A COMPARATIVE PERFORMANCE ANALYSIS OF A 1 MW CIS PV SYSTEM AND A 5 KW CRYSTALLINE-SI PV SYSTEM UNDER THE TROPICAL CLIMATE OF INDONESIA

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ABSTRACT

Despite being a tropical country with great potential for solar power, knowledge about the actual performance of photovoltaic (PV) systems in Indonesia remains limited. In this paper, using 5-minute resolution data from 2016 to 2018 obtained from a 1 MW Copper Indium Selenide (CIS) and a 5 kW crystalline silicon (c-Si) PV plant in West Java, we aim to answer the question of how a CIS PV plant performs and degrades in Indonesia's tropical climate and how it compares to a PV system that contains c-Si technology. The methodological approach used includes performance analyses of these PV systems according to IEC standard 61724 and an investigation of the degradation rate using NREL/RdTools. The following results were derived from the analyses: the total annual H_i was 1500 kWh/m^2 or around 4.2 kWh/m^2/day. The daily-averaged performance ratio, PR, was 91.7 % $\pm$ 4 % and 87.4 % $\pm$ 7 % for the CIS system with string inverters and a central inverter, respectively. The mean PR of the CIS systems was 12 % higher than that of the c-Si system, which was 79.8 %. Concerning the final yield, Y_f, the CIS system with a mean Y_f of 3.85 kWh/kWp outperformed the c-Si system by 14 %. The CIS system degraded by 1.53 % per year, which is less than the c-Si system with a degradation rate (R_d) of 3.72 % per year. From these results, it can be concluded that, in this case, CIS technology performs better than c-Si in Indonesia's tropical climate. Uncertainties in the calculation and high values of R_d could be areas for further investigation.

Keywords: Degradation; Indonesia; Performance; PV systems; Tropical climate

1.   INTRODUCTION

Indonesia has many rural areas and remote islands that are suitable for distributed renewable power generation such as solar photovoltaic (PV) systems. PV systems are reliable power systems and play an essential role in climate change mitigation (Creutzig et al., 2017). The market for PV systems is beginning to grow rapidly worldwide owing to, among other factors, their increased efficiency, the increased lifespans of the components, and a rapid reduction in their cost (Fraunhofer ISE, 2019).

The first PV system applications in Indonesia can be traced back to 1978 and the installation of a 5 kWp solar water pumping system (Dasuki et al., 2001). Various other projects then followed, such as a solar home systems (SHS) pilot project (Reinders et al., 1999), desalination plants, basic medical applications, remote televisions, and water pumping systems (Veldhuis & Reinders, 2015). A large SHS demonstration project with a total capacity of 50 MWp was launched in 1994 (Veldhuis & Reinders, 2015), and the first urban PV system was introduced in 2003 (Ministry of Energy and Mineral Resources, 2012).

Since then, many other PV systems have been constructed and created employment (Elfani, 2011). However, it is only relatively recently that Indonesia has gained experience in the performance of PV systems (Kunaifi & Reinders, 2018), and it continues to be in the research and demonstration phase (Veldhuis & Reinders, 2015). To date, Indonesia has 12 utility-scale PV plants in operation, mainly for off-grid or industrial applications. The dominant PV technology applied is typically crystalline silicon (c-Si) technology.

The PV market in Indonesia is emerging and is expected to grow over the coming years across the vast expanse of Indonesia's archipelago. The factors driving its growth include Indonesia's unique geography, comprising six large and more than 17 thousand smaller islands. This type of geographical factor presents a challenge in terms of extending the conventional power grid to reach the whole of the country's population of more than 260 million. The other motivations for solar electrification in Indonesia include, among others, the increasing demand for electricity (around 5.5 % annual growth) and economic growth of 5 % per year.

PV systems are suitable for use on the large islands (urban areas), particularly with respect to increasing the quality of the power supply (Nazir et al., 2016) as Indonesia is characterized by the relatively low reliability of its electricity supply (Kunaifi & Reinders, 2018). Meanwhile, on the smaller islands and in more remote areas, PV systems could play a significant role in providing electricity to local people who have not had it before, replacing fossil-fuel-generated electricity with renewables, and increasing the electrification ratio (PLN, 2018).

It is essential to monitor the operation of a PV system in order to identify performance trends. Monitoring data is also crucial for the localization of potential faults and to enable a comparison of PV system performance against design expectations and guarantees and between the different configurations and locations (The International Electrotechnical Commission, 2017). However, most PV systems in Indonesia are not monitored, with only a few equipped with basic monitoring systems. Accordingly, we have limited knowledge about the actual performance of PV systems operating under real environmental conditions in Indonesia. The two PV systems presented in this paper are among the few that are monitored.

Figure 1 Aerial view of the 1 MW PV plant in Cirata, West Java, Indonesia (Photo: PJB Cirata).

In September 2015, PT. Pembangkitan Jawa-Bali (PJB), a subsidiary of PLN, Indonesia's state-owned utility company, commenced its entry into the PV business. PJB is a power generation company that operates mainly in Java and Bali, which are the islands with the largest and densest electrical power systems in Indonesia. PJB constructed and now operates and maintains nine power plants with a total capacity of more than 7 GW (PJB, 2019). Among those in operation by PJB is a 1 MW PV system located in the province of West Java, which at the time of its construction was the largest PV system on the island of Java (Figure 1). At the same location, PJB also installed other, smaller PV systems. After three years of operation, we can now, for the first time, analyze the monitoring data from the PV systems in West Java.

In this paper, we therefore seek to answer the following questions:

- How is PJB's 1 MW CIS-based thin-film plant performing, and how has it degraded in Indonesia's tropical climate?
- How do its performance and degradation compare to that of a 5 kW crystalline (c-Si) plant at the same location?

The motivation for analyzing the performance and degradation of PV systems lies in the fact that the long-term performance and stability of PV plants have a significant impact on the economics of such projects.

Besides performance, degradation is one of the most critical characteristics to consider in the solar PV business. Degradation describes the rate at which a PV module experiences a decline in output. The degradation rate, R_d, is therefore the rate at which the PV performance of a module decreases per year. R_d is an important measure for comparing the actual performance of PV systems against the PV performance warranty issued by the module manufacturer with respect to nominal power.

PV cells degrade (Meyer & van Dyk, 2004); however, the rate of degradation differs from one PV plant to another. Over the course of a 25-year operating life, a 20 % decline is considered a failure. Assuming linear degradation, an R_d greater than 0.8 % per year can be regarded as a problem (John et al., 2018). For a high-efficiency module, however, 50 % degradation may be acceptable (Jordan & Kurtz, 2013). Using data from outdoor field testing, the long-term behavior and lifetime of PV modules, including their degradation, can be quantified.

2. THE PV SYSTEMS AND DATASETS

The PV systems presented in this paper are located in the Village of Cadas Sari (6°674 'S, 107°355 'E), Cirata, the province of West Java. They comprise a 1 MW and a 5 kW system. The 1 MW plant is ground-mounted over an area of 0.9 ha, while the 5 kW plant is a rooftop PV installation. Both systems sit in open spaces that are free of shading throughout the year. The measurement equipment is not cleaned and calibrated. Therefore, rather than using the most recent data, we instead use two years of usable data with a starting date close to the system's commencement of operation, based on the assumption that the sensors performed better during their earlier operational period than more recently.

2.1. 1 MW Thin-Film CIS PV System
The 1 MW PV plant has 170 Wp Japanese Solar Frontier thin-film PV modules made of Copper Indium Selenide (CIS) technology with a nominal module efficiency, η_{mod}, of 13.8 %. This efficiency is derived from the module's specification sheet. It has two clusters. One cluster has a capacity of 530.4 kW and comprises 26 arrays, each with 120 modules. This cluster has an SMA 550 kW central inverter that delivers AC power to the grid through a transformer. The other cluster, with a total capacity of 510 kW, comprises 25 arrays, each containing 120 modules. Each array is connected to an SMA 20 kW string inverter. The PV modules are tilted 10°, which is an optimum angle for Indonesia (Setiawan & Setiawan, 2017), and have an

azimuth angle of 15º clockwise from the North.

The monitoring system measured both electrical and meteorological variables at 5-minute intervals over the course of two years between 2016 and 2018. The electrical parameters (inverter-based) include DC current (I_{dc}) in Amperes, DC voltage (V_{dc}) in Volts, DC power (P_{dc}) in Watts, I_{ac} in Amperes, V_{ac} per line in Volts, AC power (P_{ac}) in Watts, power frequency in Hertz, and cumulative energy production (E_{out}) in kWh. There were no data for the months of October 2017 and February 2018. To compensate for these missing data, and in order to ensure two full years' analysis, we used data from 11 March 2016 to 10 May 2018. The total number of daytime records was 95,546, 9 % of which were missing or were removed due to outliers, or were wrong, with abnormal values resulting in a monitoring faction (MF) of 0.91.

As the 1 MW CIS system consists of two separate clusters, we analyzed each cluster individually. For the cluster with a central inverter, we use the term CIS Central (CIS_C), and for the cluster with string inverters, the name CIS String (CIS_S) is used. The PV module and configuration specifications are shown in Table 1.

Table 1 Specifications of the PV modules in Cirata

PV Module	CIS	pc-Si
Manufacturer	Solar Frontier, Japan	Victron Energy (cells), Azet (module assembling)
Model	SFSF170-S	ASL-M100E
P_{max} (Wp)	170	100
V_{OC} (V)	112	22.3
V_{MPP} (V)	87.5	18.0
I_{SC} (A)	2.2	6.00
I_{MPP} (A)	1.95	5.60
Efficiency	0.138	NA
$T_{coeff,Pmax}$ (%/K)	-0.31	-0.48
$T_{coeff,Isc}$ (%/K)	0.01	0.037
$T_{coeff,Voc}$ (%/K)	-0.30	-0.34
NOCT (°C)	47	NA
Length (mm)	1,257	1,000
Width (mm)	977	670

2.2. 5 kW Crystalline PV System

The 5 kW PV plant has 100 Wp poly-crystalline modules that use Victron Energy solar cells assembled into PV modules by an Indonesian company named Azet. It is connected to the local grid through an SMA Sunny Mini Central 5000 inverter. The PV modules are mounted on a building rooftop with a tilt angle of 10º and an azimuth angle of 15º clockwise from the North. The monitoring system measures similar parameters to those of the CIS PV system and features the same recording interval of 5 minutes.

For both the CIS and c-Si systems, critical meteorological variables were measured. They include relative humidity (RH) as a percentage, ambient temperature (T_a) in °C, module temperature (T_m) in °C, global horizontal irradiance (G_h) in Watt/m^2, global in-plane irradiance (G_i) in Watt/m^2, and wind speed (v) at a 1-metre height in m/s. Table 2 shows the PV module and configuration specifications.

3. METHODS

All of the monitoring data were checked for consistency and gaps to identify anomalies according to the following method. The daytime data were selected by eliminating irradiance values below 200 W/m^2 and above 1,500 W/m^2. For the ambient temperature, T_a, only values between -40 and 60 ºC were used. For the module temperature, T_m, values between the ambient temperature and ambient temperature plus 40 ºC were included. As such, any T_m values lower than T_a that might occur in the early morning due to irradiation to the sky were excluded from the analysis. For the electrical data, the array voltage between 0 and 1.3 x $V_{oc,stc}$ was used. Also, the array current values outside 0 and 1.5 x $I_{sc,stc}$ were excluded from the analysis. Abnormal data, such as large negative values and dead values that stuck for more than one hour, were also removed. Any records missing from the 5-minute data for a period of up to one hour were linearly interpolated.

3.1. Performance Calculations

The monitoring standard IEC 61724 was applied to the analysis of the PV systems' performance (The International Electrotechnical Commission, 2017). The performance indicators presented include final yield (Y_f) in kWh/kWp; array yield (Y_A) in kWh/kWp; reference yield (Y_r) in kWh/kWp; capture losses (L_C) in kWh/kWp; system losses (L_S) in kWh/kWp; performance ratio (*PR*) as a percentage or a decimal between 0 and 1; efficiencies (η) as a percentage or a decimal between 0 and 1; and capacity factor (*CF*), also given as a percentage.

Yield refers to the ratio of an energy quantity to the array power rating, P_{rated}, of the installed PV array at standard test conditions (STC) of 1,000 W/m^2 solar irradiance and 25 °C cell temperature. Thus, yields indicate the actual operation of the array relative to its rated capacity. The unit of yield is kWh/kW. The ratio of unit is equivalent to hours, and the yield ratio indicates the equivalent amount of time for which the array would be required to operate at P_{rated} to provide the particular energy quantity measured during the reporting period.

The final yield, Y_f, is defined as the annual, monthly, or daily net AC energy output in kWh, E_{ac}, of the PV system per installed rated power, P_{rated}, and is given by Equation 1. The final yield can be used to compare PV plants with different systems operating in different climates.

$$Y_f = \frac{E_{ac}}{P_{rated}} \left(\frac{kWh}{kW}\right) \tag{1}$$

The array yield, Y_A, is defined as the amount of array energy produced, E_{dc}, from each installed rated power, P_{rated}, over the analysis period, as defined by Equation 2. It is equivalent to the number of hours over which the PV array produces its rated power. The unit of Y_A is kWh/kWp.

$$Y_A = \frac{E_{dc}}{P_{rated}} \left(\frac{kWh}{kW}\right) \tag{2}$$

The reference yield in kWh/kWp, Y_r, is the total amount of available in-plane solar irradiance in kWh/m^2, H_i, divided by the reference irradiance, $G_{i,ref}$, of 1,000 W/m^2 (Equation 3).

$$Y_r = \frac{H_i}{G_{i,ref}} \left(\frac{kWh}{kW}\right) \tag{3}$$

If the reporting period is equal to one day, then Y_r would be the equivalent number of sun hours at the reference irradiance per day.

Normalized yield losses are calculated by subtracting yields. The yield losses also have units of kWh/kW or hour (h). They represent the amount of time for which the array would be required to operate at its rated power, P_{rated}, to provide for the respective losses during the reporting period. Two types of losses can be calculated once the yields have been determined. These are capture losses, L_C, and system losses, L_S.

L_C represents the losses incurred due to the array operating below what would be expected in STC. Losses are typically caused by the effect of temperature, high incidence angles, shading, array circuit losses, including mismatch, low irradiance, and soiling of the array (Pryor et al., 2013). L_C is defined by Equation 4.

$$L_C = Y_r - Y_A \ \left(\frac{kWh}{kW}\right) \tag{4}$$

L_S represents the losses in the balance of system (BOS) components, including the inverter and all wiring and junction boxes. L_S is defined by Equation 5.

$$L_S = Y_A - Y_f = \frac{E_{dc} - E_{ac}}{P_{rated}} \ \left(\frac{kWh}{kW}\right) \tag{5}$$

PR is a useful metric that shows how closely a PV system is operating in relation to its ideal rated operation. PR indicates the total losses from the system output due to both array temperature and system component inefficiencies or failures, including the BOS components. The array-level performance ratio, PR_A, and the system level, PR, are defined by Equation 6 and Equation 7. PR_A is the ratio of the actual energy produced by the PV array to the available solar energy that can be produced from the PV array at STC efficiency. PR is the ratio of actual energy output to the available solar energy that can be produced from the PV array at STC efficiency. The PR is either unitless or it can be represented as a percentage.

$$PR_A = \frac{Y_A}{Y_r} \ (dimensionless) \tag{6}$$

$$PR = \frac{Y_f}{Y_r} \ (dimensionless) \tag{7}$$

The efficiency, η, of a PV system can be calculated as rated array efficiency, $\eta_{A,rated}$, mean actual array efficiency, η_A, mean system efficiency, η_f, and inverter efficiency, η_{inv}, using Equation 8 to Equation 11.

$$\eta_{A,rated} = \frac{P_{rated}}{G_{i,ref} \, x \, A} \ (dimensionless) \tag{8}$$

$$\eta_A = \frac{E_{dc}}{H_i \, x \, A} \ (dimensionless) \tag{9}$$

$$\eta_f = \frac{E_{ac}}{H_i \, x \, A} \ (dimensionless) \tag{10}$$

$$\eta_{inv} = \frac{E_{ac}}{E_{dc}} \ (dimensionless) \tag{11}$$

where A is the effective PV module area in m^2.

Finally, CF is defined as the ratio of the actual annual energy output, E_{ac}, to the amount of energy the PV system would generate if it operated at full P_{rated} for 24 h per day for a year. CF is calculated using Equation 12.

$$CF = \frac{E_{ac}/AC_{rating}}{24 \, x \, days} \ (dimensionless) \tag{12}$$

where AC_{rating}, in kW, is calculated from the sum of the inverter ratings, and the term *days* is typically 365 or 366 for one year of analysis.

3.2. Degradation Calculations

For the R_d calculation, NREL/RdTools (Jordan et al., 2018; NREL, 2018) was implemented using Python. RdTools is a set of algorithms for calculating the R_d of PV systems based on year-on-year (YOY) analysis using a minimum of two years' time-series data (Jordan et al., 2018).

RdTools was developed according to the method initially proposed by Hasselbrink et al. (Hasselbrink et al., 2013) based on a review of 3 million module-years of live site data. Using RdTools, PV system production data are evaluated over several years to obtain rates of performance degradation over time. RdTools features an improvement in degradation analysis in that it avoids errors due to irradiance sensor drift, calibration, soiling, or misalignment using the clear-sky method; however, this is outside the scope of this study.

Within RdTools, the computation of the degradation rates from time-series data follows three main steps: normalization, filtering, and data analysis (Jordan et al., 2017). The normalization step involves the calculation of the *PR* metric normalized by temperature to generate a temperature-corrected *PR* using Equation 13.

$$PR = \frac{P}{P_{rated} * \frac{G_i}{G_{i,ref}} * \left(1 + \gamma * \left[T_{cell} - T_{ref}\right]\right)} \textit{ (dimensionless)} \tag{13}$$

where P is the measured dc power (P_{dc}) or ac power (P_{ac}) of the PV system in watts, γ is the maximum power temperature coefficient in relative %/K, T_{cell} is the cell temperature in °C, and T_{ref} is the reference temperature in °C with the value of 25 °C for STC or annual-averaged temperature.

In the filtering step, biasing and nonrepresentative data were removed, as well as data recorded at times when the solar resource was poor or variable. A low irradiance cutoff of 200 W/m^2 was applied in order to exclude start-up irradiance without removing winter data from high-latitude locations. We filtered out data during high dc/ac ratio in which power was >99 % of the maximum value. Finally, data outside of a ± 30 % band around a three-month rolling median performance index were also excluded.

The final step, data analysis, involved the calculation of R_d using the remaining data based on three approaches. First, for the YOY method, the rate of change was computed between two points at the same time in subsequent years. This resulted in a histogram of rates of change, the central tendency of which represented the overall system performance. Second, standard least squares (SLS) regression, in contrast, used all data points in a single regression by minimizing the difference between the model and the data. Finally, quantile regression used quantiles instead of the response mean. Prior to analysis of the degradation, the normalized, filtered 15-min data were aggregated over a variable period. Further details on the degradation rate analysis methodology are available in (Hasselbrink et al., 2013) or (Jordan et al., 2017).

4. RESULTS

4.1. System Performances

The performance analysis covered the evaluation of the solar irradiance on-site and the energy produced by the PV system over time. The mean and maximum daytime values of G_i on a surface tilted 10° during the analysis period were 410 W/m^2 and 1,250 W/m^2, respectively. Figure 2a shows the G_i for the PV array tilted angle in Cirata during the analysis period. As shown, the majority of G_i values were in the range from 250 W/m^2 to 800 W/m^2, although a significant frequency of G_i below 250 W/m^2 was also observed.

The total annual H_i was 1,500 kWh/m^2, with the highest value of 143.5 kWh/m^2 in August (hot season) and the lowest value of 90.3 kWh/m^2 in February (rainy season) (Figure 2b). The monthly average H_i was 125 ± 15 kWh/m^2 or around 4.2 kWh/m^2/day. The monthly-averaged T_m ranged from 39 ^{0}C to 43 ^{0}C (Figure 2b). However, with a data resolution of 5 minutes, T_m ranged from 21 ^{0}C to 68 ^{0}C.

During the reporting period, the energy amounts supplied to the grid from the CIS and c-Si PV plants were resp. 1,258 MWh (≈3.4 MWh/day) and 6,012 kWh (≈16.5 kWh/day). The average

daily Y_f was 3.66 kWh/kWp for CIS_S, 3.84 kWh/kWp for CIS_C, and 3.31 kWh/kWp for the c-Si system. In general, the Y_f values of the PV systems in Cirata were high, thus demonstrating the significant potential of PV systems in Indonesia (Kunaifi & Reinders, 2017).
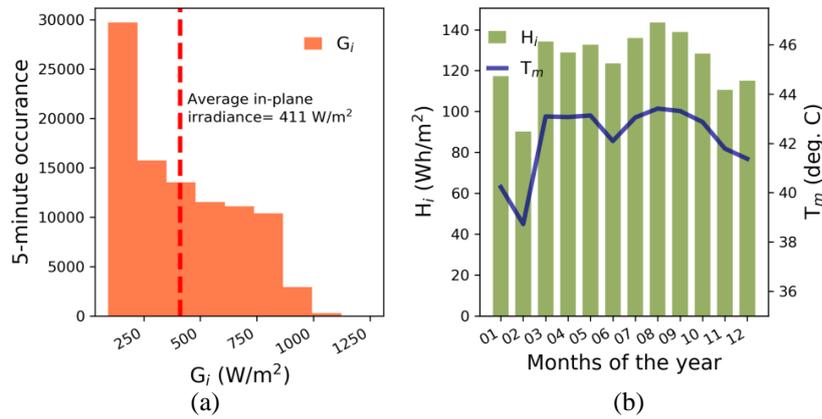

Figure 2 Meteorological variables in Cirata. (a) Frequency distribution of in-plane irradiance, (b) total monthly irradiation and PV module temperature during daytime hours

Figure 3 shows the *PR* of the PV systems in Cirata. The daily-averaged *PR* values for the CIS_S and CIS_C systems during the reporting period were 91.7 % ± 4 % and 87.4 % ± 7 %, respectively. The CIS_C system has a higher L_C and L_S than the CIS_S system, which created a significant difference in *PR* between the two CIS systems. *PR* for the c-Si system was 79.8 % ± 4 %. Table 2 shows the main performance indicators of the three PV systems in Cirata. Using the mean values from CIS_C and CIS_S, it can be seen that the CIS system performed better than the c-Si system. The Y_f of CIS was 14.1 % higher than that of the c-Si, which confirms the finding from a recent study (Honrubia-Escribano et al., 2018).
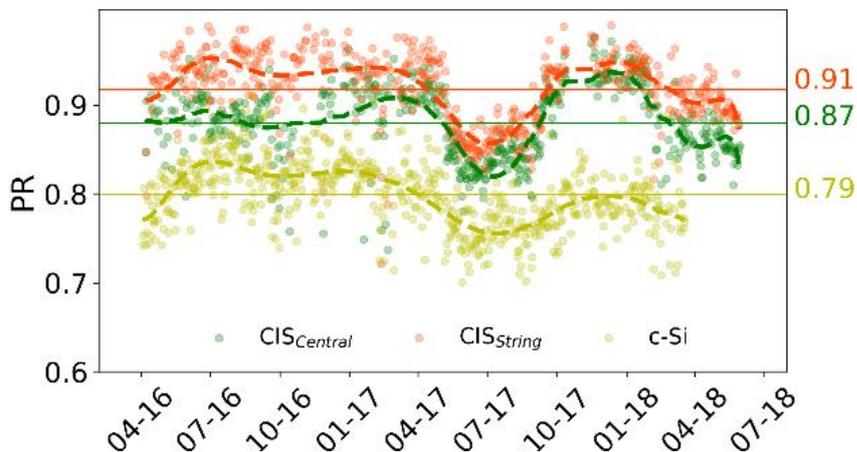

Figure 3 Performance ratios of the PV systems in Cirata; green for CIS_C, orange for CIS_S, and magenta for c-Si

The most significant difference between the two systems concerns the losses, where the c-Si system yielded a 47 % higher L_c and a 45 % higher L_s than the CIS. One of the reasons for the lower losses in the CIS systems is the higher frequency of module cleaning compared to the c-Si system. The values for $\eta_{A,rated}$ of the CIS and c-Si system were respectively 13.8 % and 14.9 %. The annual-averaged *CF* was 16.3 % for CIS_S, 16.0 % for CIS_C, and 14.1 % for the c-Si system.

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4.2. Degradation Rates

Figure 4 shows the R_d of the PV systems in Cirata based on data from April 2016 to July 2018. The degradation rate is a rate of change, with a negative rate representing a decrease in performance. For the CIS system, the calculation is based on the power produced by the central inverter (CIS$_C$). The calculation shows that the c-Si system degraded at an average of 3.72 % per year, which is faster than the CIS system with its annual R_d of 1.53 %. The values for the confidence interval of the R_d of the CIS and c-Si system were 0.87 % to 2.06 % per year and 2.98 % to 4.31 % per year, respectively.

Table 2 Performance indicators of PV systems in Cirata

Indicators	Unit	510 kW (CIS$_S$)	532.4 kW (CIS$_C$)	5 kW (c-Si)	CIS/c-Si (%)
Y_f	kWh/kWp	3.92	3.77	3.37	14.09
Y_A	kWh/kWp	4.00	3.91	3.58	10.47
Y_r	kWh/kWp	4.27	4.32	4.22	1.78
L_c	kWh/kWp	0.27	0.41	0.64	-46.88
L_s	kWh/kWp	0.08	0.15	0.21	-45.24
PR	%	91.7	87.4	79.8	12.22
$\eta_{A,rated}$	%	13.8	13.8	14.9	-7.38
η_A	%	13.0	12.6	12.7	0.79
η_f	%	12.7	12.1	11.9	4.20
η_{inv}	%	97.8	96.2	94.0	3.19
CF	%	16.3	16.0	14.1	14.54

The maintenance practices applied to the PV modules and measurement equipment can introduce uncertainties that result in high values of degradation. The measurement equipment in the PV systems in Cirata was not cleaned and calibrated, the CIS PV modules were sometimes cleaned, and the c-Si PV modules were never cleaned during their operation. Soiling and drifting of the irradiance sensors increase the uncertainty of the R_d calculation, which is an interesting topic for further investigation.
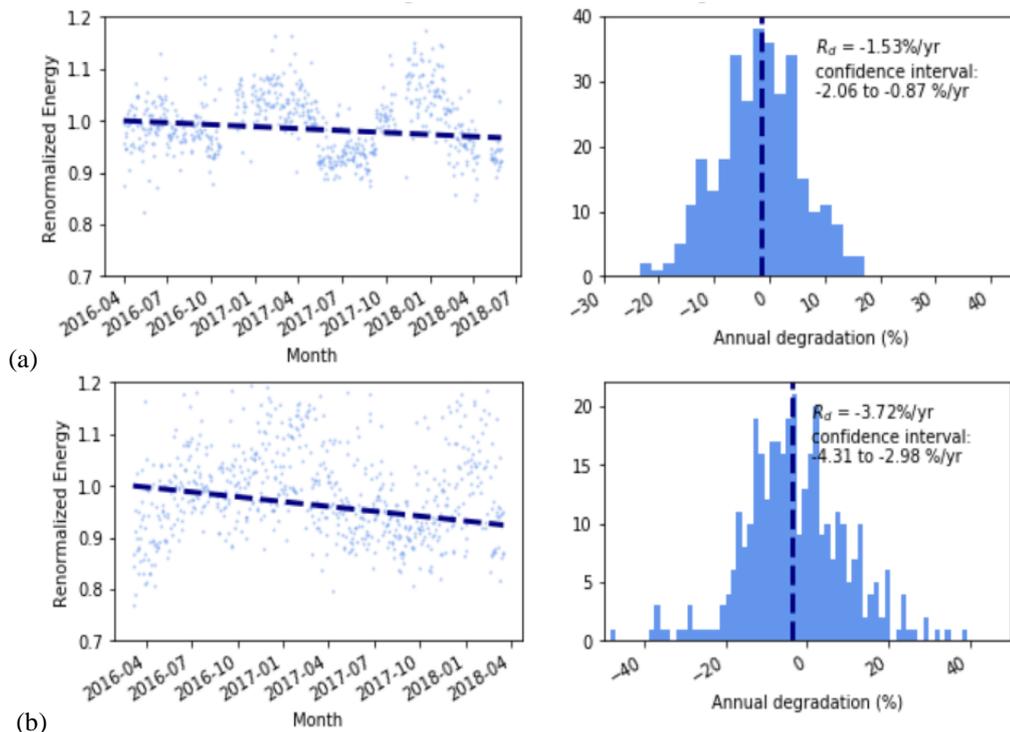

Figure 4 The annual degradation rate of the PV systems in Cirata: (a) CIS$_C$ system, (b) c-Si system

The degradation rates of the PV systems in Cirata at module level were higher than those reported in the literature, where the average degradation rates for silicon and thin-film technology are respectively 0.7 % and 1.5 % per year. However, when looking at the system level, the R_d values from Cirata are within the boundaries as presented in other literature (Jordan & Kurtz, 2013).

For silicon technology, the average rate of degradation at module level is 0.5 %/year. However, it is possible for the rate of system degradation to reach 2.5 %/year. This also indicates that BOS and soiling affect degradation (Jordan & Kurtz, 2013). For the CIS module, the examination of yields from NREL found that the R_d of CIS can range from moderate, at 2 % to 4 % per year, to negligible or small, at less than 1 %/year (Del Cueto et al., 2008).

5. CONCLUSION

We compared the performance and degradation rate of a 1 MW CIS PV system and a 5 kW crystalline-Si PV system operating in the real tropical climate of Indonesia. Concerning the Y_f, the CIS system outperformed the c-Si system by 14 %. The daily-averaged PR of the CIS system was 89.6 % (mean PR of the central and string clusters), which is 12.2 % higher relative to the PR of the c-Si system of 80 %.

Based on monitored P_{ac}, the R_d of the PV systems in Cirata at the module level was high. The CIS system degraded by 1.53 % per year, while the R_d of the c-Si system was 3.72 % per year. However, at the system level, the R_d values were within acceptable boundaries. By considering the other technical performance indicators, it can be concluded that CIS technology performs better than c-Si in Indonesia's tropical climate. However, there may be some uncertainty with respect to the calculation of the R_d. Such uncertainties are caused by soling and the relatively short two-year monitoring period.

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