by 20 grams of fly ash | Deposited by 20 grams of coal ash |
The experiment setup was configured similar to the configurations designed for the Coal Ash Pond installation to represent actual PV system. This includes, PV panel tilted at 5° and facing south. The PV panel bottom surface temperature was measured. The solar irradiance adjacent to the PV panel was also measured. Theoretically, solar energy generated by the PV panel will be at its peak during the highest solar irradiance of the day.

Figure 3 and Figure 4 show the deposition of coal ash and fly ash on PV panels, respectively.

![Figure 3. PV panel deposited with coal ash.](image1)

![Figure 4. PV panel deposited with fly ash.](image2)

3. Results and Discussion

The results were presented based on weekly setups. Results considered were based on the power produced by each panel. This power produced were compared amongst different configuration setup of PV panel as described in Table 2. As described, Panel 1 is the control PV panel, which was cleaned every morning. Therefore, all other panels were compared against Panel 1 power performance.

Figure 5 shows the typical power profile observed by all panels at the highest irradiance time of the week, which is roughly between 11.30 am to 2.45 pm. It can be seen from the figure that 5 grams of dust deposition weight increment gives a consistent power drop trend for Panel 3 (fly ash) and Panel 4 (coal ash). This is apparent in Figure 5, which illustrates the power drop trend for Panel 3 and Panel 4 when deposited with 10, 15 and 20 grams of dust. Panel 2 shows a similar power drop trend, however the drop is minimal as compared to Panel 3 and Panel 4. To rank the panel in terms of power drop, Panel 2 < Panel 3 < Panel 4. It is also observed from the figure that the power obtained during the period is spiking with different trends when compared weekly. This observation results from the variation in daily weather. However, the effect of weather condition does not affect the results, as the experiment compares the power produced among the panels within the same time period and the same dust deposition weight.

This variation of weather becomes more apparent when the daily maximum power was compared within its weekly setup. This is illustrated in Figure 6. From the figure, it is observed that the naturally deposited panel (Panel 2) shows consistent trend of slight power drop across Day 1 until Day 7 for all three weekly setups. However, for Panel 3 and Panel 4, the power drop trend is insignificant for two days, namely Day 6 and 7 for Week 1, and Day 3 and 4 for Week 2.
Figure 5. Graphs of power vs time for maximum daily power of the week for (a) Week 1, (b) Week 2, (c) Week 3.

Figure 6. Graphs of maximum daily power vs time for (a) Week 1, (b) Week 2, (c) Week 3.

Week 3 shows even more bizarre observation where Panel 3 and Panel 4, which were deposited with dust, produced almost as much power as the Control Panel (Panel 1), towards the end of the week (Day 5, 6 and 7). These observations can be related to the fact that, towards the end of Week 3, it was
raining every day, especially during the afternoon. The heavy rain is believed to have washed away all of the dust deposited during the experiment. The weather is also susceptible for the variation of power drop during Week 1 and 2. Although it was not raining during Week 1 and 2, gust during windy day was believed to have blown away small amount of the dust deposited on the panels.

Nevertheless, in general, the power drop trend can be considered consistent throughout Week 1, 2 and 3. As in daily results in Figure 5, naturally deposited panel’s power performance (Panel 2) is just slightly dropped compared to Panel 1 (control), while Panel 3 (fly ash) and Panel 4 (coal ash) power performance and quite similarly substantially dropped compared to Panel 1, with Panel 4 power drop being the worst consistently. This trend is described numerically in Table 3 which list the average power drop of all panels, except for Panel 1, which is the control PV panel.

| Week | Panel 1 Control (Average Power Drop, %) | Panel 2 Natural (Average Power Drop, %) | Panel 3 Fly Ash (Average Power Drop, %) | Panel 4 Coal Ash (Average Power Drop, %) |
|------|----------------------------------------|-----------------------------------------|----------------------------------------|-----------------------------------------|
| 1    | -                                      | 2.72                                    | 11.40                                  | 12.73                                   |
| 2    | -                                      | 2.83                                    | 16.50                                  | 18.23                                   |
| 3    | -                                      | 2.59                                    | 11.57                                  | 16.51                                   |

4. Conclusion
The research project was performed to measure and analyze the performance of a PV system subject to different particle sizes of dust deposition. The research project is a case study of a PV system installed in coal-fired power plant. Three categories of dust were studied which are natural dust, coal ash and fly ash. Coal ash and fly ash samples were obtained from the coal-fired power plant.

Four PV panels were used in this research project. Panel 1 was cleaned every day and set as the control unit. Panel 2 was left to be naturally deposited by environmental dust. Panel 3 was deposited with fly ash while coal ash deposited on Panel 4. The average power drop compared to the control PV panels based on the types of dust deposition are; natural dust (2.72%), fly ash (13.16%) and coal ash (15.82%). PV panel deposited with coal ash, which has larger particle size compared to fly ash by about seven times, has performance drop of about 3% higher than the PV panel deposited with fly ash.

Challenges came through nature since outdoor experiment is prone to weather conditions. The setup of the outdoor experiment, the length of the experiment, the amount and frequency of the dust deposition are among the areas that can be explored further.

5. References
[1] Malaysia sets new goal of 20% clean energy generation by 2030 The Edge Markets 2018
Available from: http://www.theedgemarkets.com/article/malaysia-sets-new-goal-18-clean-
energy-generation-2030
[2] Tanesab J, Parlevliet D, Whale J and Urmee T 2018 Energy and economic losses caused by dust on residential photovoltaic (PV) systems deployed in different climate areas Renew. Energy 120 401–12
[3] Javed W, Wubulikasimu Y, Figgis B and Guo B 2017 Characterization of dust accumulated on photovoltaic panels in Doha, Qatar Sol. Energy 142 123–35
[4] Fountoukis C, Figgis B, Ackermann L and Ayoub MA 2018 Effects of atmospheric dust deposition on solar PV energy production in a desert environment Sol. Energy 164(January) 94–100
[5] Menoufi K, Mohamed HFM, Farghali AA and Khedr MH 2017 Dust accumulation on photovoltaic panels: A case study at the East Bank of the Nile (Beni-Suef, Egypt) Energy Procedia 128 24–31
[6] Sulaiman SA, Mat MNH, Guangul FM and Bou-Rabee MA 2015 Real-time study on the effect of dust accumulation on performance of solar PV panels in Malaysia Proc. Int. Conf. Electr. Inf. Technol. ICEIT p 269–74
[7] Abderrezek M and Fathi M 2017 Experimental study of the dust effect on photovoltaic panels’ energy yield Sol. Energy 142 308–20
[8] Zaihidee FM, Mekhilef S, Seyedmahmoudian M and Horan B 2016 Dust as an unalterable deteriorative factor affecting PV panel’s efficiency: Why and how Renew. Sustain. Energy Rev. 65 1267–78
[9] Shaharin AS, Haizatul HH, Nik Siti HNL and Mohd SIR 2011 Effects of Natural Dust on the Performance of PV Panels Int. J. Mech. Mechatronics Eng. 5(10) 2028–33
[10] Sulaiman SA, Singh AK, Mokhtar MMM and Bou-Rabee MA 2014 Influence of dirt accumulation on performance of PV panels Energy Procedia 50 50–6
[11] Ahmed Z, Kazem H and Sopian K 2013 Effect of Dust on Photovoltaic Performance: Review and Research Status Latest Trends Renew. Energy Environ. Informatics 193–99

Acknowledgments
The research project is part of a larger research activity funded by Tenaga Nasional Berhad’s (TNB) R&D fund via Generation Division, TNB. The authors would like to express sincere gratitude to personnel involved in this research project, directly or indirectly.