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Optimization Design of 600 Wp Solar Tree System Design According to Tilt Angle

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Abstrak

Optimasi sistem berbasis tenaga surya diperlukan untuk mendukung pengembangan perancangan energi terbarukan di lingkungan kampus secara efektif. Penelitian ini bertujuan untuk menentukan sudut kemiringan optimal dari STS berkapasitas 600 Wp yang dipasang di tiga lokasi berbeda di lingkungan kampus Universitas Jenderal Achmad Yani (UNJANI). Sudut kemiringan *Photovoltaic* (PV) merupakan faktor penting dalam *Solar Tree System* (STS) karena secara langsung memengaruhi jumlah iradiasi matahari (kWh/m^2) yang diterima. Simulasi dilakukan menggunakan perangkat lunak PVsyst dengan variasi sudut kemiringan antara 15° hingga 30° dan azimuth tetap 0°. Hasil simulasi pada sudut 15° menunjukkan performa terbaik dengan iradiasi tahunan sebesar 1912 kWh/m² dan Solar Fraction (SF) tertinggi sebesar 92.66%. Sistem juga menunjukkan efisiensi baik dengan Performance Ratio (PR) sebesar 57.76%.

Kata kunci: *Photovoltaic, Performance Ratio, Solar Fraction, Solar Tree System*, UNJANI

Abstract

Optimizing solar based systems plays a crucial role in advancing renewable energy applications within campus environments. This study aims to identify the optimal tilt angle for a 600 Wp Solar Tree System (STS) installed at three designated sites on the campus of Universitas Jenderal Achmad Yani (UNJANI). The tilt angle of photovoltaic (PV) modules significantly affects the quantity of solar irradiation (kWh/m²) received, influencing overall system performance. Simulations were performed using PVsyst software with tilt variations between 15° and 30°, maintaining a constant azimuth of 0°. The results indicate that a 15° tilt angle yields the highest annual irradiation of 1,912 kWh/m² and achieves a Solar Fraction (SF) of 92.66%. Additionally, the system demonstrated efficient operation with a Performance Ratio (PR) of 57.76%.

***Keywords**: Performance Ratio, Photovoltaic, Solar Fraction, Solar Tree System, UNJANI*

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Introduction

Photovoltaic is a renewable energy technology that can help satisfy the world's energy demands (Michel et al., 2024). Based on IRENA 2023 estimates, Indonesia currently has 313 MW of renewable energy capacity. (*International Renewable Energy Agency*, 2023)(Alrubaie et al., 2023). As one of the ecologically friendly energy plants, photovoltaics may help reduce carbon emissions in compliance with the Indonesian government's goal of net-zero emissions (Menteri Energi Dan Sumber Daya Mineral Republik Indone, 2021) and in compliance with the Indonesian government's commitment to the Paris Agreement in 2016 (Undang Undang RI, 2016), (Ariawan et al., 2022). Photovoltaics facilitate the advancement of integrated renewable energy technologies, including solar trees that optimize energy in both urban and rural settings, therefore promoting the sustainability of green energy ecosystems (Naushad et al., 2024).

In addition to the aforementioned context, the implementation of photovoltaic systems, the tilt angle(Yunus Khan et al., 2020) is a crucial factor that influences the absorption efficiency of solar energy(Ullah et al., 2019). The optimization of the tilt angle is refined by the unique properties of solar radiation and varying weather patterns across different locations, particularly in subtropical climates(Khatib et al., 2015) and regions with elevated radiation levels, such as Southeast Asia. These Asian regions are anticipated to effectively leverage photovoltaic technology(Choi & Bhakta, 2024). The ideal tilt angle may fluctuate based on geographical location and season (Zhao et al., 2017), as well as the characteristics of the surrounding environment(Karafil et al., 2015). Determining the right tilt angle on a PV panel system makes a significant contribution to improving the overall performance of the system(Xu et al., 2017). The aforementioned background elucidates that the optimization of the solar PV system's slope angle is contingent upon geographical location, solar energy potential, and shading that influences the properties of the PV panel(Iskandar et al., 2018)(Iskandar et al., 2024a), and the dust(Zaman & Ratu, 2024). Consequently, it is essential to further develop and assess the azimuth angle according to the maximum yearly radiation at various places chosen in this study.

Although the adoption of solar energy continues to grow across various sectors, the implementation of solar tree systems remains uncommon in campus environments, particularly in Indonesia. Previous research has predominantly concentrated on conventional photovoltaic (PV) installations, such as rooftop and floating systems. However, investigations focusing on medium-scale solar tree systems, like 600 Wp configurations, within tropical academic settings are still limited. Addressing this research gap, the present study aims to evaluate and optimize the tilt angle of solar panels in a 600 Wp solar tree installation at Universitas Jenderal Achmad Yani. The outcomes of this analysis are expected to contribute a valuable reference for the advancement of innovative solar energy solutions within the educational sector.

Method

The study procedure starts by identifying the site's solar energy potential using solar radiation data processed through PVsyst software. After determining the geographical coordinates, relevant meteorological inputs such as global horizontal irradiance (GHI), temperature, and wind speed are collected. With these inputs, monocrystalline photovoltaic (PV) modules are selected for the system design, which is based an off-grid configuration. The orientation of the PV panels, particularly azimuth and tilt angles, is then calculated. Load estimation is conducted based on the energy consumption of selected devices, including electric bicycles and electronic gadgets. This estimation serves as the basis for determining the required capacity of PV modules, battery storage, and inverter. A simulation is then carried out to identify the optimal panel inclination and system efficiency. Subsequently, a simulation using PVsyst software is conducted to determine the optimal panel inclination and evaluate system efficiency. The study concludes with an analysis of simulation results, resulting in recommendations for implementing a 600 Wp solar tree system on campus. See figure 1 below.

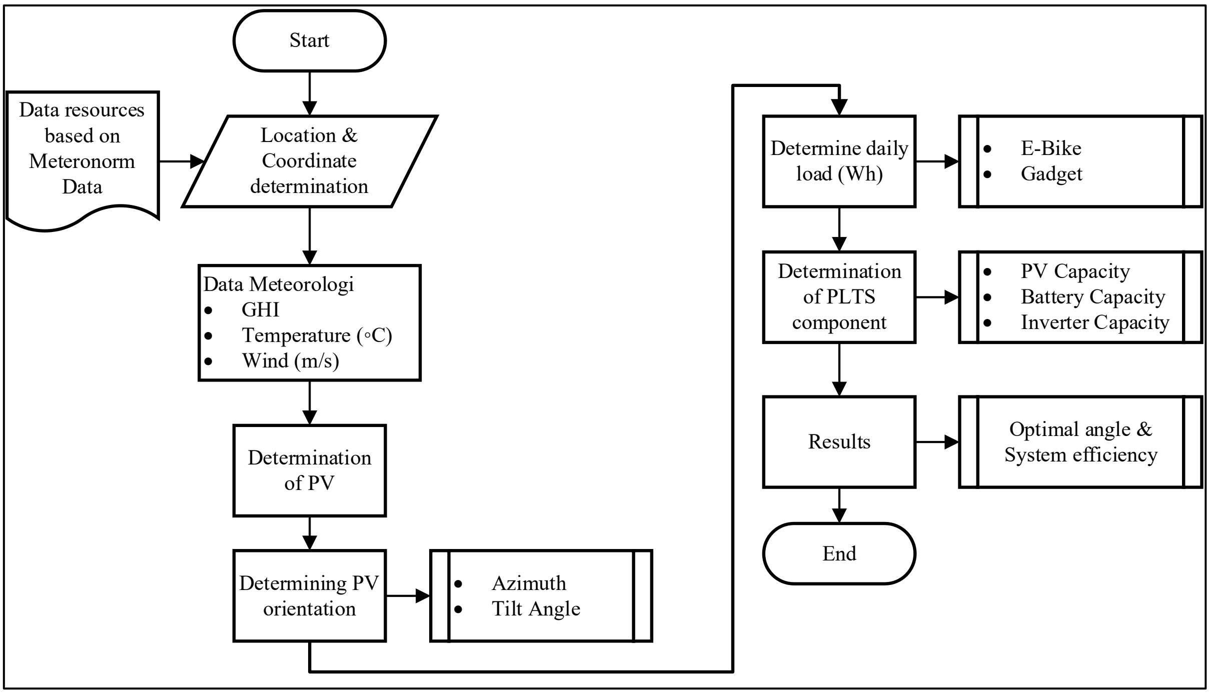

Figure 1. Flowchart of Tilt Angle Simulation of Solar Tree System 600 Wp

A. Location and Meteorological Characteristics

Three main areas have been identified for the installation of a solar tree system at Jenderal Achmad Yani University (UNJANI) using PVsyst software. The first location is situated in front of the UNJANI auditorium at coordinates -6.89°S and 107.53°E, offering a spacious area and strategic advantages due to high pedestrian traffic from academics, making it an optimal site for educational activities and demonstrations of renewable energy technology. The second location is beside the Pharmacy Faculty building, chosen for its extensive open area, exceptional solar radiation potential, and ability to enhance solar panel efficiency. The third location is adjacent to the Faculty of Pharmacy building, chosen for its large open area, exceptional solar radiation potential, and ability to enhance solar panel efficiency. The second and third locations have identical coordinates, indicating their proximity, but the first location is slightly further east due to the difference in longitude.

All selected sites were situated in open and obstacle free environments to prevent any interference from shading. Recognizing that shadows from surrounding objects can adversely affect photovoltaic output, each location was deliberately chosen based on its clear exposure to sunlight without obstruction from trees, buildings, or other structures. Although PVsyst's shading analysis was not applied in this simulation, direct field assessments confirmed that every site maintains uninterrupted sunlight throughout the day. This ensures that shadowing does not influence the simulation outcomes.

Figure 2. Designated Site for the Solar Tree System 600 Wp

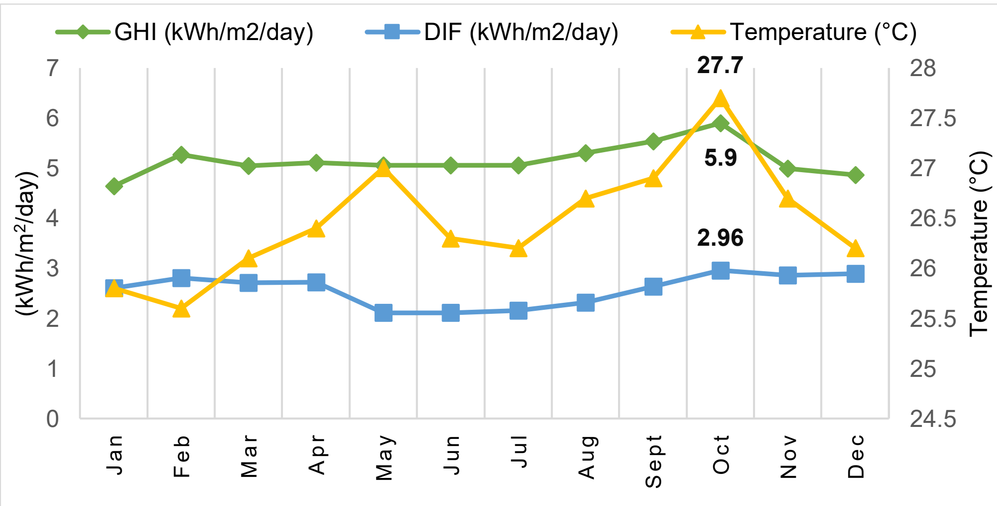

Figure 3. Monthly Weather at the Solar Tree System 600 Wp Research Site

Table 1. Characteristics of Meteorological Data by Location

Month	Glob. Hor. Irradiation ($kWh/m^2/day$)	Hor. Diffuse Irradiation ($kWh/m^2/day$)	Temp. (°C)	Wind Velocity (m/s)	Linke Turbidity (-)	Relative Humidity (%)
Jan	4.64	2.60	25.8	1.10	4.316	85.9
Feb	5.27	2.81	25.6	0.99	4.506	87.2
Mar	5.05	2.71	26.1	0.90	4.622	84.9
Apr	5.11	2.72	26.4	0.81	4.855	84.8
Mei	5.06	2.11	27.0	0.90	4.767	80.4
Jun	5.06	2.11	26.3	1.00	4.771	79.3
Jul	5.06	2.16	26.2	1.29	4.749	74.0
Agu	5.30	2.32	26.7	1.50	5.059	69.3
Sep	5.54	2.64	26.9	1.50	5.219	70.1
Okt	5.90	2.96	27.7	1.30	6.205	71.0
Nov	4.99	2.86	26.7	1.00	6.255	80.2
Des	4.86	2.89	26.2	0.91	4.949	84.7
Av. Year	5.15	2.57	26.5	1.1	5.025	79.3

Figure 3 and table 1 illustrate Global Horizontal Irradiation (GHI) at the research site varies from 4.64 $kWh/m^2/day$ (January) to 5.90 $kWh/m^2/day$ (October), with an average of 5.15 $kWh/m^2/day$, indicating good solar potential. Horizontal Diffuse Irradiation (HDI) is relatively stable at 2.57 $kWh/m^2/day$. Air temperature was consistent (25.6 – 27.7°C) with an average of 26.5°C, supporting PV performance. Average wind speed was 1.1 m/s, with a maximum of 1.50 m/s (August – September). Linke turbidity increased to 6.255 in October – November, indicating a more hazy atmosphere during that period. Relative humidity ranged from (69.3 – 87.2%) with an average of 79.3%.

B. Calculation of PV Tilt Alignment

Based on the simulation results using PVsyst software, annual and seasonal global irradiation data was obtained for various solar panel tilt angles with a fixed azimuth of 0°. The analysis was conducted to determine the variation in solar energy reception throughout the year and to determine the optimal tilt angle that provides the best performance.

Table 2. Annual Data from Many Perspectives at Places A, B, And C

No.	Tilt Angle in Azimuth 0°	Global Irradiance in the collector field (kWh / m^2)		
		Yearly Irradiance	Season (April – Sept.)	Season (Oct. – March)
1.	15°	1912	1031	880
2.	16°	1910	1035	875
3.	17°	1908	1038	870
4.	18°	1906	1041	864
5.	19°	1903	1044	859
6.	20°	1900	1046	853
7.	21°	1896	1049	847
8.	22°	1892	1051	841
9.	23°	1887	1052	834
10.	24°	1882	1054	828
11.	25°	1877	1055	821
12.	26°	1871	1056	814
13.	27°	1865	1057	807
14.	28°	1858	1057	800
15.	29°	1851	1057	792
16.	30°	1843	1057	785

Table 2 shows that 15° is the optimal angle, producing an annual irradiation of 1912 kWh/m², which is the highest value among all angles tested. At a tilt angle of 15°, the distribution of solar radiation shows a good balance between summer and winter. During the winter (October – March), a tilt angle of 28° - 30° records the highest irradiance, at 880 kWh/m^2. The total irradiance value gradually decreases as the tilt angle increases. The study results indicate that for the studied location, a 15° angle at an azimuth of 0° is the most effective for maximizing solar radiation reception.

C. Configuration of PV System

This study, the Telecom-STV TSM 100 (monocrystalline module) was selected based on the PVsyst library.

Table 4. PV Module Specifications

No.	Parameters	Information
1.	Max. Op. Voltage (V_{mp})	33.6 V
2.	Max. Op. Current (I_{mp})	2.98 A
3.	Short Operating Circuit Voltage (V_{oc})	42 V
4.	Short Circuit Current (I_{sc})	3.25 A

Equation (1) shows that P_{mp} is the maximum power that can be generated by the PV system, while V_{mp} and I_{mp} are the voltage and current at maximum power(Iskandar et al., 2024).

$$P_{mp} = V_{mp} I_{mp} \quad (1)$$

There are three main factors that influence the determination of PV capacity, namely; total daily load requirements, solar insulation, and adjustment factors, as shown in Equation (2). Solar insulation values are obtained based on the geographic coordinates of the solar tree system installation site. The PV capacity can be calculated using the following formula(Setia et al., 2021).

$$PV = \frac{Total\ load\ per\ day}{Solar\ insulation} \quad (2)$$

Assuming a 15% system loss the adjusted PV capacity and the number of PV modules required can be calculated using Equations (3) and (4):

$$PV_{15\%} = PV + (PV \times 15\%) \quad (3)$$

$$Number\ of\ PV\ numbers = \frac{PV_{15\%}}{PV\ Capacity_{\ (market)}} \quad (4)$$

By using Equation (5), the Fill Factor (FF) of the PV module can be calculated based on the nameplate specifications.

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \quad (5)$$

Off grid solar power systems rely on solar energy as their primary energy source. Therefore, solar power systems require battery capacity to meet electrical load requirements when sunlight intensity decreases, also known as self sufficient conditions. Battery capacity calculations can be determined based on the AS/NZS 4509.2 standard from 2010, using Equations (6), (7), (8), and (9)(Iskandar, 2020):

$$Batt_{Storage}\,(Wh) = Daily_{Energy} \times Otonom_{day} \tag{6}$$

$$C_{x\_AH} = \frac{E_{tot} \times T_{aut}}{Batt_{volt} \times DOD_{maks}} \tag{7}$$

$$\Sigma Battery = \frac{Batt_{Storage}(Wh)}{DOD_{max}(\%) \times Batt_{curr}(Ah) \times Batt_{Volt}} \tag{8}$$

$$Storage\ energy\ (Wh) = Batt_{volt} \times Batt_{curr} \times DOD_{maks} \tag{9}$$

Equation (10) shows that the capacity of the inverter is determined by the total load power in the system design. The greater the total load power value, the larger the inverter capacity required. The inverter sizing formula is provided as follows:

$$Inverter\ capacity\ (W) = P_{total\ load\ (Watt)} \times 125\% \tag{10}$$

Equation (11) defines the Reference Yield as the theoretical daily energy per unit of installed PV capacity (kWh/kWp/day) under ideal conditions. It represents the total solar irradiance received on the module surface and serves as a baseline for assessing system performance.

$$Y_r = Reference\ Yield \tag{11}$$

Equation (12) presents the Array Yield (Y_a), which refers to the actual energy output generated by the PV array, normalized to the system's nominal installed capacity. This value represents the gross energy delivered by the array prior to accounting for system-level losses such as inverter inefficiencies or storage limitations.

$$Y_a = \frac{E_{array}}{P_{nom}} \tag{12}$$

System Yield (Y_f) represents the usable energy output delivered to the load, normalized to the system's nominal capacity. It reflects real system performance after all operational losses, as shown in Equation (13):

$$Y_f = \frac{E_{user}}{P_{nom}} \tag{13}$$

Equation (14) represents the Collection Loss (L_c), calculated as the difference between the Reference Yield $(Y_{r)}$and the Array Yield (Y_a)This value quantifies energy losses arising from environmental and technical factors, including temperature effects, module mismatch, dirt accumulation, and suboptimal system configuration.

$$L_c = Y_r - Y_a \tag{14}$$

System Loss (L_s) captures the gap between energy produced and energy delivered, typically caused by inverter and storage inefficiencies, as defined in Equation (15).

$$L_s = Y_a - Y_f \tag{15}$$

Performance Ratio (PR), as defined in Equation (16), evaluates system efficiency by comparing actual energy output to the maximum possible under ideal irradiation, offering a location independent performance indicator.

$$PR = \frac{Y_f}{Y_r} \tag{16}$$

Unused Energy (L_u) in Equation (17) denotes the portion of generated energy that cannot be used due to storage limits or demand mismatch, often occurring in off grid systems when batteries are full or load is minimal.

$$L_u = Y_a - L_c - Y_f \tag{17}$$

The temperature loss factor (f_{temp}) quantifies the decline in photovoltaic (PV) module performance due to increased cell temperature. As outlined in AS/NZS 4509.1:2009(Standards Australia, n.d.), this effect is mathematically expressed in Equation (18):

$$f_{temp} = 1 - \gamma(T_{cell_{eff}} - T_{STC} \tag{18}$$

The effective cell temperature ($T_{cell_{eff}}$) can be estimated using Equation (19) as the sum of the ambient temperature during the day $(T_{a_{day}})$ and the standard test condition temperature T_{STC} which is typically 25°C:

$$T_{cell_{eff}} = T_{a\_day} + T_{STC} \tag{19}$$

In this formulation, $(T_{a_{day}})$ denotes the ambient temperature measured on site, and (T_{STC}) is a fixed reference used for standard testing of photovoltaic modules. The correction factor (f_{temp}) is calculated using a temperature coefficient (γ), generally assumed to be 0.0041/°C, which indicates the rate of efficiency decline per unit increase in cell temperature. Based on this, the correction factor for typical operating conditions is approximately 0.89. This adjustment is essential for ensuring the precision of PV system performance estimates under varying thermal environments.

Result

At an angle of 15°, both direct and diffuse radiation can be effectively captured, allowing the solar panels to maximize their electrical output. Enabling the solar panels to maximize their electrical output. With this configuration, the simulation yields normalized production (NP) and performance ratio (PR) values for locations A, B, and C, as illustrated in Figure 4 and Figure 5.

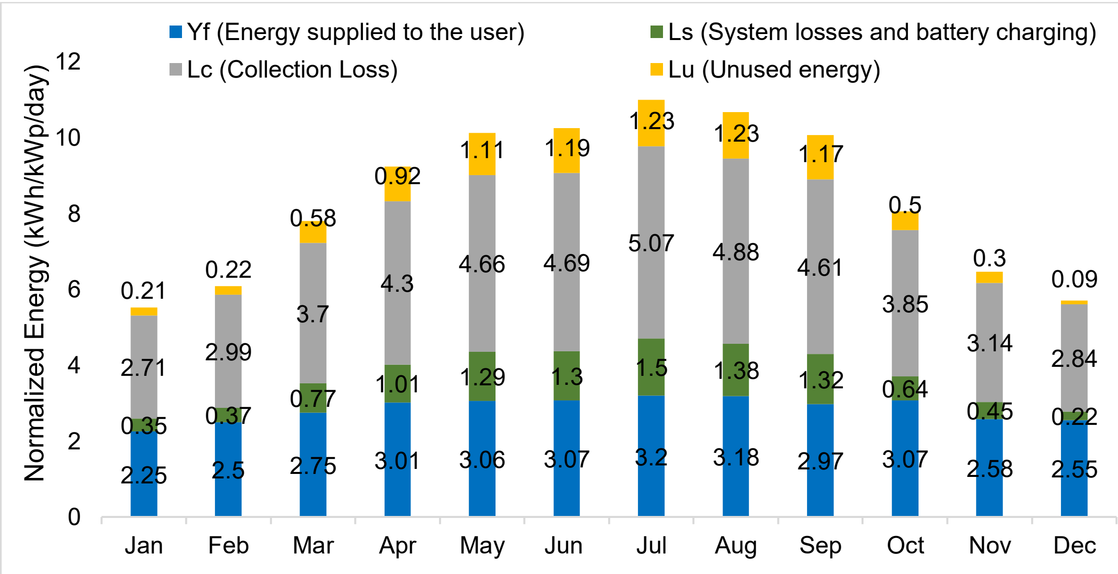

Figure 4. Normalized Output at Location A, B, and C

Figure 4 illustrates the normalized energy output throughout the year at locations A, B, and C. The highest generation occurred in July, reaching 11.2 kWh/kWp/day, comprising 3.2 (Yf), 5.07 (Lc), 1.5 (Ls), and 1.23 (Lu). Although July shows the maximum energy delivered to the user, the significant collection loss and unused energy values highlight surplus production that was not fully utilized. In contrast, December marked the lowest output, totaling 5.7 kWh/kWp/day, with user supplied energy (Yf) at only 2.55. Overall, the system performs better during the dry season and declines during the rainy season, emphasizing the need for proper energy management and storage strategies.

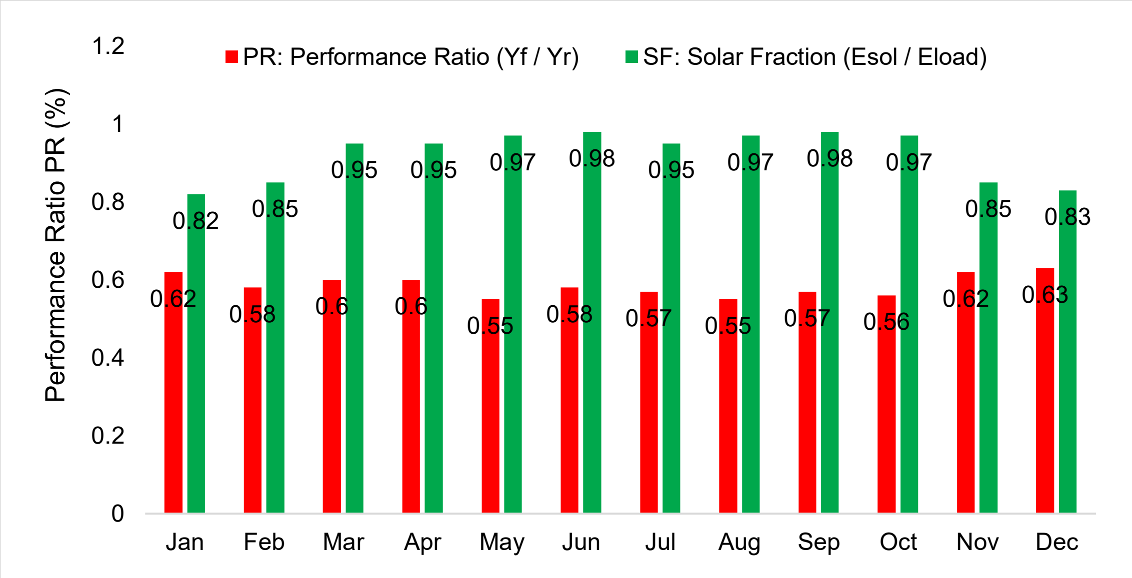

Figure 5. Performance Output at Location A, B, and C

As shown in Figure 5, the Performance Ratio (PR) ranged from 0.5 to 0.67 throughout the year, indicating good system efficiency despite seasonal variations. The consistently high Solar Fraction (SF) value, particularly above 0.90 from March to October, proves that the system is capable of meeting almost all of the daily load requirements from solar energy.

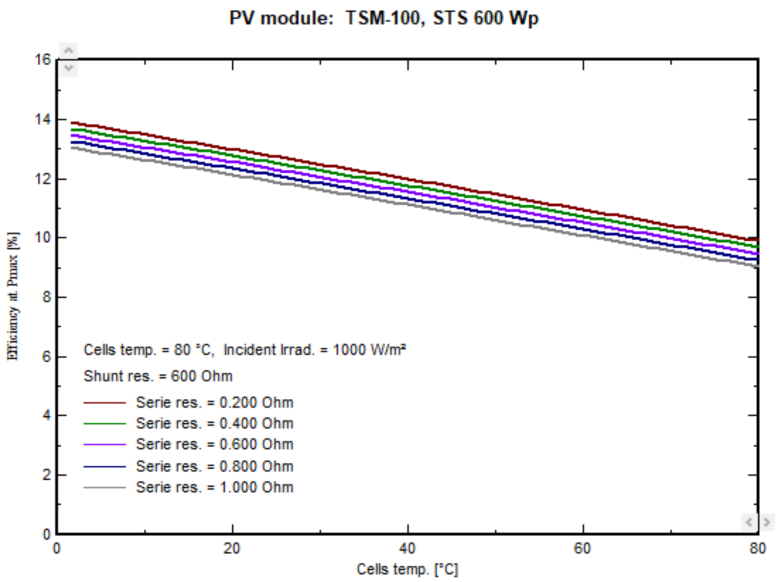

Figure 6. PV Efficiency Under Different Temperatures

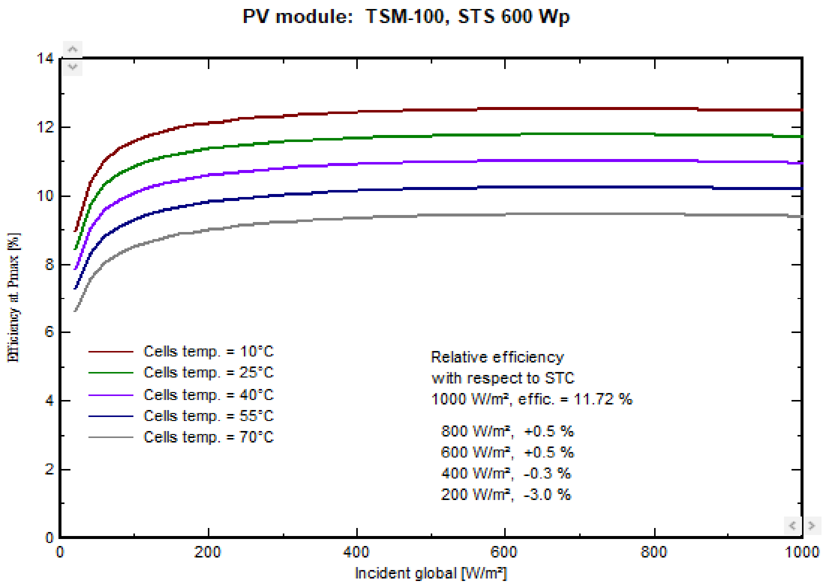

Figure 7. Global Irradiance Influences Maximum Power Output

Figure 6 shows the output efficiency under maximum power conditions (P_{max}), peaking at 14%. It depicts how the PV module responds to different values of series resistance (ranging from 0.200 to 1.000 Ohms) while exposed to a consistent irradiance of 1000 W/m². The cell temperature varies from 0°C to 80°C, and the trend reveals a steady decline in efficiency as the temperature increases. Figure 7 shows the efficiency of the PV module declines as cell temperature increases and irradiance decreases. The highest efficiency is recorded at 1000 W/m^2 and 2°C, while a significant drop is observed at 200 W/m² with a 3% reduction. Optimal PV performance relies on low cell temperatures and sufficient irradiance.

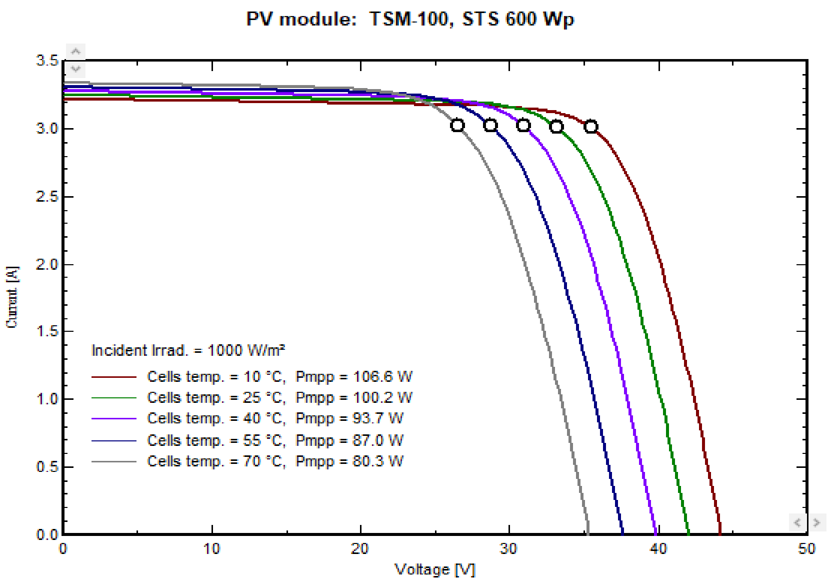

Figure 8. I-V Characteristics Under Varying Irradiance Conditions at Constant Temperature

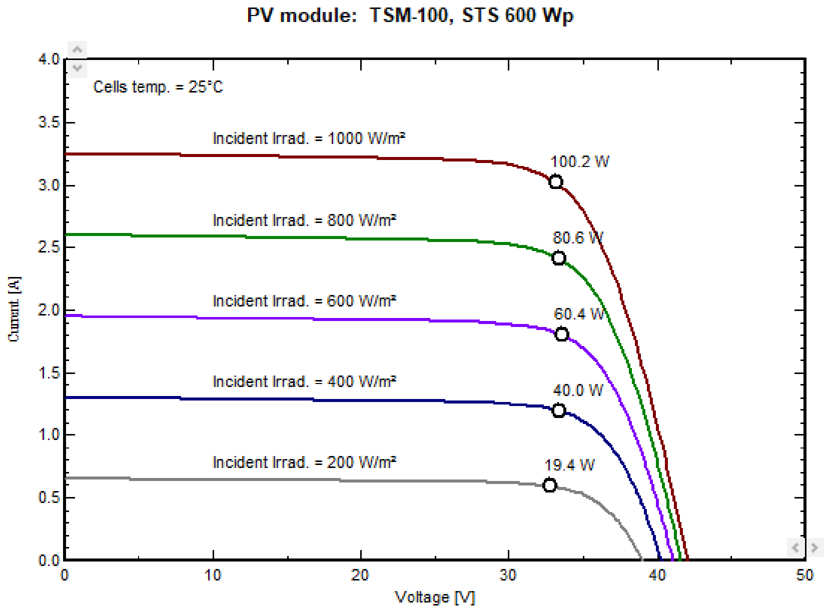

Figure 9. I-V Characteristics Under Different Cell Temperatures at Fixed Irradiance

Figure 8 shows the simulation results the influence of temperature and irradiance on the power characteristics of a 600 Wp PV system. It highlights the relationship between (I_{mp}) and (V_{mp})in a 600 Wp PV module, with temperature variations analyzed under Standard Test Conditions (STC). Figure 9 illustrates the correlation between current and voltage, showing that current output varies proportionally with irradiance levels. Lower irradiance results in reduced current generation, which in turn affects the overall output performance of the PV system.

Discussion

This study was conducted in an open area free from visual obstructions such as trees or buildings, allowing the potential influence of shading on system performance to be considered negligible. Although shading analysis was not explicitly performed using PVsyst software, the site selection process involved direct field observation to ensure full exposure to sunlight throughout the day. In addition, dust accumulation on the surface of the photovoltaic panels was identified as a factor that could impact system efficiency. Based on the AS/NZS 4509.1:2009 guidelines, efficiency losses attributed to dust accumulation are categorized according to the panel surface cleanliness, where correction values range from 1.00 (indicating a clean surface) to 0.92 (representing heavy soiling). In this study, the simulation assumes the panels are in a clean condition with a correction factor of 1.00, thereby excluding the impact of dirt-related performance losses. This assumption allows the analysis to isolate the influence of system configuration and environmental variables under optimal surface conditions.

Based on calculation results, each PV module achieves a maximum voltage (V_{mp}) of 33.6 V, an open circuit voltage (V_{oc}) of 42 V, and a maximum current (V_{mp}) of 2.98 A, resulting in an estimated power output $(P_{mp})$of 100.13 W. When configured with six modules, the system yields a cumulative capacity of approximately 600.78 W. This output is sufficient to power predetermined loads, such as an E-Bike rated at 576 W and gadgets (65 W), indicating the system's practical feasibility. Nevertheless, one limitation of this study lies in the use of static load assumptions, which may not adequately capture fluctuations in real world energy consumption scenarios.

Based on the simulation results generated using PVsyst software, a tilt angle of 15° demonstrated the most favorable performance compared to other tested angles (20°, 25°, and 30°). At 15°, the system received the highest annual solar irradiation, reaching 1912 kWh/m², surpassing all other tilt variations. Additionally, the Solar Fraction (SF) at this angle was recorded at 92.66%, indicating that the system could fulfill nearly all daily load demands using solar energy alone. The Performance Ratio (PR) was also highest at 57.76%, reflecting a more consistent and efficient system output relative to the other configurations. These results collectively support 15° as the optimal tilt angle for maximizing solar energy capture and system efficiency under the given conditions.

Conclusion

This study evaluated the performance of a 600 Wp solar tree system located at coordinates -6.88808° latitude and 107.52422° longitude. The simulation results demonstrate that configuring the system at an 15°, is capable of fulfilling daily energy demands for standard campus applications, including E-Bike (576 W) and Gadget (65 W). Nonetheless, the study is constrained by its limited load profile, which focuses solely on these two specific device categories. The system achieved the highest levels of solar irradiance (1912 kWh/m²), Solar Fraction (92.66%), and Performance Ratio (57.76%), indicating strong suitability for deployment in tropical academic settings. It is important to note that the simulation was conducted under idealized assumptions, excluding the influence of real time weather variations, surface soiling, and fluctuations in energy demand. Future research is encouraged to overcome these limitations by incorporating dynamic environmental parameters, energy storage solutions, and exploring the potential use of excess energy through intelligent system integration or by adapting the system across various regional settings.

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