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Design and Analysis of 1.0 KVA Grid-Connected Micro-Grid PV-Systems for a Residential Setting in Delta State, Nigeria

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Abstract

The design and analysis of the 1.0 KVA solar systems was based on a thorough load assessment, precise calculation of required solar panel quantity, proper battery selection and appropriate inverter sizing. The purchase included a high-quality complete solar panel with an impressive rating of 180 W, along with two dependable 200 Ah solar batteries, a reliable 800 W inverter and a durable charge controller. These elements were meticulously put together with essential protective mechanisms such as cut out switches to ensure optimal performance and safety standards for the anticipated power output of 1.0 KVA. To optimize sun exposure for efficient energy collection, the strategic installation of the solar power consist of 6 x 180 W solar panel,2 x 200Ah battery connected in parallel and 1.0 KVA power inverter. Based on the design analysis, this well-planned setup is expected to effectively fulfill all electrical requirements even in situations without access to central power supply, presenting itself as a dependable and sustainable solution for off-grid or unreliable power scenarios.

Keywords: Solar, Photovoltaic, Off-grid power, System efficiency, Energy

Introduction

In the current time, humanity is encountering a crisis of energy depletion as non-renewable resources are gradually diminishing and most sources of energy come with considerable pollution (Abdul Latif *et al.*, 2021; Noroozian & Gharehpetian, 2016; Mahmood *et al.*, 2012). The increasing demand for energy coupled with the worsening living conditions necessitate exploration and utilization of alternate forms such as wind, tidal, or solar power (Abeshi *et al.*,, 2023; Emegha *et al.*, 2022). Among these alternative choices, solar power has become widely popular. Solar energy derived from photovoltaic technology is an environmentally sustainable and renewable source that relies on the absorption of sunlight (Terzioglu *et al.*, 2015). Notably, photovoltaic solar energy has distinct advantages such as being freely available for consumption, requiring no additional fuel inputs, and generating zero waste or pollution during its utilization (Wolniak & Skotnicka-Zasadzien, 2022). The utilization of photovoltaic solar electricity has demonstrated to be a viable solution for providing alternative electrification in off-grid rural areas that lack access to modern energy sources (Noroozian & Gharehpetian, 2016). This limited supply of electricity often hinders development efforts within these communities. However, the implementation and use of photovoltaic solar systems offer an effective means of addressing this issue by harnessing

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renewable energy from sunlight (Terzioglu *et al.,* 2015). By doing so, it enables these rural areas to overcome their reliance on traditional energy sources and promotes sustainable development (Rolland, 2011).

Oyedepo (2012) and Kamalapur & Udaykumar (2011) have attempted to highlight the advantages of solar energy compared to conventional sources such as coal, oil, and natural gas. It is evident that these conventional energy sources are limited in quantity and at the current rate of consumption; they will be depleted within a few decades. On the contrary, solar energy presents a unique value proposition as it is clean, environmentally friendly, and offers an abundant supply that can never be exhausted (Abdul Latif *et al*., 2021; Terzioglu *et al.,* 2015). Importantly, the transition from fossil fuel to renewable energy sources is imperative in order to mitigate the depletion of fossil fuel reserves and reduce greenhouse gas emissions (Terzioglu *et al.,* 2015).

Nigeria, much like numerous other developing countries and specifically African nations, continues to grapple with the absence of dependable, efficient, and adequate electricity in many regions. This challenge is particularly acute in rural areas and off-grid locations, resulting in significant setbacks for development initiatives within these communities as well as across the entire country (Rolland, 2011). The absence of dependable electricity access impedes economic development, restricts educational possibilities, and impacts the wellbeing of numerous Nigerians (Matungwa, 2014). It is also believed that achieving access to electricity through the national grid in rural and underserved areas will not happen anytime soon (Matungwa, 2014). There are several significant challenges associated with this issue. One of these challenges stems from the nature of rural settlements, which make it difficult for electricity infrastructure to reach all remote locations efficiently (Matungwa, 2014). Additionally, the cost of transmitting grid electricity is considered prohibitively expensive, making it impractical for widespread implementation in such areas. Furthermore, even if grid electricity were accessible, its affordability by the rural population poses another challenge altogether. To tackle these difficulties, other options like stand-alone power systems and small-scale grid networks powered by local sustainable sources have been widely viewed as more feasible alternatives (Johnson & Ogunseye, 2017).

Nigeria is located in the West African region and spans a total land area of 923,768 square kilometers. It is positioned between longitude 3 degrees and 14 degrees, as well as latitudes 4 degrees and 140 degrees (Oyedepo, 2012). Nigeria receives abundant sunlight all year round as it is located just above the equator. Solar radiation levels in Nigeria vary from 3.5 to 7.0 (Figure 1), positioning the country favorably for solar energy development due to its proximity to the equatorial region (Okoro & Chineke 2021). While solar energy distribution across Nigeria is generally uniform, the northern part experiences slightly higher access to this renewable resource (Akinboro *et al*., 2019).

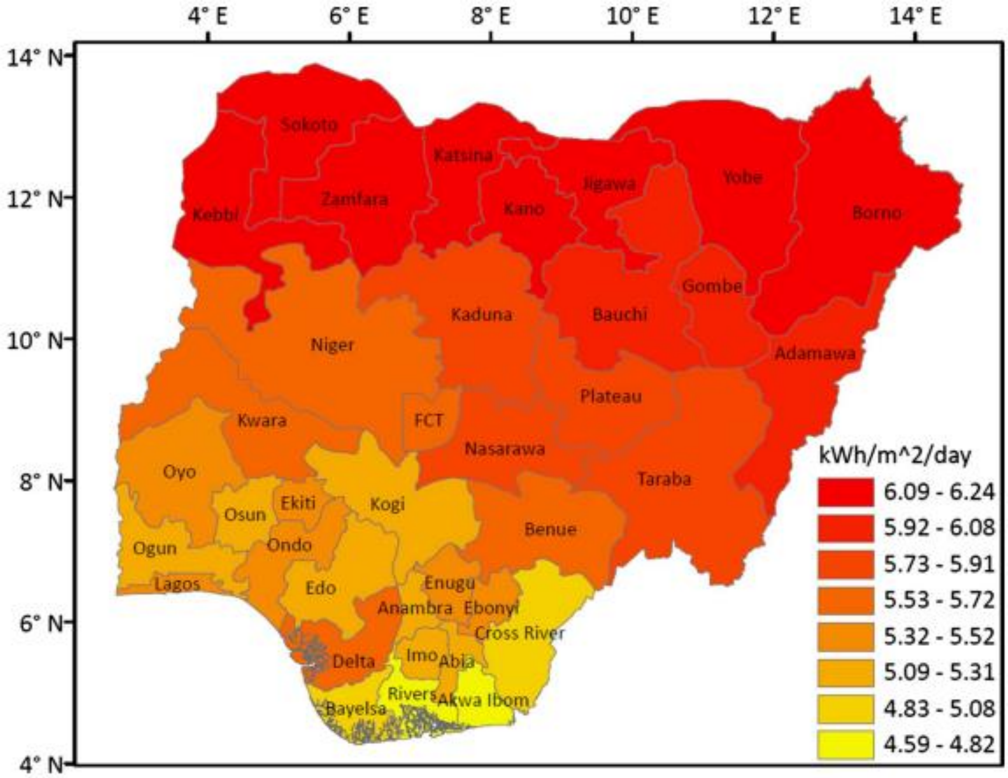

Figure 1: Nigeria's average sun hours' map (Okoro & Chineke 2021).

The emphasis on renewable energy, particularly solar power, offers a chance to reduce social and economic marginalization in rural communities. Because it takes a long time to install grid electricity in these areas, utilizing photovoltaic solar energy becomes crucial for enhancing education and healthcare access (Rolland, 2011). This initiative also supports efforts to eradicate poverty as research consistently emphasizes the importance of solar-generated electricity in driving development within marginalized regions such as rural areas (Goldemberg, 2006). It plays a significant role in promoting the use of electric lighting for studying at night and powering electrical appliances like televisions, radios, and charging cell phones. Furthermore, it significantly supports income-generating activities by providing essential electricity (Rolland, 2011; Kamalapur & Udaykumar, 2011).

To effectively enhance the standards of living in rural communities, it is crucial to consider alternative sources of energy such as solar (Johnson & Ogunseye, 2017). Solar power, for instance, holds immense potential and can greatly contribute toward transforming the lives of people residing in rural areas (Johnson & Ogunseye, 2017). Rather than focusing solely on conventional energy sources that present numerous challenges, exploring sustainable options becomes both important and necessary. Therefore, a thorough examination should be conducted regarding alternative energy solutions like solar power to bring about positive changes in the livelihoods of those living in rural communities. This work is based on the design and analysis of a 1.0 KVA solar system that is connected to the power grid; it is a novel system that improves efficiency and power quality. The materials that will assist in the design include the panels, charge controllers, 800 W inverter, batteries and connecting wires.

Methodology

Energy Consumption Analysis and Evaluation

An initial task involves documenting the electrical devices present at the residence, including their power ratings and operating durations throughout the day (Ezugwu, 2012). This information allows for the calculation of the average daily energy demand in Watt-hours, as depicted in Table 1. The total average energy consumption is then utilized to determine appropriate sizes and ratings for equipment components such as solar arrays, system wiring, and cost estimates accordingly (Ezugwu, 2012). However, from Table 1, the total power (TP) and the energy demand (ED) in Watt-hour are given as 568 W and 3,180 Wh respectively.

Table 1: Residence Devices and Energy Consumptions

S/N	Load Types	Power (W)	Quantity	Total Power (W)	Duration	Watt-Hour (Wh)
1.	Television	45	2	90	5	450
2.	Light Bulbs	10	12	120	8	960
3.	Fans (Standing)	50	2	100	5	500
4.	Fans (Ceiling)	70	2	140	5	700
5.	Decoder	18	1	18	5	90
6.	Refrigerator	60	1	60	8	480
	Total Usage			**568**		**3,180**

System Sizing

The process of determining the appropriate size for a photovoltaic system is crucial in its design, taking into account multiple factors to ensure that the voltage and current specifications of each part align with the electrical needs of the household (Ezugwu, 2012). This process also involves carefully calculating the overall cost of the system from its initial design phase until it becomes fully functional (Al-Shamani *et al.,* 2015). By accurately assessing these requirements, we can achieve optimal performance and cost-effectiveness for a successful implementation.

Battery Bank Sizing

Before sizing the array, the total daily energy in Watt-hours (E), the average sun hour per day (Ts) and the DC-voltage of the system (VDC) must be determined. Once these factors are made available then, the sizing process can commence (Ezugwu, 2012).

To avoid under sizing, losses must be considered by dividing the total power demand in Wh/day by the product of efficiencies of all components in the system to get the required energy (E_r). To avoid under sizing, we begin by dividing the total average energy demand per day by the efficiencies of the system components to obtain the daily requirement from the solar array (Al-Shamani *et al.,* 2015):

$$E_r = \frac{Energy\ demanded}{system\ Efficiency} \qquad (1)$$

To obtained the battery bank (B_b), the required energy (E_r) must be divided by the maximum Depth of discharge (DoD). The DoD is the percentage of a battery's capacity that can be used on a regular basis relative to its overall capacity (Terzioglu *et al.,* 2015). Usually, DoD is assumed to be 0.8 or 80%.

$$B_{b=} \frac{E_r}{DoD} \qquad (2)$$

Therefore (Al-Shamani *et al.,* 2015):

$$\text{Battery Capacity } (B_c) = \frac{E_r}{System\, Voltage} \quad (3)$$

The connection of the battery bank can be then easily figured out. The number of batteries in series equals the DC voltage of the system divided by the voltage rating of one of the batteries selected. Thus, then number of parallel paths (Np) is obtained by dividing the total number of batteries by the number of batteries connected in series (Al-Shamani *et al.,* 2015).

Sizing of the Solar Array (S_z)

The Panels' size is determined by dividing the Energy Demand by the system efficiency of 0.85 and the daily average sun hours specific to the geographical location. For Delta State, the sun hour per day is between 3 to 5 hours. However, using an average of four (4), we have:

$$S_z = \frac{E_d}{4\, x\, 0.85} \quad (4)$$

Modules must be connected in either in series or parallel and a combination of both connections depending on the desired voltage and current of the design.

Sizing of the Voltage Controller

According to its function, it controls the flow of current. A good voltage regulator must be able to withstand the maximum current produced by the array as well as the maximum load current (Ezugwu, 2012). Sizing of the voltage regulator can be obtained by multiplying the short circuit current of the modules connected in parallel by a safety factor (F_{safe}). The result gives the rated current of the voltage regulator (Al-Shamani *et al.,* 2015):

$$I = I_{SC} * N_p * F_{safe} \quad (5)$$

The factor of safety is employed to make sure that the regulator handles maximum current produced by the array that could exceed the tabulated value. And to handle a load current more than that planned due to addition of equipment, for instance. In other words, this safety factor allows the system to expand slightly (Al-Shamani *et al.,* 2015):

$$N_{controller} = \frac{I}{Amps\, each\, controller} \quad (6)$$

The number of controller equals the Array short current Amps divided by the Amps for each controller (Al-Shamani *et al.,* 2015).

Sizing of the Inverter

The first step in sizing the inverter is to calculate the combined power requirements of all appliances that will be used simultaneously (Al-Shamani *et al.,* 2015). This involves totaling the wattage with surge, without taking there durations into account, thus (Al-Shamani *et al.,* 2015):

$$Inverter\ Size = \frac{Total\ Power\ (W)}{Power\ factor\ (0.8)} \quad (7)$$

Sizing of the System Wiring

Selecting the correct size and type of wire will enhance the performance and reliability of a photovoltaic system (Al-Shamani *et al.,* 2015). The National Electrical Code is the Nigerian Electricity Regulatory Commission (NERC).

RESULTS AND DISCUSSION

The design and installation of a solar photovoltaic system requires careful consideration to ensure successful implementation. This involves conducting an energy audit or rating, determining the appropriate sizing for components such as panels, batteries, charge controllers, inverters, wires, and assessing the market value of all necessary components essential for a seamless installation of solar PV power supply (Ezugwu, 2012). The important parameters for the design of 1.0 KVA PV-systems are listed in Table 2.

Table 2: Components of 1.0 KVA PV-Systems

S/N	Parameters	Specifications
1.	Energy Demand	3180 W
2.	System Efficiency	0.85
3.	Maximum DoD	0.8
4.	System Voltage	12 V
5.	Battery Requirements	$2 x 200 Ah$ (connected in parallel)
6.	Panels	$6 x$ 180 W

Determining the Installation Site

When selecting a site for photovoltaic system installation, it is crucial to carefully consider factors such as available space, accessibility to the system, structural integrity and weatherproofing of roof penetrations, and labor needs for mounting supports. Additionally, the geographical location and climate of the installation site play a significant role in determining the potential solar energy generation and overall system performance (Ramírez-Revilla *et al*., 2022).

The solar panel was mounted on the roof. The energy produced by the PV system varied from 5 to 10 watts per square foot, influenced by the type of technology utilized and the different efficiencies of various PV products. In this research, the decision to install the solar panels on the rooftop was made to reduce costs and enhance property value. As a result, it is generally recommended to place the PV array on top of the building. Approximately 40 square feet of unobstructed space were needed for a 1.0-kVA PV system installation, with additional consideration given for access requirements that increased the necessary mounting space. Precise attention to both structural integrity and weatherproofing when creating roof penetrations was essential for proper PV system installation. Labor-intensive efforts were involved in securing support brackets for each solar panel module during installation - typically requiring two support brackets per module.

Installation Procedure

The installation process of the PV system involved a set of fundamental procedures (Terzioglu *et al.,* 2015; Ezugwu, 2012):

1. The suitability of the roof area for installation was verified, ensuring its capacity to accommodate the size or dimensions of the system.
2. Careful attention was paid to identify and seal any roof penetrations using approved methods endorsed by the roofing industry.
3. Installation of the PV system adhered strictly to manufacturer specifications, including compliance with requirements such as appropriate wire gauge and utilization of nuts and bolts specified by manufacturers.
4. To mitigate potential risks associated with electrical surges that could cause electric shock hazards, meticulous grounding measures were implemented throughout all components of the PV system.
5. The proper wire with the correct polarity was carefully considered when connecting the solar panel to the charge controller.
6. Compliance with local utility interconnection requirements was verified to ensure that the design aligned with specifications.

Figure 2: Pictorial view of the system arrangement (a) Power Battery (b) Inverter System (c) Solar PV array (d) Charge controller and Service box

Relationship between the System Energy Demand and Power Factor

The power factor is an important aspect of electrical systems that affects efficiency and energy utilization. It is one of the key figures used by designers of electrical and electronic devices to meet the power requirements and regulations within several countries and other organizations (Milan & Yungtaek, 2005). Figure 3 shows the correlation between the Energy demand of the system and the Power factor. The analysis of the curve indicates that the Power factor is inversely proportional to the Energy demands of the system. This suggests that raising the power factor of the system decreases energy consumption, thus providing more power to households. However, a lower power factor is not only inefficient but can also become costly over the lifespan of an electrical system. Therefore, understanding and improving power factor is crucial for optimizing energy utilization and reducing wastage in systems.

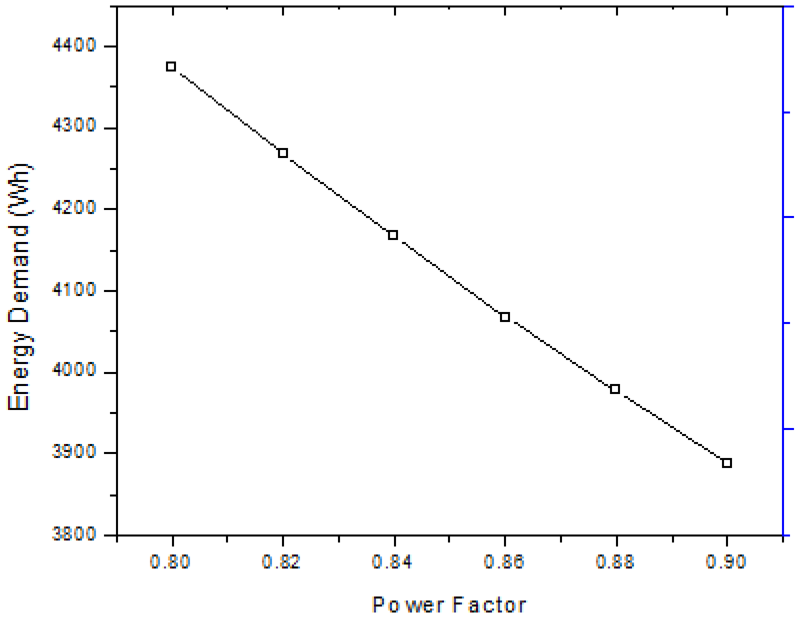

Figure 3: Energy Demand against the Power factor of the System

Connection between the Load System and Power Factor

In a solar PV design, the load system refers to the electrical appliances or devices that are connected to the solar system and consume the electrical power generated by the solar panels. These appliances or devices can include lights, fans, refrigerators, televisions, and other household or commercial electrical equipment. To ensure the successful operation of a solar PV system, it is important to carefully consider the load system and its power requirements when designing and sizing the system. Figure 4 demonstrates the relationship between the Load system and the Power factor, indicating an inverse proportionality. This suggests that improving the system power factor enhances its efficiency. However, it is important for installers and engineers to thoroughly assess the inverter power factor before utilization, as it significantly impacts system efficiency.

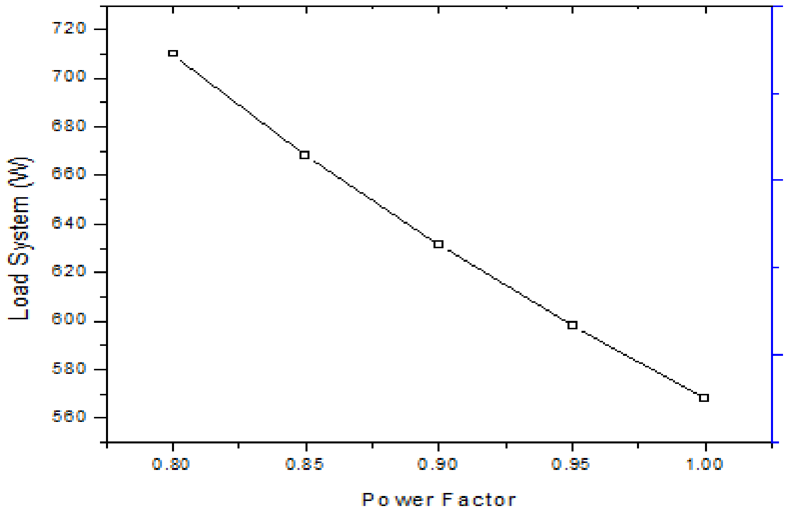

Figure 4: Load systems against the Power factor of the PV-System

Relationship between the System Peak Power and Sun Hours

To assess the effectiveness of a solar system in a specific location, it is essential to have accurate information about the amount of solar radiation received at that site. This energy is influenced by two primary elements: the extraterrestrial solar irradiance and the atmospheric conditions (Augustine & Nnabuchi, 2016). The extraterrestrial solar irradiance is the rate at which solar energy arrives on a horizontal surface at the top of the atmosphere. The amount of daylight varies based on the location's latitude, Earth's distance from the Sun, and the season. The level of solar radiation varies throughout the day, reaching a peak at noon and then returning to zero at sunset (Liou, 1980). However, in Delta State, the sun hour radiation ranges between 3 and 5 hours. Thus, understanding the correlation between the peak power of the system and sun hours is essential for assessing the efficiency of solar PV systems. Figure 5 depicts the correlation between the system's peak power and the geographical sun hour's radiation of the location. This relationship signifies the system's capacity to generate power based on sunlight duration; hence, more sun hours result in higher power generation while fewer sun hours lead to lower output. In essence, the availability and duration of sunlight directly impact the system's peak power.

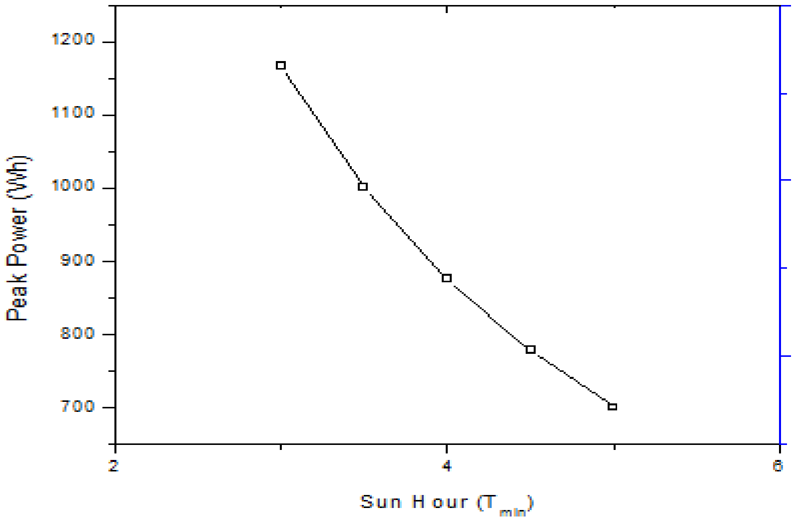

Figure 5: Peak Power against the Sun Hours of the System

Relationship between the numbers of panel and Sun Hours

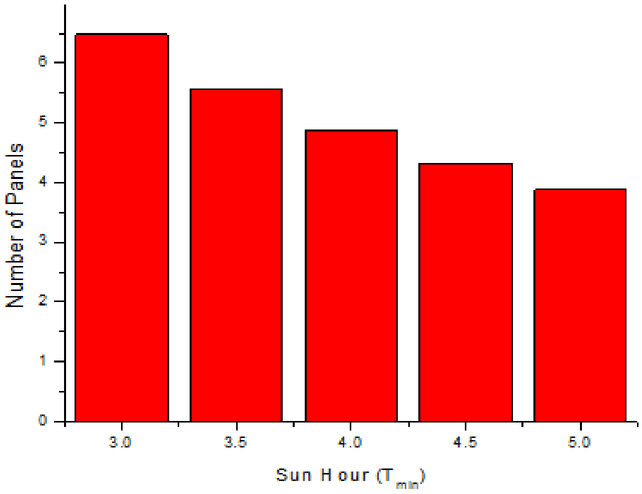

Figure 6: The Link between Sun hours and Number of Panels

The relationship between the number of panels and sun hours is a key factor to consider in the design and analysis of grid-connected micro-grid PV systems. By increasing the number of panels, the system can generate more electricity from sunlight during the hours when it is available. This can result in higher energy production and improved efficiency of the system. In addition, the relationship between the number of panels and sun hours also affects the overall capacity and reliability of the system (Chen et al., 2017). Therefore, it is important to carefully assess the sun hours in the specific location where the PV system will be installed and determine the optimal number of panels to achieve the desired level of energy production and system performance (Iqbal & Iqbal, 2019). Figure 6 illustrates the correlation between the number of panels in the system and the sun hour rating of the location. It is evident that as the sun hours decrease, more panels are required for efficient functioning of the system. This inverse proportionality should be carefully considered when optimizing panel numbers based on different locations.

Conclusion

The designed PV-system functioned efficiently and incurred no additional operating costs. In comparison to a 1.0 KVA petrol generator, it initially appeared more expensive due to the initial expenses involved. However, over time, it proved to be cost-effective as the system did not require petrol for operation but relied on sunlight, which is freely provided by nature. Consequently, there was no need to restrict or schedule power supply according to fluctuations in the grid electricity source.

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