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The Effect of Photovoltaic Module Tilt Angle on the Power Analysis of the Solar-Powered Seaweed Drying Machine

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Abstract *Solar energy is a renewable energy source that can serve as an alternative for electricity generation. Indonesia, as a tropical country, possesses significant solar energy potential and is also an archipelagic nation rich in marine resources. One of these resources is seaweed, a multifunctional marine product that requires drying. A seaweed drying machine utilizes solar panel energy as its power source, enabling an efficient and effective drying process under various weather conditions. The research method employed involved a series of calculations followed by data analysis derived from the results, along with literature review, discussion, and field observation. The analysis was conducted using a 20 Wp solar panel with tilt angle variations of 0°, 15°, and 30°, oriented southward. The experiment was carried out over a 9-hour period each day, from 07:00 to 15:00 local time (WIB), spanning from January 15 to March 8, 2024. The results demonstrate that the highest power efficiency was achieved with a photovoltaic module tilt angle of 15°, reaching 99.47%, with an average output power (Pout) of 4.53 Watts.*

Keywords *Photovoltaic module tilt angle comparison, solar panel dryer, power calculation.*

INTRODUCTION

Indonesia is an archipelagic country endowed with abundant marine resources. One of these marine commodities that can be processed through drying is seaweed. Seaweed holds substantial economic value due to its versatility; it can be processed into a variety of food products such as agar and dried seaweed, as well as serve as a raw material in non-food industries, including pharmaceuticals and cosmetics. In 2022, Southeast Sulawesi alone produced approximately 3,951 tons of dried seaweed, which was subsequently distributed across various food and non-food industries (Sutrisno n.d.).

Drying is a method used to remove or eliminate a significant amount of water from a material through the application of thermal energy (Cahyani 2011). It is also one of the oldest methods of food preservation. The drying process is carried out until the moisture content of the material reaches an equilibrium with the surrounding environment, thereby inhibiting the activity of mold, enzymes, microorganisms, and insects that could otherwise cause spoilage (Noviani 2019).

However, the drying process is relatively time-consuming and highly dependent on natural conditions. Conventional drying methods rely heavily on solar exposure. In the

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event of rainfall or during nighttime when there is no sunlight, drying cannot be performed, which hinders subsequent processing stages.

Typically, seaweed drying is carried out by spreading the seaweed in an open field and exposing it to direct sunlight, a process that generally takes about three to four days. To improve the efficiency of this process, a cost-effective drying device that operates independently of weather conditions is required (Khansa 2021)ka. This is made possible through the use of a solar-powered drying machine. Solar energy utilization is one of the most accessible and promising innovations in the field of renewable energy.

The Indonesian Ministry of Energy and Mineral Resources (ESDM) continues to promote the adoption of renewable energy among communities and industry players, including the utilization of photovoltaic solar energy systems (PLTS). This effort aligns with the national target of achieving a 23% share of renewable energy in the national energy mix by 2025 (Cahyadi, Anam, and Effendy 2023). Indonesia is an archipelagic country endowed with abundant marine resources. One of these marine commodities that can be processed through drying is seaweed. Seaweed holds substantial economic value due to its versatility; it can be processed into a variety of food products such as agar and dried seaweed, as well as serve as a raw material in non-food industries, including pharmaceuticals and cosmetics. In 2022, Southeast Sulawesi alone produced approximately 3,951 tons of dried seaweed, which was subsequently distributed across various food and non-food industries (Sutrisno n.d.).

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Sunlight can be converted into electrical energy through photovoltaic (PV) modules, which are composed of semiconductor materials. Semiconductors are semi-metallic substances characterized by the presence of charge carriers electrons and protons that, when energized by an external energy source, can release electrons, thereby generating electric current and creating electron-hole pairs (Hasan 2012).

Photovoltaic modules are capable of absorbing sunlight, which contains electromagnetic waves or photon energy. The photon energy in sunlight imparts kinetic energy to electrons, enabling them to escape into the conduction band, which in turn generates electric current. This kinetic energy increases proportionally with the intensity of sunlight. The highest intensity of solar radiation received by Earth occurs during midday, when solar energy production can reach approximately 120,000 terawatts (Hasan 2012).

Photovoltaic modules come in various types, each designed to meet specific installation needs. Different PV module types exhibit distinct characteristics. The following outlines one of the primary types of photovoltaic modules:

Monocrystalline panels represent the most efficient PV technology available, offering the highest power output per unit area. These panels are specifically designed for applications requiring high electricity consumption, particularly in locations with extreme climates and harsh environmental conditions. Monocrystalline modules can achieve efficiencies of up to 15%. However, a significant drawback of this type is its reduced performance under shaded conditions or during overcast weather, where efficiency may decrease substantially (Tarigan 2020).

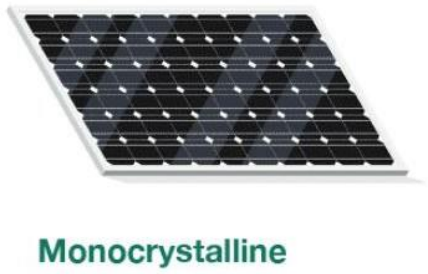

Figure 1 Monocrystalline Photovoltaic Module (Ekayana 2016)

Sunlight can be converted into electrical energy through photovoltaic (PV) modules composed of semiconductor materials. Semiconductors are semi-metallic materials characterized by particles known as electrons and protons. When energized by an external energy source, these particles release electrons, resulting in an electric current and the formation of electron-hole pairs (Hasan 2012).

The polycrystalline photovoltaic module is fabricated through a casting process, resulting in randomly arranged crystals. This type requires a larger surface area than monocrystalline modules to produce the same amount of electrical energy. Consequently, polycrystalline modules tend to have lower efficiency and are generally more affordable (Saputra 2021).

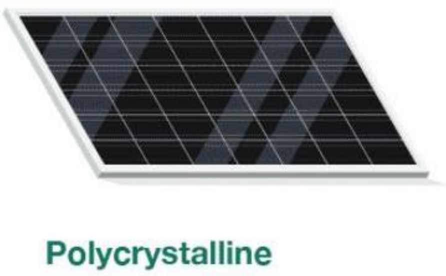

Figure 2 Polycrystalline Photovoltaic Module (Ekayana 2016)

The thin-film photovoltaic module consists of two layers: a microcrystalline silicon layer and an amorphous layer. This configuration provides a module efficiency of up to 8.5%. However, to generate the same wattage as monocrystalline or polycrystalline modules, a larger surface area is required. The latest innovation in this category is the

Thin-Film Triple Junction Photovoltaic, which utilizes three layers and performs efficiently under heavily overcast conditions, producing up to 45% more electrical energy compared to other module types with equivalent rated power (Purwoto et al. 2018).

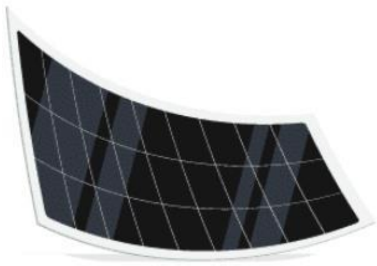

Figure 3 Thin Film Photovoltaic Module (Ekayana 2016)

In designing photovoltaic (PV) systems, several critical parameters must be calculated to ensure the system functions efficiently and effectively. These include determining the fill factor, calculating input power (Pin) and output power (Pout), solar cell module efficiency, and the total daily load demand (Hasrul 2021).

The fill factor is one of the essential parameters for improving solar panel efficiency and is calculated using Equation (2.1) (Hasrul 2021). Power calculation is a universal metric for evaluating the maximum performance of a solar cell. Power is derived by multiplying the PV surface area with the solar irradiance received. Battery capacity can be estimated using Equation (Hasrul 2021).

$$FF = \frac{V_{mp}\ x\ I_{mp}}{V_{oc}\ x\ I_{oc}}$$

FF : *Fill Factor*
Vmp : Tegangan maksimum (Volt)
Imp : Arus maksimum (Ampere)
Voc : Tegangan *open circuit* (Volt)
Isc : Arus *source circuit* (Ampere)

The output power (Pout) generated by a solar panel is calculated by multiplying the open-circuit voltage (Voc), open-circuit current (Ioc), and fill factor (FF). This is expressed in Equation (Hasrul 2021).

$$P_{in} = V_{OC} \; x \; I_{SC}$$

P_{in} : Input power due to solar irradiance (Watt)

V_{OC} : Open Circuit Voltage (Volt)

I_{SC} : Short Circuit Current (Ampere)

The solar cell module efficiency is the ratio of the output power (Pout) to the input power (Pin) derived from solar irradiance, multiplied by 100% to express it as a percentage. Once Pin and Pout values are obtained, efficiency can be calculated using Equation (Hasrul 2021).

$$P_{out} = V_{mp} \; x \; I_{mp} \; x \; FF$$

P_{out} : Power output generated by the solar panel (Watt)

V_{mp} : Maximum Voltage (Volt)

I_{mp} : Maximum Current (Ampere)

FF : *Fill Factor*

$$\eta = \frac{P_{out}}{P_{in}} \; x \; 100\%$$

η : Maximum Efficiency

P_{out} : Power output generated by the solar panel (Watt)

P_{in} : Input power due to solar irradiance (Watt)

To ensure optimal system design, it is crucial to determine the maximum daily load consumed by the solar-powered seaweed drying machine. The total daily load requirement can be estimated using Equation (Hasan 2012).

$$\text{Energy Consumption Load } (Wh) = P \; x \text{ Time}$$

P : Power required to operate all components of the drying machine (Watt).

Solar energy is a clean and abundant resource, especially in equatorial regions such as Indonesia, and is freely available. To address unpredictable weather conditions, solar drying systems are often supplemented with heat generated from biomass combustion (Hasrul 2021). A solar dryer is a drying device specifically designed to harness solar energy. This differs from a sun dryer, which involves direct sun exposure in open air. Solar dryers are classified based on their method of solar radiation utilization, the use of auxiliary devices, and the types of products being dried (Saputra 2021). Solar dryers can be categorized into several types based on:

1. Heat transfer method:
   - Direct-type: solar radiation directly heats the drying material.
   - Indirect-type: solar radiation heats the air, which is then used to dry the material.
   - Hybrid-type: combines both direct and indirect methods.
2. Use of auxiliary devices:
   - Active-type: incorporates mechanical components such as fans or blowers.
   - Passive-type: relies solely on natural convection without mechanical assistance.
3. Type of product dried:
   - Single-product dryers
   - Multi-product dryers

Solar dryers operate by collecting and transferring solar heat into a drying chamber where the materials are placed. In the chamber, heated air circulates through the material, evaporating moisture and discharging it from the system, thereby accelerating and improving the drying process.

In direct-type dryers, solar radiation directly contacts the material. In indirect-type dryers, solar radiation is used to heat air that is then directed to the material. Hybrid dryers combine both mechanisms. Active dryers use mechanical aids such as fans or blowers, while passive dryers rely on natural air circulation (Khansa 2021).

Several factors influence the power efficiency of a solar dryer, including solar irradiance, solar panel orientation, and installation location. Power output is determined by the product of current and voltage, both of which are affected by light intensity. The performance of a solar panel depends on the amount of sunlight absorbed, as its electricity-generating ability is influenced by solar intensity. As a result, the surface temperature of the panel increases over time, impacting the panel junction and overall power generation, which depends on how much solar radiation and photons are absorbed.

Solar panel efficiency becomes unstable when there are fluctuations in input power (Pin). This implies that efficiency is not solely dependent on Pin but is also affected by factors such as panel layout and tilt angle. The daily movement of the sun from east to west presents a challenge in optimizing output power (Pout), as fixed panels may not effectively capture sunlight throughout the day. Therefore, performance efficiency is closely tied to solar intensity and the timing of sunlight availability. Additionally, altitude plays a role, as higher elevations may receive reduced solar intensity, further affecting panel performance.

METHODS

This study adopts an applied quantitative approach that integrates experimental measurement, system design, and theoretical computation to evaluate the performance of a photovoltaic-powered solar dryer for seaweed. The methodology is structured into several stages: literature review, system design, data acquisition, power analysis, and performance evaluation.

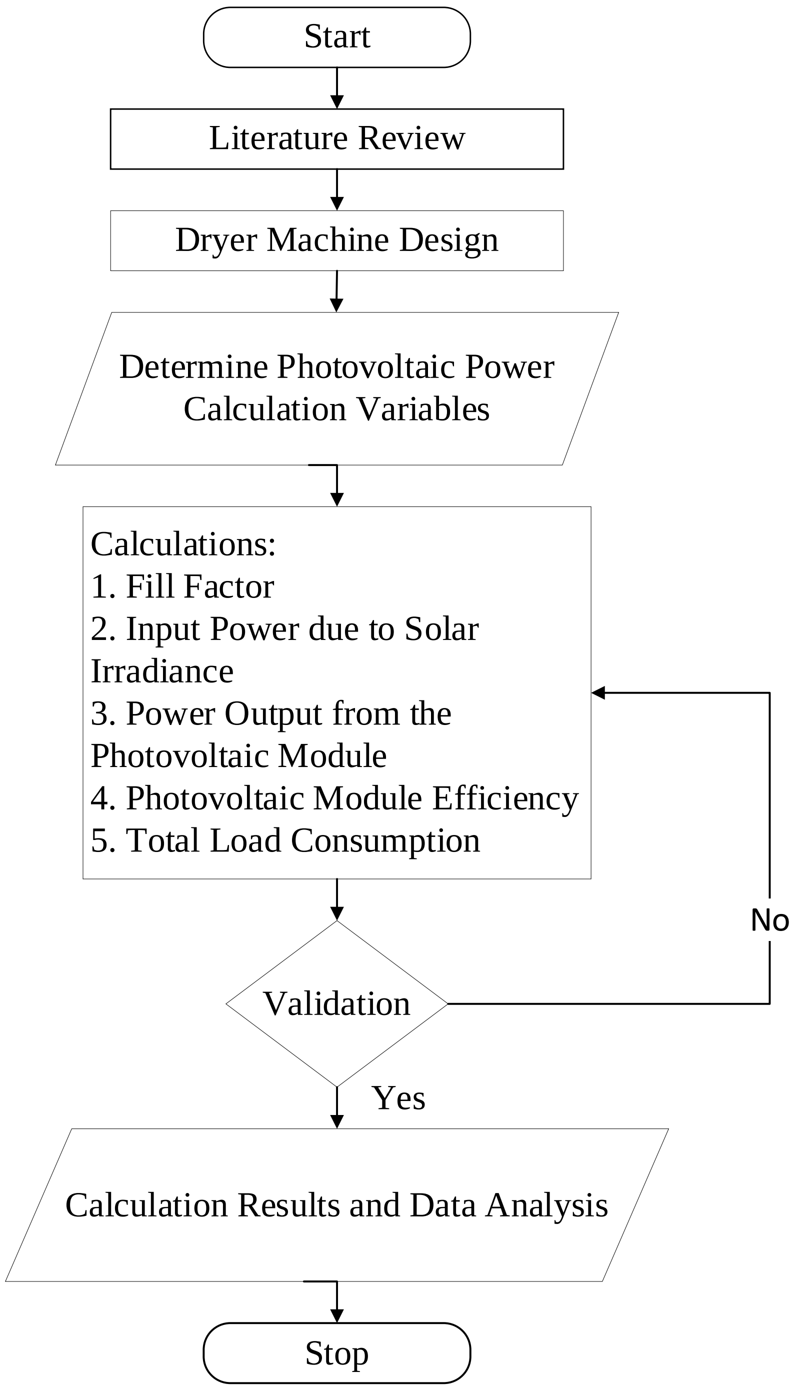

Figure 4 Flow Diagram of Photovoltaic Module Power Calculation Process

The research followed an applied engineering design methodology involving prototype development, mathematical modeling, and empirical validation. The primary goal was to assess the electrical performance of a PV system under varying tilt angles (0°, 15°, and 30°) in powering a seaweed drying machine. Data were gathered through a combination of literature review, direct measurement, and simulation. Primary data included solar irradiance and electrical output measurements from a 20 Wp PV module. Observations were conducted daily from 07:00 to 15:00 (WIB), over the period of January 15 to March 8, 2024. The tools used include a multimeter, lux meter, and recording instruments integrated into the PV system.

The solar dryer was designed using SolidWorks 2022, consisting of key components such as a drying rack, intake and exhaust fans, heating element, and a control panel. The PV system included a 20 Wp solar panel, a 9 Ah battery, 20A solar charge controller, 150W inverter, and associated electrical protections (MCB).

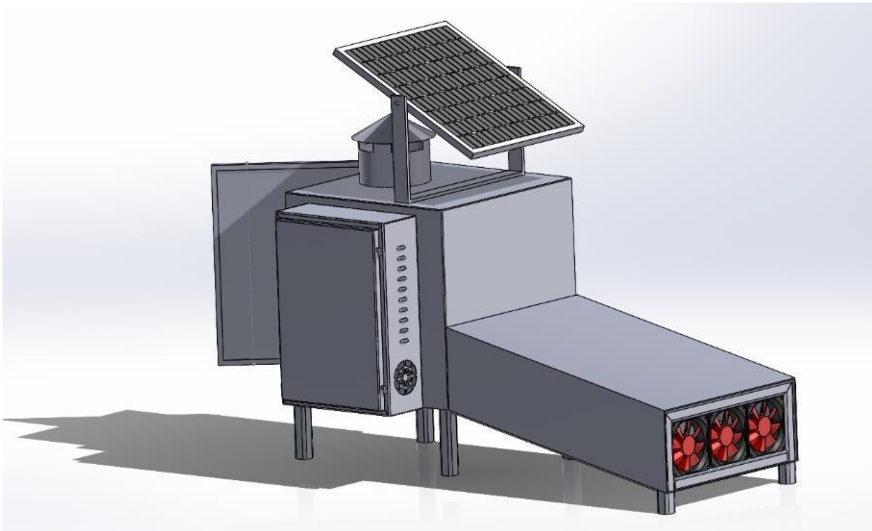

Figure 5 Prototype Design of Solar-Powered Seaweed Drying Machine

Analytical calculations were conducted to determine electrical parameters including power output and system efficiency. The Origin software was utilized for plotting and visualizing data trends. Graphic representations were generated based on structured data tables derived from measurement and computation.

This section presents the electrical schematic design for the photovoltaic (PV) system, which will be utilized as the primary energy source for the seaweed drying machine. The schematic includes key components such as the photovoltaic modules, a solar charge controller, an inverter, a battery/accumulator, electrical outlets, and a circuit breaker panel. These components are interconnected to supply power to the machine's electronic components, including the fan and heating elements. The solar charge controller regulates the power flow from the PV modules to the battery, ensuring efficient energy storage, while the inverter converts the stored DC power into AC power for the operation of the machine. The battery/accumulator stores excess energy for use during periods of low sunlight, enabling continuous machine operation. The circuit breaker panel ensures safety by protecting the system from potential overloads, and the electrical outlets allow for the connection of the drying machine's essential components.

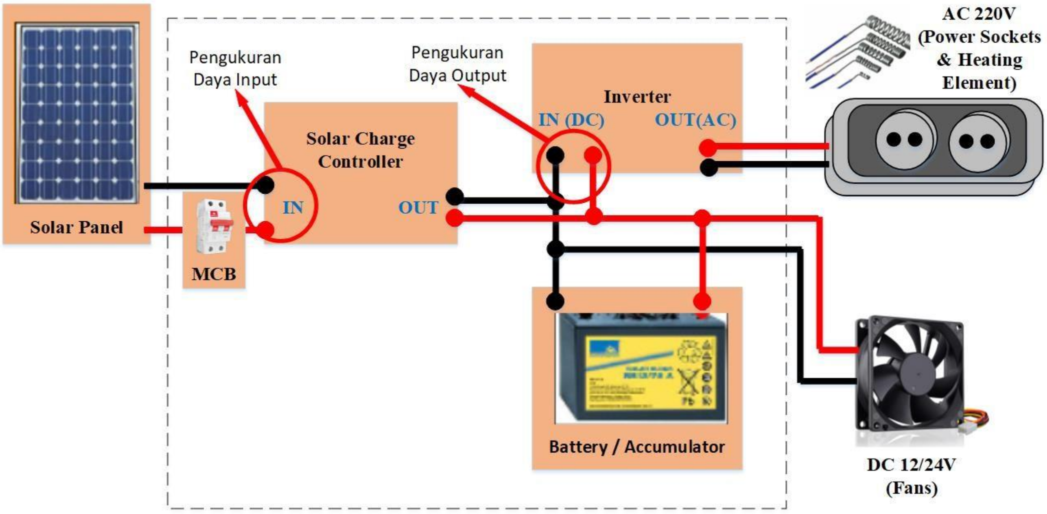

Figure 6 Photovoltaic Module Electrical Schematic

Graphical representation is a widely used method for data presentation, as it provides an easily interpretable format capable of displaying multiple variables simultaneously. In this study, graphs will be generated using the data analysis and plotting software, Origin (Saputra 2021). Origin is a versatile data analysis and graphing software employed across various fields, including commercial industries, academia, and government laboratories. One of its key features is the ability to automatically update graphs and analysis results in response to changes in data or parameters, making it particularly useful for repetitive tasks and batch operations via its user interface, without the need for programming. Furthermore, Origin supports integration with other applications such as MATLAB™, LabVIEW™, and Microsoft® Excel, and allows for custom routines through scripting with embedded C, Python, or R languages (Cahyadi, Anam, and Effendy 2023).

RESULTS

The calculation process for the electrical performance of a photovoltaic module requires several variables obtained from observations and previous research. These observed variables include observation time, module temperature, Voc, Isc, Vmp, and

Imp.

The observational data for this study were obtained using a photovoltaic module with a peak watt (Wp) rating of 20Wp, located at coordinates -6.34609, 106.85345. The data collection took place between 07:00 and 15:00 WIB, under typical weather conditions that ranged from clear to partly cloudy. This time frame was chosen to capture the diurnal performance of the photovoltaic module in various sunlight conditions. The results of the data collection, as presented in the following daily graph, provide crucial insights into the performance of the module under local weather conditions.

The findings indicate that the photovoltaic system exhibited notable variations in energy output, corresponding with changes in solar irradiance, cloud cover, and the angle of incidence throughout the day. These results significantly contribute to the understanding of how environmental factors such as weather and sunlight intensity influence the efficiency of photovoltaic systems in real-world conditions. Furthermore, the findings align with previous studies that have investigated the impact of local climate conditions on solar energy generation, yet offer new insights into the specific effects of intermittent cloud cover on power output, particularly in the tropical region.

In comparison to earlier research, which primarily focused on ideal conditions, this study expands the current understanding by examining how variable cloud conditions throughout the day can cause fluctuations in photovoltaic performance. The graphical representation of the daily data, as shown in the following figure, highlights these variations and offers a more nuanced perspective on optimizing the performance of photovoltaic systems in regions with variable weather patterns. The results underscore the need for further investigation into adaptive systems and technologies that can mitigate the effects of fluctuating environmental factors on solar power generation.

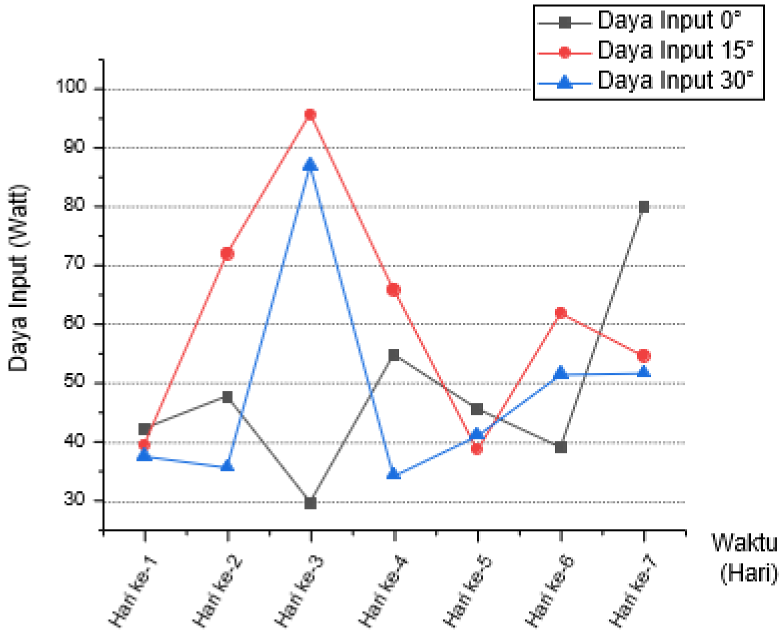

Figure 7 Graph of Total Daily Input Power of Solar Panel at Angles 0°, 15°, and 30°.

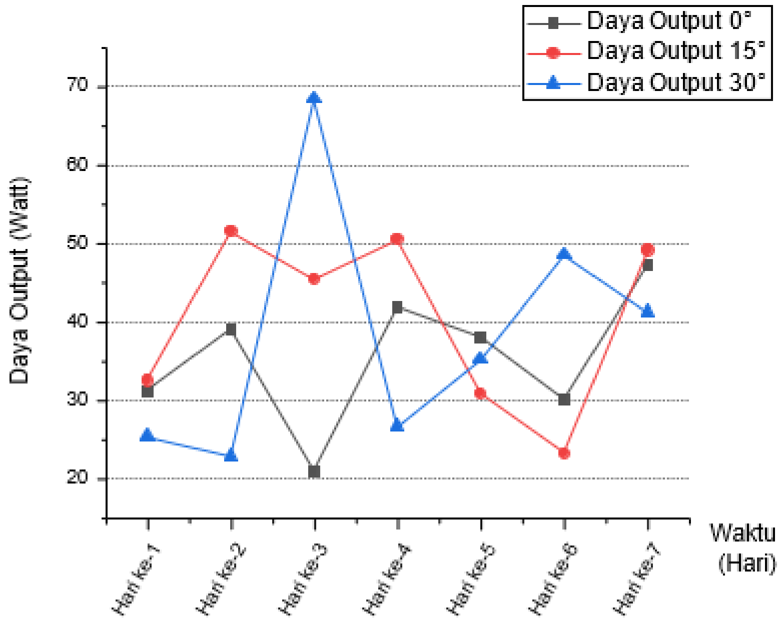

Figure 8 Graph of Total Daily Output Power of Solar Panel at Angles 0°, 15°, and 30°

The electrical energy generated and accumulated by the photovoltaic module is utilized to power the solar-powered seaweed drying machine. Based on the calculations performed, it has been identified that during the 9-hour operation of the solar module from 07:00 to 15:00 WIB, the average output power over a 7-day period (one week) for tilt angles of 0°, 15°, and 30° were 3.95, 4.5, and 4.26 Watts, respectively. This data provides key insights into the performance of the photovoltaic system at different tilt angles, highlighting the influence of angle optimization on the energy generation efficiency of solar modules. The findings indicate that a tilt angle of 15° provides the highest average output, suggesting that this angle may be optimal for solar energy capture under the local climatic conditions observed during this study.

DISCUSSION

In terms of the energy consumption of the seaweed drying machine, the total power load required is 66 Watts per hour, with 16 Watts allocated for the intake and exhaust fan, and 50 Watts required to power the heating element. Despite the fact that the energy required by the machine exceeds the average energy output of the photovoltaic system, the peak output of the module can reach up to 150 Watts, depending on the inverter capacity used in the photovoltaic electrical system. This peak power capacity indicates that the system can provide sufficient energy during periods of high solar irradiance, ensuring uninterrupted operation of the seaweed drying machine.

These findings significantly contribute to the understanding of photovoltaic system performance in real-world applications, particularly in relation to energy generation efficiency at different tilt angles and the challenges of meeting the energy demands of low-power industrial applications, such as seaweed drying. The results are consistent with previous studies that have explored the impact of module tilt angles on energy output, but they extend the knowledge by quantifying the actual energy production over a week and comparing it against the operational energy requirements of a specific application. Furthermore, the capacity of the photovoltaic system to supply peak power during sunlight peaks underscores the potential for integrating solar power in small-scale industrial operations. These insights are relevant for future studies aimed at optimizing solar energy systems for similar applications, especially in regions with fluctuating solar radiation and varying energy demands.

CONCLUSION

After designing and calculating the photovoltaic-based electrical system for the seaweed drying machine, The electrical system of the solar-powered seaweed drying machine consists of a photovoltaic module, an MCB (Miniature Circuit Breaker), a solar charge controller (SCC), an inverter, and a battery. The output components in this system include the intake and exhaust fans (12 V DC) as well as a heating element and a power outlet (220 V AC). The photovoltaic module was tested at the coordinates -6.34609, 106.85345 with tilt angles of 0°, 15°, and 30°, from 07:00 to 15:00 WIB. The highest efficiency was achieved at a 15° tilt at 12:00, with a power efficiency of 99.47%, an input power (Pin) of 7.53 W, and an output power (Pout) of 7.49 W. The photovoltaic module used in this study is rated at 20 Wp (Watt-peak). At tilt angles of 0°, 15°, and 30°, the module produced an average output power (Pout) over seven days of 3.95 W, 4.53 W, and 4.26 W, respectively. The corresponding average power efficiencies for these tilt angles were 71.83%, 72.53%, and 70.75%, respectively. The total power load of the seaweed dryer components is about 66 W, which corresponds to approximately 594 Wh over a 9-hour operating period. Even though the total daily output (Pout) at a 15° tilt the angle with the highest efficiency in testing was only 51.55 W, the photovoltaic module was still able to power the components. This is because the system can provide up to 150 W of electrical power at a time, according to the capacity of the inverter used.

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