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Performance evaluation of a standalone solar PV system: a case study in Kendari, Southeast Sulawesi, Indonesia

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Abstract

Rising energy demand and environmental concerns are driving efforts to find alternative energy sources. Photovoltaic (PV)-based power generation is a clean energy solution that continues to be developed for reliable energy supply. This study aimed to analyze global horizontal irradiance (GHI) and evaluate the performance of a PV-based power generation model in Southeast Sulawesi, Indonesia (latitude: -4.002°, longitude: 122.6°). The study was conducted from March to May 2024 using a commercial PV panel with a rated maximum power of 50 Wp. Instantaneous values of GHI, voltage, and electric current were recorded simultaneously. GHI data were closely related to the clearness index (Kt) and the diffuse fraction of solar irradiance. The highest hourly average GHI was observed in March, reaching 1.08 kW/m², while values in April and May ranged from 0.97 to 0.99 kW/m². The system achieved a daily average maximum power output of 34.53 watts and an instantaneous peak of 49.03 watts. The maximum daily efficiency, 12.48%, was recorded in May. Power conversion performance was found to correlate strongly with GHI and Kt values, with greater stability in these parameters leading to more effective energy harvesting. Additionally, solar energy was available for more than 8 hours per day under clear sky conditions during the transitional season. These empirical results provide new insights into PV performance in the region. However, long-term data collection and incorporation of temperature effects, especially in the dry season, will provide power reliability assessment and extend system usability in off-grid applications in the region

Keywords:
global horizontal irradiance, photovoltaic, efficiency, power generation

1 Introduction

The solar PV cell is one of the most significant and rapidly developing renewable-energy technologies, and its potential future uses are notable. Solar radiation is a clean energy source, and PV systems are relatively benign environmentally. Currently, PV applications increase in many countries and it can be observed throughout the residential, commercial, institutional and industrial sectors. The clean, renewable and in some instances economic features of PV systems attracted attention from business and environmental sectors both institution and individual such in [1], [2].

Solar photovoltaic (PV) panels have been experienced rapid development in recent decades, both in terms of technological efficiency and decreased production costs. PV technology enables the direct conversion of solar energy into electricity, making it an environmentally friendly and sustainable option. These advantages make PV an ideal solution to reduce dependence on fossil energy, especially in countries with abundant solar energy potential, such as Indonesia [3], [4].

Indonesia, as a tropical country located on the equator, has enormous solar energy potential. By having an average daily solar radiation intensity of 4.8 kWh/m², Indonesia has a solar energy potential equivalent to a 112,000 gigawatt peak (GWp). This high solar radiation makes solar energy one of the most potential renewable energy sources to meet national energy needs. The distribution of solar radiation in Indonesia varies based on geographic location, atmospheric conditions, and weather patterns. In general, eastern parts of Indonesia, such as Nusa Tenggara, Sulawesi, and Papua, have higher solar radiation intensity compared to western regions, such as Sumatra and Java. Eastern regions tend to have lower levels of cloud cover and a cleaner atmosphere, so the intensity of solar radiation is maximized. The Meteorology, Climatology and Geophysics Agency (BMKG) of Indonesia reported that the regions with the best solar energy potential is Kupang, Sumba, and Merauke, where daily sunlight reaches 8-9 hours [1], [2].

Indonesia's new renewable energy (EBT) utilization still faces various challenges. According to data from the Ministry of Energy and Mineral Resources (ESDM), in 2023, the EBT mixture in national primary energy reached 13.09%, an increase of 0.79% from the previous year but still below the target of 17.87%. The installed capacity of renewable power plants reached 13,155 megawatts (MW), with the largest contribution coming from hydropower at 6,784.2 MW. In contrast, solar power plants (PLTS) only reached 573.8 MW. Nevertheless, a positive trend i-based solar power plants in Indonesia is growing. The government committed to fostering the accumulated installed capacity of PV panels to reach 770.7 MW by 2023. For the first semester of 2023, the total installed capacity of PV-based solar power plants was 322.6 MW. The energy mix target for solar PV installed capacity reached 5.4 GW by 2030 [5].

Energy transition and renewable energy development in Indonesia have been stipulated by renewable energy development policy until 2030. The new and renewable energy mix target of 23% in the national energy mix can be achieved by 2025 [6] with a focus on the PV-based solar power development of rooftop solar power plants, large-scale solar power plants, and hydropower plants. By 2030, the renewable energy mix is targeted to be 28%, including expanding supporting infrastructure such as power grids and battery storage. The implementation of new and renewable energy programs in the national energy mix is also driven by the government's target to reduce coal-fired power plant (PLTU) operation by 2045 [7].

Southeast Sulawesi is located near the equator, whose average daily solar radiation, ranging from 4.5 to 5.5 kWh/m²/day. The data has possibility for the development of PV-based solar power plants (PLTS). Average sunshine duration of 8-10 hours of sunshine per day, this region has an optimal duration for the operation of PLTS systems, even though the solar intensity may differ from each region or island in southeast Sulawesi [8],[9]. New satellite-based GHI data over the Southeast Sulawesi area were presented in [10]. The study indicated that the Kendari area received a moderate level of total irradiation. However, references [9] and [10] were solely based on 22 years of statistical satellite data, and one-month experiment dataset during dry season for September.

The Southeast Sulawesi government energy has considered renewable energy as part of the Regional Energy General Plan (RUED) [11], including the potential for PV-based solar power plant development to increase the renewable energy mix. A small-scale solar PV model that has been implemented in the Kendari City area is the Halu Oleo University solar PV unit of 33kWp. Meanwhile, street/garden lighting scale PLTS, and off-grid connections are scattered in several places/regions in Southeast Sulawesi, such as 71.9 Kwp PLTS Tambolosu, 89,38 Kwp PLTS Towea Muna Barat, etc.[12]. However, performance data and analysis of those plants have not yet been provided. The assisted PV-power model in Kendari was also ever tested by reference [13]. The boat model was successfully fully operated by PV-power as a prime mover during testing.

Photovoltaic (PV) performance characteristics depend on solar irradiation, which can vary significantly between different locations. These variations are related to climate conditions, as solar intensity fluctuates with weather patterns. Environmental factors have a direct impact on PV panel performance [12], [13]. Therefore, studies on PV panel technologies—such as orientation, tilt angle (to address shading effects and optimize exposure time), cooling mechanisms, and other engineering improvements—are still actively being developed [14], [15], [16].

However, analysis of specific field research data related to the potential and utilization of solar power was still needed for the references in the utilization and development of PV-based solar power technology as a source of electricity specifically at the selected region. The focus of this research is to analyze hourly data from solar radiation in the city of Kendari at a designed data location for solar power assessment. The electrical power performance of the PV model is also presented in this study.

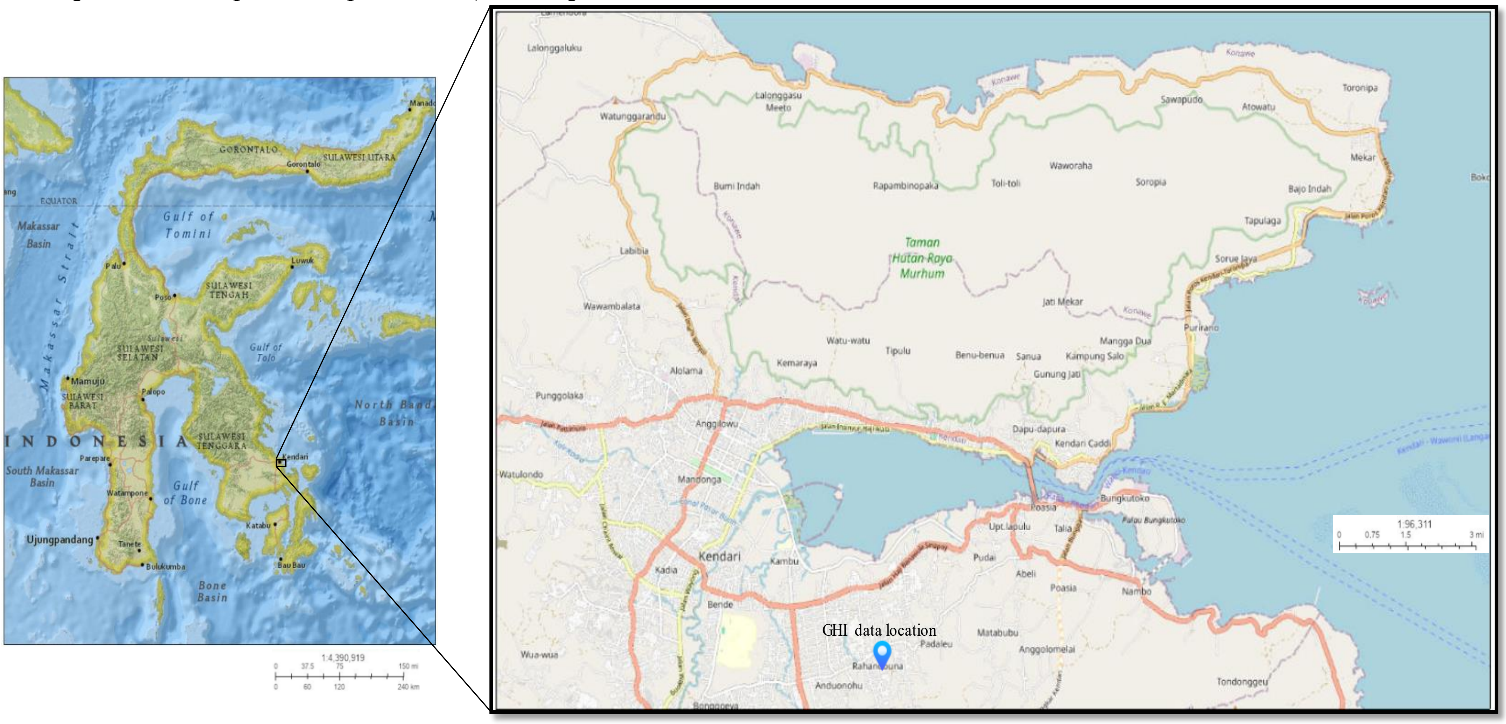


Fig. 1. Map of the selected location South Sulawesi is located near the equator with 3^0–6^0 south latitude.

2 Research methodology

Kendari City is located in southeast Sulawesi and having abundant solar resources. Specifically, the location where solar data was collected was at the Rahandouna sub-district area. The geographical data location, where the PV panel was mounted is presented in Table 1 and Fig. 1.

Table 1**.** Field data of the experiment

No	Description	Data Location	
1	Longitude	*L*	-4.002
2	Latitude	*A*	122.6
3	The tilt of PV, orientation	*β*	15°, N
4	Terrain Elevation	*E*	72mdpl
5	Time zone	GMT	+8

In this preliminary study, field data of solar irradiance was taken experimentally from March to May 2024. The selected days during the month were chosen in 3rd week of the month. In this situation, the specified location was under a transition period of the rainy season [8]. Averaged hourly solar data was taken from 8.00 AM to 16.30 PM, with 5-minute intervals using ground-mounted solar power meter SM206-SOLAR, *Shenzhen Sanpo Instrument,* to record the data of total global irradiance. This method provides high-frequency and accurate data measurement for the selected location. The PV-panel performance of commercial PV-module *SP-50-P36, S-Series PUL, poly-crystalline* (see table 2 for the panel specification), was measured simultaneously using multi-meter *WEILAI-WL9205A, Shenzhen TDC Technology*. Additionally, satellite-based data from NASA POWER at the selected location was also shown for reference. The schematic data collection is presented in Fig 2.

Tilt angle of fixed PV panel system affect PV performance due to total density solar radiation received by the PV panel installation. The optimum tilt angle of the PV system for high performance may differ depending on the observed location [14]. For the sake brevity, this study set up the PV panel system by 15° facing to the north, fixed for all days of data measurement.

Table 2. PV panel data

No	Description	Specification	
1	Module Type; *SP-50-P36, S-Series PUL, Polycrystalline*		
2	Rated Max Power	(P_{max})	50WP
3	Open Circuit Voltage	(V_{oc})	22.3V
4	Short Circuit Current	(I_{sc})	2.91A
5	Current at P_{max}	(I_{mp})	2.75A
6	Voltage at P_{max}	(V_{mp})	18.2V
7	Panel Area	(A_{pv})	0.357m^2

2.1 Solar irradiance parameter

Solar irradiance at the specified location and time may vary over the hours. The atmosphere clearness index (K_t) describes the ratio of the actual solar radiation received at PV ' 'panel's surface to the extraterrestrial solar radiation available at the top of the atmosphere. The parameter describes the transparency of the atmosphere and its effect on solar radiation received by the surface, which is defined by the Eq. (1) and Eq. (2).

$$K_t = \frac{I_g}{I_G} \tag{1}$$

$$I_G = I_{sc} \times \left(1 + 0.033 \cos\left(\frac{2\pi n}{365}\right)\right) \cos\theta_z \tag{2}$$

where I_G and I_g represent extraterrestrial solar radiation at the top of the atmosphere and global solar radiation received at a surface, respectively. I_{sc} is 1367 W/m^{2,} which is a solar constant, n is the day of the year. For instance, n = 32 for February 1. The factor of 0.033 is the Earth's orbital eccentricity correction factor, and θ_z is the zenith angle Eq. (2). Erbs, et al., 1981 [14] correlated hourly diffuse solar irradiance by considering K_t of the equation (1). The diffuse fraction (D_f) is defined by Eq. (3), and K_t parameter is shown in Eq. (4).

$$D_f = \frac{I_d}{I_g} \quad (3)$$

The diffuse fraction (D_f) is defined by Eq. (3), and K_t parameter is shown in Eq. (4)

- $K_t \leq 0.22$, $D_f = 1 - 0.09Kt$ (4)
- $0.22 < K_t \leq 0.8$, $D_f = 0.9511 - 0.1604Kt + 4.388Kt^2 - 16.638Kt^3 + 12.336Kt^4$)
- $K_t > 0.8$, $D_f = 0.165$

Meanwhile, Nethwadi and Winkle, 2019 [15] correlated diffuse fractions using a Slob Algorithm model in Gauteng condition as the equation (2).

Fig. 2. Field experimental arrangement at the designed location

$$0.331 - 0.2333K_t = \frac{I_d}{I_g} \quad (5)$$

The model has flexibility because of it does not require a sky clearness index (K_t) interval as ' 'Erb's correlation, which allows wider application for location differences. Then hourly global horizontal irradiation can be estimated by Eq. (6). where $I_b = I_{bn} \cos \theta_z$, I_{bn} represents beam solar irradiance normal to the PV panel surface [14], [16]

$$I_g = I_b + I_d \quad (6)$$

2.1 PV panel key performance

The following parameters generally evaluate PV system performance:

1. The ideal power received from the sun Eq. (7), where; I_G : solar energy irradiance on the panel (W/m^2), and A_p: effective area of the panel (m^2):
2.

$$P_{in} = I_G \times A_p \quad (7)$$

3. The power output of the PV Panel is calculated by Eq. (8), Where, I_{sc} : short circuit current (A), and V_{oc}: open circuit voltage output (V)

$$P_{out} = I_{sc} \times V_{oc} \quad (8)$$

4. The PV panel efficiency of the PV is determined by Eq. (9):

$$\eta_{pv} = \frac{P_{in}}{P_{out}} \times 100\% \quad (9)$$

3 Results and discussion.

3.1 Solar irradiance characteristics

Global irradiance intensity in tropical areas such as Kendari City is stable over the years due to the sun position being relatively close to the zenith. However, the intensity of radiation reaching theEarth's surface is affected by air pollution, humidity, and cloud coverage. In this case, season variation i.e., dry and rainy seasons are two essential factors for irradiance time in tropical areas.

Data satellite from NASA POWER [17] was presented in Fig. 3 to reveal five years of consecutive solar irradiation data at selected locations.

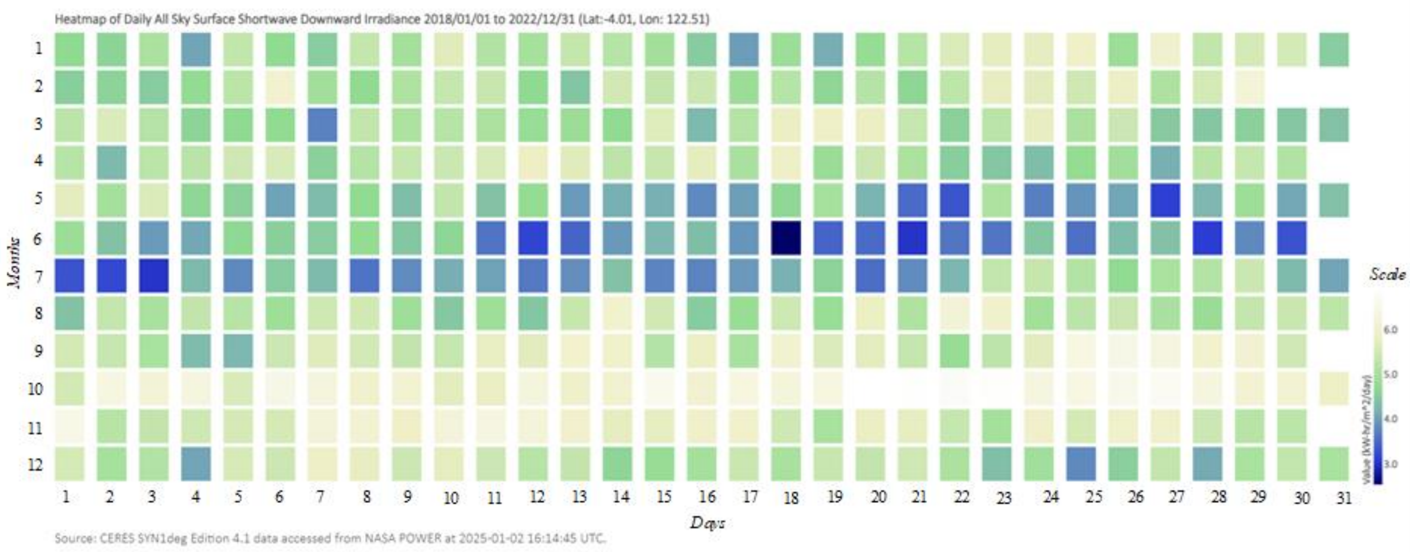


Fig. 3. Daily global horizontal irradiance (GHI) data from NASA POWER at the selected location (2018 – 2022)

It showed that the irradiation quantity was unstable around midyear, i.e., from May to July. Those periods are the transition phase of dry season at the selected location [8]. Solar irradiation intensity fluctuated more than that of the dry season period. Peak of solar irradiation occurs from September to November, with October reaching the highest peak of solar irradiation quantity.

During October, the flux radiation can reach more than 6 kWh/m^2/day, while the lowest takes less than 3 kWh/m^2/day in June. The radiation flux is influenced by irradiation time. Cloudy , the intensity of the sky, and rainy time are essential factors for irradiation time [18].

Hottel 1976 [19] predicted global horizontal irradiance (GHI) quantity at clear sky state. It is also calculated using the ASHRAE standard [20]. In this Study, the theoretical GHI for selected days and locations is presented in Fig. 4.

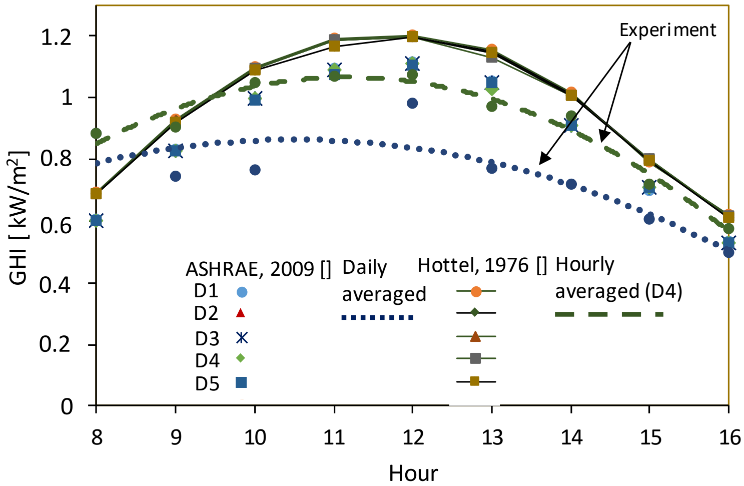


Fig. 4. Predicted Global horizontal irradiance using ' 'Hottel's correlation [19] and ASHRAE standard [20].

' 'Hottel's correlation presented a GHI quantity that was higher than ASHRAE calculation. Peak hours of GHI occur at 11 – 13 when solar beam incident approach the minimum zenith angle. Conversely, GHI descends when the solar position shifts far away from the perpendicular position of the PV-panel (zenith angle enlarged). Daily average of GHI calculation was overestimated by ' 'Hottel's and ' 'ASHRAE's prediction because of they calculate based on a clear sky state. However, the hourly average at *Kt* (=0.78) of measured GHI data was reasonably matched by ASHARE prediction method. The deviation (inconsistency) of the trendline of GHI experimental data compared to the ASHRAE calculation during days with hourly Kt > 0.6 (10:00 – 15:00) was acceptable (with an error of less than 1%).

Fig. 5 presents the hourly average of GHI and clear sky parameter data (Fig. 5b). Intensity of the cloudy sky is clearly defined by Kt parameter shown in Fig. 5b. The *Kt* parameter is closely related to GHI intensity, which is shown in Fig. 4a. In the 3rd week of March (around March 21) the sun approach equator line (0° latitude), which affects solar intensity.

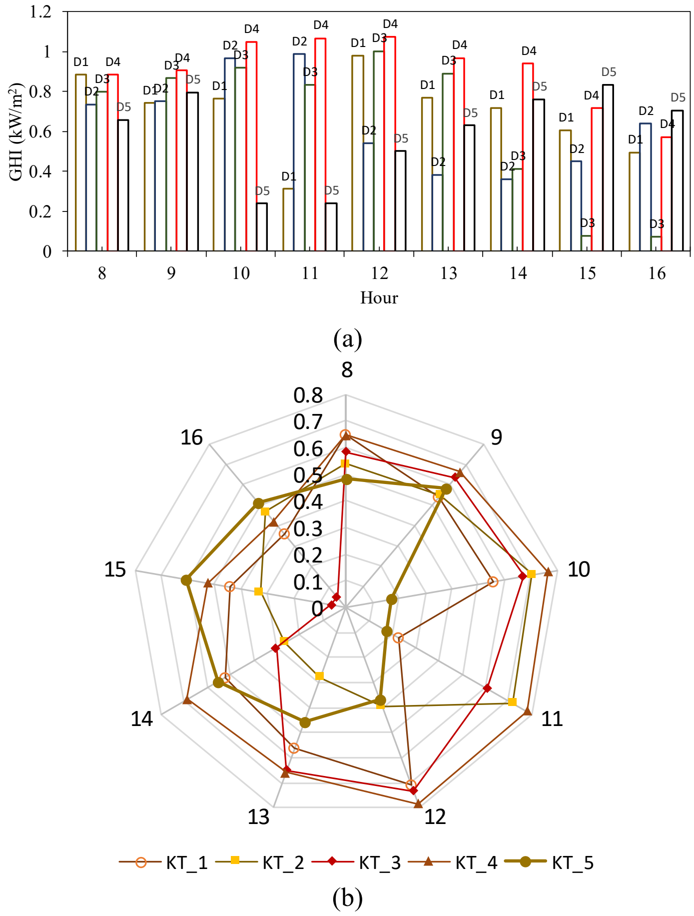
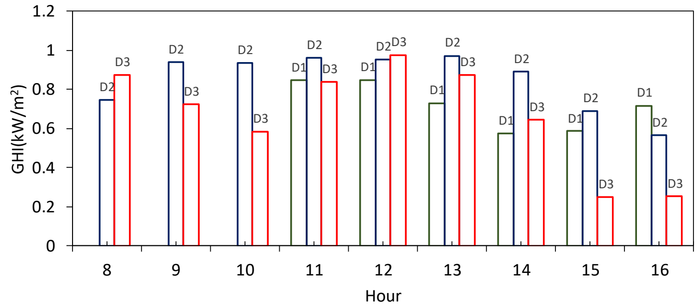


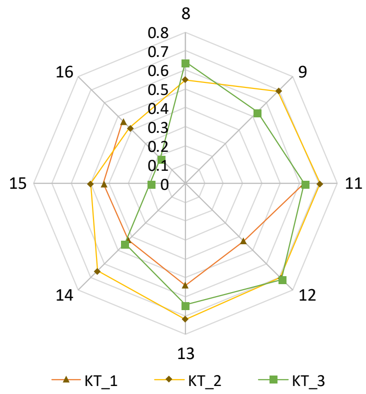
Fig. 5. (a) Variation of hourly GHI for some days in march (b) Clear sky coefficient over the days

GHI of the first day of data collection (D1, March 23) was lower than that of the fourth day (D4, March 29) at the peak season, 11 – 13 hours of solar irradiance due to the difference in clearness index quantity of the sky (see Fig. 5b). The GHI intensity approached about 1 kW/m^2 at the peak season of March. It is reasonable that sun position was located close to the equator.

Kt parameter of April data was lower than that of March at the peak season (Fig. 6). The days with clear sky state were less in 3rd week of April, which directly impacted the instantaneous of GHI. Therefore, the GHI peak in April acquired data was lower than in March.

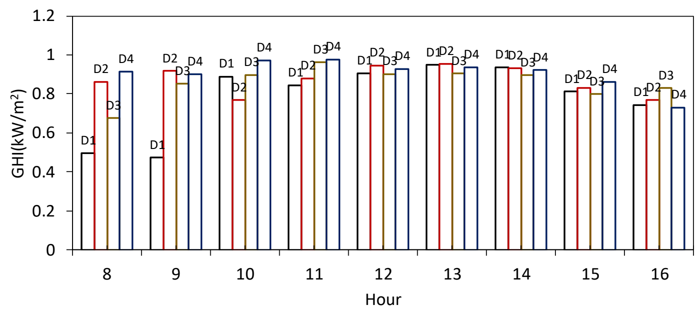


(a)

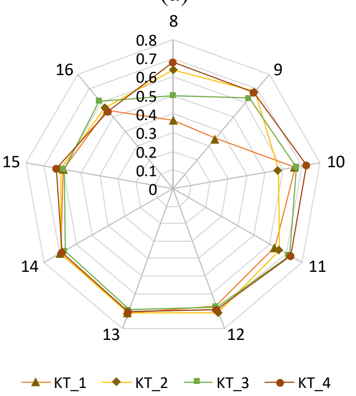


(b)

Fig. 6. (a) Variation of hourly GHI for some days in April; (b) Clear sky coefficient over the day.



(a)



(b)

Fig. 7. (a) Variation of hourly GHI for some days of may (b) Clear sky coefficient over the days

Instantaneous solar irradiance for May seemed stable at the peak season, as shown in Figure 7. It can be seen that *Kt* parameter variation revealed a similar trend with solar irradiance data (Figure 7(b)). However, the peak season of flux irradiance was still slightly lower than those recorded in March. It implies that ' 'sun's position at the end days of May was farther from the equinox (March 21), resulting in a difference in solar radiation distribution compared to the equinox period [16].

The relation between beam and diffuse irradiation is shown in Fig.8. The quantity of the parameters is closely related to the *Kt*. Direct beam irradiation (I_b) to the PV panel was reduced by cloud, scattered in the atmosphere, and increased diffuse.

The peak season data in Fig. 8 (D4) clearly showed that high Kt reduced diffuse fraction. Conversely, diffuse fractions were high in the early and the end day of data collection or heavy cloud.

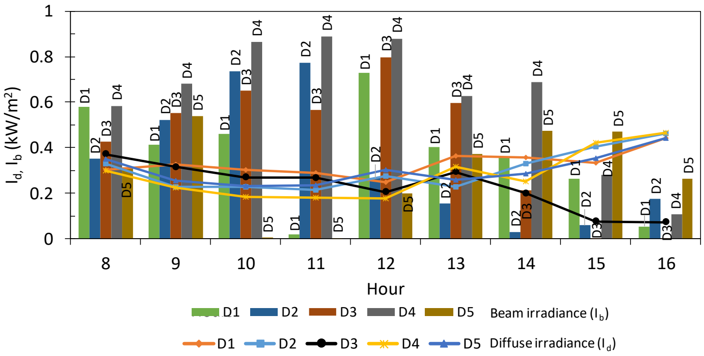


Fig 8. Instantaneous of hourly beam and diffuse irradiance in 3rd week of March data session

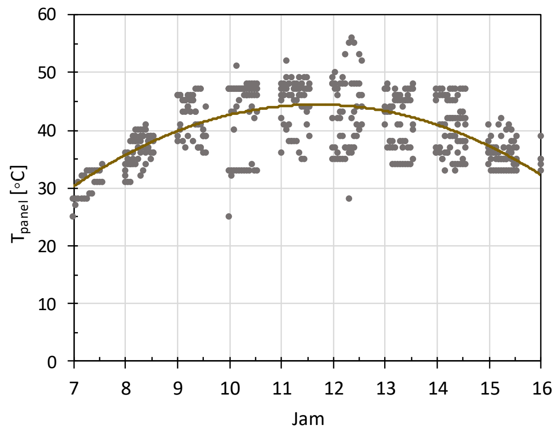


Fig. 9**.** PV-panel temperature at march sampling data

The surface temperature of the PV panel during the experiment conducted in March is presented in Figure 9. A quadratic trend line illustrates that the surface temperature of the PV panel peaked around 12–13, coinciding with the highest solar irradiance intensity. Theoretically, irradiance intensity is linearly correlated with solar energy harvesting. However, as shown in Figure 11b, the energy conversion efficiency of the PV panel decreased due to the increase in surface temperature. This phenomenon has also been reported in previous studies [21], [22], [23].

3.2 Power harvesting performance

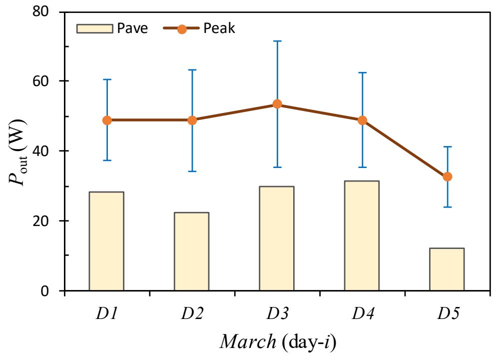
Power generation of the PV panel at the selected month is presented in Fig. 10(a), dan (b). March data session presented maximum power generation of 31 W at D4, and an instantaneous power peak of 48.93 W.

It is linear with irradiance data presented in Fig. 4(a). Meanwhile, the peak of instantaneous power generation occurred at D3 with higher fluctuation compared to all-day data (D_i). This phenomenon is directly related to averaged power generation presented in Fig. 10.

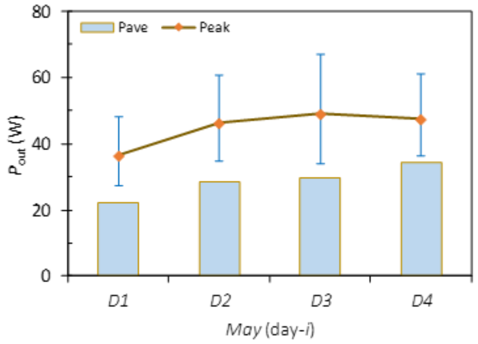
Power harvesting fluctuation in Fig. 10 is defined as the standard deviation of the data sample, which is defined by the root mean square of power (P_{rms}) in equation (11).

$$P_{rms} = \sqrt{\frac{\sum_{t-1}^{N}(|P_t|-P_{ave})^2}{N}}, \qquad P_{ave} = \frac{\sum_{t=1}^{N}|P_t|}{N} \qquad (11)$$

where N is the number of data samples, and P_t is instantaneous power generation at t time interval.

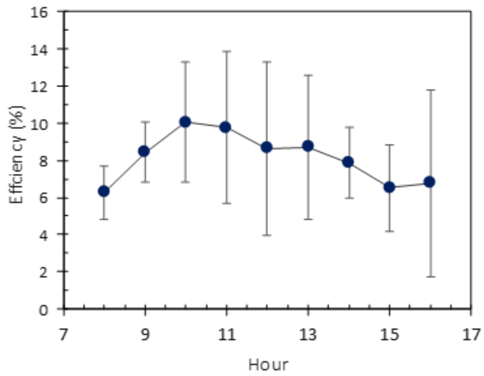


(a)

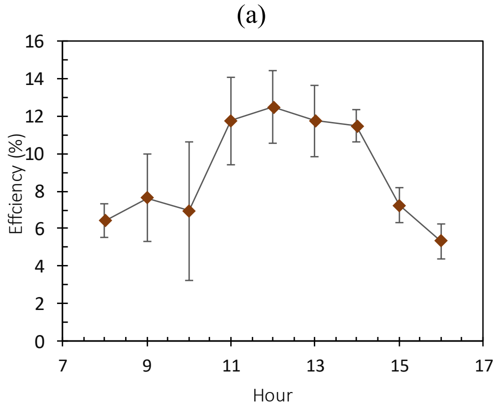


(b)

Fig. 10. (a) Hourly average of the power generation performance of PV panel in march, and (b) power generation performance of PV panel in may



(a)



(b)

Fig. 11**.** Daily average of PV system performance (a) In march data session (D1−D5), and (b) In may data session (D1−D4)

The maximum hourly average of power generation in the May data session was 34.53 W at D4, and instantaneous peak power was 49.02 W at D3. Similar to March data collection high power harvesting fluctuation occurred at D3, which impacted the averaged maximum power.

The error bars (standard deviation) of Figure 10 reflect the instability in power harvesting by the model, which was influenced by GHI intensity. GHI and *K*t are interdependent parameters that have a significant impact on PV performance [18].

PV-base power generation system efficiency is presented in Fig. 10(a), and (b). The maximum PV power conversion was 10.02% and 12.48% for the March and May data sessions, respectively.

Fig. 9(a) shows the panel works efficiently at 10 AM. However, peak hourly efficiency still occurred at the peak season time, i.e. 11 AM − 1 PM when the sun delivered the peak irradiance. Instantaneous peak efficiency was 13.84% at 11 AM (D2). Fluctuations in daily power generation hindered the PV system from reaching its maximum performance during periods of peak solar irradiance. This behavior is primarily attributed to the variability in atmospheric conditions, such as intermittent cloud cover, which affects the consistency of global horizontal irradiance (GHI). Hence, the power conversion efficiency of PV panels is also affected by seasonal variations, which are related to irradiation intensity, ambient temperature, and humidity [19],[20]. Figure 11(a) confirmed that peak irradiation at 12 – 1 PM does not solely indicate peak energy conversion efficiency. This is likely due to an increase in PV-panel operational temperature, as previously described. Hence, the power output conversion efficiency in this study was reasonably consistent with those references.

Figure 11(b) exhibits that maximum power conversion of the PV system occurred at the peak hours of solar irradiance. Maximum power conversion efficiency at the May data session occurred at 12 PM. Daily power generation fluctuation was also reasonably stable at the peak hours. It confirms that *K*t parameter is closely related to PV-panel performance. The fluctuation of instantaneous power conversion efficiency was smaller than that of the March session, which is considered related to Kt parameter. Hence, average PV performance in the May data session was higher than that of March. *K*t parameters in March and May were concomitant with GHI data quantity, as presented in the previous section.

4 Conclusions.

This study demonstrated the feasibility of standalone PV-based power generation in Kendari, Southeast Sulawesi, through experimental analysis conducted over three months. The highest global horizontal irradiance (GHI) was observed in March at 1.08 kW/m², with daily power outputs averaging 34.53 W and peaking at 49.03 W. The clearness index (Kt) and beam irradiance significantly influenced energy harvesting, with May achieving the highest system efficiency of 12.48%, owing to more stable irradiance. Power output was found to correlate closely with GHI stability, and solar energy was available for more than 8 hours on clear days. The GHI measurements were consistent with ASHRAE clear-sky models during peak sun hours (09:00–15:00). Although data variability was observed due to the transitional season, the findings support the potential of PV systems for reliable off-grid energy supply in tropical regions. Future studies should involve year-round data collection and consider temperature effects and economic analysis to strengthen system optimization and scalability.

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