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Performance Monitoring and Evaluation of a CIGS Roof-Integrated Photovoltaic System under the Unique Tropical Environment of Darwin, Northern Territory

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Abstract

Building-integrated photovoltaic (BIPV) technologies are gaining interest from both the research community and the building industry due to their versatile capability to be incorporated to both old and new building designs. From the literature, not much research was done on investigating real-world performance assessment of Copper Indium Gallium di-Selenide (CIGS) thin-film systems in a tropical locale. This paper addresses this gap. The Northern Territory (NT) was chosen to conduct this study due to its unique climate; a distinct wet and dry cycle and a cyclone-prone environment. The objective of this research is to evaluate the performance of a 1.5kWp CIGS BIPV system under these real-world environmental effects; dust accumulation, fauna droppings, natural shading and rig temperature. 5-minute measured data were obtained, over 4 months, and three clear sunny days (each for every month) were identified for analysis. Experimental results showed a qualitative relationship between the aforementioned environmental effects on the system efficiency. In particular, the effect of dust accumulation and bird droppings were the two identified dominant causes of the gradual decrease in the expected peak power output of the system. The effects of natural shading and temperature on the system efficiency were also presented in this paper. This study forms a solid foundation for further studies of the environmental effects on PV efficiency. This work is important due to the increasing uptake of PV systems in the NT and the understandings of these environmental effects enable such PV systems to be maintained efficiently.

1. Introduction

The building sector is a high energy consuming sector in many countries. In the US, over 40% energy consumption comes from the building industry, making it the largest energy consumer (Chae et al., 2014). The building-integrated photovoltaic (BIPV) technology records an increased interest from the commercial, industrial and residential sectors due to their physical and performance characteristics, as well as its versatility. Moreover, their capability of being incorporated into both traditional and modern building designs makes it suitable for both new building developments and retrofits. BIPV offers a new look to commercial/industrial buildings and houses, while this technology also provides pathway to gain socio-economic and environmental benefits. The energy payback time (EPBT) and greenhouse gas (GHG) emissions of thin-film PV systems are within 0.75 to 3.5years and 1.05 to 50 gCO_2eq/kWh respectively (Ng and Mithraratne, 2014). The technology has also the potential to further lower the upfront costs of a PV system through its integration with building components (such as walls and roofs). Various architectural challenges could also be addressed through the integration of such systems directly as a building component.

There are a number of theoretical (i.e. modelling-based) and experimental (i.e. laboratory-based) studies on the effect of various parameters on the efficiency and performance of different types of photovoltaic (PV) systems under different climate zones. These include the effect of slope (Wittkopf et al., 2012), the operating cell temperature (Trinuruk et al., 2009), high cell/module temperature and the effect of dust over the surface of the modules (Meral and Diner, 2011). Khatib et al., 2013 performed an experimental study on the actual performance and characteristics of a grid-connected PV system in the tropical Malaysian climate and demonstrated that the ratio of the theoretical to the actual performance is 73.12%. Ismail et al., 2013, in their comparative performance study of grid-integrated PV under tropical environment in medium radiation region (0.4-0.7 kW/m^2), indicated that the captured losses were minimal in the case of amorphous silicon (a-Si) modules and the highest performance ratios were shown by copper indium selenium (CIS) modules when the ambient temperature is relatively low. They concluded that the second generation PV technologies could operate at higher temperature levels on a wider range of the solar spectra with a-Si modules are best suited for tropical environments. However, in the same paper, the authors mentioned a similar study done in Malaysia (in the high and low radiation regions) having low performance ratios for a-Si. This comparison indicated that a-Si modules may only be favorable for medium radiation intensity regions.

Ng et al., 2013 performed an energy analysis on a semi-transparent BIPV in Singaporean buildings to determine the changes in its efficiency (i.e. increase/decrease of cooling energy, artificial lighting energy and electricity generation). Results showed the potential to adopt semi-transparent BIPV across all orientations in tropical climates. Zomer et al., 2014 carried out a performance evaluation of BIPV and building applied photovoltaic (BAPV) at two airport buildings in tropical Brazil and found that the installed peak power and generation density were higher for BIPV. However, the final annual energy yield through BAPV was 7% higher than BIPV. Ng and Mithraratne, 2014 performed a lifetime environmental and economic performance study of semi-transparent BIPV glazing systems in the tropics of Singapore and found that, after factoring government subsidies, some modules were more economical than the prevailing windows. Note that BIPV differ from BAPV systems. The former are generally installed with building architecture which may or may not form part of the building materials/structure whereas the latter are just installed, complementing the existing building structure (Zomer et al., 2014).

The review of the literature indicated that there had been little focus in investigating the real-world performance of BIPV systems in tropical regions. Darwin, in the Northern Territory (NT), Australia, has a unique climate; high monthly and annual solar radiation, a distinct wet and dry season annually, and a cyclone-prone environment. This work addresses this gap through experimental work to analyse the performance of a CIGS BIPV system focusing on the impact of simple environmental effects (dust accumulation, fauna droppings, natural shading and rig temperature) on the system efficiency.

2. System Description

Figure 1 shows the constructed monitoring and evaluation experimental rig, located at the Casuarina Campus, Charles Darwin University (CDU). It consists of an outdoor structure made from pre-cast slabs, steel sections and BIPV material in the form of roof sheeting, which was fastened directly to the steel structure. The CIGS BIPV modules are bonded to the composite sheet at a distance from the borders of the steel structure. This is to avoid any direct heat transfer to the modules from the steel structure. The CIGS modules are affixed using pressure sensitive adhesives to a Category 4 cyclone wind resistant glass reinforced composite backing with a trapezoidal profile. This testing station is surrounded by local vegetation, which is home to numerous local flora and fauna (mainly birds).

Generally, conventional PV systems are covered with a glass surface and often are so brittle that they are expected to be damaged by the impact of mobilized objects during high winds. This is one of the most important aspects of this experimental setup to experience the impact of high wind weather conditions, such as cyclones, on these non-brittle thin-film panels. The actual production data is continuously logged through a smart inverter where the data can be remotely accessed.

Figure 1: The experimental facility located at Casuarina Campus, CDU

3. Results and Discussions

The system started power production in March 2014. The CIGS modules were exposed to the environment for a sufficient length of time before performing any data analysis to avoid any initial environmental exposure effects on power generation. According to Sarvar et al., 2013, the degradation progresses more rapidly during the first 30 days of exposure. Thus, data collection commenced on May 2014. The experimental dataset consists of 5-minute power output from the grid-connected CIGS system and the respective logging time.

For this study, three distinct clear days were selected for analysis; one day each for May, July and August. The reason for selecting clear days from each of the months is to investigate the gradual reduction in efficiency of the system due to environmental conditions. Their respective climate data is shown in Table 1.

3.1. Shading Effect

Figures 2 to 4 show the 5-minute interval power output profiles of the system on the three selected clear days: 7th May, 7th July, and 27th August 2014 respectively. As expected, the power profiles are smooth with the peak around mid-day.

However, it can be observed that there are clear differences in the power output profiles between the mornings from 8:00am to 9:00am for all the three days. This can explain by referring to Figure 5 which shows the natural shading effect at around 8:00am. In addition, the difference in the trajectory of the sun over the months explains the difference in the power profiles that time.

Table: 1 Climate Data on 7th May, 7th July and 27th August 2014. Source: (http://www.bom.gov.au/climate/dwo/IDCJDW8014.latest.shtml)

Paramter	7th May 2014	7th July 2014	27th August 2014	StDeviation
Sunshine (hours)	11.1	10.8	11.1	0.17
Minimum temperature (°C)	19.8	17.6	16.2	1.81
Maximum temperature (°C)	31.5	30.5	32.9	1.21
Rainfall (mm)	0	0	0	0.00
Evaporation (mm)	6	6.4	9.6	1.97
Direction of maximum wind gust	E	E	E	
Speed of maximum wind gust (km/h)	28	35	52	12.34
Time of maximum wind gust	8:48	13:33	11:27	0.10
9am Temperature (°C)	24.6	21.4	24.3	1.77
9am relative humidity (%)	51	42	48	4.58
9am cloud amount (oktas)	0	5	0	2.89
9am wind direction	E	SE	ENE	
9am wind speed (km/h)	20	15	13	3.61
3pm Temperature (°C)	30.5	30.4	32.2	1.01
3pm relative humidity (%)	41	19	13	14.74
3pm cloud amount (oktas)	1	1	1	0.00
3pm wind direction	E	WNW	E	
3pm wind speed (km/h)	9	22	22	7.51

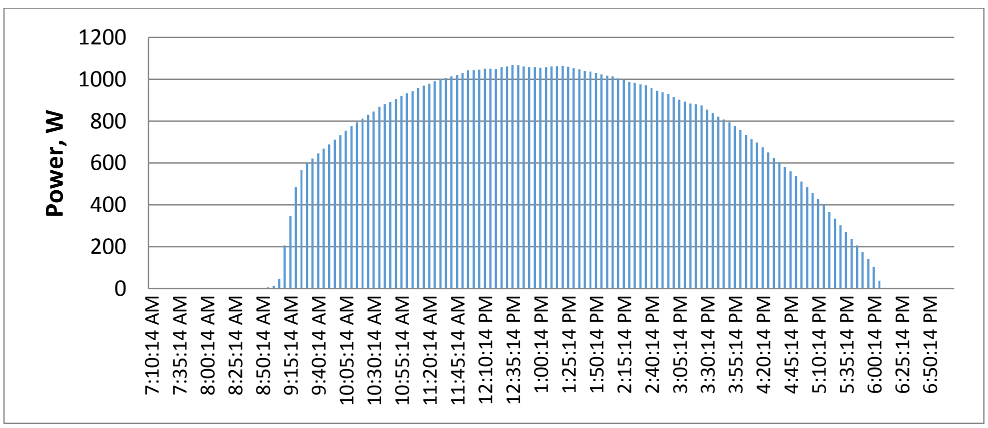


Figure 2: System power output profile - 7th May 2014

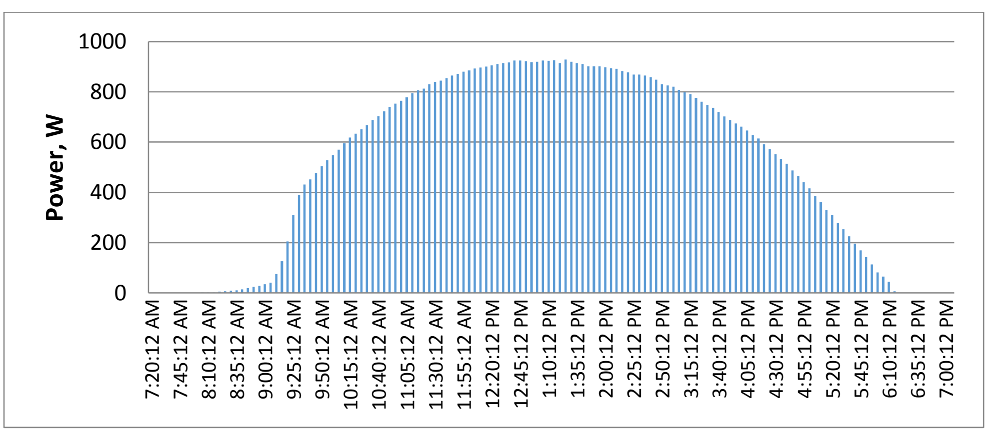


Figure 3: System power output profile - 7th July 2014

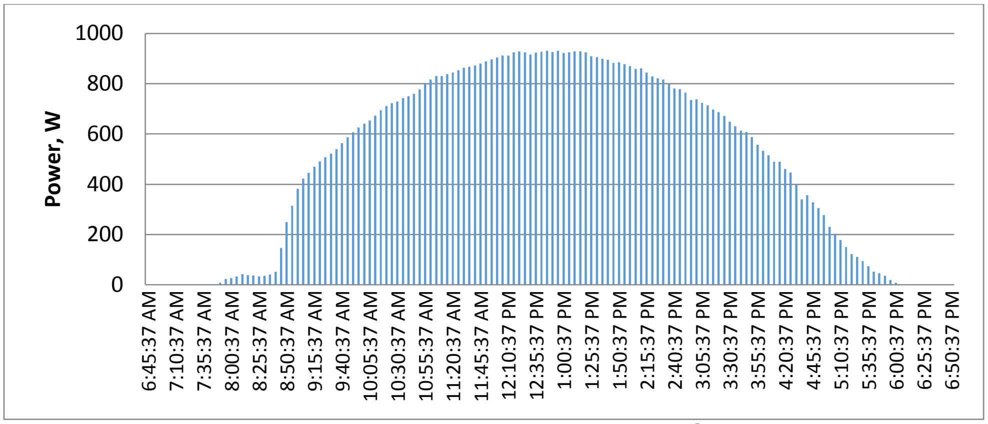


Figure 4: System power output profile - 27th August 2014

Figure 5: Shading Effect in Early Morning

3.2. Effects of dust accumulation and bird droppings

Table 2 shows the number of days where power production falls within the defined range of values from May to August 2014. It can be observed that May 2014 has the highest number of days in which the system produces above 6kWh, and its total production is the highest among all the months investigated. However, May in Darwin is an early dry season for tropical Darwin with occasional rain and some presence of cloud-cover can be expected.

Table 2: Number of Days of Monthly Production

Month	Less than 4.5 kWh	Less Than 5.5 kWh	Around 6 kWh	Above 6 kWh	Total Production (kWh)
May	2	6	5	18	184.32
June	1	1	15	13	179.15
July	0	3	25	3	180.79
August	0	0	22	7	179.46

Figure 6 shows how daily energy produced by the system has dropped gradually from the early dry season of May to the peak dry season months of July and August (with no rain or significant cloud cover recorded).

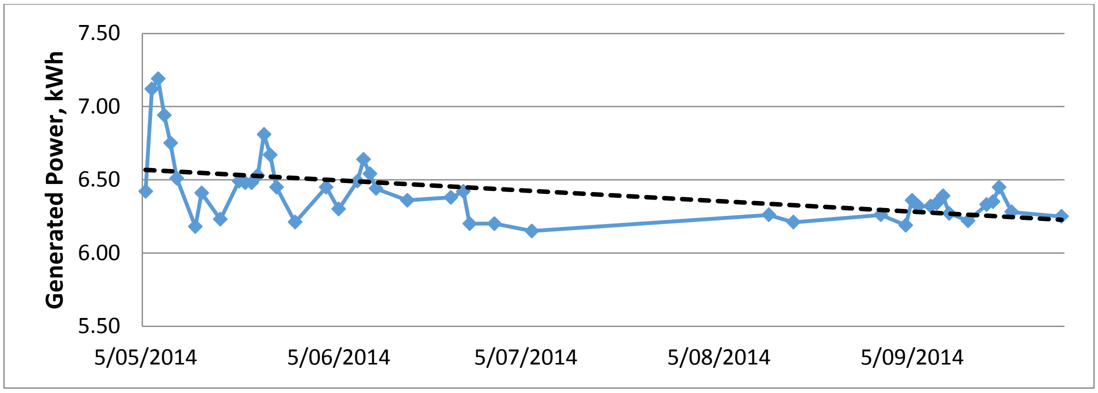


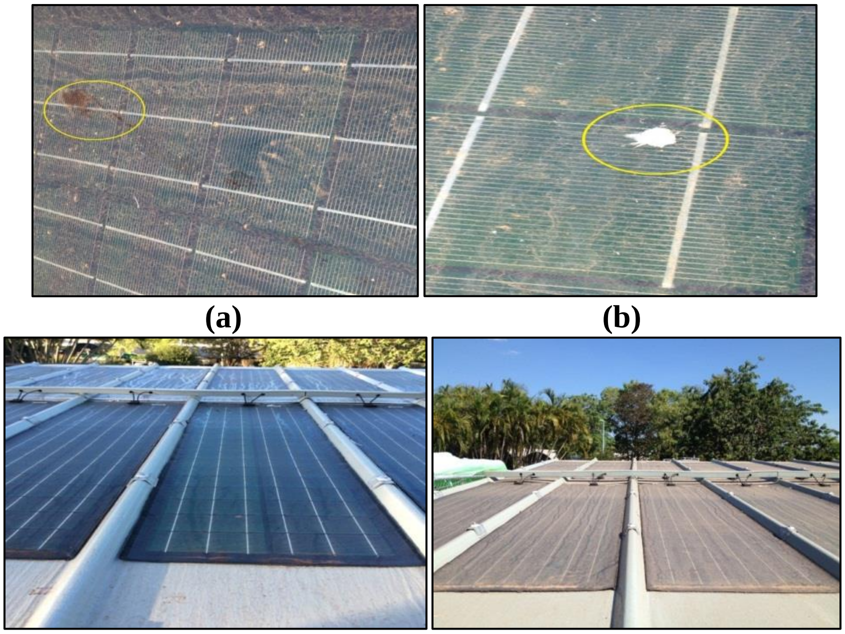
Figure 6: Above average production days over the months

Intuitively, the energy production should have increased accordingly, throughout the dry season. However, this is not the case. There are a number of possible explanations for this system degradation. Firstly, the presence of dust (soil adhesion) or any other forms of particles on the surface of the PV modules reduces the amount of the incoming solar radiation on the cell. Secondly, the effect of bat and bird droppings is evident in this case. Figures 7 (a) to (d) show the physical state of the module surface affected by these conditions. Figures 7(a) and (b) show the surface of the PV modules stained by bat and bird droppings (taken 4th July 2014).

Bat droppings normally stay longer than bird droppings on the module surface. These droppings (Figure 7(a)) had managed to stay on the cell for a period approximately 2 months; whereas the bird droppings (Figure 7(b)) are self-washed gradually in the morning by natural dew. Figure 7(c) shows the clean modules due to dew every morning during the observation period. As soon as the layer of water evaporates (normally around 10.00am), the dust carried by the wind will accumulate on the module surface, as shown in Figure 7(d).

3.3. *Effect of temperature*

According to Ye et al., 2013, the efficiency of crystalline PV modules exhibits about 0.45% drop for every 1°K rise in temperature and nearly half of that value for thin-film PV modules. Looking at the qualitative relationship between the declines in the peak power generation at peak sunshine hours for the three days, it was assumed that the continuous heat supply to the module surface does not allow the cells to cool down in time and therefore its performance was somewhat degraded. At this stage, although the temperatures of the modules were not recorded, the observed results are very much consistent with the literature. Through this study, the further effects of temperature on the modules will be investigated more in-depth, as identified in the future work for this project.



(a) (b) (c) (d)

Figure 7: (a) Surface with bat droppings, (b) Surface with bird droppings, (c) Clean modules after morning dew, (d) Natural dust accumulation

4. Conclusion and future work

This paper investigates the real-world environmental effects on a CIGS BIPV system under the unique tropical climate of Darwin, NT. The effects of dust accumulation, fauna droppings, shading and temperatures on the system efficiency were presented. These important and crucial effects have not been investigated in great detail in the literature. This study addresses this gap. This study also serves as an alternative and complements the research setting in a laboratory, where the values of all influencing parameters are controlled and does not mimic the real-world conditions. Initial observation has shown how tropical environmental factors such as bat and bird droppings and dust accumulated on the surface of the modules. These factors, which were not quantified in this study, have been identified as the likely causes of performance degradation of the system as it was continuously exposed to degrading tropical environment. The effect of natural shading on the power output was obvious during the 8:00am to 9:00am period.

From this study, it is evident that simple environmental effects can have an enormous influence on power production of the BIPV system. Thus, some future work were identified; the installation of a dedicated weather station and additional measuring equipment in the experimental rig to better capture and quantify these effects in relation to simple climate data, investigating the effect of self-cleaning mechanisms to reduce system degradation, and analysing the BIPV at different heights and angles.

In conclusion, this study established a solid basis for further investigation of these environmental effects on the PV efficiency. This work is important due to the increasing uptake of PV systems in the NT and the understandings of these environmental effects enabled such PV systems to be maintained efficiently. The continuous performance monitoring of the system will offer further understanding of the quantitative relationships of the environmental effects on CIGS BIPV systems in the tropical environment. In addition, the recorded observations through real-world experimentation will also aid designers, developers and modellers for more accurate estimation of the output from PV systems.

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