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Design of an Off-Grid Solar PV System for a Renewable Energy-Based Home in Bengkulu

Reza Satria Rinaldi[1]*, Afriyastuti Herawati[1], Ika Novia Anggraini[1], Helmizar[2]

ABSTRACT

Bengkulu Province has a solar energy potential of 3,475 MW, with an average daily solar irradiance duration of 5.9 hours in 2022 and 8.3 hours in 2023. This study designs an off-grid solar PV system for a renewable energy-based home (REH) model in the coastal area of Bengkulu City. The REH is a home with electrical energy independence that utilizes renewable energy systems to generate electricity. This study focuses on the REH powered by solar energy, intended for a modest home with a power capacity equivalent to a 900 VA PLN customer classification. The data on solar energy potential in the coastal area of Bengkulu City used in this study is from the Global Solar Atlas. The data analysis confirmed the need for the REH model to generate electricity from solar energy, requiring 12 units of 120Wp PV modules in a PV array. An appropriate solar charge controller for this REH model is the MPPT SCC with a rating of 48 V 30 A. Based on the selected PV modules and the daily load of the REH model, the required 48 V battery capacity is 300 Ah, and the PSW Inverter 2,000 VA 48 V.

Keywords
Off-grid solar PV system, renewable energy-based home, PV module, Bengkulu

[1] Electrical Engineering, Faculty of Engineering, University of Bengkulu
Jl. W. R. Supratman Kandang Limun, Kecamatan Muara Bangkahulu, Kota Bengkulu, Bengkulu, Indonesia
[2] Mechanical Engineering, Faculty of Engineering, University of Bengkulu
Jl. W. R. Supratman Kandang Limun, Kecamatan Muara Bangkahulu, Kota Bengkulu, Bengkulu, Indonesia
* Corresponding Author: reza_s_r@unib.ac.id

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INTRODUCTION

There is abundant solar energy potential in countries near the equator, including Indonesia. However, most of the region still relies on fossil fuel power generation, which is environmentally detrimental and economically inefficient. Off-grid photovoltaic (PV) solar systems present a viable alternative, offering clean, self-sufficient, and cost-effective solutions for expanding energy access Off-grid photovoltaic (PV) solar systems present a viable alternative, offering clean, self-sufficient, and cost-effective solutions for expanding energy access [1][2][3][4][5].

The growing relevance of solar energy as an alternative electricity source reflects a global response to mounting challenges, such as dependency on fossil fuels and the rising cost of conventional energy. As a clean and renewable resource, solar energy holds significant potential to reduce household electricity costs, particularly in tropical countries like Indonesia. Its optimization within the domestic sector is crucial for enhancing national energy efficiency and advancing broader sustainability objectives [6].

Empirical studies from countries such as Kenya further reinforce the benefits of off-grid solar PV systems, including extended lighting hours, reduced reliance on polluting fuels, lower energy expenditures, and increased user satisfaction [7][8][9][10]. These outcomes highlight the viability of decentralized solar energy solutions in addressing energy poverty across developing regions.

In Indonesia, PV solar energy has been recognized as a renewable energy source with exceptional technical, environmental, and economic potential, surpassing other renewable alternatives. Comprehensive assessments suggest that Indonesia's solar energy capacity far exceeds its current and projected energy demands. With increasingly competitive system costs, PV technology represents a viable and strategic solution to support the nation's energy transition and to ensure long-term energy security [11].

However, most previous studies in Indonesia have focused more on technical aspects and general energy potential, with few specifically examining off-grid PV system designs tailored to the characteristics of renewable energy-based home (REH), particularly in coastal areas like Bengkulu. This research gap is crucial to fill given the differences in microclimates, household energy consumption patterns, and unique geographic conditions in these areas, which necessitate more contextually relevant and practical energy system solutions.

In this context, the Province of Bengkulu is notable for its abundant solar energy resources. Aligned with its regional vision for energy resilience and independence, Bengkulu has an estimated solar power potential of 3,475 MW. In 2022, the region recorded an average of 5.9 daily peak sun hours, which increased to 8.3 hours in 2023, indicating a favorable trend for solar energy utilization [12][13].

Bengkulu City has a significant solar energy potential that can be utilized as a renewable energy source. Geographically, as part of Bengkulu Province, the city is located between 3°45' and 3°59' South Latitude and 102°14' to 102°22' East Longitude, stretching along the western coast of Sumatra Island and directly bordering the Indian Ocean to the west. In 2023, it was recorded that the average air temperature in Bengkulu City reached 28.3°C, with the lowest temperature of 19.8°C and the highest of 35.5°C [14]. A study conducted in Suka Merindu Subdistrict, Sungai Serut District, reported that the average peak solar irradiation period reaches approximately five hours daily, typically between 10:00 AM and 3:00 PM local time [15]. The existing potential makes Bengkulu City the right location for applying off-grid solar PV systems for modest home scales.

In this context, the REH concept emerged as an innovative model that integrates off-grid PV systems with technically and geographically tailored home designs. REH not only provides a self-sufficient electricity source but also facilitates the wider adoption of renewable energy technologies in rural and coastal areas, which are often inaccessible to the main electricity grid. This model can increase energy independence, lower household operating costs, and strengthen local environmental resilience.

The objective of this research is to design an off-grid solar PV system tailored to the energy needs of a modest, renewable energy-based home in Bengkulu City. The uniqueness of this research lies in the use of the latest local solar data and the integration of the off-grid PV system design with a miniature REH model developed based on the technical and geographical characteristics of the area. Thus, this research provides a practical and contextually relevant initial reference for household-scale applications in coastal areas, while filling a research gap that has not been widely addressed in Indonesia regarding off-grid systems combined with the REH concept.

Off-Grid Solar PV System and Its Main Components

An off-grid solar PV system is a standalone solar power generation system that consists of several main components, such as PV modules, solar charge controllers (SCCs), energy storage batteries, and inverters. This system converts sunlight into electricity through PV modules installed in an open area. The electricity generated is directed to a storage system, usually in the form of batteries, for later use when needed [16].

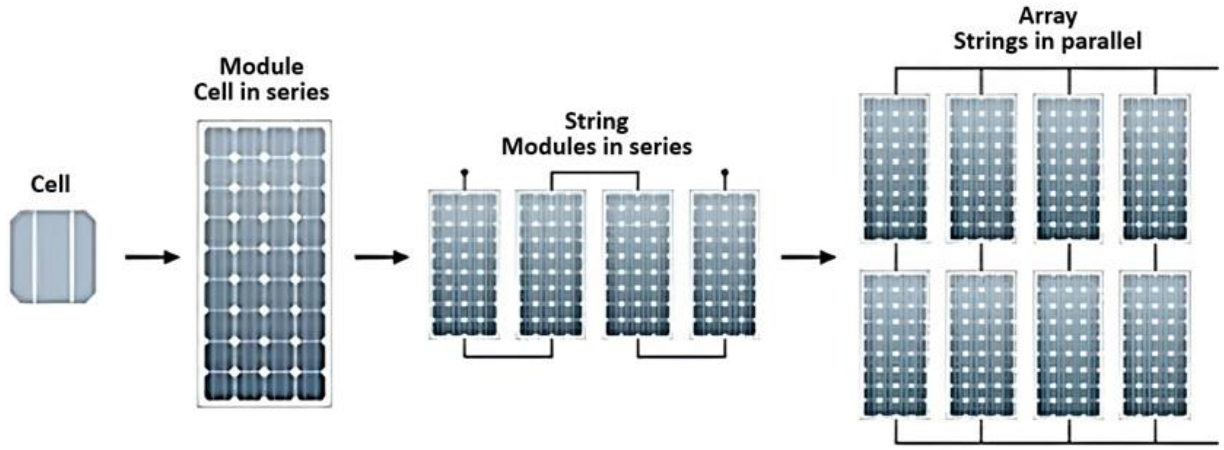

Figure 1. PV Technology Taxonomy [17]

Figure 1 shows the taxonomy of PV technology. The PV cell is the fundamental unit that converts solar energy into electricity. A PV module consists of some PV cells connected in a circuit. A PV string is a set of PV modules installed sequentially or in series within a single frame or structural unit. The size of a PV array can vary from a few modules to thousands, arranged in series and/or parallel configurations, depending on energy requirements [17].

In off-grid solar systems, PV modules are available in various sizes, technologies, power ratings, and operating voltages. PV modules typically come in nominal voltages of 12V, 24V, and 30V. The current and voltage of PV modules can vary depending on the intensity of solar radiation received and the operating temperature of the module [16]. There are two common types of PV modules: polycrystalline and monocrystalline. Polycrystalline modules use less pure silicon material, whereas monocrystalline modules use pure silicon crystal material. With the same capacity, monocrystalline PV modules deliver higher electrical power than polycrystalline PV modules. Additionally, monocrystalline modules have higher efficiency than polycrystalline modules, with a difference of up to 1%-2% [18][19][20].

A solar charge controller (SCC) regulates the current flow from PV modules to the battery, protecting it from overcharging or deep discharging that can damage the battery. SCCs are equipped with low-voltage disconnect (LVD) and high-voltage disconnect (HVD) features to prevent both damage [16]. Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT) are common SCC technologies. PWM controllers regulate battery charging by adjusting the pulse width using wider pulses when the battery is low to charge more quickly and narrower pulses as the battery approaches full capacity to avoid overcharging. In contrast, MPPT controllers optimize the voltage and current to match the battery's requirements, even when the PV module's voltage is higher than the battery voltage [21].

MPPT technology offers better performance. It enables more efficient battery charging compared to PWM controllers [21][22][23][24]. Studies have shown that MPPT controllers are more efficient than PWM types. Moreover, MPPT technology provides higher power yield and more stable voltage and current output [23][24]. However, at high temperatures, the performance of the MPPT controller gradually decreases as cell temperature increases. The efficiency offered by the MPPT decreases significantly when the cell temperature reaches 52°C, until its performance is equivalent to a PWM controller [25]. Selecting the appropriate SCC technology, particularly MPPT, can significantly improve power conversion efficiency and extend the overall lifespan of the off-grid solar PV system [26].

The batteries recommended for solar PV systems are generally deep-cycle, designed to provide continuous power over extended periods and capable of undergoing repeated charge and discharge cycles. The most commonly used battery type in such applications is the lead-acid battery. It is available in various voltage ratings: 2V, 6V, and 12V. It's typically in hard plastic casings. Based on their construction characteristics, lead-acid batteries are categorized into several types. Sealed maintenance-free lead-acid batteries, also known as Valve Regulated Lead-Acid (VRLA) batteries, are gaining popularity due to their low maintenance requirements and the ability to deliver more stable and reliable operational performance. It's generally used in off-grid solar PV systems [16].

In Indonesia, various types of batteries are available for solar applications, including VRLA Gel, VRLA AGM, and lithium-ion technology, with capacities ranging from 1 to 3,000 Ah [27]. Battery quality greatly influences system efficiency, with determinant factors such as capacity, battery life, and durability during charge and discharge cycles [28]. Proper battery use is critical to maintaining the continuity of the power supply and increasing the efficiency of an off-grid solar PV system's overall durability [29].

Inverters are crucial power conditioning units in standalone PV systems, especially for applications with alternating current (AC) loads. In off-grid solar PV systems, inverters must provide stable and high-quality power for a long time, even decades, without experiencing failure. To support the operation of reactive loads and sensitive loads simultaneously, inverters must be able to produce surge power that far exceeds their nominal capacity [16]. Typically, standalone inverters operate at DC input voltages of 12V, 24V, 48V, or 120V and can produce AC output voltages of 120V or 240V at frequencies of 50/60 Hz. Based on their output waveform characteristics, classification inverters are square wave inverters, modified sine wave inverters, and pure sine wave inverters. For off-grid PV systems, the recommended inverter is a pure sine wave inverter. It is because of their ability to support sensitive electronic equipment efficiently [16].

Design of an Off-Grid Solar PV System

The initial stage in designing an off-grid solar PV system is a site survey, which includes identifying existing loads, their operational duration per day, and local climate data such as solar irradiance and temperature. Solar irradiance values are available by accessing data from meteorological sources for the system installation location. The data is in the form of daily or monthly average Global Horizontal Irradiation (GHI) adjusted for geographic position (latitude and longitude). The capacity and specifications of the main components such as PV modules, batteries, charge controllers, and inverters can be determined based on load and irradiance data [16].

The daily energy requirements estimate is the basis for determining the capacity of the PV module array. This estimation must take into account the load diversity factor as well as the estimated daily operating duration of each load. All equipment or loads, along with their wattage, operating hours, and daily energy consumption, are listed. The total daily energy requirement in watt-hours ($E_{Wh,\,d}$) can be obtained by summing up all equipment energy requirements. Equation (1) shows that the daily energy requirement in ampere-hours ($E_{Ah,d}$) can be determined by dividing the total daily energy consumption $E_{Wh,d}$ by the system's DC voltage (V_{DC}), which is essential for calculating the total current needed per day or determining the required capacity of the PV module array [16].

$$E_{Ah,d} = \frac{E_{Ah,d}}{V_{Dc}} \quad (1)$$

The selection of the VDC plays a crucial role in determining the configuration and sizing of key system components, including the charge controller, battery, and inverter. The operating voltage range of the inverter and controller, and the total capacity of the available PV module array, determine the value of the system DC voltage. The system DC voltage for various solar array capacities is shown in Table 1 [16].

Table 1. System Voltage For Different Loads [16]

System DC Voltage (V)	PV Module Array Capacity (Wp)	Load (W)
6.0	<10.0	2-3
12.0	11-100	10
24.0	101-1,000	100
48.0	1,001-5,000	1,000
96.0	5,001-10,000	2,500
120.0	10,001-15,000	5,000
>120.0	>15,000	>5,000

Using equation (2), the capacity requirement of the PV module array (C_{array}) is obtained by dividing $E_{Ah,d}$ by the total system efficiency, which is the result of multiplying the efficiency of the main component, namely the efficiency of the charge controller (η_{cc}), battery efficiency (η_{bat}), and efficiency due to the battery discharge process (η_{dis}). In the design, the values of η_{cc}, η_{bat}, and η_{dis} can be taken respectively as 95%, 93%, and 99.5% [16].

$$C_{array} = \frac{E_{Ah,d}}{\eta_{cc} \cdot \eta_{bat} \cdot \eta_{dis}} \tag{2}$$

Each PV module has key electrical parameters such as short circuit current (I_{sc}), open circuit voltage (V_{oc}), maximum power voltage (V_{mp}), and maximum power current (I_{mp}). The end-of-life (EoL) V_{mp} of the module (EoL V_{mp}) obtain by considering several factors, namely the V_{mp} degradation factor (F_{Vmp}) of 15% for 25 years, the voltage temperature coefficient (β), the module temperature (T_{mod}) at the highest air temperature ($T_{a,max}$) at the location, and the STC (Standard Test Conditions) temperature (T_{STC}). By calculating $T_{a,max}$, GHI irradiation in W/m2 (S_G), and the difference between NOCT (Nominal Operating Cell Temperature) and STC temperatures (**Δ**T), T_{mod} was the result. The NOCT temperature is usually 45 °C, so the **Δ**T value is 20 °C. Equations (3)-(5) are solutions for these calculations [16][30].

$$\eta_{Vmp} = 1 - F_{Vmp} \tag{3}$$

$$\text{EoL } V_{mp} = (V_{mp} \cdot \eta_{Vmp}) + \beta \cdot (T_{mod} - T_{STC}) \tag{4}$$

$$T_{mod} = T_{a,max} + \left(\frac{S_G}{800\ W/m^2} \cdot \Delta T\right) \tag{5}$$

The I_{mp} of the PV module also changes due to the influence of temperature and various other loss factors. Although I_{mp} tends to increase slightly with increasing temperature, the actual value must be adjusted for multiple system loss factors, such as losses due to dirt (L_d), cables (L_c), mismatch between modules (L_m), and non-ideal array orientation (L_o), each of which is 2%, and long-term degradation (L_d) of 8% for 20 years of use. Equation (7) produces the I_{mp} at the end of service life (EoL I_{mp}) of the PV module after adjusting for the current temperature coefficient (α) and various loss factors [16][30].

ηImp= 1−Ld1−Lc1−Lm1−Lo1−Ld

$$\eta_{Imp} = (1 - L_d) \cdot (1 - L_c) \cdot (1 - L_m) \cdot (1 - L_o) \cdot (1 - L_d) \tag{6}$$

$$\text{EoL } I_{mp} = (I_{mp} \cdot \eta_{Imp}) + \alpha \cdot (T_{mod} - T_{STC}) \tag{7}$$

Determining the PV module's daily operating hours (T_S) is essential to its capacity in ampere-hours (C_{PV}). T_S was determined based on the average daily irradiance derived from GHI data ($H_{G,d}$) at the off-grid solar PV system installation location and the irradiance value based on the irradiance under STC listed (G_{STC}) on the PV module. For example, if the G_{STC} value listed on the PV module is 1,000 W/m^2, and the $H_{G,d}$ is 4.39 kWh/m^2, the resulting T_S is 4.39 hours. Equation (8) calculates C_{array} by multiplying EoL I_{mp} and T_S. Equation (9) calculates a string or the number of series-connected PV modules, and equation (10) calculates the number of parallel-connected PV modules in (N_{PVpar}) [16].

$$C_{PV} = \mathrm{EoL}\ I_{mp} \cdot T_S \quad (8)$$

$$N_{PVseries} = \frac{V_{DC}}{\mathrm{EoL}\ V_{mp}} \quad (9)$$

$$N_{PVpar} = \frac{C_{array}}{C_{PV}} \quad (10)$$

$$C_{bat} = \frac{E_{Wh,d}}{\eta_{inv} \cdot \eta_{bat} \cdot DoD \cdot V_{bat}} \cdot D_{aut} \quad (11)$$

Battery capacity (C_{bat}) can be calculated using equation (11) by calculating the values of $E_{Wh,d}$, inverter efficiency (η_{inv}), battery efficiency (η_{bat}), battery depth of discharge (DoD), battery nominal voltage (V_{bat}), and number of days of autonomy (D_{aut}). The values of η_{inv} and η_{bat} in the design are usually 0.85 and 0.93. For deep-cycle batteries, the DoD value used is up to 0.8. V_{bat} can use the V_{DCsys} value. Day_{ot} is the number of days the system must operate without energy contribution from the solar panels due to cloudy or rainy conditions, which is usually 3 days [16].

Solar charge controllers are typically rated based on their current capacity (amperes) and working voltage, so their selection must be adjusted to the voltage and current of the PV module array configuration and the battery voltage of the off-grid solar PV system. Equation (12) calculates the current rating of the solar charge controller (I_{CC})as the product of the I_{sc} of a PV module, N_{PVpar}, and a safety factor (SF) of 1.3 or 30% higher than the maximum current value. This safety factor is incorporated to handle variations in temperature, light intensity, and potential current surges.

$$I_{CC} = \left(N_{PVpar} \cdot I_{SC} \right) \cdot SF \quad (12)$$

Equation (13) calculates the inverter capacity in volt-amperes (C_{inv}) by considering the total AC load power (P_{AC}), overload capacity (C_{OL}), ambient temperature derating factor (F_{Tamb}), and power factor (PF). Typically, in the design, values of C_{OL} are 1.3 and 0.8 for each F_{Tamb} and PF. Equation (14) calculates the maximum DC input current of an inverter (I_{DCmax}) [16].

$$C_{inv} = \frac{P_{AC} \cdot C_{OL}}{F_{Tamb} \cdot PF} \quad (13)$$

$$I_{DCmax} = \frac{P_{AC}}{V_{DC}} \quad (14)$$

A well-designed system can provide a stable and reliable electricity supply, improving the quality of life for residents and reducing energy costs [29][30]. Energy needs for modest households vary significantly depending on the appliances in use. For instance, with a total load of 395 watts, an Off-grid solar PV system using 300 Wp PV modules and a 12V 100Ah battery can supply power for approximately 2 hours and 20 minutes [31][32]. In Mawokau Jaya Village, Timika, Central Papua, a solar energy system uses a 150 Wp PV module and a 12V 100Ah battery capable of lighting a 100-watt incandescent lamp for 8 hours [33]. An off-grid solar PV system using a 115 Wp PV module, 12 V 100 Ah VRLA battery, and a PSW (Pure Sine Wave) inverter can supply the daily load requirement of 570 Wh for 11 hours [34]. Meanwhile, for basic needs such as lighting (e.g., five 5-watt LED lamps), an Off-grid solar PV system comprising two 100 Wp PV modules and a 12V 50Ah battery has been proven to be sufficiently reliable [35].

METHOD

The methodology begins with a literature review on renewable electrical energy, with emphasis on off-grid solar PV systems. The Renewable Energy House (REH), adapted to coastal conditions in Bengkulu City, provides the basis for system design. Data for assessing solar energy potential were obtained from meteorological databases, scientific literature, and international online sources. Daily energy requirements were estimated from usage patterns of electrical appliances in the REH model. The REH functions as a framework for simulating renewable energy integration in modest coastal homes lacking reliable grid access, while also serving as a replicable prototype for energy-independent housing in rural areas. Figure 2 illustrates the structured step-by-step design process.

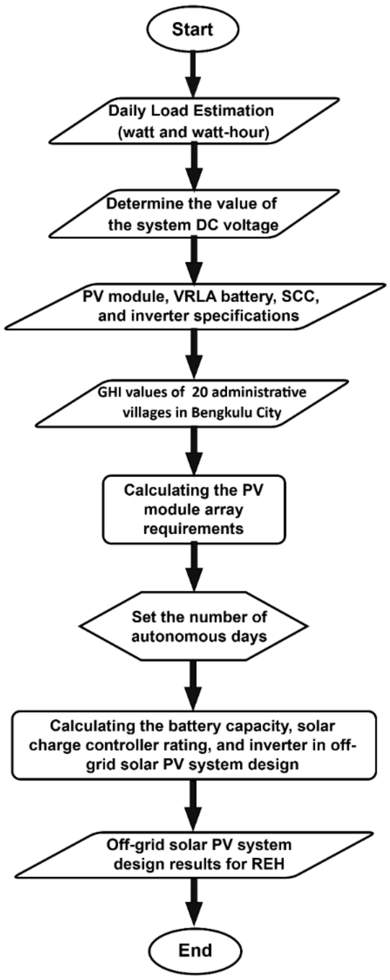

Figure 2. Flow diagram of the step-by-step design process

Figure 3 is a floor plan of the REH model used in this study. The REH building is designed in miniature at a 1:8 scale to represent the actual electrical load distribution in each room. The electrical equipment configuration, load point locations, and usage duration are designed to reflect real-world conditions. Therefore, the design calculations for the off-grid solar PV system for REH are directly scalable and reflect the expected performance of the system when applied to a full-sized residential unit.

The REH model includes six lighting points (L1-L6), four light switches (S1-S4), and four power outlets (C1-C4). The lighting load consists of one 30W lamp (L1), three 20W lamps (L2, L3, and L4), and two 10W lamps (L5 and L6). A double switch (S1) controls lamps L1 and L6, while L2 and L5 are controlled by another double switch (S2). Lamps L3 and L4 are each controlled by single switches, S3 and S4, respectively.

The daily loads described in Table 2 for this REH model consist of lamps, fans, water pumps, televisions, and other electrical appliances. Under simultaneous operation, the total load remains within the 900 W limit. This model is designed based on the maximum electricity usage capacity specified for PLN customers in the 900 VA class. Assuming the duration of each load shown in Table 2, the total daily use of electrical energy in the REH model is 3,010 W.

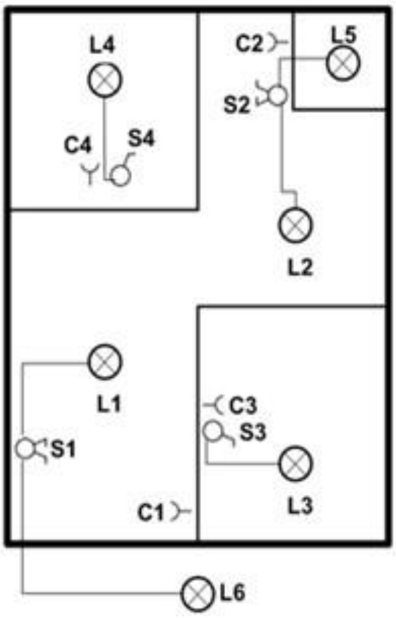

Figure 3. REH Model Floor Plan

Table 2. Daily Load Estimation on the REH Model

Detail of Load	Load Quantity	Wattage of Load (W)	Daily Duty Cycle (h)	Daily Energy (Wh)
Lamp for living room (L1)	1	30	7	210
Lamp for kitchen (L2)	1	20	8	160
Lamp for bedroom (L3-L4)	2	20	8	320
Lamp for restroom (L5)	1	10	3	30
Lamp for terrace (L6)	1	10	12	120
Electrik fan	2	50	8	800
Water pump	1	125	3	375
TV	1	60	7	420
Other electrical appliances	1	575	1	575
Total		**900**		**3,010**

Considering previous studies, this study selects monocrystalline PV modules for the design analysis of off-grid solar PV systems. The coastal areas of Bengkulu City experience consistently strong solar radiation potential throughout the year; therefore, high-efficiency PV modules such as monocrystalline are considered ideal for maximizing electricity generation, particularly in addressing the energy needs of modest households with limited roof space. Besides efficiency, monocrystalline PV modules generally have better protective coatings, making them suitable for applications in coastal areas with high humidity and winds that can carry dust or salt particles. With a moderate average air temperature (around 19.8-35.5°C) in Bengkulu City, the effects of temperature degradation on monocrystalline PV modules are still tolerable.

Figure 4 shows the PV modules used and their specifications. This PV module produces a peak power of 120W. The main parameters listed in the PV module specifications are crucial for calculating the number and configuration of PV modules in designing an off-grid solar PV system in the REH model. Table 3 presents these data. However, the PV module specification label does not include the β and α values of the PV module required in the design calculation. In monocrystalline PV modules that do not include β and α values on their specification labels, the design uses values of -0.112 V/°C for β and 0.004 A/°C for α [36].

In this study, the design of the off-grid Solar PV system is intended for a renewable energy-based home in Bengkulu City, with a particular emphasis on those located in coastal areas. Therefore, solar irradiation data using the potential solar energy in the coastal region of Bengkulu City is needed to determine the ampere-hour (Ah) of the PV module. The data used in this study is from the Global Solar Atlas, which provides reliable information on solar energy potential.

Figure 4. Monocrystalline PV module 120 Wp

Table 3. The main parameters listed in the PV module specifications

Electrical Parameter	Symbol	Value	Unit
Short circuit current	I_{SC}	6.65	Ampere (A)
Maximum power voltage	V_{mp}	19.2	Vollt (V)
Maximum power current	I_{mp}	6.25	Ampere (A)
STC: Irradiance	G_{STC}	1,000	Watt per meter square (W/m^2)
STC: Module temperature	T_{STC}	25	Degree Celsius (°C)

The Global Solar Atlas, an online platform developed by the NDC Partnership in collaboration with the World Bank, provides comprehensive datasets and geospatial maps on global solar resources and solar power generation potential. The platform, currently available in version 2.11.2 released in December 2024 (https://globalsolaratlas.info), was selected in this study due to its accessibility, scientific credibility, and reliability in delivering high-resolution solar resource data. Figure 5 presents a screenshot of the Global Solar Atlas interface, illustrating the selection of a specific coastal point in Bengkulu City used to obtain Global Horizontal Irradiance (GHI) values. These GHI data serve as critical indicators of solar energy potential and represent one of the most accurate and location-specific measures available for coastal regions.

Table 4 summarizes the average daily GHI values across 20 administrative villages (kelurahan) in Bengkulu City. These data function as fundamental inputs for the design and optimization of off-grid photovoltaic (PV) systems. By providing a spatial distribution of solar irradiance, the dataset allows for the identification of variations in solar potential among villages, which directly influence PV system configuration, sizing, and expected performance. For instance, villages with relatively higher GHI values may require smaller PV modules to achieve the same energy output, whereas areas with lower irradiance necessitate larger or more efficient systems. Such differentiation is crucial to ensuring equitable and efficient energy access for coastal communities, particularly in regions where grid connectivity remains limited.

Incorporating high-resolution irradiance data from the Global Solar Atlas not only enhances the technical accuracy of system simulations but also strengthens the sustainability of the proposed energy solutions. By aligning PV system design with local environmental conditions, the methodology supports the development of tailored, replicable, and resilient energy models for rural and coastal communities in Bengkulu City and beyond.

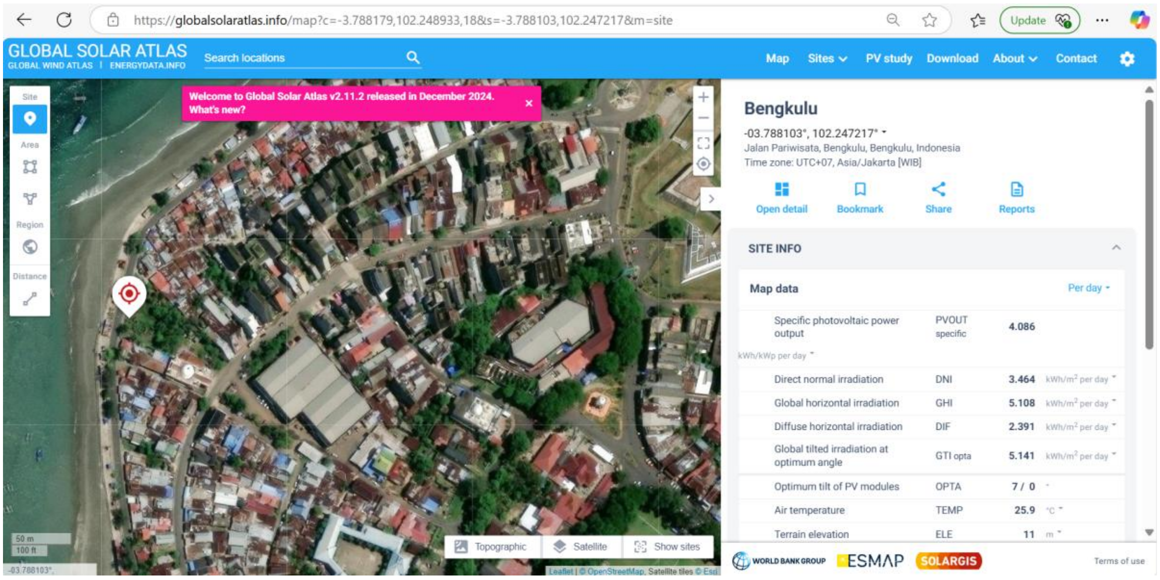

Figure 5. A Screenshot of the Research Data from the Administrative Village of Malabero

Table 4. Data from the Global Solar Atlas

No.	Administrative villages	GHI (kWh/m²)	No.	Administrative villages	GHI (kWh/m²)
1.	Kandang Limun	5.119	11.	Pondok Besi	5.112
2.	Beringin Raya	5.112	12.	Kebun Keling	5,110
3.	Rawa Makmur Permai	5.120	13.	Malabero	5.108
4.	Rawa Makmur	5.124	14.	Pasar Jitra	5.114
5.	Kampung Kelawi	5.122	15.	Pasar Melintang	5.115
6.	Kampung Bali	5.120	16.	Pantai Berkas	5.115
7.	Bajak	5.120	17.	Anggut Atas	5.117
8.	Suka Merindu	5.124	18.	Anggut Bawah	5.121
9.	Tengah Padang	5.116	19.	Penurunan	5.124
10.	Pasar Bengkulu	5.117	20.	Lempuing	5.129

RESULT AND DISCUSSION

Based on the total daily load requirement of the REH model of 900 watts in Table 2, a DC voltage of 48 V was selected for the designed off-grid solar PV system. With an estimated daily energy consumption of 3,010 Wh, the daily energy requirement in ampere-hours (EAh, d) is 63.33 Ah, calculated using equation (1).

$$E_{Ah,d} = \frac{3{,}010\ Wh}{48\ V} = 62.7083\ Ah$$

Furthermore, using equation (2), the capacity requirement for the PV module arrangement for the designed off-grid solar PV system can be obtained as 72.04 Ah.

$$C_{array} = \frac{62.7083\ Ah}{0.95 \cdot 0.93 \cdot 0.995} = 71.3338\ Ah$$

Calculating the number of series-connected and parallel-connected PV modules can determine the configuration of PV modules for designing an off-grid solar PV system. The number of series-connected PV modules can be determined using equation (9), and parallel-connected strings of PV modules can be determined using equation (10). For these calculations, the EoL V_{mp} and the EoL V_{mp} values must first be determined based on the V_{mp} and I_{mp} listed in the PV module specifications using equations (3)-(8).

$$\eta_{Vmp} = 1 - 0.15 = 0.85$$

$$\eta_{Imp} = 0.98 \cdot 0.98 \cdot 0.98 \cdot 0.98 \cdot 0.92 = 0.8486$$

The PV performance calculation takes into account local environmental conditions by utilizing GHI data obtained from the Global Solar Atlas. Figure 5, obtained from the Global Solar Atlas, is used to identify average solar irradiation and air temperature in each of the 20 administrative villages in Bengkulu City. These data serve as input for estimating module temperature (T_{mod}) and adjusting the V_{mp} and I_{mp} of the PV modules accordingly, making the analysis site-specific and contextually robust.

T_{mod} under 35.5 °C, the highest air temperature in Bengkulu City, was determined using the S_G based on the GHI in Table 2. For example, in the Malabero administrative village with a GHI of 5,108 kWh/m2, the calculation process is carried out as follows.

$$T_{mod} = 35.5\ °C + \left(\frac{\left(\frac{5.108\ kWh/m^2}{12\ h}\right)}{800\ W/m^2} \cdot 20\ °C \right) = 46.1417\ °C$$

$$EoL\ V_{mp} = (19.2\ V \cdot 0.85) + (-0.112\ V/°C) \cdot (46.1417\ °C - 25\ °C) = 13.9521\ V$$

$$EoL\ I_{mp} = (6.25\ A \cdot 0.8486) + 0.004\ A/°C \cdot (46.1417\ °C - 25\ °C) = 5.3882\ A$$

$$C_{PV} = 5.3882\ A \cdot 5.108\ h = 27.5228\ Ah$$

$$N_{PVseries} = \frac{48\ volt}{13.9521\ volt} = 3.4403 \cong 4$$

$$N_{PVpar} = \frac{71.3338\ Ah}{27.5228\ Ah} = 2.5918 \cong 3$$

Table 5 shows that all 20 administrative villages result in the same final PV configuration of 4 modules in series and 3 strings in parallel (4S3P), totaling 12 PV modules rated at 120 Wp each.

Table 5. The Results of the PV Module Configuration Design Calculation

No	Administrative Village	T_{mod}	EoL V_{mp} (V)	EoL I_{mp} (A)	$N_{PVseries}$	N_{PVpar}	N_{PV}
1.	Kandang Limun	46.1646	13.9496	5.3883	3.4410 ≅ 4	2.5862 ≅ 3	12
2.	Beringin Raya	46.1500	13.9512	5.3882	3.4406 ≅ 4	2.5898 ≅ 3	12
3.	Rawa Makmur Permai	46.1667	13.9493	5.3883	3.4410 ≅ 4	2.5857 ≅ 3	12
4.	Rawa Makmur	46.1750	13.9484	5.3883	3.4413 ≅ 4	2.5836 ≅ 3	12
5.	Kampung Kelawi	46.1708	13.9489	5.3883	3.4411 ≅ 4	2.5847 ≅ 3	12
6.	Kampung Bali	46.1667	13.9493	5.3883	3.4410 ≅ 4	2.5857 ≅ 3	12
7.	Bajak	46.1667	13.9493	5.3883	3.4410 ≅ 4	2.5857 ≅ 3	12
8.	Suka Merindu	46.1750	13.9484	5.3883	3.4413 ≅ 4	2.5836 ≅ 3	12
9.	Tengah Padang	46.1583	13.9503	5.3883	3.4408 ≅ 4	2.5877 ≅ 3	12
10.	Pasar Bengkulu	46.1604	13.9500	5.3883	3.4409 ≅ 4	2.5872 ≅ 3	12
11.	Pondok Besi	46.1500	13.9512	5.3882	3.4406 ≅ 4	2.5898 ≅ 3	12
12.	Kebun Keling	46.1458	13.9517	5.3882	3.4404 ≅ 4	2.5908 ≅ 3	12
13.	Malabero	46.1417	13.9521	5.3882	3.4403 ≅ 4	2.5918 ≅ 3	12
14.	Pasar Jitra	46.1542	13.9507	5.3882	3.4407 ≅ 4	2.5887 ≅ 3	12
15.	Pasar Melintang	46.1563	13.9505	5.3882	3.4407 ≅ 4	2.5882 ≅ 3	12
16.	Pantai Berkas	46.1563	13.9505	5.3882	3.4407 ≅ 4	2.5882 ≅ 3	12
17.	Anggut Atas	46.1604	13.9500	5.3883	3.4409 ≅ 4	2.5872 ≅ 3	12
18.	Anggut Bawah	46.1688	13.9491	5.3883	3.4411 ≅ 4	2.5852 ≅ 3	12
19.	Penurunan	46.1750	13.9484	5.3883	3.4413 ≅ 4	2.5836 ≅ 3	12
20.	Lempuing	46.1854	13.9472	5.3884	3.4415 ≅ 4	2.5811 ≅ 3	12

$$C_{bat} = \frac{3{,}010\ Wh}{0.85 \cdot 0.93 \cdot 0.8 \cdot 48\ \mathrm{V}} \cdot 3 = 297.48\ \mathrm{Ah} \cong 300\ \mathrm{Ah}$$

$$I_{CC} = (3 \cdot 6.65\ \mathrm{A}) \cdot 1.3 = 25.935\ \mathrm{A} \cong 30\ \mathrm{A}$$

$$C_{inv} = \frac{900\ \mathrm{W} \cdot 1.3}{0.8 \cdot 0.8} = 1{,}828.125\ \mathrm{VA} \cong 2{,}000\ \mathrm{VA}$$

$$I_{DCmax} = \frac{900\ \mathrm{W}}{48\ \mathrm{V}} = 18.75\ \mathrm{A}$$

Based on the daily energy consumption of 3.01 kWh (3,010 Wh) as presented in Table 2, and considering a design autonomy of 3 days to ensure reliability during periods of low solar irradiance, the main components of the off-grid solar PV system were determined through detailed calculations using Equations (11) to (14). The calculated energy storage requirement resulted in a 48 V, 300 Ah VRLA battery bank, providing sufficient capacity to meet the autonomy period and load demands of 900 W.

Maximizing energy harvest and ensuring stable system operation required the integration of a 48 V, 30 A MPPT solar charge controller, which effectively regulates power flow from the PV array. Additionally, a 48 V, 2,000 VA pure sine wave inverter with a maximum input current of 18.75 A was specified to reliably convert DC power to AC and supply the household load. The PV array configuration consists of 12 modules rated at 120 Wp, arranged in three parallel strings of four modules in series. Such an arrangement effectively meets the voltage and current requirements necessary for reliable and efficient system operation.

The inclusion of a 3-day autonomy improves system resilience against intermittent solar availability, making the design well-suited for the coastal climate of Bengkulu City. Furthermore, the use of modular, commercially available components enhances the potential for cost-effective installation, maintenance, and scalability. These design results provide a strong technical foundation to support further evaluation of the system's economic viability, environmental benefits, and policy alignment.

CONCLUSION

An off-grid solar PV system was successfully designed for a modest, renewable energy-based home in Bengkulu City, utilizing a DC system voltage of 48 V to meet a power demand of 900 W and a daily energy consumption of 3.01 kWh. The configuration derived from the system design includes 12 PV modules arranged into three parallel strings, each string consisting of four modules connected in series. The system also requires a 48 V, 300 Ah VRLA battery bank, a 48 V, 30 A MPPT solar charge controller, and a 48 V, 2,000 VA pure sine wave inverter with an input current of 18.75 A. This design demonstrates the technical feasibility of deploying off-grid solar PV systems for small-scale residential use in coastal areas of Indonesia. Economically, such systems have the potential to reduce long-term electricity costs and reliance on diesel generators, particularly in remote or underserved regions. From an environmental perspective, the system helps reduce carbon emissions and aligns with Indonesia's transition to renewable energy.

From a policy standpoint, the model aligns with national energy resilience goals outlined in the National Energy Policy (RUEN), particularly in promoting decentralized renewable energy access in remote and coastal regions. The system's modularity and relatively low cost enhance its scalability and adaptability for replication in other tropical regions of Indonesia, including areas in Sumatra, Kalimantan, and eastern Indonesia where electrification challenges remain. Future research is encouraged to investigate real-time performance monitoring, evaluate cost optimization through alternative battery technologies, and explore hybrid integration with other renewable sources such as wind or micro-hydro to enhance system reliability and support broader regional deployment strategies.

REFERENCES

[1] W. E. Juwana, R. A. Rachmanto, N. F. Alfaiz, S. D. Prasetyo, and Z. Arifin, "Economic Analysis of PV-Generator Hybrid Off-Grid Systems in Underdeveloped Indonesian Regions," *Journal Europeen des Systemes Automatises*, vol. 56, no. 4, hal. 519–527, 2023, doi: 10.18280/jesa.560401.

[2] D. R. Adhikari, R. Jariyaboon, and K. Techato, "Reducing Carbon Emissions Through Sustainable Energy Integration at Off-Grid Cellular Sites: A Case Study of Nepal," *International Journal of Ambient Energy*, vol. 45, no. 1, hal. 2366496, 2024, doi: 10.1080/01430750.2024.2366496.

[3] B. Radley and P. Lehmann-Grube, "Off-Grid Solar Expansion and Economic Development in The Global South: A Critical Review and Research Agenda," *Energy Research and Social Science*, vol. 89, no. December 2021, hal. 102673, 2022, doi: 10.1016/j.erss.2022.102673.

[4] M. Tawalbeh, A. Al-Othman, F. Kafiah, E. Abdelsalam, F. Almomani, and M. Alkasrawi, "Environmental Impacts of Solar Photovoltaic Systems: A Critical Review of Recent Progress and Future Outlook," *Science of The Total Environment*, vol. 759, hal. 143528, 2021, doi: 10.1016/j.scitotenv.2020.143528.

[5] B. J. Alqahtani and D. Patino-Echeverri, "Identifying Economic and Clean Strategies to Provide Electricity in Remote Rural Areas: Main-Grid Extension vs. Distributed Electricity Generation," *Energies*, vol. 16, no. 2, 2023, doi: 10.3390/en16020958.

[6] N. C. Pradana, M. A. Rizki, A. Wahyuni, and B. Harsono, "Solar Panel Implementation for Household Electricity in Indonesia: Environmental and Economic Implications," *Academia Open*, vol. 8, no. 2, hal. 6–10, 2023, doi: 10.21070/acopen.8.2023.7860.

[7] I. J. Mwakitalima, M. Rizwan, and N. Kumar, "Standalone Solar Photovoltaic Electricity Supply to Rural Household in Tanzania," *IETE Journal of Research*, vol. 69, no. 6, hal. 3871–3886, 2023, doi: 10.1080/03772063.2021.1920854.

[8] N. Wagner, M. Rieger, A. S. Bedi, J. Vermeulen, and B. A. Demena, "The Impact of Off-grid Solar Home Systems in Kenya on Energy Consumption and Expenditures," *Energy Economics*, vol. 99, hal. 105314, 2021, doi: 10.1016/j.eneco.2021.105314.

[9] H. C. O. Unegbu, D. S. Yawas, B. Dan-asabe, and A. A. Alabi, "An Investigation of Renewable Energy Solutions for Off-Grid Sustainable Housing in Rural Nigeria," *Journal of Sustainable Construction*, vol. 4, no. 1, hal. 37–59, 2024, doi: 10.26593/josc.v4i1.8112.

[10] H. Audu and A. Adamu, "Expanding Energy Access In Rural Off-Grid Communities: A Study On Household Adoption and Affordability of Solar Home Systems in Kwara State, Nigeria," *Journal of Global Economics and Business*, vol. 3, no. 11, hal. 181–201, 2022, doi: 10.58934/jgeb.v3i11.166

[11] D. F. Silalahi, A. Blakers, M. Stocks, B. Lu, C. Cheng, and L. Hayes, "Indonesia's Vast Solar Energy Potential," *Energies*, vol. 14, no. 17, 2021, doi: 10.3390/en14175424.

[12] Gubernur Bengkulu, *Peraturan Daerah Provinsi Bengkulu Nomor 7 Tahun 2019 Tentang Rencana Umum Energi Daerah Provinsi Bengkulu*. Indonesia, 2017. [Daring]. Tersedia pada: https://jdih.bengkuluprov.go.id/produk/detail_produk/429-peraturan-daerah-provinsi-bengkulu-nomor-7-tahun-2019-tentang-rencana-umum-energi-daerah-provinsi-be.html.

[13] BPS Provinsi Bengkulu, *Provinsi Bengkulu Dalam Angka 2024*, Volume 37. Bengkulu: BPS Provinsi Bengkulu, 2024. [Daring]. Tersedia pada: https://bengkulu.bps.go.id/id/publication/2024/02/28/c6321e59609376455eeab025/provinsi-bengkulu-dalam-angka-2024.html.

[14] BPS Kota Bengkulu, *Kota Bengkulu Dalam Angka 2024*, Volume 18. Bengkulu: BPS Kota Bengkulu, 2024. [Daring]. Tersedia pada: https://bengkulukota.bps.go.id/id/publication/2024/02/28/cb9e749bba81a2b21fb98b1b/kota-bengkulu-dalam-angka-2024.html.

[15] D. A. Efriansyah, A. Herawati, I. N. Anggraini, R. S. Rinaldi, and Y. Rodiah, "Analisis Potensi Energi Matahari and Pembangkitan Daya Pada PLTS Sebagai Sumber Rumah Energi Terbarukan Sederhana di Kota Bengkulu," *Serambi Engineering*, vol. 9, no. 1, hal. 8258–8267, 2024, [Daring]. Tersedia pada: http://jurnal.serambimekkah.ac.id/index.php/jse/article/view/960/714.

[16] R. Satpathy and V. Pamuru, "Off-grid Solar Photovoltaic Systems," in *Solar PV Power*, Lisa Reading, Ed., London: Academic Press, 2021, 7, hal. 267–315. doi: 10.1016/b978-0-12-817626-9.00007-1.

[17] R. A. Efryansah, "Mengetahui Perbedaan Sel, Modul, String, dan Array Surya," Kelas Teknisi. Diakses: 24 Juni 2024. [Daring]. Tersedia pada: https://www.kelasteknisi.com/2024/05/perbedaan-sel-modul-string-dan-array-surya.html.

[18] M. Y. Puriza, W. Yandi, and Asmar, "Perbandingan Efisiensi Konversi Energi Panel Surya Tipe Polycrystaline dengan Panel Surya Monocrystaline Berbasis Arduino di Kota Pangkalpinang," *Jurnal Ecotipe (Electronic, Control, Telecommunication, Information, and Power Engineering)*, vol. 8, no. 1, hal. 47–52, 2021, doi: 10.33019/jurnalecotipe.v8i1.2034.

[19] D. Dahliya, S. Samsurizal, and N. Pasra, "Efficiency of a 100 Wp Capacity Solar Panel Due to the Effect of Temperature and Wind Speed," *Jurnal Ilmiah SUTET*, vol. 11, no. 2, hal. 71–80, 2021, doi: 10.33322/sutet.v11i2.1551.

[20] M. Anggara and W. Saputra, "Analisis Kinerja Sel Surya Monocrystalline dan Polycrystalline di Kabupaten Sumbawa NTB," *Jurnal Flywheel*, vol. 14, no. 1, hal. 7–12, 2023, doi: 10.36040/flywheel.v14i1.6521.

[21] P. S. Acharya and P. S. Aithal, "A Comparative Study of MPPT and PWM Solar Charge Controllers and their Integrated System," in *Journal of Physics: Conference Series*, 2020, hal. 1–7. doi: 10.1088/1742-6596/1712/1/012023.

[22] N. Ghadirinejad, F. Ottermo, R. Nowzari, N. Alsaadi, and M. Ghadiri Nejad, "Optimizing a Green and Sustainable Off-Grid Energy-System Design: A Real Case," *Sustainability (Switzerland)*, vol. 15, no. 17, 2023, doi: 10.3390/su151712800.

[23] Fianti, A. Y. Perdana, B. Astuti, and I. Akhlis, "Analysis of PWM- And MPPT-solar charge controller efficiency by simulation," *Journal of Physics: Conference Series*, vol. 1918, no. 2, hal. 1–6, 2021, doi: 10.1088/1742-6596/1918/2/022004.

[24] E. Faizal, Y. A. Winoko, M. S. Mustapa, and M. Kozin, "Solar Charger Controller Efficiency Analysis of Type Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT)," *Asian Journal Science and Engineering*, vol. 1, no. 2, hal. 90, 2023, doi: 10.51278/ajse.v1i2.546.

[25] H. Adamu, F. Njoka, and G. Kidegho, "Performance of MPPT Charge Controller Under Moderate - to High - Temperature Field Condition," *Journal of Sustainable Development of Energy, Water and Environment Systems*, vol. 12, no. 3, hal. 1–15, 2024, doi: 10.13044/j.sdewes.d12.0504.

[26] Midun S, Vibhishan A, and Avinash R, "Pv Off Grid System with Improved Charge Controller Using Closed Loop Control," *International Research Journal on Advanced Engineering Hub (IRJAEH)*, vol. 2, no. 02, hal. 248–253, 2024, doi: 10.47392/irjaeh.2024.0040.

[27] I. P. G. I. Dwipayana, I. N. S. Kumara, and I. N. Setiawan, "Status of Battery in Indonesia to Support Application of Solar PV with Energy Storage," *Journal of Electrical, Electronics and Informatics*, vol. 5, no. 1, hal. 29-40, 2021, doi: 10.24843/jeei.2021.v05.i01.p06.

[28] S. M. Jawd, N. H. Chekhyor, and A. M. Sabea, "Types of Solar Cell Batteries and their Energy Charging Methods," *Journal of Thermal Engineering and Applications*, vol. 8, no. 2, hal. 16--22, 2021, [Daring]. Tersedia pada: https://engineeringjournals.stmjournals.in/index.php/JoTEA/article/view/5858.

[29] S. Emiralioglu, S. Karatay, and F. Erken, "The Design and the Application of Off-Grid Solar Power System for a House in Kastamonu," *Journal of Advanced Applied Sciences*, vol. 3, no. 1, hal. 23–31, 2024, doi: 10.61326/jaasci.v3i1.253.

[30] D. L. King, W. E. Boyson, and J. A. Kratochvil, "Photovoltaic array performance model, SANDIA Report SAND2004-3535," New Mexico, 2004. [Daring]. Tersedia pada: https://www.sandia.gov/research/publications/details/photovoltaic-array-performance-model-2004-08-01/

[31] A. T. Dare, D. T. Wemimo, S. T. Emmanuel, S. C. Titilayo, and D. Joseph, "Design Methodology and Implementation of Stand-Alone Solar Photovoltaic Power System for Daily Energy Consumption of 9.16 kWh," *Engineering Research Express*, vol. 5, no. 4, hal. 045033, 2023, doi: 10.1088/2631-8695/acfdf5.

[32] F. Fadhlurrahman and H. Purnomo, "Rancang Bangun Pembangkit Listrik Tenaga Surya (PLTS) 300 Wp Dengan Sistem Automatic Transfer Switch (ATS) Untuk Rumah Sederhana," *Schrodinger*, vol. 3, no. 2, hal. 145–157, 2022, [Daring]. Tersedia pada: https://jim.unindra.ac.id/index.php/schrodinger/article/view/8248

[33] A. E. Mirnawati and V. D. Pertiwi, "Rancang Bangun Sistem Pemanfaatan Energi Matahari Berbasis Panel Surya Untuk Penerangan Rumah Tinggal Masyarakat Kampung Mawokau Jaya Timika – Papua Tengah," *Jurnal Sosial and Teknologi Terapan AMATA*, vol. 03, no. 1, hal. 34–38, 2024, doi: 10.55334/sostek.v3i1.200.

[34] H. Riafinola, I. K. L. N. Suciningtyas, I. Sholihuddin, and W. R. Puspita, "Rancang Bangun Pembangkit Listrik Tenaga Surya pada Penggunaan Listrik Rumah Tangga," *Journal Of Applied Electrical Engineering*, vol. 6, no. 2, 2022, doi: 10.30871/jaee.v6i2.4809.

[35] P. Megantoro, A. Ma'arif, D. F. Priambodo, Iswanto, H. F. A. Kusuma, and S. D. Perkasa, "Mini Solar Home System for Electricity Supply in Coastal Rural Area, Case Study: Yogyakarta, Indonesia," in *2022 International Conference on Information Technology Systems and Innovation (ICITSI)*, Bandung, Indonesia: IEEE, 2022. doi: 10.1109/ICITSI56531.2022.9970836.

[36] G. Takyi and F. K. Nyarko, "Investigation of the Effect of Temperature Coefficients on Mono-Crystalline Silicon PV Module Installed in Kumasi, Ghana," *Journal of Power and Energy Engineering*, vol. 08, no. 09, hal. 20–34, 2020, doi: 10.4236/jpee.2020.89003.