471: Dust accumulation and PV power output in the tropical environment of Barbados

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Barbados has implemented attractive incentives geared towards increasing its renewable energy capacity to at least 29% of the total energy mix by 2029. Existing incentives include the removal of import duties for renewable energy systems and the introduction of net metering in the form of a renewable energy rider, effectively establishing compensation of up to US$0.16 per kWh for energy supplied to the grid. These changes, in addition to the rapid reduction in price of global solar photovoltaic (PV) modules – from US$4 per Wp in 2009 to under US$1 (Wp) at the end of 2014 – have resulted in a considerable increase in PV installations on the island. Grid-connected solar PV installed capacity has risen from zero in 2009 to over 7MWp by the end of 2014.

As installations continue to increase, there is a need to fully understand the effect of the Caribbean's unique environment on PV performance. Barbados, the easternmost island in the Caribbean, has a strong solar irradiance with 'cooling' winds, and is a good environment for PV utilisation. However, as dust concentrations in the atmosphere vary, so will their accumulation rates onto module surfaces and hence the irradiance received by the cells. Dust accumulation rates are increased by lower tilt angles and increased relative humidity. Rainfall and wind are considered good natural methods for cleaning module surfaces, however they are only effective during intense showers and high winds. In addition, the properties of the dust determine the rate of accumulation based on the ability of dust particles to stick to the module surface.

In this paper, we describe the effect of dust accumulation on four types of PV modules installed at three sites in Barbados – designated as urban, suburban and rural-coastal sites. Crystalline silicon modules were connected separately across resistors and the power output obtained at each site. The power output for April 2015 is described, including a period before and after cleaning.

Keywords: solar PV, module performance, dust accumulation, Caribbean

1. INTRODUCTION

Caribbean territories are considered as small island developing states and all except Trinidad and Tobago are heavily dependent on imported fossil fuels. With electricity tariffs averaging US$0.35 per kWh, policies geared towards increasing renewables in the local energy mix have been drafted and are starting to be implemented (REN21, 2014).

With earlier success in the development of a solar water heating industry (Epp, 2009), Barbados has taken steps toward achieving its target of 29% renewables in the energy mix by 2029 (REN21, 2014, Ministry of Housing, 2004). Attractive incentives promoting RE technologies include the suspension of import and environmental duties for renewable energy systems and the introduction of net metering in the form of a renewable energy rider in 2009, which allows the customer to obtain up to US$0.16 per kWh in compensation for energy supplied to the grid (FTC, 2013). The steep decline in global photovoltaic (PV) module prices, from US$4/Wp in 2009 to US$0.78/Wp as of January 2015 along with the abovementioned incentives has greatly encouraged the local PV market (Solarbuzz, 2015). This is demonstrated by the increased PV capacity from 1.2MWp in 2012 to over 7MWp in January 2015, which is encouraging for a country with a peak demand of 155MW (Shirley and Kammen, 2013).

PV systems are an excellent alternative source of energy compared to that of imported fossil fuels and as such, the effect of the local environment on PV performance needs be fully understood. This includes not only the effect of local weather, but also of non-direct parameters in the form of dust accumulation. In this paper, we look at PV modules installed at three locations, locally defined as urban, suburban and rural-coastal. These locations are classified based on their approximate distance from the major conurbation of Bridgetown, the commercial centre of Barbados. It was expected that there will be higher levels of organic-based dust particles in the urban setting due to an increased human presence and hence activity, especially during the daytime. This also includes exhaust from vehicular traffic. This increased amount of carbon-based dust can affect PV performance due to absorption of irradiance, with less transmission to the solar cells when compared to dust-types (El-Shobokshy and Hussein, 1993). The dust composition in suburban locations is expected to be more vegetation-based as well as soil-based. Rural-coastal regions are expected to have higher concentrations of inorganic-based dust particles due to rocky terrain and proximity to the sea. The rural-coastal installation is located on a cliff overlooking the Atlantic sea and is subject to the sea spray from prevailing trade winds, and hence increased sea salt accumulation.

2. DUST

Dust is defined as small dry solid particles with diameters less than 500μm (Mekhilef et al., 2012, Mani and Pillai, 2010). Dust accumulated on a surface causes a chain reaction of more accumulation, resulting in an exponential decline in irradiance reaching PV cells, ultimately causing a reduction in the output current and hence power (Qasem et al., 2012). The particles of dust are a combination of both naturogenic and anthropogenic activities occurring at or near the location (Al-Ammri et al., 2013). Naturally occurring activities include the migration of dust plumes from North Africa via the Atlantic trade winds, known colloquially as Saharan dust (Prospero, 2011). This approximately week-long journey from Africa brings a mineral based dust consisting of potassium, calcium, iron, phosphorous and other trace minerals (Prospero and Mayol-Bracero, 2013). Human activities producing significant dust in the atmosphere include construction, exhaust from gasoline-based vehicles and the burning of cane fields during the annual dry-period at the end of the sugar-cane season.

Dust in the atmosphere settles onto the surface of PV modules, reducing the irradiance received by the solar cells, thus reducing module power. A further increase in atmospheric dust will therefore increase dust accumulation rates onto module surfaces. Factors affecting dust accumulation rates on a PV module surface include dust properties, PV tilt and orientation, wind velocity, ambient temperature, and humidity (Catelani et al., 2012, Mekhilef et al., 2012, Prospero, 2011). The local environment includes not only weather patterns but also vegetation coverage, the local anthropogenic activities and surface properties (Prospero, 2011, Mani and Pillai, 2010).

2.1 The Barbados Environment and Dust

Barbados, the easternmost island of the Caribbean and located at 13.2°N and 59.6°W, has a hot, humid climate all year round with little variation. A 30-year mean of climatological data gives average temperatures varying from 25.7°C to 27.8°C and rainfall between 41 mm (February) and 185mm

(November) with an average of 12 rainy days per month. Relative humidity values vary from 77% to 83% and average wind speeds of 4.9 m/s (at 10m height) in the direction of ENE to ESE (Barbados Meteorological Services, 2011). Barbados experiences a daily average of eight hours of sunshine producing an insolation of 5.7 kWh/m^2/day year round (Rogers et al., 2012). With such a high solar resource and cooling winds, Barbados is a very good environment for solar PV use.

PV modules are installed at lower tilt angles in Barbados due to the country's latitude as well as for hurricane damage prevention for roof-mounted installations. Hence dust settlement is greater with increased accumulation rates. However higher wind speeds reduce the amount of dust that settles onto a surface and also increases the amount of dust in the atmosphere (especially during dry periods) (Mekhilef et al., 2012). According to Hoffman and Maag (1980), this is based on the properties of dust and relative humidity. Finer dust particles affect PV performance compared with coarser particles as their smaller size increases the chances of uniformly covering a surface. Carbon based particulates from combustion has the greatest negative effect as they more effectively absorb solar radiation which in turn never reaches the modules and leads to elevated module temperatures (El-Shobokshy and Hussein, 1993).

3. METHODOLOGY

Three sites were located along the south of Barbados, and together represent typical urban, suburban and rural-coastal conditions for the island, and indeed the Caribbean. The urban assembly was located at Harrison College in Bridgetown (labelled as 'HC'), the suburban assembly was located The Caribbean Institute for Meteorology and Hydrology (CIMH) in Husbands, St. James, and the rural-coastal assembly was located at Deebles Point (DP) in St. Phillip which are all shown in Figure 29. Figure 30 shows that the assemblies at Harrison College (a) and CIMH in (b) were rooftop installations, while the Deebles Point assembly in (c) was ground-mounted. These installation heights were used to be representative of solar PV systems typically installed in these different terrain types.

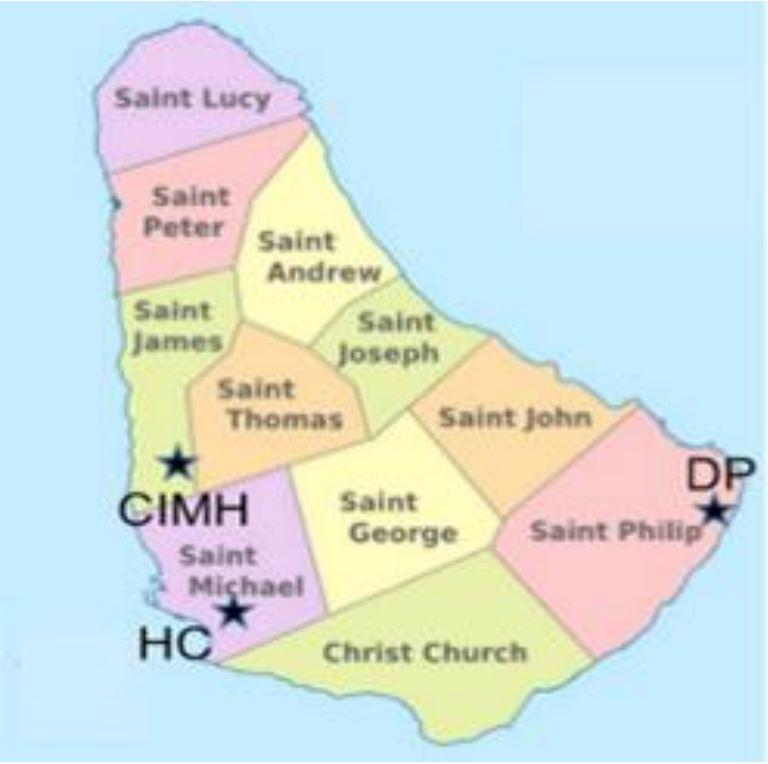


Figure 29. Locations of urban (HC), suburban (CIMH) and rural-coastal (DP) sites in Barbados

The modules used in this study are common to those used by local installers of PV systems. Each module was connected separately to a load of equivalent resistance (4.5Ω). Current, voltage and temperature of each module, along with module planar irradiance, were recorded at 5-minute intervals from 5am through to 7pm. Weather data, which included ambient temperature, wind speed, relative humidity and rainfall were collected from weather stations installed at each site. The rated power for each module and temperature coefficients are given in Table 14.

Table 14: Rated power and temperature coefficients of modules used in this study

Label	Technology	Rated power (W)	Temperature coefficient for P_{MAX}(%/°C)
mo-1	monocrystalline	270	0.45
mc-2	Multicrystalline	250	0.44
mc-3	Multicrystalline	255	0.40
mc-4	Multicrystalline	250	0.43

(a) (b) (c)

Figure 30: The three assemblies at HC (a), CIMH (b) and DP(c).

4. RESULTS AND DISCUSSION

The modules at all sites were cleaned after one-month exposure. The modules from the rural-coastal site (DP) were only exposed for three weeks as data collection begun one week after the other two assemblies were cleaned. The power was computed from the current and voltage values obtained. However, the increased power output would not have been immediately observed from cleaning the module surfaces as there are other parameters affecting performance which obscure the results. The main parameters affecting performance are temperature and irradiance (Field, 2011). It is therefore necessary to exclude their effects and isolate the effect of dust accumulation.

4.1 Excluding the Effect of Temperature

The raw power was corrected by determining the new value had the modules been in operation at 25°C. This temperature-corrected power, P_T, was determined based on the difference in operational temperatures of the modules and adjusted based on the temperature coefficient values given in the manufacturers' specifications. These P_T are now such that the temperature effect is excluded.

Figure 31 shows that the normalised temperature-corrected power (in Watt per peak Watt) generated by each module for the month of April. It is observed that there is a direct and strong relationship with irradiance and the changes in power correspond to the changes in irradiance regardless of cleaning.

Irradiance levels at the rural-coastal location were 28% and 12% higher than urban and suburban locations respectively. One reason could be the reduction in tall structures as one moves out of the urban location. Also tall trees were not located along the cliffs of the coastal location. This increased irradiance was one reason for the increased PV performance in the rural-coastal location. Module performance at the urban site was noticeably lower and this could also be attributed it having the lowest irradiance level of the three sites.

At the same site all modules' performance were within an average of 2.5% of each other except for the urban site where performances varied by as much as 10%. Mc-3 and mc-4 were the top power generators and the output from mo-1 should have been greater based on its higher efficiency and so was considered the worst performing module. This further concludes that monocrystalline does not work best in tropical climes.

As the P_T values are still heavily affected by irradiance and the effect of dust accumulation is still obscured. The effect of irradiance still had to be excluded.

4.2 Excluding the Effect of Irradiance

Figure 31 shows the overwhelming effect on PV power output. To therefore further isolate the effect of cleaning the irradiance effect will now be done by developing a relationship between irradiance and power output. P_T values were plotted against planar irradiance from two days before to two days after cleaning and the relationship was evaluated using the curve-fitting tool in MATLAB. This was determined to be a fifth degree polynomial given by Equation 6 and illustrated by Figure 32 using mc-3 at each of the three sites. Equation 6 was then used to compute the power based on irradiance values and the respective constant coefficients for each module. This would be the power change due to only irradiance, P_H.

Equation 6: Equation representing the relationship between power output and irradiance

$$P_T = aH^5 + bH^4 + cH^3 + dH^2 + eH + f$$

Where:

- P_T = temperature-corrected power output from each module (W)
- H = incident planar irradiance incident on the module surface (W/m^2)
- *a, b, c, d, e, f* = constant coefficients

4.3 Isolating the Effect of Dust Accumulation

We have now excluded the dependence of PV power output on temperature and irradiance. To further isolate the effect of cleaning, a comparison of the change in power from the day before cleaning (labelled as -1) and the day after cleaning (labelled as +1) was done. The indicators in this comparison were the changes in irradiance corresponding to the change in P_T ($\triangle P_T$) and to the change in P_H (ΔP_H). If the irradiance decreased from day -1 to day +1, then ΔP_T would be less than ΔP_H. If, however ΔP_T is larger than ΔP_H, then there is an increase in power that will be attributed to the cleaning of the modules and which would lessen the decrease in power due to reduced irradiance. These values are shown in Table 15. The negative signs represent a decrease in power (due to reduced irradiance) from day -1 to day +1. The power output the day before cleaning and the day after cleaning was observed.

Table 15: Change in power output for each module from cleaning. Note: The negative signs shows that there was a decrease in power (due to irradiance) from day -1 to day +1.

	Change in power output values computed from the normalised real data, ΔP_T			Change in power output values computed from Equation (1), ΔP_H			$\Delta P_H - \Delta P_T$		
	HC	CIMH	DP	HC	CIMH	DP	HC	CIMH	DP
mo-1	0.053	-1.01	5.38	-0.508	-12.26	19.04	-0.561	-11.25	13.66
mc-2	4.52	-2.55	13.94	-4.0883	-10.70	17.63	-8.61	-8.15	3.69
mc-3	0.0056	-5.20	13.24	-15.47	-17.82	19.42	-15.48	-12.62	6.18
mc-4	2.02	-4.14	12.71	-10.21	-16.99	19.34	12.23	-12.85	6.63

Table 15 showed that the power output was positively affected by the environment of the rural-coastal location (DP). One reason for the increase in power after cleaning was the increased sea salt in the atmosphere coming from the Atlantic Ocean coastline, which was in close proximity to the assembly (20m). The solubility of the salt crystals allow them to use the humid air as a vehicle for transportation. They are therefore more able to cleave to the module surfaces, especially during the dawn when dews evaporate. This adherence reduces the effectiveness of high winds in removing dust from the surfaces.

It should also be noted that the phenomenon of particles adhering to the modules' surfaces, at the urban and suburban locations also occurred. This was due to evaporation of water off the surfaces after rainfall which is mainly due to the low tilts of the modules. This is usually observed at the base of the modules, which results in a degree of shading of the bottom row of cells. The other cells of these modules however would not experience this phenomenon as acutely as the sea salt in the rural-coastal location, and so would be cleaned from higher winds and rainfall. It was expected for the urban environment to be most affected

due to the absorption ability of carbon-based dust. However, due to the components of the dust, the wind was more able to clean the module surfaces than the salt deposits.

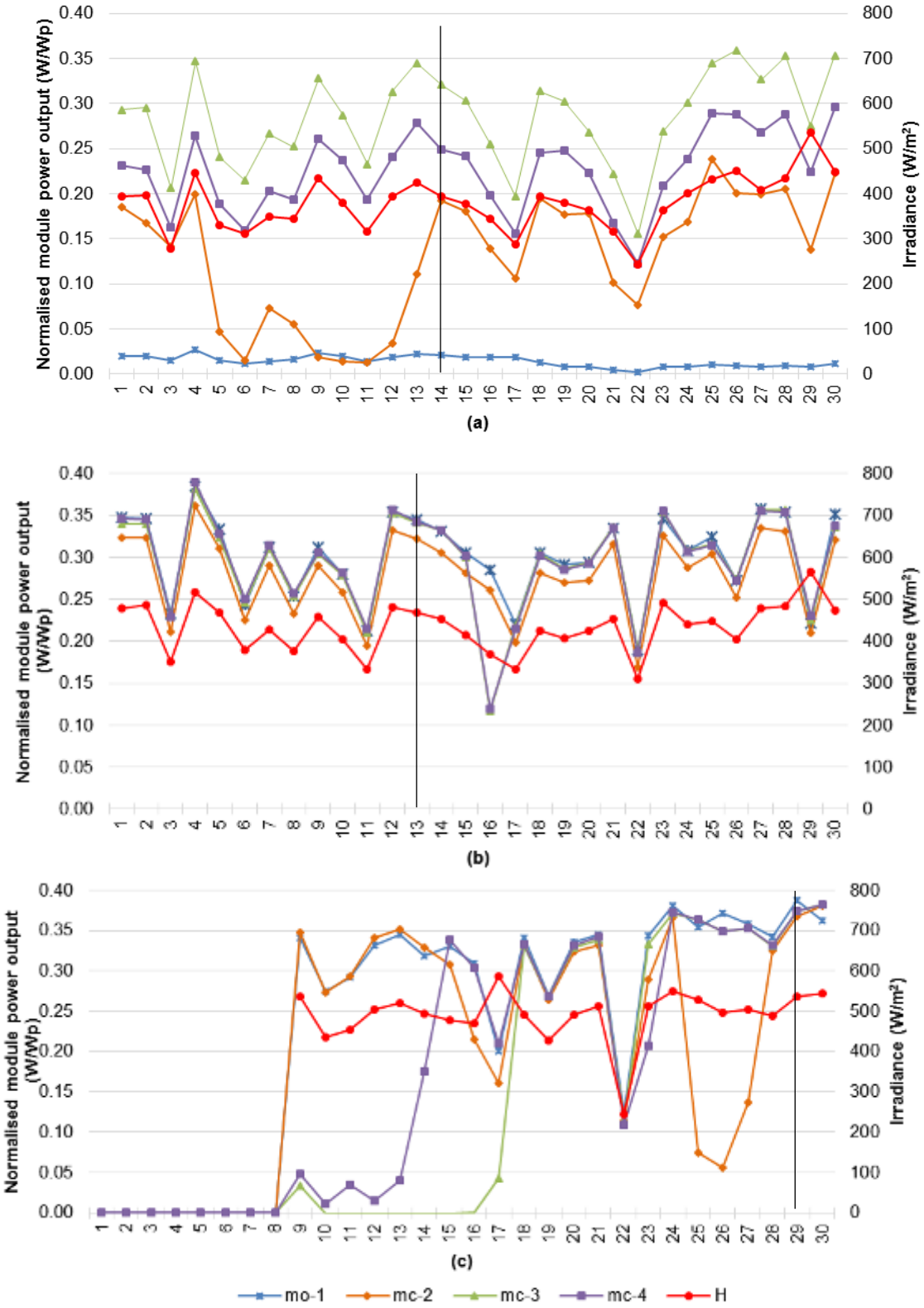
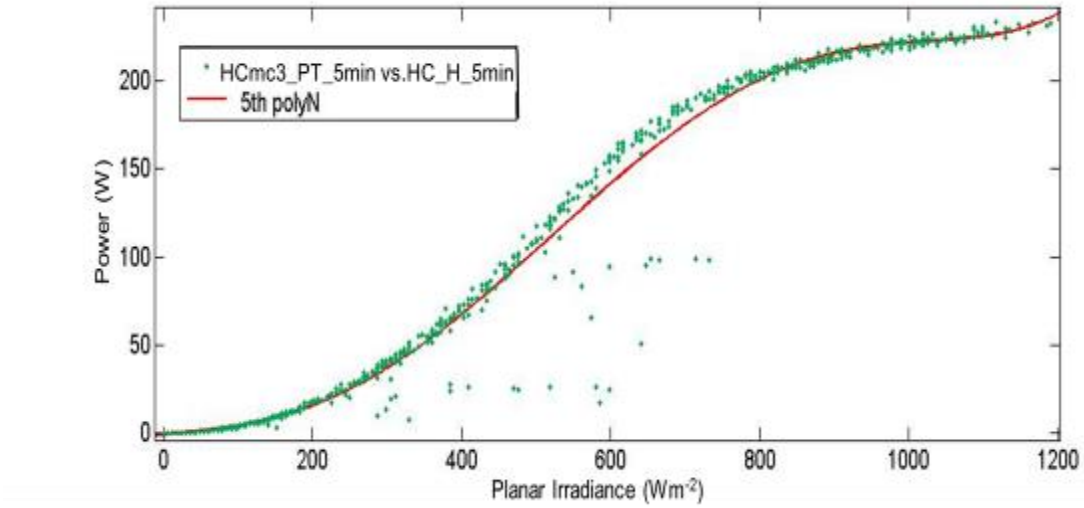
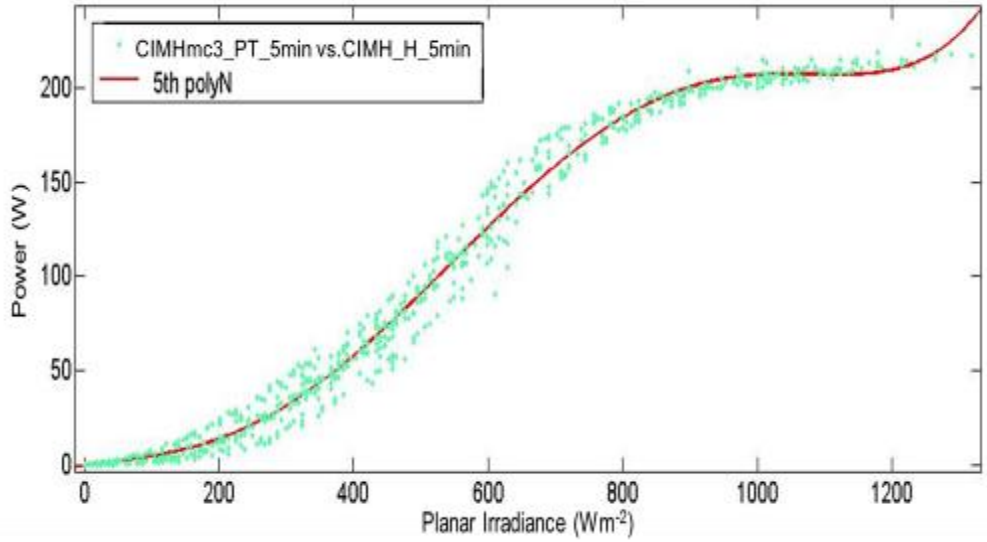


Figure 31: Module power output and irradiance profiles for April 2015 at (a) urban location (HC), (b) suburban location (CIMH) and (c) rural-coastal location (DP). The black lines indicate cleaning days.



(a)



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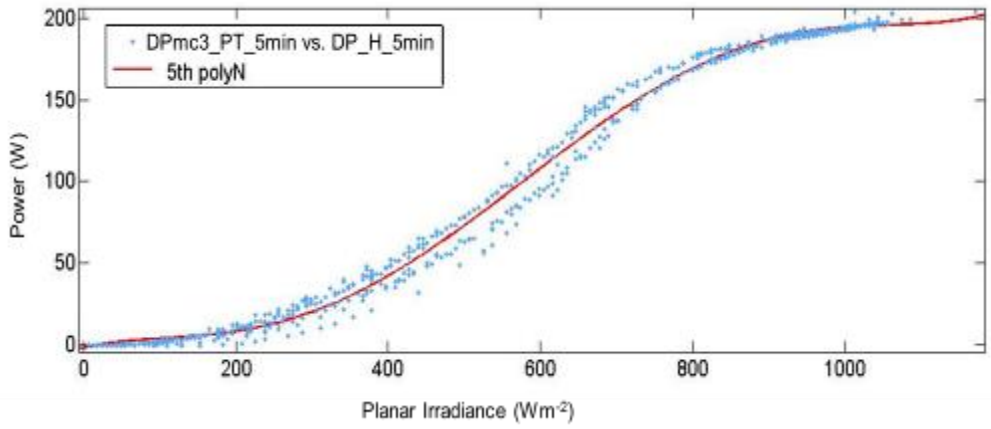

(c)

Figure 32: Polynomial curve fit, one for each site, illustrating the relationship between the temperature-corrected power and planar irradiance for mc-3 at the urban site (a), suburban site (b), and the rural-coastal site (c).

5. CONCLUSION

For the island of Barbados, irradiance levels within three locations differed by as much as 28% and at a given site in the month of April, and normalised module power output were different from each other by as much as 10%. Irradiance had a strong influence on module power output which obscured the effect of other parameters. The relationship between irradiance and power output was therefore determined and characterised as a fifth degree polynomial. This relationship was then used to obtain a power profile of each solar PV module performance at the different locations; thus excluding the effect of irradiance.

After excluding the effects of both irradiance and temperature, it was observed that dust accumulation was strongly affected by terrain and particulate properties. Sea salt in the atmosphere sticks to module surfaces thereby reducing the effectiveness of high wind speeds to remove dust from module surfaces. This occurred especially at daybreak, when dew evaporates from module surfaces increasing the amount of salt particles that accumulate onto them. It was noted that only the modules at the rural-coastal site showed a substantial increase in performance after cleaning.

The main limitation of this experiment was the cleaning of one of the three sites two weeks after the other two. This was due to that site being set up after the others. The differing conditions for those two weeks could have affect the power output and changes that were not included in the study. Another limitation was that rainfall was not tracked with data which would have aided comparative cleaning of the modules at some of the sites. Finally dust accumulation included bird droppings especially at the CIMH site, which may have elevated the decrease in power output due to dust. Future work will focus on collecting data on the same days. The amount of dust collected will be based on the days of no rainfall.

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