Performance analysis of thin-film photovoltaic (PV) technologies in an embedded generation network

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Abstract. Thin-film photovoltaic (PV) technology has varying performance for different technologies. Even though the efficiency of the thin-film modules are less than that of crystalline silicon modules, the thin-film modules do have advantages in certain locations, due to their spectral and thermal responses. In this study, the performance of thin-film PV modules operating in an outdoor environment is monitored and analysed. An embedded generation network has been established by the PV Research Group at the Outdoor Research Facility (ORF) located on the South Campus of Nelson Mandela University. This network contains three kW-scale grid-connected PV arrays comprising cadmium telluride (CdTe), copper indium diselenide (CIS) and amorphous silicon (a-Si) thin-film technologies. This paper presents and discusses the performance data of these three arrays over an extended period. A thorough comparison of the energy production is given, together with preliminary performance loss and degradation. From the data acquired, it is observed that the CIS and CdTe systems have higher performance ratios of the order of 85 %, while the performance ratio of the a-Si system is consistently below 75 %.it was found that the a-Si array lost 30% of its rated power in a period of 4 years, indicating that its operational lifespan is much less than that of the other thin-film modules studied.

1. Introduction

Thin-Film PV modules have lower efficiencies compared to crystalline silicon PV modules. The thin-film modules therefore need larger surface areas to produce the same peak output power as that of crystalline silicon modules. Furthermore, the thin-film modules guaranteed operational lifespan has improved significantly and has become similar to that of crystalline silicon modules. The advantages that thin film PV modules do have over crystalline silicon modules is they have a lower temperature coefficient as well as a very good response to the shorter wavelengths of the sunlight's spectrum. This means that in hotter environments the power of the thin film materials will be less effected and as well as in overcast conditions [1]. The performance of these PV modules is strongly dependent on the location; as temperature, and the spectrum of the sunlight play a big role in how the modules perform [2]. It is therefore important to monitor these modules for a significant timespan to evaluate them in an operational setting.

1.1. Performance parameters of PV systems

The in-field monitoring of the performance of thin-film PV systems is of great importance as it allows one to better understand how the systems work under real outdoor grid-tied conditions. In addition to the array parameters, the performance parameter investigated in this work is:

Performance Ratio (PR): The performance ratio is a measure used to determine the efficiency with which the PV plant handles the available radiation energy. This parameter is defined as the ratio between the final specific yield, Y_F and the reference yield, Y_R [3]:

$$PR = \frac{Y_F}{Y_R} \tag{1}$$

1.2. I-V Curve

An I-V curve (current-voltage characteristic curve) is a graphical representation of the relationship between the voltage applied across the PV module or array and the current flowing through it. The shape of the curve is also significant as one can detect any deviations from what should be observed, and the causes of these deviations can then be investigated further [4]. Another curve that is plotted together with an I-V curve is a P-V curve (power-voltage curve) which indicates the power that the module or string produces at each voltage value .

Important points on these curves are I_{sc}, I_{mp}, V_{mp}, V_{oc} and P_{max}, where I_{sc} is the short-circuit current which is the largest current that can be drawn from the PV module or string, V_{oc} is the open-circuit voltage which is the maximum voltage available from the PV module or string and I_{mp} and V_{mp} is the maximum power current and maximum power voltage respectively and these are the values that correspond to the P_{max} value, which is the maximum power point [4]. Another quantity that one can obtain from the above-mentioned points is the fill-factor (FF) which is the ratio of the maximum power and the product of V_{oc} and I_{sc}:

$$FF = \frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}} \tag{2}$$

Graphically, the FF is a measure of the "squareness" of the I-V curve, and it is also the largest rectangle that will fit into the IV curve [4].

2. Experimental Procedure

A grid-tied PV network, consisting of three thin-film systems of approximately 1kWp each, is installed at the Outdoor Research Facility (ORF) situated at Nelson Mandela University. The three thin-film PV arrays make use of copper indium diselenide (CIS), cadmium telluride (CdTe) and amorphous silicon (a-Si) technologies respectively. An aerial image of the three PV arrays together with diagrams illustrating how they are connected is shown in figure 1.

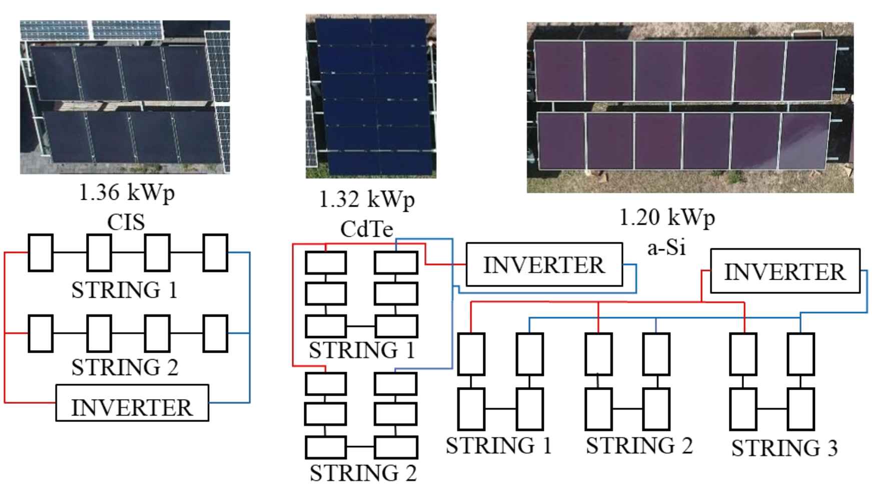


Figure 1. an Aerial image of the three thin-film PV arrays, together with a schematic of how they are connected. The peak output power of the arrays and the thin-film material of each array are also included.

2.1. Data Acquisition
The plane of array irradiance (POA) was obtained from a CMP3 Kipp & Zonen pyranometer, located above the CIS array. The DC current/voltage and power as well as AC current/voltage and power together with the module temperatures of each array was monitored by using a custom build datalogger unit for each PV array [5]. The dataloggers are programmed to collect data from the sensors every second. After every 10 seconds, the data is averaged, and the averaged value is recorded in the database on the datalogger. Every 15 minutes the data from the datalogger is transferred to the computer via an ethernet cable. The software used for acquiring the data from the data loggers is LoggerNet. The data retrieved from the datalogger is stored on the PC in a text file for the selected time interval. Due to the data being in text format, it is not easy to manipulate or perform analysis. A custom-built LabVIEW program was used to process and examine the data in the text files.

2.2. I-V curve measurements.
The I-V curves of the strings of the three arrays were taken on clear sunny days as close as possible to solar noon to minimise the uncertainty in the measurements. The first measurement is when they were installed or shortly thereafter to have the initial performance values of the arrays. The I-V curve measurements were obtained with the use of a Solmetric's PV analyser and I-V Curve Tracer, the PVA-1000S and the SolSensor 200 which measures the irradiance. The measured I-V curves were then corrected to Standard Test Conditions (STC), temperature of 25 ºC and irradiance of 1000 W/m^2, according to the standard translation equations [6]. These equations consider the measured irradiance, temperature and uses the temperature coefficients specified by the manufacturer to obtain how the modules would have performed at STC. This is done so that I-V curves taken at different conditions could be compared to one another.

3. Results
The results illustrated in this report for the PR of the arrays are for the period of November 2019 to February 2020 and November 2020 to February 2021. The reason for the gap in between the results is due to a technical fault resulting in no data collected for that period and this fault could only be fixed after the first COVID-19 lockdown.

3.1. Performance Ratios
The monthly averaged performance ratios obtained for the three thin-film arrays for the period of November 2019 to February 2020 and November 2020 to February 2021 together with two of the array's back of module temperature is showing in figure 2.

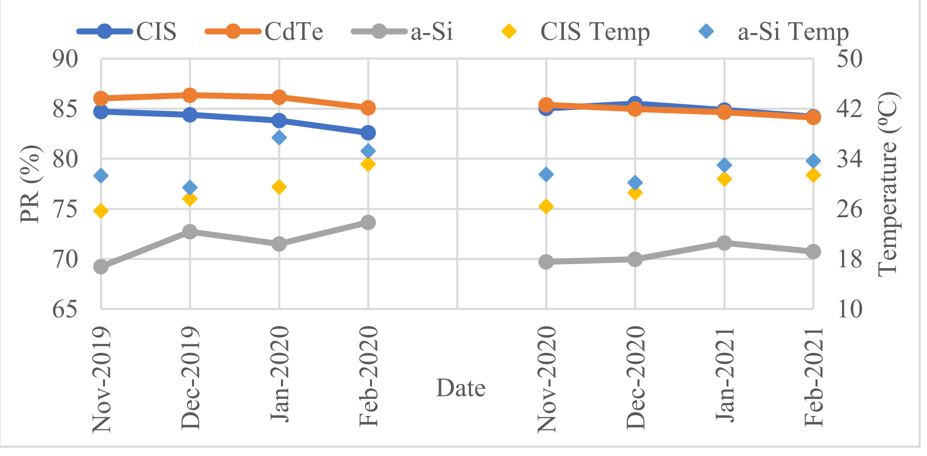


Figure 2. Monthly average performance ratios of the three PV arrays together with two of the arrays back of module temperature.

The Performance ratios obtained for the CIS and CdTe systems throughout the periods are comparable, in this first period the CdTe had a higher performance ratio but in the second period, the performance ratios were almost the same. For the a-Si array on the other hand it was found that its performance ratio was much less, around the 70% mark. This is due to the modules in the a-Si array degrading as these modules have been in operation since 2018. One interesting trend observed with the performance ratio of the a-Si system is that as the back of module temperature increases so too does the performance ratio of the a-Si array. This is seen in both earlier and later measurements. The reason for this improvement in the performance ratio of the a-Si array is due to the thermal regeneration of the a-Si material [7]. The CIS and CdTe array's performance ratios decreased as the back of module temperatures increased, which is expected.

3.2. I-V Curves
The I-V curves obtained for one string of each of the three arrays are showing in figures 3 to 5. Figure 3 shows the I-V curves obtained for string 1 of the CIS array, figure 4 shows the I-V curves obtained for string 1 of the CdTe array and figure 5 shows the I-V curves obtained for string 2 of the a-Si array. The other strings of the various arrays show the same features as seen in these I-V curves.

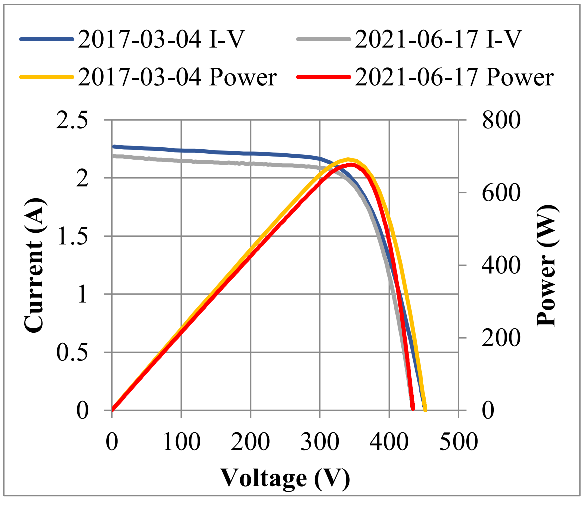


Figure 3. CIS string 1.

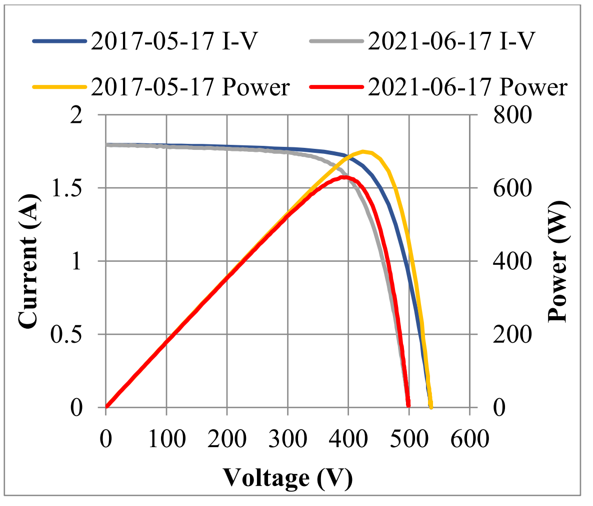


Figure 4. CdTe string 1.

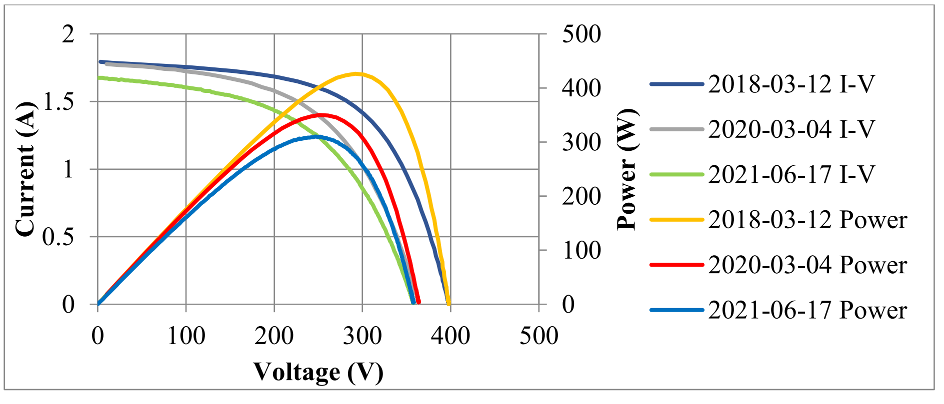
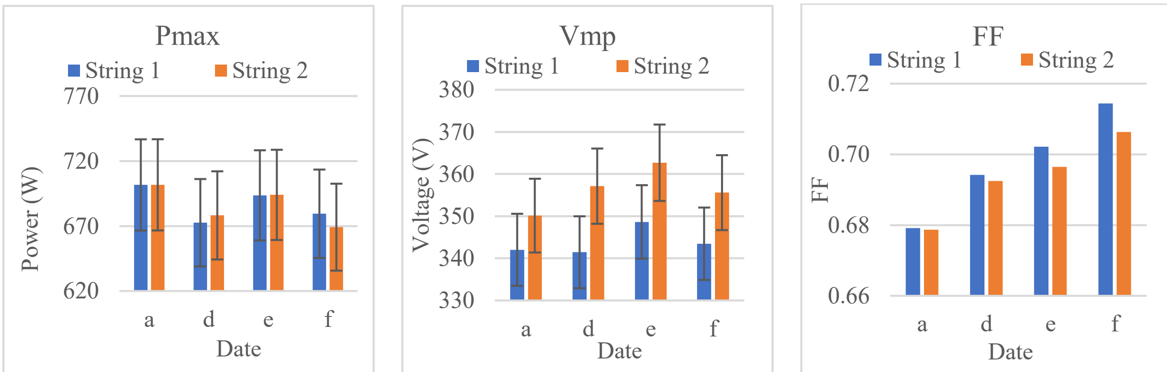


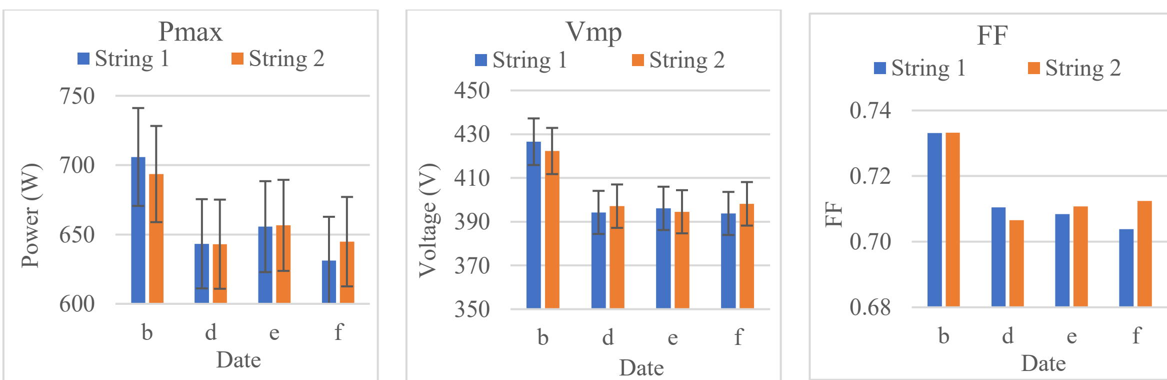
Figure 5. a-Si string 2.

The shape of the I-V curve for the CIS and CdTe strings is quite similar with regards to the knee of the curves. The shape of the I-V curve obtained for the a-Si strings differs quite significantly from those obtained for the other two arrays as it has a much "rounder" knee. These differences in the shape of the I-V curves can also be seen in the FF values for the strings of the three arrays. the CIS and CdTe strings FFs are round about 0.70 but the a-Si strings FFs starts at 0.60 and decreases to 0.50 in the last measurement. These FF values together with the P_{max} and V_{mp} points measured for the strings of the three PV arrays are shown in figures 6 – 8. Figure 6 shows the values obtained for the 2 CIS strings; figure 7 for the 2 CdTe strings and figure 8 for the 3 a-Si strings. In these figures the dates are replaced by alphabetical letters to make the results more visible. The initial values measured for the strings in the 3 arrays are labeled alphabetically, where "a" represents 2017-04-03, "b" represents 2017-05-17 and "c" represents 2018-03-12. The rest of the measurements for the 3 arrays were obtained on the same dates and these dates were 2019-12-05, 2020-03-04 and 2021-06-17 which are represented by the letters, "d", "e" and "f", respectively.



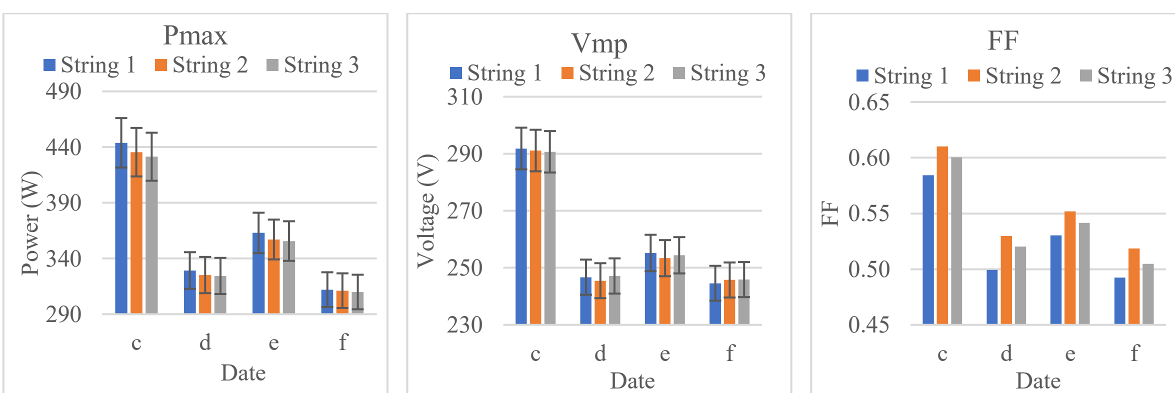
(a) (b) (c)

Figure 6. I-V curve parameters obtained for the 2 strings in the CIS array.



(a) (b) (c)

Figure 7. I-V curve parameters obtained for the 2 strings in the CdTe array.



(a) (b) (c)

Figure 8. I-V curve parameters obtained for the 3 strings in the a-Si array.

The Power values obtained for the two strings of the CIS array are consistent from the time of installation till the last measurement, with only minor variations which all fall within the ±5% uncertainty. What is interesting to note is that these two strings produced the same power values, even though they have different V_{mp} and I_{mp} values. The FF of the two strings increased which is mainly due to the decrease in the V_{oc} values of the strings.

The decrease in the power values of the CdTe strings, from the first to the second measurement, is due to degradation as the period between these two measurements is 2.5 years. The reason for this degradation requires further investigation and will be looked at in future work. The power measurements decreased from the first measurement to the last measurement by 10% for string 1 and 7% for string 2. This decrease observed in the power values and the FF is mainly due to the decrease in the V_{mp} values. This decrease in voltage values of the CdTe strings was also observed in another study for a CdTe module [8].

The power of the a-Si strings decreased by 30% from the initial measurement to the last measurement, which is due to light-induced degradation. Furthermore, the power values increased by 10% from 2019-12-05 (d) to 2020-03-04 (e), which confirms the thermal regeneration seen in the performance ratio of the a-Si array [7]. This regeneration is also seen in the increase of the V_{mp} for that period.

4. Conclusion

The performance of three different thin-film PV technologies, situated at the outdoor research facility at Nelson Mandela University, was investigated. It was found that the array consisting of CdTe modules had the overall best performance ratio, around 85%. The array consisting out of CIS modules had the most consistent performance ratio and power measurements. The a-Si array performance ratio was the lowest of the three arrays but showed an increase in performance over the summer period due to thermal regeneration and this is confirmed by the increase in their power measurements in that period [7]. Comparing the results obtained here to that of a similar study done in Poland, with a similar operational time frame of 4 years, it was found that out of the thin-film materials the copper indium gallium selenide (CIGS) had the highest PR which was followed by the a-Si, which in the summer had similar PRs seen in the current study and the CdTe had the lowest PR of 42% [2]. In that study the CdTe modules have degraded. In the current study the a-Si modules have degraded and lost 30% of its rated peak power. Indicating that the operational lifetime of the a-Si modules is much less than that of the other two thin-film module types.

References

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