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The Impact of Vegetation on the Performance of Polycrystalline and Monocrystalline Silicon Photovoltaic Modules

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ABSTRACT

The performance of a photovoltaic (PV) module decreases with increasing temperature. An emergent method developed to reduce temperature rise is vegetation that refers to cultivating crops under the shade of PV modules. This study aims to investigate the impact of caisim (brassica chinensis var. parachinensis), a popular tropical vegetable, on the performance of two polycrystalline silicon (pc-Si) and two monocrystalline silicon (mc-Si) PV modules. Initially, electrical parameters, solar irradiation, and temperature of the four PV modules were examined without vegetation. Furthermore, the same management was repeated with a treatment of two PV modules (pc-Si 1 and mc-Si 1) were vegetated and the other two modules (pc-Si 2 and mc-Si 2) were designated as reference modules, left without vegetation. Results of the experiments carried out in clear sunny days and analyzed with a least squares method revealed that, for the modules of the same technology, the efficiency of pc-Si 1 (vegetated) was higher than pc-Si 2 (reference), whereas mc-Si 2 (reference) outperformed mc-Si 1 (vegetated). Test results on mc-Si technology indicated that there was no contribution of vegetation to lowering temperature of the vegetated PV module, thereby failing to improve its efficiency. This might be related to the design and material of the mc-Si modules which support conductive heat losses. The conduction effect seemed to be more dominant than the evapotranspiration impact which may be low due to the wind and the greater distance between the vegetation and the modules. The results of this research imply that it is necessary to consider the application of vegetation for pc-Si technology for the design and optimization of the performance of solar power plants in Kupang, Indonesia. This research contributes to shining a light on the intricate relationship between PV module performance and vegetation. In a broader scope, this study provides a motivation for future investigations regarding efforts to overcome land competition to produce energy and food.

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1. INTRODUCTION

The development of renewable energy applications, especially solar power plants, is increasing rapidly. The International Energy Agency (IEA) noted that the application of solar power plants in the world has experienced significant growth (3.5% of the total power in the world) since 2016. Even though its capacity was still below that of wind power plants in the year, the development of solar power plants' applications continued to climb and shared the same figure with wind power in 2020, namely 9.4% of world electricity generation. The institution then predicted that solar power would overtake wind power by the end of 2023. The application of the technology was predicted to increase and to become the leader in 2027 with a contribution of 2.35 TW (22.2%), followed by coal (20.9%), natural gas (19.1%), wind (14.4%), hydropower (14.1%), and bioenergy

(2.0%). Rapid progress from 2022 to 2027 was claimed to be driven by the decline of PV components' prices, advances in PV research, and increase of supportive government policies especially in the European Union, India, China, and the United States [1].

One of the main components of a solar power plant that converts solar radiation into electricity is photovoltaic (PV) module. The performance of a PV module is affected by several factors including temperature. As the temperature rises, the performance of the PV module represented by power generation and efficiency decreases [2]-[5]. Currently, the efficiency of PV modules on the market ranges between 15% and 20% [6]. Rahmanian *et al*. in [7] a study found that the efficiency of PV modules decreased between 0.5% to 0.65% for every 1°C increase in temperature. Sheik *et al*. [8] found that the degradation rate of PV modules doubled every 10°C rise in operating temperature. PV modules' temperature deployed in the field increases rapidly and reaches a highest value due to exposure to sunlight. Studies showed that more than 60% of solar energy was turned to waste heat rather than electricity. Furthermore, the heat degraded the efficiency of the PV modules [7], [8] which led to economic losses. An assessment of the financial impact of temperature rise on a grid rooftop PV system in India revealed that a degree increase in module temperature lengthened the energy payback period by 8.5 days and escalated the unit cost of electricity by 0.021 INR [9]. Energy and economic losses caused by rising temperatures certainly reduce the sustainability of a solar power plant [10].

Given these significant negative effects, cooling methods were developed to reduce the temperature rise which lead to performance improvement of PV modules. In general, cooling methods can be divided into 2 groups i.e., active and passive. Active cooling refers to a method that uses auxiliary equipment such as a pump to circulate water or force air to eliminate the heat. Luboń *et al*. [11] in a study circulating water on the surface of a module found that the reflection and temperature of the module reduced by up to 3.6% and 20 ºC, respectively. As a result, generated energy increased by 10.3%. Shalaby *et al*. [12] studied the cooling effect by splattering water on the front surface of a PV module using DC pumps. It was found that the temperature of the module decreased by around 5-10 ºC leading to a power output increase as much as 14.1%. Meanwhile, the passive method is a cooling technique by installing fins at the rear of a PV module to improve natural convection and radiation heat transfer. Bayrak *et al*. [13] in Turkey carried out a test using aluminum fins installed behind a polycrystalline module with a capacity of 75 Wp. It was found that the temperature difference between the covered module and the reference module was 2.4 ºC. The output power of the covered module increased by 2.14%.

In addition to the cooling methods mentioned previously, a vegetation method, which refers to cultivating plants under the shade of PV modules, was developed as well. This method is believed can reduce temperature of a PV module through a transpiration cooling process between the module and the vegetation [14]. As the temperature drops, the performance of the PV module increases [2]-[5]. A 200 kWp vegetated solar power plant in Tucson, USA can produce about 4 MWh more electricity annually than without vegetation [14]. Two units PV modules of 1 kWp each installed on a roof in a tropical region of Malaysia, increase the systems power production by 1.6% [15]. Vegetation also increases economic value of solar power plants. Catalbas *et al*. [16] in a study in Turkey proclaimed that a green roof PV system brought profits about 3 years earlier than a conventional system.

The adverse effect of high temperature on the performance of PV modules varies with their technology. Gulkowski *et al*. [17] in their study compared the temperature coefficient for the efficiency of crystalline and thin film cells. It was found that the temperature coefficient (η) for the power of thin film (0.01 %/°C) was lower than crystalline cells (0.07 %/°C). This indicates that performance of thin film is better than crystalline at higher ambient temperatures. Mulcué-Nieto *et al*. [18] in an experiment on two grid-connected PV systems separately installed and operated under climatic conditions in Manizales, Colombia argued that daily efficiency of monocrystalline (13.23%) was better than polycrystalline modules (10.98%). Jiang *et al*. [19] in a study conducted in Jiangsu, China claimed that power loss due to temperature rise experienced by pc-Si was 10% higher than mc-Si PV modules.

Compared to other cooling methods, vegetation is a method that not only improves the performance of solar modules but also produces agricultural products to overcome land competition which is a problem of large ground-mounted PV power plants [14]. Literature review shows that several studies have been done to investigate the impact of vegetation to improve PV module performance affected by elevated temperatures. The method is widely applied in temperate [20], semi-arid [21], and sub-tropical [22] climate regions featuring vegetation such as peppermint, aloe vera, ocimum sanctum. It is claimed that different vegetation possesses different contents [23] that may exhibit varied transpiration cooling which would have a variable effect on temperature and PV module's performance. To the best of our knowledge, few studies [15], [24] have been conducted to examine the effect of vegetables commonly found in tropical areas on the performance of PV modules. In addition, previous studies were carried out partially on certain PV module technology so that the results cannot be generalized to others. The present study went further by investigating the effect of a vegetable cultivated in a tropical region on operating temperature and performance of ground-mounted pc-Si and mc-Si PV modules.

The contribution of this research is to shed a light on the intricate relationship between PV module performance and vegetation, specifically vegetation in tropical regions. In a broader scope, this study provides information for future investigations regarding efforts to overcome land competition to produce energy and food.

2. METHODS

A series of experiments were conducted at the Renewable Energy Laboratory, Department of Electrical Engineering, Politeknik Negeri Kupang during the dry season in September 2022. Two pc-Si and two mc-Si PV modules were deployed as samples for the research located in Kupang City, Nusa Tenggara Timur province, Indonesia. These two types were chosen because they are the most widely used technologies [25] and share different responses to the impact of temperature increase [2]. Technical specifications of the PV modules are depicted in Table 1.

Table 1. Technical specifications of the PV samples

Electrical and physical specifications	pc-Si PV modules	mc-Si PV modules
Maximum Power (Pmax)	100 Wp	100 Wp
Current at Pmax (Imp)	5.62 A	5.26 A
Voltage at Pmax (Vmp)	17.8 V	19.0 V
Short Cirrcuit Current (Isc)	6.05 A	5.53 A
Open Cirrcuit Voltage (Voc)	21.8 V	23.0 V
Weight	8 Kg	6.4 Kg
Wide	0.7004 m^2	0.6130 m^2
Maximum System Voltage	1000 VDC	1000 VDC

This study aims to determine the impact of vegetation on PV module performance by measuring the values of short circuit current, Isc (the current flowing through a PV module when there is no voltage across the module) and open circuit voltage, Voc (a situation in which the rates of photogeneration and recombination are equal and no current passes through the PV module). In addition to the electrical parameters, solar irradiation and temperature of the modules are recorded. The research process comprises the following stages:

1. First, set up PV modules on the mounting structure. In general, PV module receives maximum solar irradiation throughout the day when it is installed at a tilt angle corresponding to the latitude of the installation location and facing the equator [26], [27]. In this case, the four modules were mounted on the supporting structure with a tilt angle of 10° (the latitude of Kupang city), and facing North [28], [29]. Arrangement of the four PV modules without vegetation is shown in Fig. 1.

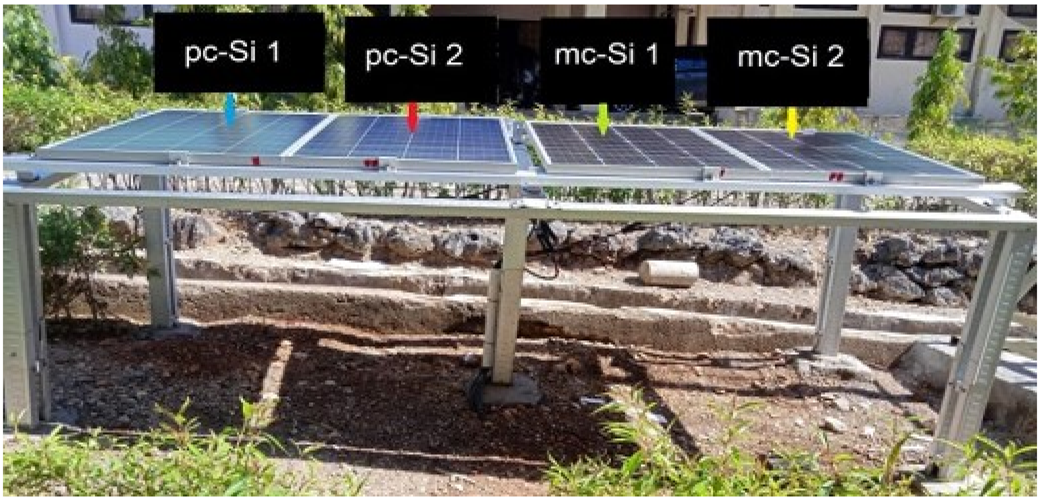

Fig. 1. PV modules without vegetation

2. Second, measurement of performance of PV modules without vegetation. Isc and Voc parameters of the four PV modules without vegetation were measured sequentially using a Sanwa CD800a multimeter

which has ± 2.2% and ± 0.7% accuracy for current and voltage, respectively [30]. To maintain stable readings, the Sanwa test leads must be attached tightly to the PV module cables. In this measurement, the test leads were connected with alligator clips so that they clamped tightly at both ends of the solar modules' output cables. The Isc and Voc test circuits are shown in Fig. 2. Parallel to the electrical parameters, backsheet PV modules' temperature and solar irradiation were assessed also using a Fluke 714B temperature thermocouple with an accuracy of 0,010% [31] and a SM206 solar power meter with an accuracy of ± 5% [32], respectively. Temperature sensor of the Fluke 714B was attached to the backsheet of the PV modules with 2 points of polyester tape, 5 cm length and 2 cm width, as recommended by IEC 61724-1 standard [33]. Meanwhile, the solar power meter was installed in a perpendicular position to one of the examined PV modules. The measurement processes are shown in Fig. 3. It is important to note that the measurement time interval between the PV modules was very short to avoid significant changes in temperature and solar intensity which understandably affected the performance of the PV modules. Observation of the performance of the four PV modules was carried out from the morning (9 a.m.) to the afternoon (4 p.m.) with an interval of 10 minutes.

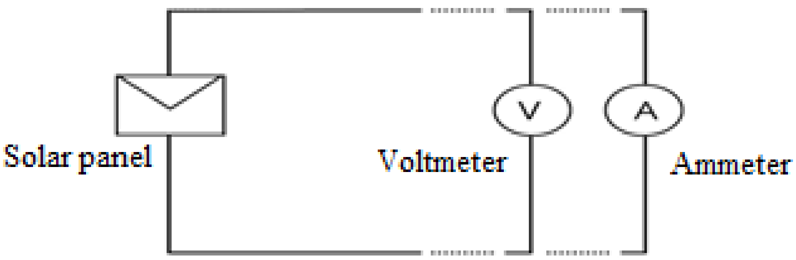

Fig. 2. Circuit diagram to measure Isc and Voc parameters

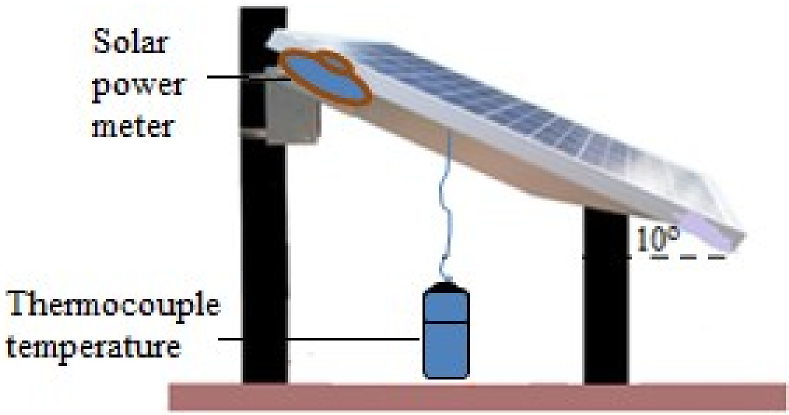

Fig. 3. Illustration of measurement of back sheet temperature and solar irradiance

3. Third, placement of vegetation under PV modules. The vegetation was placed according to the length and width of two PV modules (pc-Si 1 and mc-Si 1). The other two modules (pc-Si 2 and mc-Si 2) designated as references were left without vegetation. Caisims (brassica chinensis var. parachinensis) planted in growbags were used as vegetation under the PV modules. The type of vegetation was selected because of easy to cultivate in tropical climate areas such as Kupang, Indonesia [34]-[36] and contains 90% water [23] which certainly supports the evapotranspiration process. The casino grown in a mixture of soil, sand, and husk with a ratio of 2:1:1 were almost 3 weeks old with a height of between 25 to 30 cm at the time of testing. They are watered twice a day, morning and evening in dry conditions as suggested by [37], [38]. Appearance of the four PV modules is shown in Fig. 4**.**
4. Fourth, measurement of electrical parameters of reference and vegetated PV modules. At this stage, Isc and Voc of the four PV modules were measured in the same way as described in the second stage. Parallel to the electrical parameters, observations on the solar intensity and backsheet temperature of each PV module were conducted.

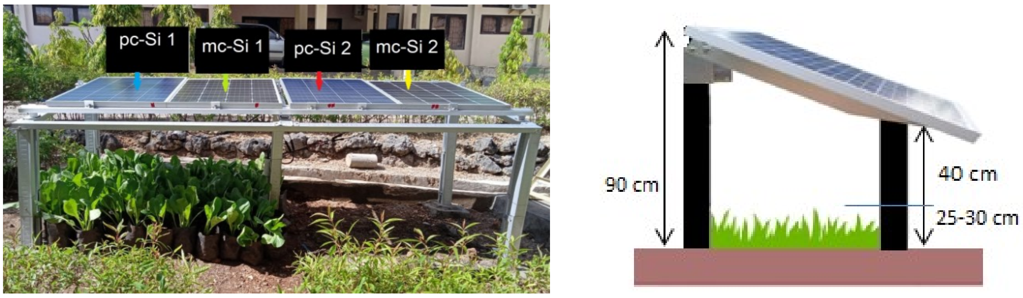

Fig. 4. Reference (pc-Si 1 and mc-Si 1) and vegetated (pc-Si 2 and mc-Si 2) PV modules

Analysis was carried out by comparing the results of the performance measurements of PV modules in conditions with and without vegetation. As shown in Table 1, the two types of PV modules have an identical capacity (100 Wp), but they share different electrical specifications. Besides, the modules exhibit different areas which understandably affect the amount of solar radiation and the output of the modules. Therefore, efficiency (η) is used as a parameter to compare the performance of these modules. The formula applied to calculate the efficiency of a PV module is as follows [39]-[42]:

$$\eta = \frac{P}{E \times A} x100\% \tag{1}$$

where, P is the output power (Wp), E is the solar irradiance (W/m²), and A = PV module surface area (m²) P is calculated by applying the following (2)

$$P = Isc \times Voc \tag{2}$$

In addition to the electrical parameters, the results of temperature and solar radiation intensity of the two types of PV modules in conditions with and without vegetation are also compared to support the performance analysis of these modules.

In brief, the steps of this research include selecting modules, measuring atmospheric conditions and electrical parameters of PV modules without vegetation, determining reference and vegetated modules, placing vegetation, and measuring atmospheric conditions and electrical parameters of reference and vegetated modules with and without vegetation. A flow chart demonstrating the methodology is shown in Fig. 5.

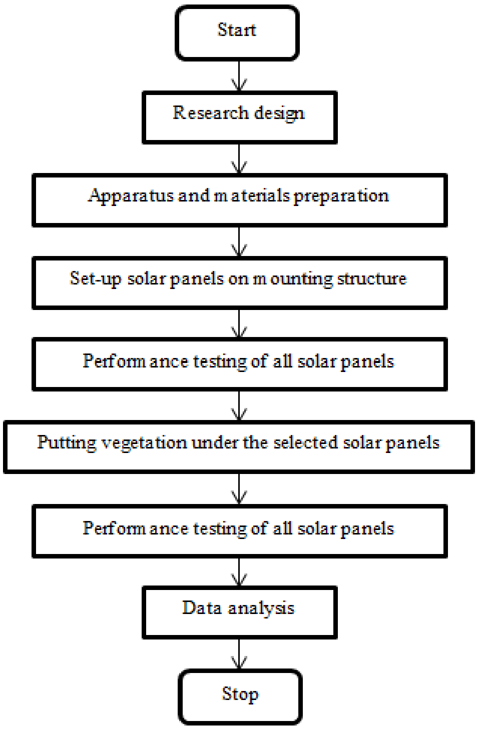

Fig. 5. Methodology of the study

3. RESULTS AND DISCUSSION

3.1. Solar irradiance and Temperature of PV Modules Without Vegetation

As mentioned in the methodology section, measurements of solar irradiance and backsheet temperature of the four PV modules were carried out from 9 a.m. to 4 p.m. with an interval of 10 minutes. Results show that temperature of the PV modules follows the variation of solar intensity (Fig. 6). In the morning (9 am), temperature of the PV modules is around 31 to 32°C, while solar intensity is approximately 452 W/m^2. The values tend to increase and reach a peak (between 58 to 63°C) during the midday (between 11 to 12 pm, solar irradiance 900 to 1100 W/m^2) and gradually decrease to the lowest point (around 32 to 34°C) at the end of measurements in the afternoon (4 p.m., solar irradiance 190 W/m^2). For further analysis of the impact of temperature on different PV technologies, the data in Fig. 6 was sorted based on solar irradiation starting from the smallest to the largest value as shown in Fig. 7.

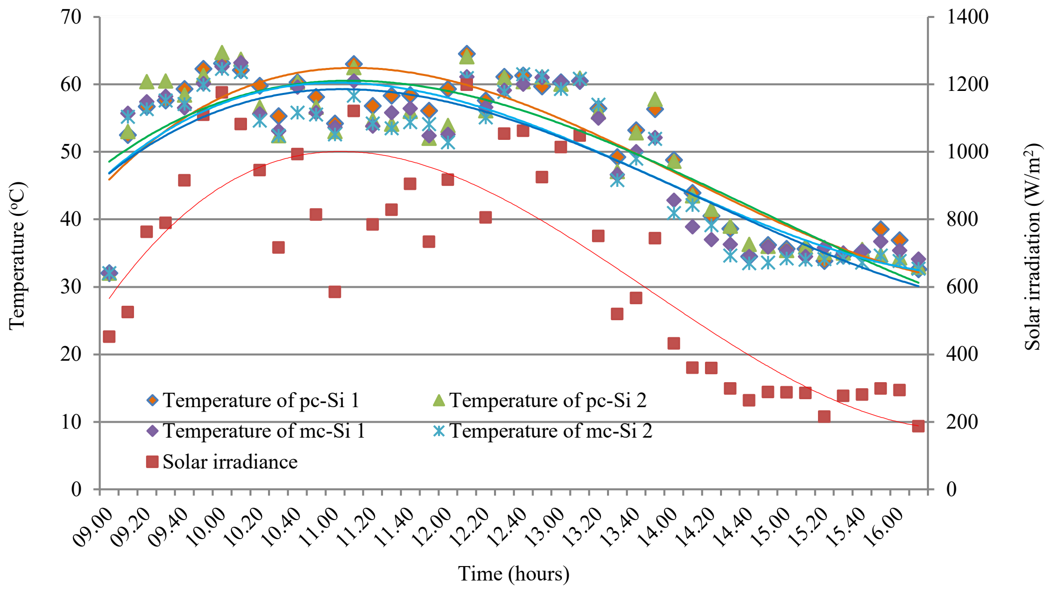

Fig. 6. Solar irradiance and temperature of the PV modules without vegetation

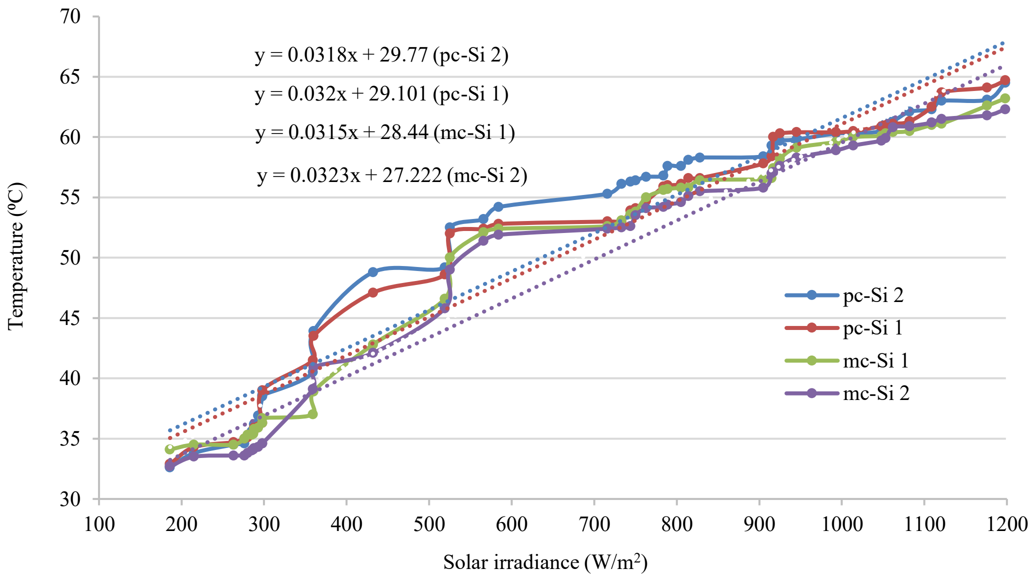

Fig. 7. Temperature of PV modules without vegetation at different solar irradiance

Fig. 7 shows a similar trend of solar intensity impact on the temperature of the tested PV modules. From the figure, it can be argued that escalation in solar irradiance increases the temperature of the PV modules. However, temperature changes between PV modules were inconsistent. For example, at low irradiance levels (200 to 250 W/m^2), temperature of the mc-Si 1 module is higher than that of the pc-Si 1 module, but at high irradiance levels (> 1000 W/m^2) the opposite occurs. This might be due to the variations of solar spectrum during the measurement period. It is known that the photon energy used for photocurrent generation by PV cells varies according to solar spectrum wavelength [43]. When the photon energy is in the energy band gap area of a solar cell material, the energy tends to be absorbed and converted into electricity, conversely, energy outside the band gap area is dissipated as heat [44].

For further analysis, a least squares method was applied to see temperature difference between the PV technologies. Visually, trendlines in Fig. 7 show that the highest impact of irradiance on escalating temperature is experienced by pc-Si 2 module (blue trendline), followed by pc-Si 1 (red trendline), mc-Si 1 (green trendline), and mc-Si 2 (purple trendline). The effect of radiation on temperature is more pronounced for pc-Si PV technology. Based on the least square's equations in Fig. 7, relative difference of temperature between the two technologies at certain solar irradiance was calculated. For example, at a solar intensity of 1000 W/m^2, temperature of pc-Si 2 module is 2.6% and 3.3% higher than that of mc-Si 1 and mc-Si 2 modules, respectively. The findings are in line with previous studies [45], [46] which revealed that, for outdoor applications, the temperature increase of pc-Si modules is higher than mc-Si which certainly shares a greater impact on the performance of the pc-Si modules.

Based on the above results, it can be argued that the solar spectra in Kupang were more dominant in the response range of mc-Si during the measurements period, as a result, more energy was converted into electricity rather than wasted into heat. Thus, temperature of mc-Si modules is lower than pc-Si modules. Apart from the spectral response, this phenomenon might be supported by the difference in thermal conductivity of the two materials. As mentioned in the literature [47], [48], the thermal conductivity of mc-Si (typically 100 W/mK) is higher than pc-si (typically 18 W/mK), consequently, mc-Si has a better ability to transfer heat either through conduction, convection and radiation to the surrounding materials leading to a lower temperature.

3.2. Performance of PV Modules Without Vegetation

Efficiency is a parameter representing the performance of PV modules featuring different technical specifications [49], [50]. Referring to the explanation in the methodology section, the efficiency values of the four PV modules were obtained by applying equations 1 and 2. Calculation results using experimental data conducted from 9 a.m. to 4 p.m. showed that the efficiency of the four PV modules varied according to solar intensity and backsheet temperature. Several previous studies [14], [15] argued that vegetation played a role in improving performance of PV modules by reducing ambient temperature through heat dissipation from backsheet PV modules to vegetation. Therefore, a comparison of the efficiency of the four PV modules concerning temperature was performed in this study. Calculated data of efficiency versus temperature of each PV module sorted from the smallest value are shown in Fig. 8.

Fig. 8 shows that the higher the backsheet temperature, the lower the efficiency of the four PV modules. However, the effect of temperature on efficiency varied with PV module technology. Higher efficiency was exhibited by the mc-Si 2 module, followed by mc-Si 1, pc-Si 1, and pc-Si 2. This result is inversely proportional to the temperature data accounted by the PV modules discussed in section 3.1 where the mc-Si modules shared lower temperatures than that of the pc-Si modules. As explained in section 3.1, one of the factors attributed to the lower temperature of the mc-Si modules was less wasted photon energy as a result of the suitability of solar spectra. Consequently, more electrons were converted into electricity leading to better efficiency of the technology. These results confirm the findings of previous researchers [17], [44], [46] in their works in several regions who found that the performance of mc-Si is better than that of pc-Si modules under real operating conditions.

It is interesting to note that when the temperatures get higher, the difference in efficiency of the two module technologies tends to decrease. Fig. 8 reveals that the change occurred when the modules' temperatures reached 60 to 65°C and solar irradiation was above 1200 W/m2 recorded from 11 a.m. to 12 p.m. (see Fig 6). It can be explained that at high temperatures, all of the PV modules' band gap narrows and the Fermi energy level moves nearer to the band gap's center. Both of these processes result in a drop in the modules' voltages by lowering the potential barrier in the band diagram of the illuminated PN junction [51].

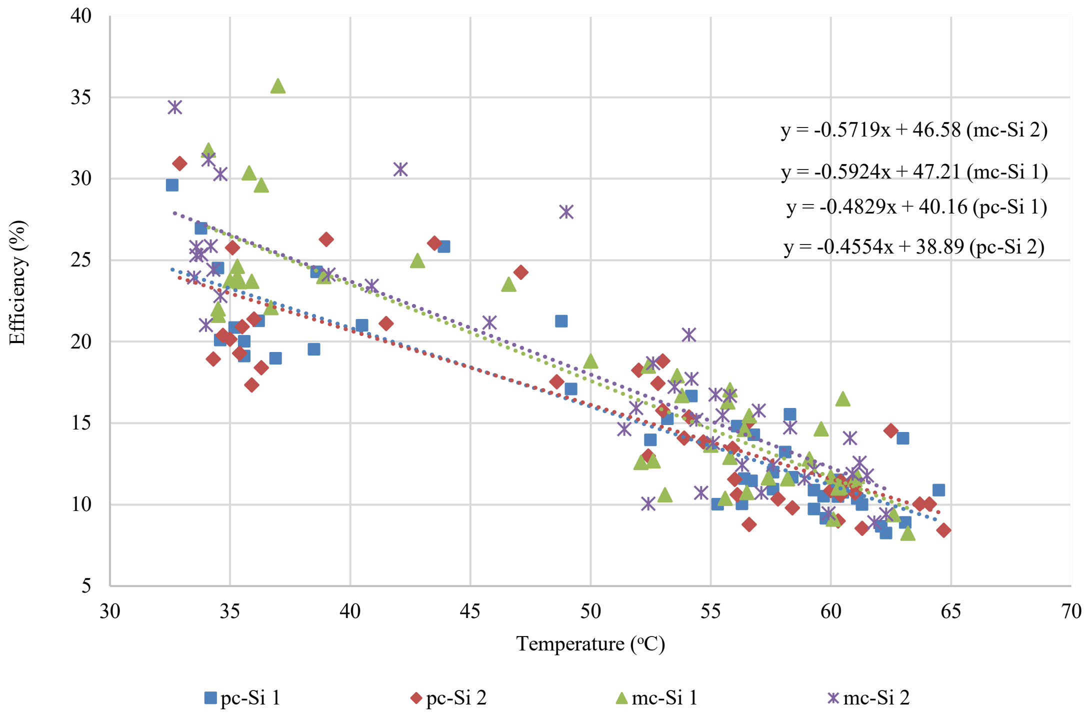

Fig. 8. Efficiency of PV modules without vegetation at different temperatures

3.3. Solar Irradiance and Temperature of Reference and Vegetated PV Modules

After measuring irradiation and temperature of the PV modules without vegetation as presented in section 3.1, the same management were carried out the next day but in a different treatment, 2 modules (pc-Si 1 and mc-Si 1) were vegetated with caisim (brassica chinensis var. parachinensis) and 2 others (pc-Si 2 and mc-Si 2) called references were left without vegetation. The measurement results show that the impact of solar irradiance on temperatures of all PV modules, both references and vegetated PV modules, shares a similar trend as shown in Fig. 6. To analyze the impact of temperature on different PV module technologies in the 2 conditions, the measurement data recorded in this stage were sorted based on solar irradiance starting from the smallest to the largest value and plotted on a graph as shown in Fig. 9.

From Fig. 9, it can be seen that the temperature of the four modules increases linearly with the increase of solar intensity. Least squares analysis shows that, for modules of different technologies, temperature of mc-Si modules is lower than pc-Si modules. As mentioned in subsection 3.1, this is attributed to the photon energy produced by incident solar radiation during measurement is more dominant in the mc-Si band gap area. As a result, less radiation is converted into heat. Additionally, the better thermal conductivity of mc-Si technology supports the distribution of heat from the cells to other components of the solar module.

Fig. 9 also reveals that, for modules of the same technology, the temperature of pc-Si 2 (reference module) tends to be higher than pc-Si 1 (vegetated module). On the other hand, the temperature of mc-Si 1 (vegetated module) is superior compared to mc-Si 2 (reference module). Results of the mc-Si modules indicate that there was no contribution of vegetation to lowering the PV module temperature as reported in some previous studies [14], [15]. The contradiction is also supported by another fact that the comparison of temperature levels of the two modules shown in Fig. 9 is consistent with their previous results in conditions without vegetation in subsection 3.1. This could be related to the design and material of the mc-Si modules' components which support conductive heat losses process. Better contact and thermal conductivity of mc-Si material cause the heat from the cells to be distributed to the other components including encapsulation, backsheet, glass, frame, and supporting structure. It can be deduced that, in this case, the conduction effect is more dominant than the evapotranspiration impact which may be low due to the wind effect [50] and the greater distance between the vegetation and the modules, namely 40 cm to 60 cm (see Fig. 4). Also, reduced soil moisture as the vegetation was only watered in the morning and afternoon. Consequently, the temperature trends of both modules are relatively similar to once recorded without vegetation.

Relative differences between the two technologies measured in this section are slightly higher than the results obtained in section 3.1. For example, at a solar intensity of 1000 W/m^2, calculation results based on the regression equations show that temperature of pc-Si 2 module is 3.2% and 3.8% higher than that of mc-Si 1 and mc-Si 2 modules, respectively. These discrepancies could be caused by the variation of atmospheric conditions during the period of study including wind velocity and ambient temperature [52], [53].

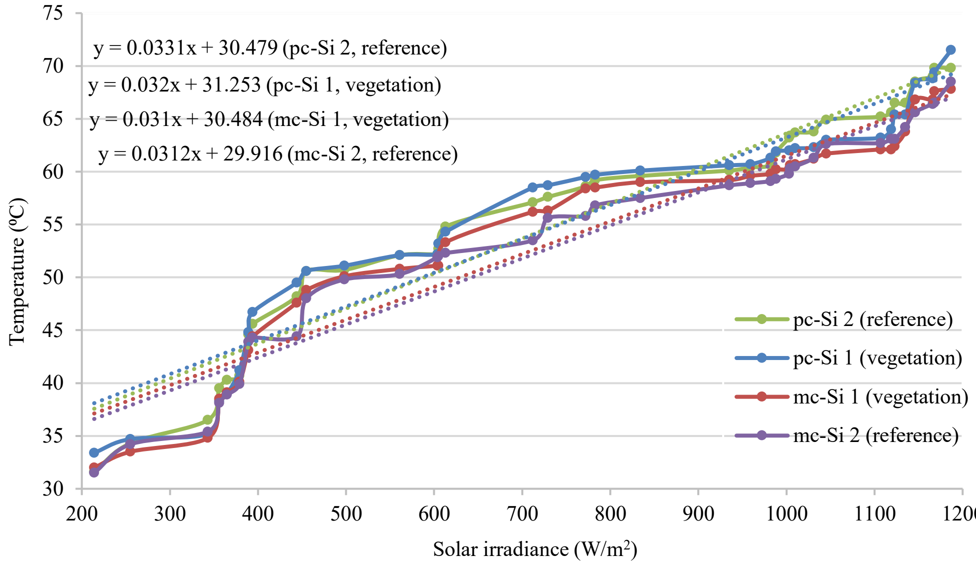

Fig. 9. Temperature of references and vegetated PV modules at different solar irradiance

3.4. Efficiency of reference and vegetated PV modules

Similar to the modules without vegetation discussed in section 3.2, calculated results using data obtained during the measurement period from 9 a.m. to 4 p.m. showed that the efficiency of the four modules varied with their backsheet temperature and solar irradiance. To assess and compare the impact of vegetation, the efficiency calculation results for the four PV modules were sorted based on their temperatures and displayed in a graph as shown in Fig. 10.

From the measurement results of the reference and vegetated PV modules (Fig. 10), it can be seen that the higher the backsheet temperature, the lower the efficiency of the modules. Least squares analysis showed that the highest efficiency was accounted by mc-Si 2 (reference module) followed by mc-Si 1 (vegetated module), pc-Si 1 (vegetated module), and pc-Si 2 (reference module). The performance sequence is inversely proportional to the temperature order in section 3.3 where the pc-Si module has the highest temperature followed by pc-Si 1, mc-Si 1 and mc-Si 2. This proves that the higher the module temperature, the lower its performance. As mentioned in subsection 3.1, one of the factors attributed to the lower temperature of the mc-Si modules was less wasted photon energy as a result of the suitability of solar spectra. Consequently, more electrons were converted into electricity leading to better efficiency of the technology.

For modules of the same technology, the efficiency of pc-Si 2 (reference module) is higher than pc-Si 1 (vegetated module). Meanwhile, the efficiency of mc-Si 2 (reference module) is better than mc-Si 1 (vegetated module). The efficiency order and trend of mc-Si PV modules in Fig. 10 is also exactly similar to the ones exhibited in condition without vegetation depicted in Fig. 8 in subsection 3.2. This indicates that there was no contribution of vegetation to reduce the temperature of the vegetated mc-Si module that lead to lower performance. As explained in subsection 3.3 that the heat distribution in the mc-Si modules is more dictated by the conduction process compared to the evapotranspiration effect. As a result, the temperature trend and performance of the two mc-Si modules are relatively similar in the conditions with and without vegetation.

Fig. 10 shows that the difference in efficiency of the two PV technologies tends to decrease when the module temperatures are getting higher, above 60°C. This phenomenon occurs at higher solar irradiation, above 1200 W/m^2 (see Fig. 6). Similar to the explanation in subsection 3.2 that above the temperature levels, both technologies operate ineffectively, the incident solar radiation received by the PV cells tends to be converted into heat rather than into electricity [54], [55].

This study examines the impact of vegetation on the performance of mc-Si and pc-Si solar modules. It was found that vegetation shared a positive contribution to improving the performance of pc-Si modules. Different results are accounted by mc-Si technology where the efficiency of the reference module is better than the vegetated one. This might be attributed to the better thermal conductivity of the mc-Si material so that heat distribution from the cells of the technology is dominated by the conduction process rather than evapotranspiration effect. The results of this research imply that it is necessary to consider the application of vegetation for pc-Si technology modules for the design and optimization of the performance of solar power plants in Kupang.

This research was carried out for a short period of time during the dry season in Kupang, Indonesia with a small number of samples and a certain vegetation distance so it is still limited to assess the contribution of vegetation to reduce temperatures which leads to improving PV module performance. Therefore, further research is still needed over a long period representing all seasons with a larger sample of modules. Besides, it is also necessary to observe the impact of varying vegetation distance on temperature and module's performance. In this way, more comprehensive results will be obtained that can inform future decisions regarding the deployment of photovoltaic systems in areas where vegetation is considered.

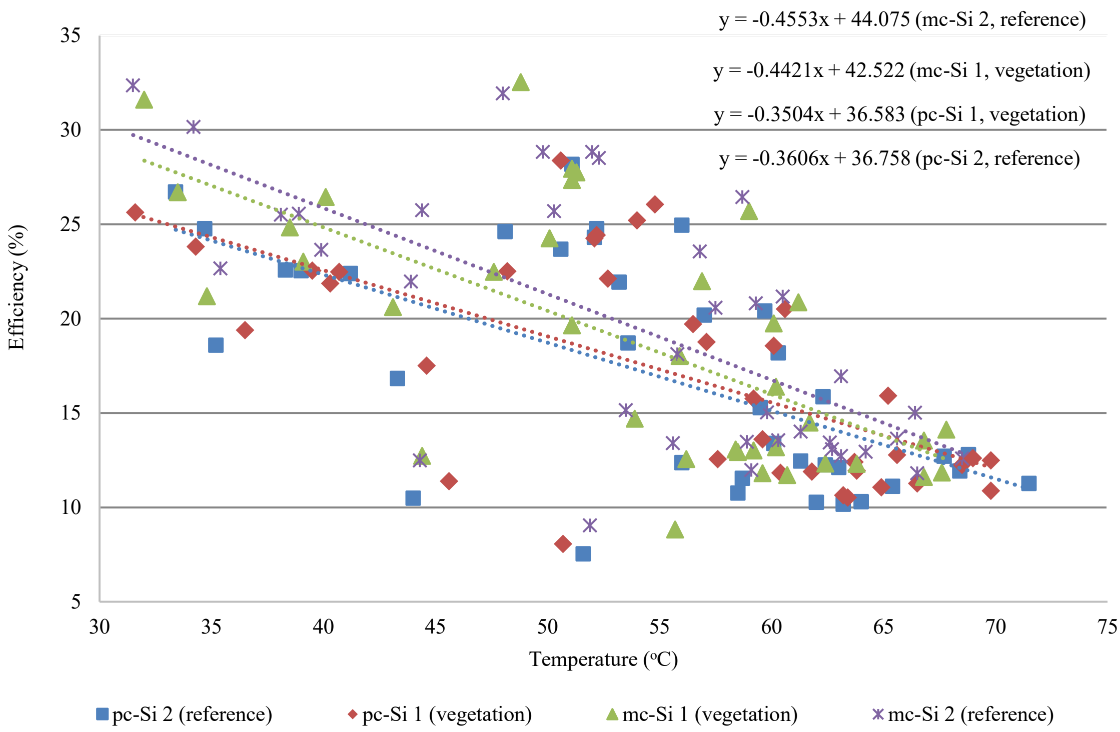

Fig. 10. Efficiency of reference and vegetated PV modules at different temperatures

4. CONCLUSION

In this study, the influence of vegetation on the performance of different photovoltaic (PV) module technologies was rigorously investigated. By deploying a total of four PV modules as research samples, we aimed to uncover the effects of vegetation on module's temperature and efficiency. To achieve this, two PV modules (pc-Si 1 and mc-Si) were equipped with caisim (brassica chinensis var. parachinensis), while the other two modules (pc-Si 2 and mc-Si 2) were designated as reference modules, left without vegetation. Our findings have revealed intriguing insights into the relationship between vegetation and PV modules' performance. Notably, we observed that for modules of the same technology, pc-Si 1 (vegetated) outperformed pc-Si 2 (reference), whereas mc-Si 2 (reference) exhibited superior performance compared to mc-Si 1 (vegetated). Surprisingly, our examination of mc-Si technology indicated that vegetation did not contribute to a reduction in PV module temperatures, thereby failing to improve their overall efficiency. This conclusion is substantiated by the parallel trends observed in the performance of reference and vegetated modules under the same conditions, without vegetation. This might be related to the design and material of the mc-Si modules which support conductive heat losses. Better contact and thermal conductivity of mc-Si modules' components cause the heat from the cells tend to be distributed to the other components including encapsulation, backsheet, glass, frame, and supporting structure. In other words, in this case, the conduction effect is more dominant than the evapotranspiration impact which may be low due to wind and the greater distance between the vegetation and the modules. Also, reduced soil moisture as the vegetation was only watered in the morning and afternoon. Consequently, the temperature and performance trends of both modules are relatively similar to once recorded without vegetation. Intriguingly, our investigation into different module technologies unveiled a consistent pattern: mc-Si modules exhibited better performance compared to pc-Si modules. This outcome mirrors the results of other researchers in various regions, attesting to the enhanced real-world performance of mc-Si modules in varying conditions. The results of this research imply that it is necessary to consider the application of vegetation for pc-Si technology modules for the design and optimization of the performance of solar power plants in Kupang. While this study contributes valuable insights, it is essential to acknowledge its limitations. The sample size was relatively small, which calls for further research involving a larger array of modules to comprehensively evaluate the impact of vegetation on both temperature and performance of pc-Si and mc-Si modules. Additionally, future studies could consider varying the distances between PV modules and vegetation to unravel the nuanced interplay between these factors. In conclusion, this research has shed light on the intricate relationship between vegetation and PV module performance. Our study has not only identified the nuances of this interaction but highlighted the need for broader research initiatives to fully understand the implications across different module technologies and environmental conditions. As solar energy continues to evolve as a pivotal renewable energy source, uncovering these dynamics becomes paramount for optimizing its utilization.

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