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Article

# Harnessing Solar Energy for Sustainable Development in Rural Communities

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## Abstract

Providing electricity to remote villages remains a major challenge, especially in off-grid areas. This study explores the feasibility of using photovoltaic (PV) solar energy as a sustainable alternative to diesel generators. A comparative analysis assesses energy accessibility, reliability, cost-effectiveness, and environmental impact. The study focuses on a village in the Shariq al-Nil Khartoum - Sudan, where the absence of a centralized grid has led to reliance on expensive and polluting diesel power. Using MATLAB for simulations, Global Solar Atlas for meteorological data, and Homer for Hybrid system optimization, the research demonstrates that solar energy offers a more reliable and cost-efficient solution. The findings highlight the long-term benefits of solar power in supporting rural electrification, improving healthcare, education, and water access while reducing environmental harm. This study underscores the need for investment in renewable energy to enhance energy security and drive sustainable development in off-grid communities.

**Keywords:** renewable energy; sustainability; rural communities; photovoltaic (PV) systems; battery storage; solar irradiance

## 1. Introduction

Sudan is in northeastern Africa, encompassing a vast geographical area between latitudes 8° and 22° North and longitudes 22° and 38° East. The country is predominantly characterized by arid and semi-arid climatic conditions, with consistent and intense solar radiation throughout the year. With an average solar irradiation ranging between 5–7 kWh/m<sup>2</sup> per day, Sudan possesses substantial potential for harnessing solar energy as a sustainable and renewable power source. Despite this abundant solar resource, access to reliable electricity remains a significant challenge, particularly in remote and rural regions [1].

The demand for electricity in rural communities has been steadily increasing due to population growth, the expansion of agricultural activities, and the growing need for essential services such as healthcare, education, and clean water supply. However, the availability of conventional energy sources—such as diesel generators and grid-connected electricity—remains severely limited. High fuel costs, logistical challenges in transporting fuel to remote areas, and ongoing economic instability exacerbate the energy crisis. Furthermore, recent armed conflicts and the ongoing civil war have resulted in the destruction of nearly all major power generation infrastructure, leaving many regions without electricity. The collapse of the national grid and chronic fuel shortages have rendered conventional energy generation increasingly unreliable [2].

Given these challenges, solar energy emerges as the most viable and sustainable solution for electrification in off-grid and rural areas. Unlike diesel generators, photovoltaic (PV) systems require minimal maintenance, entail lower operational costs, and are not dependent on fuel availability. Solar energy systems can be rapidly deployed in isolated communities, offering a decentralized and

resilient energy solution. Moreover, advancements in solar technology, coupled with the declining costs of PV panels and batteries, make solar power more accessible and economically attractive than ever before [3].

To conduct a comprehensive and accurate analysis, this study utilized several software tools and datasets. MATLAB was employed to simulate and analyze the performance of energy systems, enabling precise modeling of generation, storage, and consumption patterns. High-resolution solar radiation and meteorological data for the selected village were obtained from the Global Solar Atlas, a World Bank-developed database, to ensure realistic assessments of solar energy potential. In addition, HOMER, a professional simulation software for renewable energy systems, was used to optimize the PV system design, evaluating parameters such as efficiency, battery storage capacity, and seasonal variations in energy production. Together, these tools enabled a detailed technical and economic comparison between solar energy and diesel-generated electricity [4].

The study focuses on a remote village in the Shariq al-Nil locality, characterized by scattered households and primarily agricultural livelihoods. The village currently relies on diesel generators, which are expensive to operate and frequently affected by fuel shortages. The lack of reliable electricity hampers the delivery of critical services, including healthcare, education, and water supply. By designing and simulating a PV system tailored to the village's specific energy requirements, this research aims to demonstrate the cost-effectiveness, reliability, and environmental sustainability of solar power solutions [5].

A key component of this analysis involved assessing energy consumption patterns and peak demand scenarios. MATLAB was used to generate load profiles based on estimated electricity usage for households, irrigation systems, and communal facilities. HOMER simulations provided insights into optimal PV system sizing, battery requirements, and projected energy output under various weather conditions. Meanwhile, seasonal solar data from the Global Solar Atlas was instrumental in evaluating solar energy availability throughout the year [6].

Beyond technical feasibility, the study also examines economic and environmental aspects. The Levelized Cost of Electricity (LCOE) was calculated for both solar and diesel systems, accounting for capital expenditures, operating costs, and maintenance. The environmental impact was analyzed by comparing CO<sub>2</sub> emissions from diesel generators with those from PV systems. The findings are intended to support policymakers, investors, and local authorities in implementing sustainable electrification strategies for rural Sudan [7].

This research presents a thorough comparison between solar PV systems and conventional diesel generators in a remote Sudanese village. By integrating advanced simulation tools and high-resolution climate data, the study offers valuable insights into the potential of solar energy as a reliable and economically viable solution for off-grid communities. The results contribute to ongoing efforts to expand rural electrification, improve energy access, and promote environmentally responsible energy solutions in Sudan [8].

In many rural communities, limited access to electricity continues to hinder economic development, healthcare services, and educational opportunities. Sudan, endowed with vast solar potential, stands at a pivotal juncture where renewable energy could transform rural electrification. As the country grapples with fuel shortages and the destruction of its traditional power infrastructure, solar energy emerges as a practical and sustainable alternative. Transitioning from diesel-based systems to PV solar power is not merely a technical upgrade—it represents a shift toward greater sustainability and economic resilience.

Several previous studies have examined the feasibility and advantages of solar energy in Sudan. For instance, Abdelgadir and Abdelrahman (2017) demonstrated through MATLAB modeling that solar power is a more sustainable and cost-effective alternative to diesel generators in the eastern and northern regions of the country. Ali et al. (2019) utilized Polysun software to design solar-powered systems for off-grid villages, highlighting their economic viability in areas with abundant sunlight. Mohamed and Osman (2020) conducted a comparative study using the Global Solar Atlas and MATLAB, concluding that solar PV systems significantly reduce energy costs and dependence on fuel [9].

Further research by El-Sayed and Hassan (2021) explored the use of solar-powered water pumping systems to support agriculture and improve access to water, with positive impacts on health and economic well-being. Abdallah and Mohamed (2022) confirmed that integrating PV systems in rural health clinics enhances the reliability of power supply for medical equipment. Mohamed Gmal (Osman, 2021) emphasized the role of solar energy in strengthening energy security and supporting sustainable development in rural communities, while his subsequent work (Osman, 2022) demonstrated the long-term financial advantages of PV systems despite their higher initial investment costs [10].

Additional studies, such as those by Khalil and Nasser (2018), Ibrahim et al. (2019), and Mohamed and Ahmed (2020), underscored the feasibility of solar energy for rural development, its reliability in the face of logistical fuel challenges, and its positive socio-economic impacts. Salah and Shamsuddin (2021) validated the effectiveness of solar energy in powering off-grid electrification projects, and Ahmed and El-Mahdi (2022) explored how solar access can empower rural women through improved business, education, and healthcare opportunities [11].

Collectively, these studies highlight the pivotal role solar energy can play in overcoming Sudan's rural electrification challenges and advancing sustainable development. However, the significance of this research lies in its focused comparative analysis of solar PV and diesel generators for a specific rural Sudanese village. By leveraging advanced tools such as MATLAB, HOMER, and the Global Solar Atlas, this study delivers a detailed assessment of technical feasibility, economic efficiency, and environmental impact. Its findings aim to guide stakeholders in adopting more sustainable, affordable, and reliable energy solutions tailored to the needs of Sudan's off-grid communities [12].

## 2. Materials and Methods

### 2.1. System Configuration and Installation

A photovoltaic (PV) system functions through an organized process that ensures the efficient conversion of solar energy into usable electricity. **Figure 1** presents a detailed flowchart illustrating this energy transformation cycle, which includes essential stages such as solar radiation absorption, energy conversion, storage, and final distribution for consumption.

The process begins with PV panels capturing sunlight and converting it into electrical energy. This generated electricity can then be stored in batteries or alternative storage systems to maintain a consistent power supply. Subsequently, the stored energy is distributed to various applications, thereby enhancing the overall efficiency and reliability of the system. By visually representing these interactions, the flowchart in **Figure 1** serves as a valuable tool for understanding the functionality and operational dynamics of a PV system, highlighting its effectiveness in sustainable energy utilization [13].

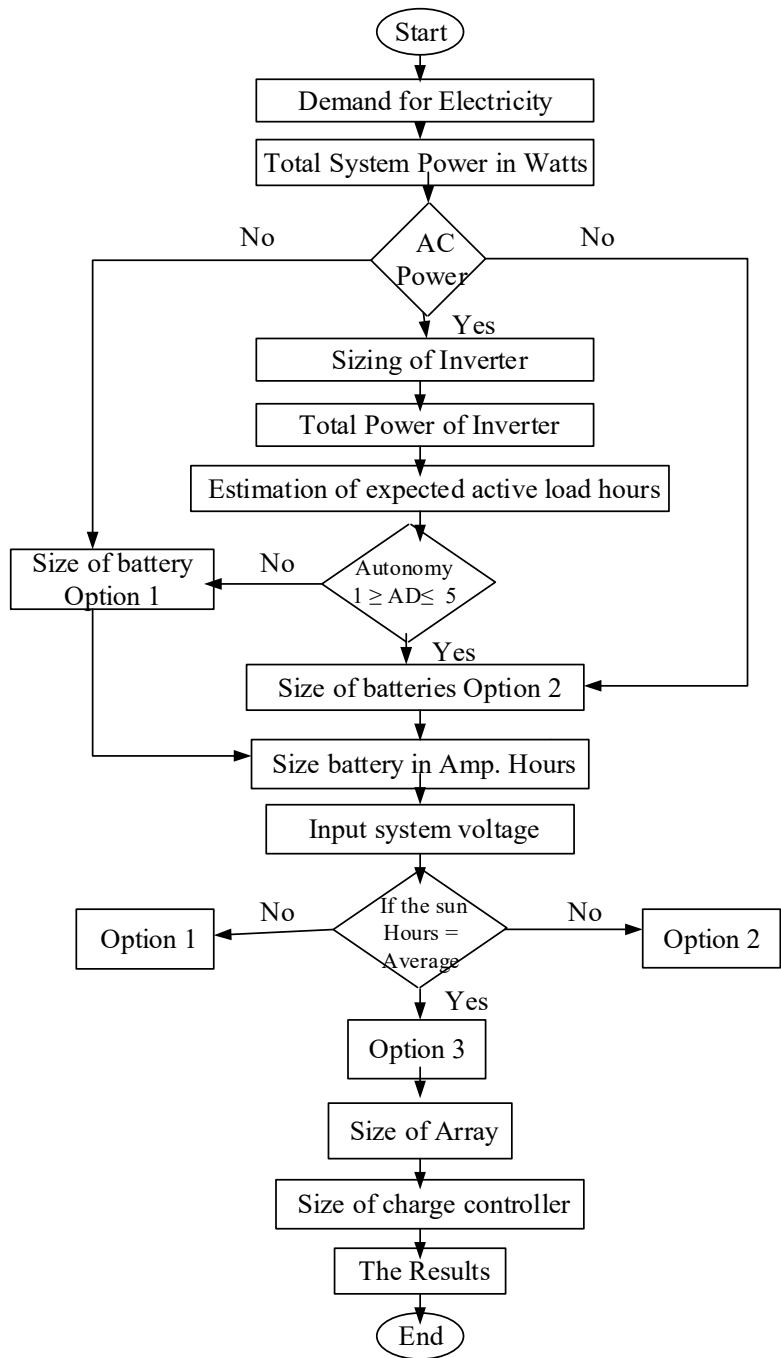


Figure 1. Flow chart of PV system.

2.2. Geographical Context

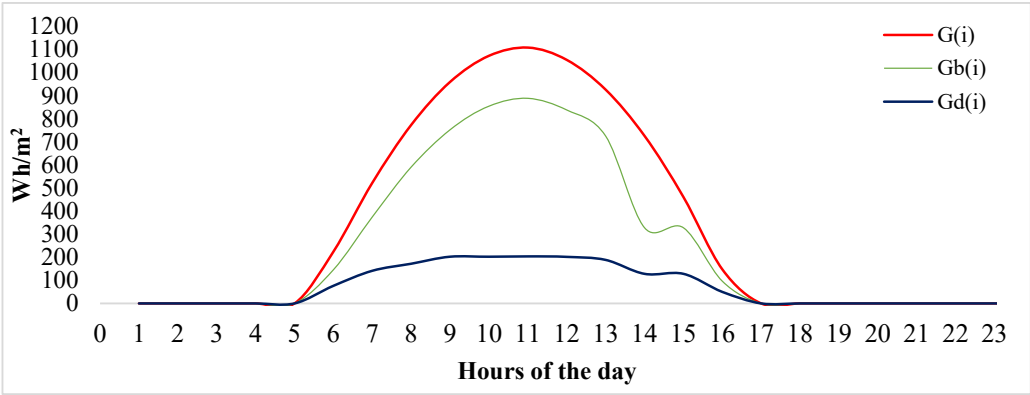
Khartoum, the capital city of Sudan, is administratively divided into six regions, one of which is Shariq al-Nil. This region is the largest in area yet remains the least developed, comprising numerous small agricultural villages that are not connected to the national electricity grid. These villages are modest in size, typically spread over an area no greater than 50 kilometers in diameter and rely mainly on local resources to meet their basic needs.

This study concentrates on one of these villages, which is currently unconnected to the national power grid and relies solely on diesel generators for electricity. However, the village’s geographic

location and climatic conditions make it particularly suitable for photovoltaic energy solutions. It lies at approximately 15.61° latitude and 32° longitude.

The village is home to an estimated 250 people, distributed among 30 family households. The community also includes a small supermarket and a medical center. Each family cultivates around three feddans of land, amounting to a total agricultural area of approximately 3.8025 square kilometers. In this rural context, three feddans per household is considered the minimum land area necessary for self-sufficient living [14].

Located in the sub-Saharan belt, Sudan benefits from high levels of solar radiation, with values reaching up to 1100 Wh/m², as illustrated in **Figure 2**.



**Figure 2.** Solar Energy Distribution (Wh/m²).

**Figure 2** depicts the distribution of solar energy received per square meter over a specific period. In this context, G(i) represents the global irradiance, while Gb(i) refers to the direct irradiance. The figure illustrates the changes in solar radiation intensity, offering a clear understanding of how solar energy availability fluctuates throughout the day or during designated intervals. Such information is crucial for evaluating the practicality and performance of photovoltaic systems, as it directly influences their energy output and overall efficiency [15].

3. Load Demand Requirements

The energy demand in this remote village is largely determined by fundamental needs such as water pumping, household lighting, and climate control through cooling and heating. A detailed breakdown of power consumption for various facilities is presented in **Table 1**.

**Table 1.** Total load of the village.

Load	No	(W)	Total Installation Load (W)
House	30	3000	90000
Street	1	600	600
Medical	1	1300	1300
Supermarket	1	200	200
Pump Water	2	11000	22000
Total Load			114100

3.1. Pumping Loads

The water demand per feddan varies throughout the year, ranging from 13 cubic meters per day during the winter season to 25 cubic meters per day in the summer. This seasonal fluctuation is also reflected in solar insolation, which decreases in winter and increases in summer, with values ranging between 4.8 and 10 kWh/m²/day. Under the most critical conditions when water consumption is high



and solar irradiance is at its minimum the total peak energy demand for the entire area is estimated at approximately 242 kWh, with a maximum power requirement of around 22 kW [16].

3.2. Household Loads

Household electrical loads play a vital role in determining the overall energy consumption within residential units. For this analysis, each household is assumed to have an estimated total load of 3 kW. **Table 2** outlines the load distribution for a typical home, providing details on the number of appliances, their individual power ratings, and the total installed capacity for each category of usage [17].

Table 2. Load Installations House.

Load Type	No	(W)	Household Loads (W)
Boiler	1	1000	1000
Lamps	5	15	75
TV	1	50	50
Refrigerator	1	75	75
Iron	1	600	600
Washing Machine	1	250	250
Fan Ventilation	2	30	60
Other	2	450	900
Installation Power			3010

As shown in **Table 2**, the total installed power amounts to 3010 watts. The highest hourly energy demand occurs during daytime hours, reaching approximately 1155 watt-hours. The total energy consumption over a full day is estimated at 11.017 kilowatt-hours. These figures are essential for accurately determining the required energy supply and distribution for each household. The load profile is illustrated in **Figure 3**.

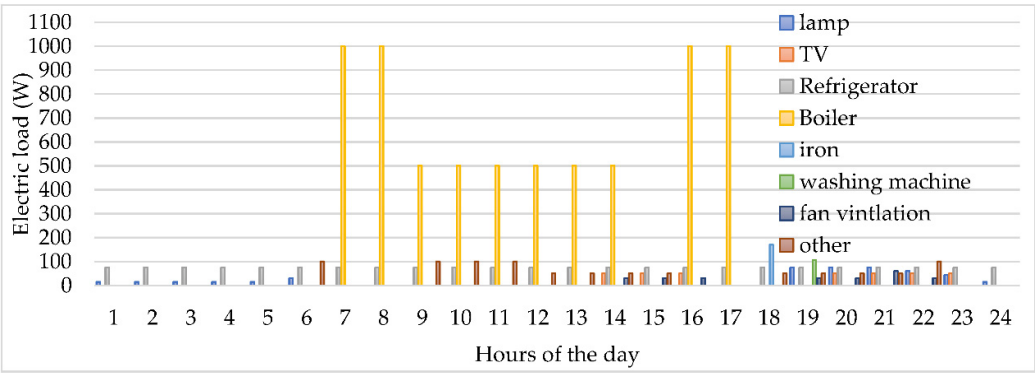


Figure 3. Household Load Demand Distribution Over 24 Hours.

3.3. Street Lighting Load

A total of fourteen light poles are installed along the village streets, each fitted with energy-efficient fluorescent or sodium lamps that deliver a minimum luminous output of 1200 lumens. These lamps function during both day and night, with an overall energy consumption of 600 watt-hours. During nighttime, an intelligent control system regulates their operation based on lighting needs, typically running for around 12 hours. Under these conditions, the maximum energy demand during the night reaches approximately 3.75 kilowatt-hours [18].

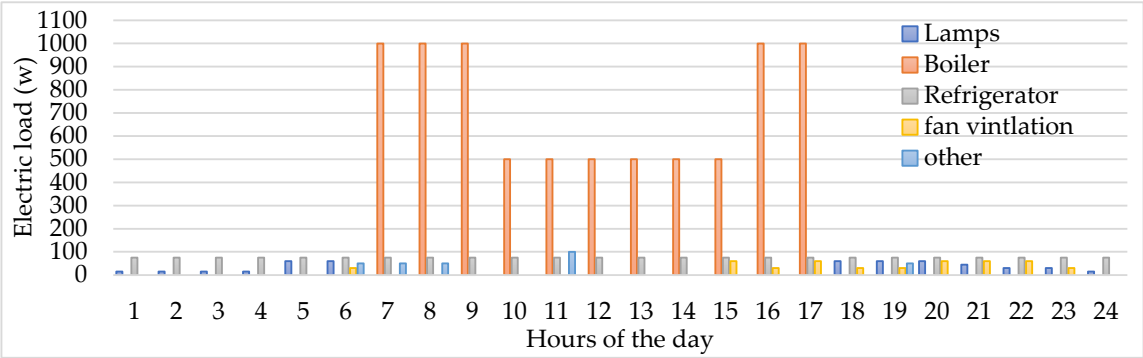
3.4. Medical Center

A small medical center serves as a vital facility within this remote community, providing essential healthcare services. The center's electrical load, outlined in **Table 3**, amounts to a total installed capacity of 1325 watts, consisting of a range of critical medical and support equipment necessary for its daily operations [19].

**Table 3.** Total Installations Power for Medical.

Load Type	No	W	Total Installations Power for Medical (W)
Boiler	1	1000	1000
Lamps	4	15	60
Refrigerator	1	75	75
Fan Ventilation	3	30	90
Other	1	100	100
Sum			1325

The 24-hour load demand profile reveals that the peak energy requirement reaches 1135 watt-hours, while the total energy consumption over the course of a day amounts to 11.03 kilowatt-hours. This distribution is visually represented in Figure 4.



**Figure 4.** Load Demand Consumptions Distributions Medical 24h.

3.5. Super Market

A small supermarket is considered an essential service within any village. In this study, it is represented with a total power load of 200 watts, comprising different categories of electrical appliances and equipment, as specified in **Table 4**.

**Table 4.** Total Installations Power for Super Market.

Load Type	No	(W)	Total Installations Power for Medical (W)
Lamps	2	15	30
Refrigerator	1	75	75
Fan Ventilation	1	30	30
Other	1	50	50
			185

The load distribution across a 24-hour period indicates that the highest hourly energy demand is approximately 135 watt-hours, while the total daily energy consumption is calculated to be around 2.210 kilowatt-hours.



3.6. Load Demand for All Village

The village under study comprises 30 residential homes. During daytime hours, the peak energy demand reaches approximately 57.860 kilowatt-hours, with a total daily consumption of 509.040 kilowatt-hours. At night, the peak demand is recorded at 11.060 kilowatt-hours, while the overall nighttime consumption amounts to 80.460 kilowatt-hours. **Table 5** provides a detailed breakdown of the village’s total energy demand [20].

**Table 5.** Load Demand distribution for the Village.

Hour s	Water Pump (W)	Total Houses (W)	Street (W)	Medical (W)	Super Market (W)	Total Consumption(W)
1	0	2700	150	90	75	3015
2	0	2700	150	90	75	3015
3	0	2700	150	90	75	3015
4	0	2700	150	90	75	3015
5	0	2700	300	135	90	3225
6	0	6150	150	215	115	6630
7	22000	32250	0	1125	75	55450
8	22000	32250	0	1125	75	55450
9	22000	20250	0	1075	75	43400
10	22000	20250	0	575	75	42900
11	22000	20250	0	675	75	43000
12	22000	18750	0	575	75	41400
13	22000	18750	0	575	75	41400
14	22000	21150	0	575	75	43800
15	22000	6150	0	635	105	28890
16	22000	34650	0	1105	105	57860
17	22000	32250	0	1135	105	55490
18	0	8850	0	165	130	9145
19	0	10110	600	215	135	11060
20	0	8400	600	195	135	9330
21	0	9300	600	180	120	10200
22	0	9450	450	165	90	10155
23	0	5100	300	135	90	5625
24	0	2700	150	90	90	3030
Sum	242000	330510	3750	11030	2210	589500
Night						80460
Day						509040

4. Determining the Size of the Solar Array and Designing the System

Designing a photovoltaic (PV) system involves careful planning and equipment selection based on factors such as location, solar radiation, and energy storage needs. In off-grid regions of Sudan, all electricity must be produced and stored locally to ensure a stable supply, especially during the night or cloudy periods. Therefore, the system must be sized to handle maximum demand during times of minimal solar generation. Proper system sizing establishes the required voltage and current ratings for each component, accounting for installation and operational costs [21].

Key Factors Influencing System Sizing:

*Load Profile:* Determined by listing all household appliances and their daily usage in watt-hours.

*Panel Positioning:* Affects tilt angle, orientation, and daily solar exposure.

*Home Design:* Optimizing sunlight exposure by clearing the southern side, orienting windows southward, and using good insulation reduces energy loss.

*Energy Efficiency:* Using low-consumption appliances such as CFLs helps minimize energy needs. Cooking and water heating can be handled separately using gas or thermal systems.

*Appliance Type:* Choosing low-voltage DC appliances reduces system cost and minimizes the need for high-rated inverters.

*Startup Loads:* High-surge appliances like refrigerators and pumps require special consideration due to their high initial current draw [22].

#### Solar Array Dimensioning

Calculate the average number of hours in the sun each day ( $T_{min}$ ) and the amount of energy used each day in Watt-hours (E) before designing the array. To determine losses and acquire the necessary energy, to avoid under-sizing, divide the total daily power consumption in watt-hours by the product of all individual efficiencies within the system .

$$E_{Array} = \frac{\text{daily average energy consumption}}{\text{product of component efficiencies}} \quad (1)$$

Divide the preceding value by the mean number calculate the maximum available power by multiplying the number of sunlight hours per day for the geographical region by  $T_{min}$ . [5].

$$P_p = \frac{\text{daily energy requirement}}{\text{minimum peak sun} - \text{hours per day}} \quad (2)$$

To find the total required current, simply divide the maximum power by the system's DC voltage.

$$I_{dc} = \frac{\text{peak power}}{\text{system DC voltage}} \quad (3)$$

To get the required voltage and current, units should be linked in series and parallel as needed. Use the formula: Divide the total DC voltage of the system by the rated voltage ( $V_r$ ) of each individual module to calculate the number of series modules.

$$N_p = \frac{\text{whole module current}}{\text{rated current of one module}} \quad (4)$$

Ultimately, the sum of the series and parallel modules equals the overall number of modules,

$$N_m = \text{The count of modules in series and parallel configuration} = N_s \times N_p \quad (5)$$

The PV module chosen in this study is Monocrystalline photovoltaic solar panel Longi LNGLR4-72HPH-455M, 144 cells, 455 W455M. It has 144 cells (6x24) monocrystalline type and provides an upper limit of 455 watts for the power output monocrystalline panel is a high one of approx. 20.9%, with very little energy loss. LNGLR4-72HPH-455M has a very big advantage compared to other photovoltaic panels, and this consists in the fact that it minimizes the impact of microcracks, showing a high tolerance to shading. The innovative technology offers superior performance and low radiation both mornings, evenings, and overcast days [6], [7].

The panel is 209.4 cm x 103.8 cm x 3.5 cm, Also, the panel helps to increase energy production, increasing the general effectiveness of the PV system. The load borne for the snow is quite important, namely 5400 Pa (on the front of the panel), and the wind load is up to 2400 Pa (behind the panel). The degree of protection is guaranteed by the IP 68 standard, the panel being resistant to adverse weather conditions, such as water and dust. The frame of the panel is made of anodized aluminum, and the surface of 3.2 mm tempered glass. The dimensions are: 209.4 x 103.8 x 3.5 cm,

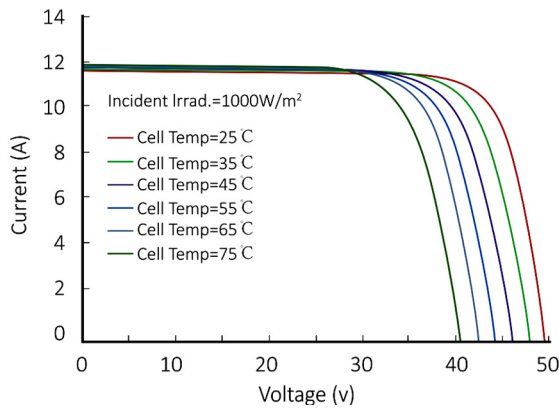


Figure 5. Current- Voltage Curve.

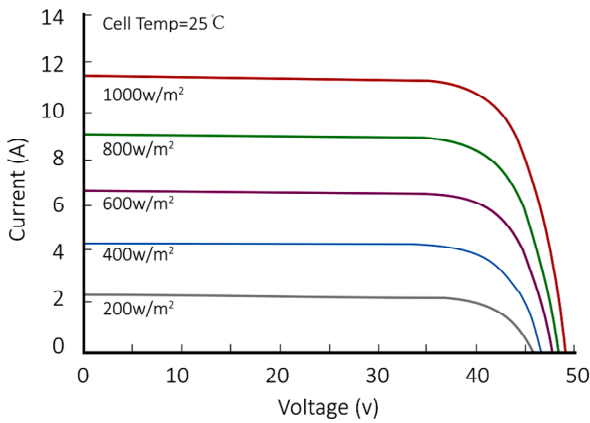


Figure 6. Current- Voltage Curve.

A Current-Voltage (I-V) curve is a graphical representation of the relationship between the current passing through panel and the voltage applied across it. **Error! Reference source not found.**depicts a specific I-V curve relevant to a system [23].**Error! Reference source not found.**depicts the Current-Voltage (I-V) curve of a solar cell. This curve is crucial in understanding the behavior and performance of solar cells under different operating conditions. **Error! Reference source not found.** Represent the Electrical and mechanical characteristics of the panel [7].

Table 6. Electrical and mechanical characteristics.

Testing Condition	STC	NOCT
Power greatest (Pmax/W)	455	339.8
Voltage on an open circuit (V <sub>oc</sub> /V)	48.5	46.4
Current on a short circuit (I <sub>sc</sub> /A)	12.66	9.43
The highest possible voltage (V <sub>mp</sub> /V)	42.7	38.8
current (I <sub>mp</sub> /A) at highest power	11.92	8.75
Efficiency of the module (%)	20.9	

*Standard Test and Operating Conditions:*  
Under Standard Test Conditions (STC), the panel operates at an irradiance of 1000 W/m², with a cell temperature of 25°C, and solar spectrum measured at AM1.5. Under Normal Operating Cell Temperature (NOCT), irradiance is 800 W/m², ambient temperature is 20°C, and the spectrum remains at AM1.5, with a wind speed of 1 m/s.

*Panel Construction and Cable Specifications:*

The module features a 4 mm<sup>2</sup> output cable, 1400 mm in length. Its frame is built from anodized aluminum alloy, while the front surface is made of 3.2 mm tempered glass. The panel operates within a temperature range of -40°C to +85°C and weighs 23.5 kg.

*Panel Quantity and Cost:*

Using the Longi LR4-72HPH-455M model (455W, 144 cells), each building requires 8 panels. For 33 buildings (30 houses, a clinic, a supermarket, and public lighting), the total number of panels is 264. At a cost of 100 USD per panel, the total investment in PV panels is approximately 26,000 USD.

*Battery Bank Sizing:*

The required battery storage capacity is calculated by multiplying the total daily energy consumption by the number of autonomy days (days without solar production). The result is then divided by the maximum allowable depth of discharge to ensure safe and efficient battery operation.

$$E_{safe} = \frac{\text{energy storage required}}{\text{maximum depth of discharge}} = \frac{E_{rough}}{MDOD} \text{ (W)} \quad (6)$$

To determine the nominal voltage ( $V_b$ ) of each battery to be used in the battery bank, we need to decide based on the required safe energy storage. This can be achieved by dividing the necessary safe energy storage by the DC voltage of one of the chosen batteries, resulting in the required capacity of the battery bank in ampere-hours (C)[9]

$$C = \frac{\text{safe energy storage required}}{\text{battery voltage}} \frac{E_{safe}}{V_b} \quad (7)$$

Once the capacity of the battery bank has been determined, the capacity ( $C_b$ ) of each individual battery within the bank needs to be established. Based on the battery voltage rating and system requirements, the battery bank is constructed by connecting batteries in both series and parallel configurations [24]. To calculate the total number of batteries required, the capacity of the battery bank (C) in ampere-hours is divided by the capacity of one of the selected batteries ( $C_b$ ):

$$N_{batteries} = \frac{\text{capacity of the battery bank}}{\text{capacity of one battery}} = \frac{C}{C_b} \quad (8)$$

At that point, it is simple to ascertain the battery bank's arrangement[10]. The rating of the voltage of one selected battery is subtracted by the system's DC voltage to obtain the number of batteries  $N_s$  linked in series:

$$N_s = \frac{\text{the system DC voltage}}{\text{battery voltage}} = \frac{V_{DC}}{V_b} \quad (9)$$

The number of parallel paths  $N_p$  is then calculated by dividing the total number of batteries by the number of batteries connected in sequence [11].

$$N_p = \frac{\text{the total number of batteries}}{\text{number of batteries in series}} \quad (10)$$

We will move on to the next system component as soon as the bank's battery size is known.

According to the system the battery size is approximative  $80000 / 12V = 6600Ah$ . In this system we can use 100Ah. Number of batteries = 66 batteries.

Lithium Battery 12V, 100Ah Storage Box Case Organizer Apply for Energy Solar, off grid, RV, etc.[12]. One battery cost \$75, making the total cost of the purchase \$5000.

*Sizing of the Voltage Regulator*

Its job is to control the flow of current. The highest current of the arrays and the maximum current of the load must both be tolerated by an effective voltage regulator. [13]. A safety factor  $F_{safe}$  can be used to double the short circuit current of the parallel modules. The rated current  $I$  of the voltage controller is the outcome:

$$I \text{ Safety factor for short circuit current in parallel modules} = N_p \times I_{sc} \times F_{safe} \quad (11)$$

where  $N_p$  is the number of parallel modules,  $I_{sc}$  is the short-circuit current of an individual module, and  $F_{safe}$  is the safety factor. The safety factor is utilized to guarantee that the regulator can

handle the highest current produced by the array, which could surpass the calculated amount. It also allows for the addition of new equipment or a larger load current than originally anticipated. This safety factor essentially permits a little system growth [25].

*Sizing of the Inverter*

Figuring out how much power the appliances that will be operating simultaneously actually need is a crucial first step in sizing the inverter [14]. Secondly, we must double the power of big motors by three to account for their beginning current. The two preceding numbers are then added together and multiplied by 1.25 as a safety precaution to allow for system growth[15]

Based on the load, a Solar Hybrid Inverter with an output power of 800W in each building is deemed suitable. The cost of each inverter is 100USD which included 33 inverters costing \$3300 USD in total. The technical specification of the inverter as shown in Error! Reference source not found.

**Table 7.** Technical specification Solar Hybrid Inverter.

Nature of Source Flow:	Active Inverter
Model No.	VG1012
Key Features	Energy-saving Solar Inverter and Hybrid Inverter
Application	Residential Solar Power Systems
Circuit Topology	Full-Bridge Type
Rated Power	800W
Voltage	220VAC
Frequency	50/60Hz
Output Voltage Regulation	±10%
Efficiency	>98%
Input/output Protection	Circuit Breaker
Low-Level Disconnect (Selectable)	20V or 21V
PWM Controller Voltage	30VDC–60V <sub>DC</sub>
Max PV Open Circuit Voltage	PWM: 60V <sub>DC</sub> , MPPT: 150V <sub>DC</sub>
Max Solar Charge Current	60A
Protections	Overload, Over Temperature, Overcharging, Low Battery, Battery Reverse Connection, High AC Voltage, etc.
LCD Indicator Status	AC Input Voltage, AC Input Frequency, PV Voltage, PV Current, Output Voltage, Output Frequency, etc.
LED Indicator Status	AC Line In: Green/Inverter: Green/Charging: Yellow/Alarm: Red
Temperature	0-40°C
Humidity	-10°C~90°C Noncondensing
Packing Size (LWH)	470335210mm

Error! Reference source not found. outlines the technical specifications of the Solar Hybrid Inverter (Model No. VG1012), featuring key attributes such as rated power, voltage, frequency, efficiency, input/output protection, and various alarm indicators.

*Diesel Generator Group*

The same life cycle cost analysis is used to determine the cost of 80 kWh generated considering the following remarks:

- It is necessary to use five separate diesel units, one as reserve, which will increase the kWh cost of diesel [16]. At the same time, due to the minimum practical size for small loads, diesel generators are often oversized, as in our case. Due to oversizing, the diesel generator runs with low utilization, which in addition to the frequent need for spare parts and overhauls leads to an increase in maintenance and repair costs [26].

The five diesel it consists of 2 x 5 kW+3x20kW= 70kW  
5kW diesel generator

Soundproof single-phase diesel generator 5kW, 18A, 3000rpm, engine YD186FAG, Stager YDE7000TD.

20kW diesel generator

Table 8. Technical specification of 20 kW diesel generator.

Nominal power	20kVA	Dimensions (LxWxH)	1890*910*1160 mm
Maximum power	22kVA	Net weight	830 kg
Nominal voltage	(AC) 230V	Starting system	12V Electric
Power factor (cos Φ)	1	Compression ratio	18.2:1
Rated current	86.9 A	Cylinder capacity	2.672 L
Nominal frequency	50 Hz	Oil bath capacity	7.6 L
Tank capacity	92 L	Insulation grade	H
Noise level (LWA)	93 dB(A)	Product code	11580000225

**Error! Reference source not found.** The technical specifications of the 20-kW diesel generator, priced at \$10000 USD per unit, detail its rated power and fuel type as diesel. When considering the total cost for five generators, including the cost of diesel, the sum amounts to \$34000 USD [27].

System Components Summary

The equipment needed to construct the standalone photovoltaic system for the hypothetical distant home mentioned above is included in Error! Reference source not found. together with certain specs and details. This is not the only equipment’s on the market, and there are many manufacturers who sell them.

Table 9. Summary of the System Components.

Component	Model	Component Rating			Size (inch)	Unit Price USD	Total Price	Warranty
		W/Ah	A	V				
Panels	Longi LNGLR4-72HPH-455M	455 /339W	10.92/8.75	41.7/38.8	209.4 x 103.8 x 3.5 cm	100	26000	25
Batteries	Lithium Battery	100 Ah	~	12	3.3x1.7x2.2	75	5000	2
Inverter	VG1012	800W	~	24/220	4.7x3.35x2.1	100	3300	5
Wires	#02 AWG				Diameter= 6.54 mm, Area= 32.0 mm²	50	100	
	#10 AWG				Diameter= 2.59 mm, Area= 5.27 mm²	50	100	
Diesel	Stager	5000	18	230	9.50 x 5.50 x 7.65	2000	4000	2
Diesel	Stager	20000	86.9	230	18.9x9.1x11.6	10000	30000	2

This means that equipment ratings and prices will differ. However, to achieve optimal performance, equipment ratings, quality, and prices are used to select this equipment.

Cost estimate of the system



The equipment used in the system costs a total of 34300USD PV and 34000 USD diesel. Additional costs must be added for design, labor, wiring, metering, monitoring, disconnect devices, and shipment, this additional expense is estimated to cost 4000USD on diesel.

5. System Design and Simulation

The proposed system includes solar panels, inverters, and supporting components designed to convert solar energy into usable electricity for the village. The system’s size is based on local energy demand, available solar radiation, and other design considerations.

5.1. Battery Backup

The battery bank stores excess solar energy, ensuring a steady power supply during the night or cloudy conditions. It also serves as a backup during outages. Its capacity is determined by daily energy needs, surplus solar generation, and the desired level of energy autonomy [28].

5.2. Auto-Sizing Diesel Generator

An auto-sizing diesel generator is included to meet demand when solar output is insufficient. It adjusts its output based on the system's needs, improving efficiency and reducing fuel use. Generator sizing is based on the energy gap not covered by the PV system.

5.3. Hybrid System Optimization Using HOMER

HOMER software, developed by NREL, is used to design and optimize hybrid systems combining solar and diesel power. While solar panels provide clean energy during the day, diesel generators ensure reliability at night or in poor weather. HOMER helps balance performance, cost, and energy availability to create a reliable and sustainable system. **Figure 7** illustrates the overall system design [29].



Figure 7. Overall system design.

Using Homer, we can create a detailed model of our village's power system and optimize it to provide reliable and cost-effective electricity in Error! Reference source not found.. With this information, we can make informed decisions about the best way to power our village and ensure that it has access to electricity around the clock.

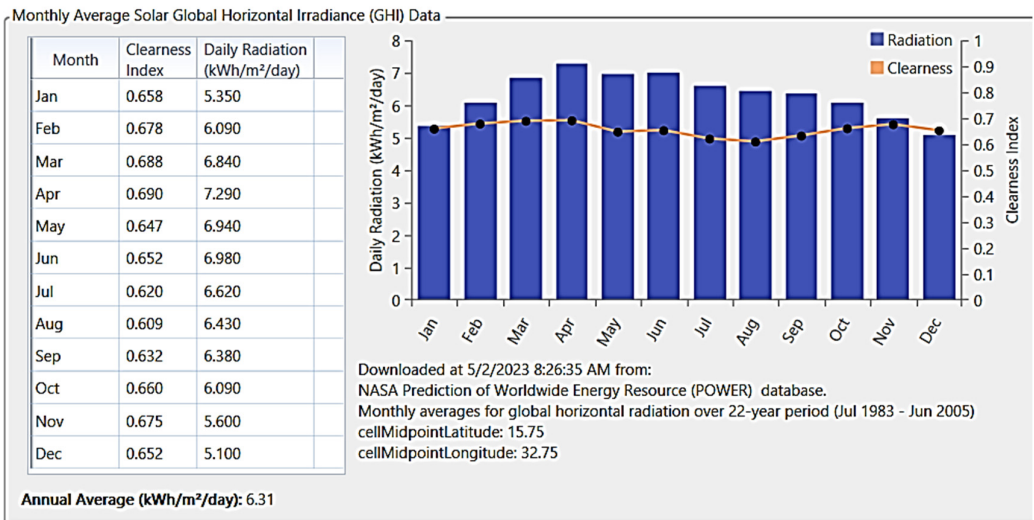


Figure 8. Monthly Average solar Global Horizontal Irradiation Data.

Error! Reference source not found. presents the monthly average solar global horizontal irradiation data. This data provides insights into the amount of solar radiation received on a horizontal surface over the course of each month. The values are typically measured in units (kWh/m<sup>2</sup>/day).

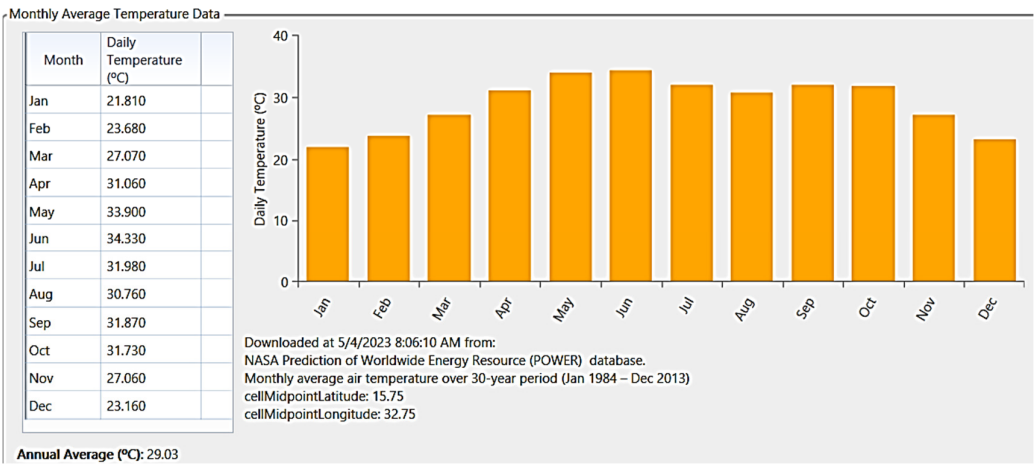


Figure 9. Monthly Average Temperature Data of the system.

Error! Reference source not found. presents the monthly average temperature data. This data provides insights into the average temperature recorded for each month over a certain period, typically measured in degrees Celsius.

The software has simulated and optimized the five different configurations of the hybrid power system that are designed.

5.4. The First Configuration

In this configuration, solar panels generate daytime electricity for the village and charge batteries. At night, batteries power lights and appliances. With a COE of \$0.673 per kWh and an NPC of \$1.58 million, the system prioritizes sustainability by emitting no carbon. While the COE is relatively high, the NPC suggests a significant upfront investment, potentially leading to long-term cost-effectiveness. Striking a balance between financial viability and environmental impact is essential for a reliable and cost-effective power solution [17].

Figure 10 displays the outcomes of a simulation conducted on the converter, likely showcasing various performance metrics, efficiency levels, and other relevant data obtained through the simulation process. Displays the outcomes of a simulation conducted on the converter, showcasing various performance metrics, efficiency levels, and other relevant data obtained through the simulation process [30].

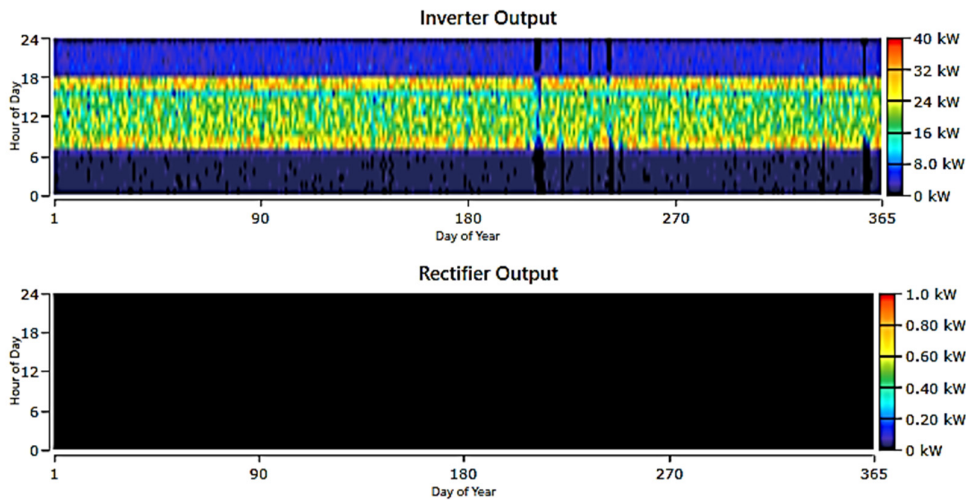


Figure 10. Simulation results of Converter.

Table 10. Specification of converter.

Quantity	Inverter	Rectifier
Capacity	35 kW	35 kW
Mean output	11.8 kW	0 kW
Minimum output	0 kW	0 kW
Maximum output	35.5 kW	0 kW
Energy in	109.172 kWh/Year	0 kWh/Year
Energy out	103.713 kWh/Year	0 kWh/Year
Hours of operation	8629 Hrs/Year	0 Hrs/Year

Based on the provided results in **Error! Reference source not found.** and **Error! Reference source not found.** we can conclude:

Capacity: The capacity of both the inverter and rectifier is 35kW. This indicates the maximum power they can handle.

Mean output: The mean output of the inverter is 11.8kW, while the rectifier does not provide any output.

Minimum output: Both the inverter and rectifier show a minimum output of 0kW.

Maximum output: The inverter's maximum output is 35.5kW, while the rectifier still shows 0kW. The inverter can generate up to its maximum capacity.

Energy in: The energy input is given as 109.172kWh per year. It indicates the amount of energy consumed by the system, possibly in the form of electricity supplied to the inverter and rectifier.

Energy out: The energy output is mentioned as 103.713kWh per year, it represents the amount of energy produced or delivered by the system.

Hours of operation: The system appears to operate for 8629 hours per year. This indicates the total duration of operation for both the inverter and rectifier [31].

Figure 11 provides a visual representation of the status of battery charging. This Figure likely includes information such as battery charge level, charging progress, and other associated indicators [32].

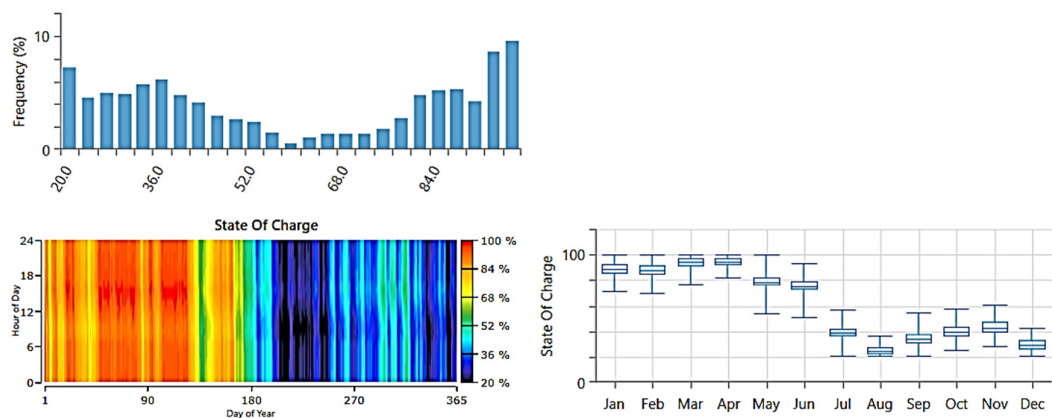


Figure 11. Status of Batteries charging.

Table 11. Specification of Batteries.

Quantity	Value	Units
Bus voltage	24	V
Nominal capacity	1613	kW/h
Energy in	37363	kWh/Year
Energy out	36706	kWh/Year
Operation hours	8473	Hours

From the results in **Error! Reference source not found.** and **Error! Reference source not found.** we can conclude:

- The bus voltage is indicated to be 24 V.
- The nominal capacity is defined as 1613 kW/h, representing the maximum capacity of the system's energy storage batteries.
- The energy input is documented as 37363 kWh/year, reflecting the total energy consumed throughout the year.
- The energy output is declared as 36706 kWh/year, representing the total energy delivered by the system over the year.
- The system has been operational for 8473 hours.

**Figure 12** depicts the annual performance of PV panels, showcasing their output or energy production throughout the year. **Figure 12** presents data on the variation in solar energy generation across different seasons and months.

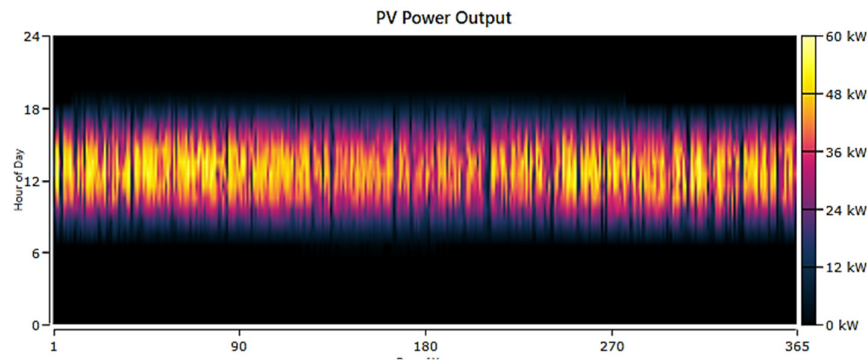


Figure 12. PV panel output over year.

Table 12. Specification of PV Panels.

Quantity	Value	Quantity	Value
Rated capacity	58.8 kW	Maximum output	57.3 kW
Mean output	307 kWh/day	PV penetration	106 %
Total production	112.017 kWh/Year	Hours of operations	Hours/Year
Minimum output	0 kW		

From the results provided in Error! Reference source not found. and Error! Reference source not found. we can conclude: The rated capacity is specified as 58.8 kW. This indicates the maximum power output or capacity of the system, typically associated with a solar photovoltaic (PV) installation.

The mean output is mentioned as 307 kWh per day. This represents the average energy output of the system over a day. It indicates the amount of energy generated by the PV installation on average.

The total production is stated as 112017 kWh per year. This value represents the overall energy output of the system over the course of a year.

The minimum output is given as 0 kW.

The maximum output is mentioned as 57.3 kW. This represents the peak power output that the system can achieve.

The PV penetration is stated as 106%.

The system has operated for 4361 hours in a year. This indicates the total duration of operation over the given period [34].

5.5. The Second Configuration

It is a hybrid power system that uses solar panels during the day and a diesel generator at night to provide power to the village. During the day, the solar panels generate electricity from the sun and power the village. At night, when the solar panels are not generating electricity, the diesel generator starts up and provides the energy needed to keep the lights on and run other electrical appliances.

In this scenario, the fact that there are carbon emissions associated with the system would be a disadvantage compared to the first option, which utilizes renewable energy sources and does not produce any carbon emissions. The COE value of \$0.935 per kWh and NPC of \$3.51 million would still be relevant for this option, but the carbon emissions should also be taken into consideration when evaluating the overall environmental impact of the system [35].

Figure 13 offers a concise overview of fuel consumption, potentially detailing usage patterns, total consumption, and other relevant metrics related to fuel usage.



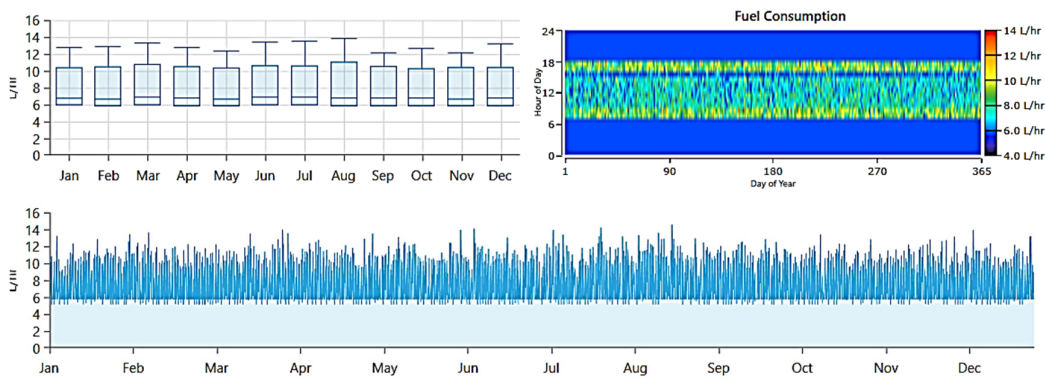


Figure 13. Fuel summary.

Table 13. Specification of fuel.

Quantity	Value	Units
Total fuel consumed	59780	L
Avg. fuel per day	164	L/day
Avg. fuel per hours	6.82	L/hours

Based on the data presented in **Error! Reference source not found.** and the information depicted in **Error! Reference source not found.**, we can draw conclusions:

The total fuel consumed is stated as 59780 liters. This represents the overall amount of fuel that has been consumed over a given period.

The average fuel consumption per day is mentioned as 164 liters/day. This value indicates the average amount of fuel consumed daily.

The average fuel consumption per hour is stated as 6.82 liters/hour. This Figure represents the average rate at which fuel is consumed within a single hour.

The provided quantities and units describe the fuel consumption of a system. It provides insights into the total fuel consumed, as well as the average fuel consumption per day and per hour. These metrics can be helpful in evaluating fuel efficiency, estimating fuel costs, or analyzing the performance of the system or machinery in terms of fuel utilization [36].

5.6. The Third Configuration

In this configuration, batteries and a diesel generator provide village power. Batteries charge during the day with diesel, ensuring reliable electricity. While emitting fewer carbon emissions than a primary generator, it relies on diesel, making it less environmentally friendly than solar-based options. The COE is 0.952\$ per kWh, lower than the second option. The NPC is \$3.83 million, higher than the first but lower than the second option. Factors like fuel cost, generator efficiency, battery capacity, and electricity demand impact the financial and environmental aspects, necessitating careful consideration for the most suitable option [37].

**Figure 14** visually represents the ongoing process of battery charging, offering insights into the current state of charge, charging progress, and another associated indicator.



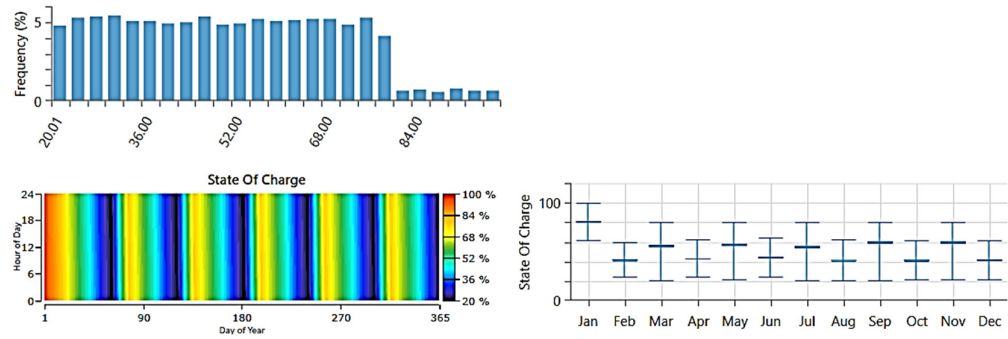


Figure 14. Status of Batteries charging.

Table 14. Specification of Batteries.

Quantity	Value
Batteries	88 Qty
Bus voltage	24 V
Nominal capacity	23654 kW/h
Energy in	72823 kWh/Year
Energy out	70821 kWh/Year
Operation hours	8760 Hours

Based on the data presented in **Error! Reference source not found.** and the information depicted in **Error! Reference source not found.**, we can draw conclusions:

- The system utilizes a total of 88 batteries.
- The nominal capacity is specified as 23654 kW/h, denoting the maximum capacity of the system or the energy storage capacity of the batteries.
- The energy input is documented as 72823 kWh/year, reflecting the total energy consumed or supplied to the system throughout the year.
- The energy output is indicated as 70821 kWh/year, representing the total energy generated or delivered by the system during the year.
- The system has been in operation for 8760 hours, representing the total duration of operation over a given period [38].

**Figure 15** provides a visual representation of the output performance of the converter. **Figure 15** likely includes data on voltage, current, power, efficiency, and other relevant parameters, offering insights into the overall performance of the converter under various operating conditions [39].

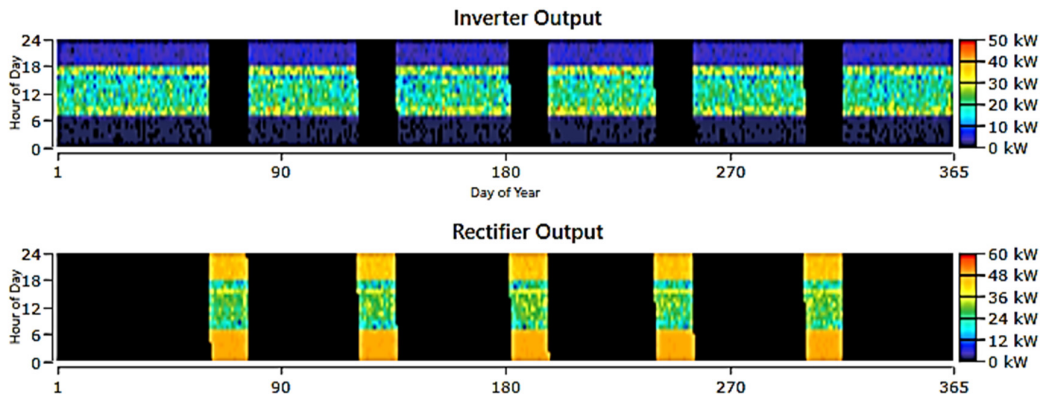


Figure 15. Performance of converter output.

Table 15. Specification of converter.

Quantity	Inverter	Rectifier	Units
Capacity power	53	53	kW
Mean output Power	9.48	8.31	kW
Minimum output Power	0	0	kW
Maximum output Power	47.7	50	kW
Energy in	87450	76656	kWh/Year
Energy out	83078	72823	kWh/Year

We can derive conclusions from the data provided in **Error! Reference source not found.** and the insights portrayed in **Error! Reference source not found.**

The capacity of both the inverter and rectifier is 53 kW. This indicates the maximum power they can handle.

The mean output of the inverter is 9.48 kW, while the mean output of the rectifier is 8.31 kW.

Both the inverter and rectifier show a minimum output of 0 kW.

The inverter's maximum output is 47.7 kW, while the rectifier's maximum output is 50 kW. These values represent the peak power outputs that the components can achieve.

The energy input for the inverter is stated as 87450 kWh/year, while the rectifier's energy input is 76656 kWh/year. These values indicate the total amount of energy consumed by each component over the course of a year.

The energy output for the inverter is given as 83078 kWh/year, while the rectifier's energy output is 72823 kWh/year. These values represent the total amount of energy produced or delivered by each component over the course of a year [40].

**Figure 16** provides an overview of the performance of the fuel, presenting data on parameters such as consumption rate, efficiency, emissions, and other relevant metrics related to the operation or utilization of the fuel source [41].

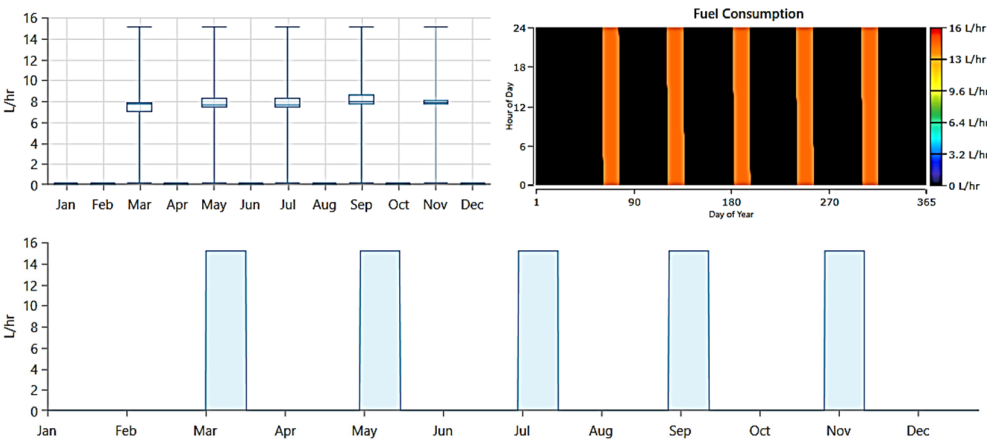


Figure 16. Performance of Fuel.

Table 16. Specification of fuel.

Quantity	Value	Units
Total fuel consumed	28470	L
Avg. fuel per day	78	L/day
Avg. fuel per hours	3.25	L/hours

Conclusions can be drawn from the data in **Error! Reference source not found.** and the details illustrated in **Error! Reference source not found.**

The total fuel consumed is stated as 28470 liters. This value represents the overall amount of fuel that has been consumed over a given period.

The average fuel consumption per day is mentioned as 78 liters/day. This value indicates the average amount of fuel consumed daily.

The average fuel consumption per hour is stated as 3.25 liters/hour. Figure 16 represents the average rate at which fuel is consumed within a single hour.

The provided quantities and units describe the fuel consumption of a system, vehicle, or machinery. It provides insights into the total fuel consumed, as well as the average fuel consumption per day and per hour. These metrics are helpful in evaluating fuel efficiency, estimating fuel costs, or analyzing the performance of the system or machinery in terms of fuel utilization [42].

5.7. The Fourth Configuration

This hybrid power system combines solar panels, batteries, and a diesel generator for reliable and sustainable electricity in the village. Solar panels generate daytime electricity and charge batteries for nighttime use. A diesel generator serves as backup, auto-sized based on demand for efficiency. This balance of renewable and backup power minimizes carbon emissions, with a COE of 0.912\$ per kWh and an NPC of 3.62\$ million. Although requiring a larger initial investment, the long-term cost-effectiveness and reduced reliance on diesel make it an environmentally friendly and reliable option [43].

Table 17. Specification of PV Panels.

Quantity	Value	Units
Rated Power capacity	58.8	kW
Mean energy output	291	kWh/day
Total energy production	106177	kWh/Year
Minimum output Power	0	kW
Maximum output Power	54.3	kW
PV penetration	100	%
Hours of operations	4361	Hours/Year

The specifications of the PV panels listed in Error! Reference source not found. include a rated capacity of 58.8 kW, with mean daily output reaching 291 kWh and total yearly production amounting to 106177 kWh, alongside a minimum output of 0 kW and a maximum output Power is 54.3 kW, achieving full PV penetration at 100%, operating for 4361 hours per year.

Figure 17 Illustrates the output of a photovoltaic (PV) panel over the course of a year, depicting variations in power generation influenced by factors such as solar irradiance, temperature, and daylight hours, which are crucial for understanding the performance and efficiency of solar energy systems.

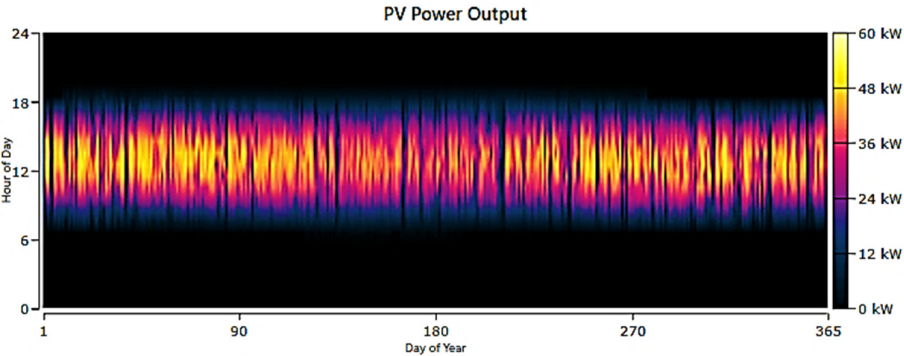


Figure 17. PV Panel output over year.

5.8. The Fifth Configuration

Using only a diesel generator for power is not recommended due to its environmental impact, high operating costs, and lack of sustainability. Relying solely on non-renewable energy sources contributes to pollution and climate change. Diesel generators are noisy, emit pollutants, and require frequent maintenance. Fluctuating fuel costs make long-term predictions challenging, especially for financially limited villages. This option has a high COE of 0.986 USD and NPC of 3.91 million USD, making it less economical and environmentally friendly compared to options incorporating renewable energy sources.

Table 18. Gas Emissions.

Quantity	Value	Units
Carbon Dioxide	156798	kg/year
Carbon monoxide	988	kg/year
Unburned Hydrocarbons	43.1	kg/year
Particulate Matter	599	kg/year
Sulfur Dioxide	384	kg/year
Nitrogen Oxide	928	kg/year

Shows the amount of carbon dioxide emitted is stated as 156798 kg/year. Carbon dioxide is a greenhouse gas primarily associated with the burning of fossil fuels. It is a major contributor to climate change.

The amount of carbon monoxide emitted is mentioned as 988 kg/year. Carbon monoxide is a toxic gas produced by incomplete combustion of carbon-based fuels. It is harmful to human health and can contribute to air pollution.

The quantity of unburned hydrocarbons emitted is provided as 43.1 kg/year. Unburned hydrocarbons are volatile organic compounds (VOCs) that are released during combustion processes. They can contribute to the formation of ground-level ozone and air pollution.

The amount of particulate matter emitted is stated as 5.99 kg/year. Particulate matter consists of solid or liquid particles suspended in the air. It includes fine particles (PM2.5) and coarse particles (PM10), which can have adverse effects on human health and contribute to air pollution [44].

The quantity of sulfur dioxide emitted is mentioned as 384 kg/year. Sulfur dioxide is a gas released during the combustion of fossil fuels, particularly those containing sulfur. It can contribute to respiratory issues, acid rain, and air pollution.

The amount of nitrogen oxide emitted is provided as 928 kg/year. Nitrogen oxides are produced during the combustion of fossil fuels and contribute to air pollution. They can react with other compounds in the atmosphere to form smog and contribute to the formation of acid rain.

**Table 19** Represent the total fuel consumed is stated as 59901 liters. This value represents the overall amount of fuel that has been consumed over a given period.

Table 19. Specification of fuel.

Quantity	Value	Units
Total fuel consumed	59901	L
Avg. fuel per day	164	L/day
Avg. fuel per hours	6.84	L/hours

The average fuel consumption per day is mentioned as 164 liters/day. This value indicates the average amount of fuel consumed daily.

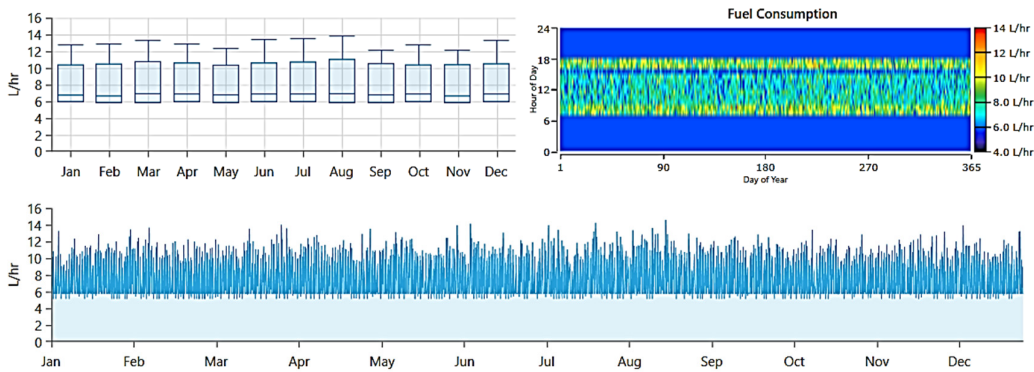


Figure 18. Fuel performance.

Error! Reference source not found. illustrates the performance of a fuel system over a certain period, providing insights into factors such as fuel consumption, efficiency, and emissions, which are essential for evaluating the effectiveness and sustainability of the fuel system.

The average fuel consumption per hour is stated as 6.84 liters/hour. Error! Reference source not found. represents the average rate at which fuel is consumed within a single hour of the generator output in one year.

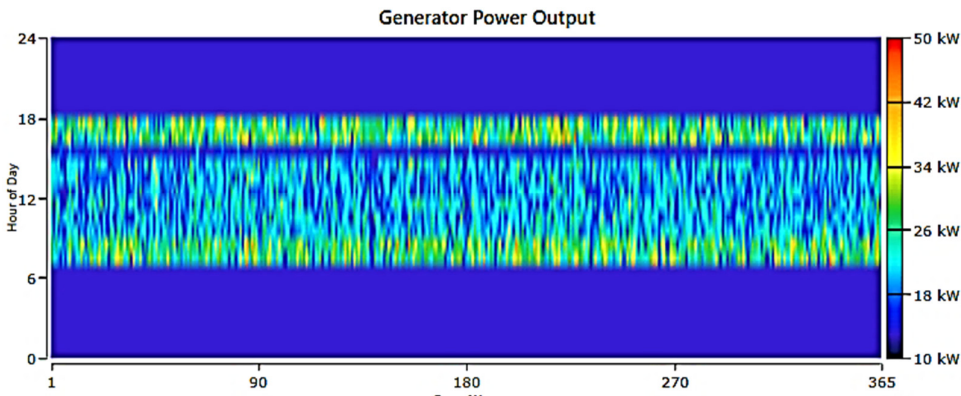


Figure 19. Generator output.

The evaluation using Homer software explored five options for village power. The most cost-effective and eco-friendly was the first option: a PV system with battery backup. However, the fourth option, combining PV panels and battery backup with diesel, also proved viable for emergency power. Other options had high costs or emissions. In our MATLAB code, parameters like energy demand and PV panel area were calculated. Costs for components like PV panels and batteries were factored in. Results showed a daily energy demand of 589.50 kWh, yearly demand of 215167.50 kWh, and system cost of 113500.00 USD. Solar energy emerged as a sustainable and cost-effective solution.

6. Conclusions

Our evaluation explored five distinct power generation options for a village, leveraging the capabilities of Homer software to assess feasibility. Among these alternatives, the standout choice was a photovoltaic (PV) system with battery backup—an option that proved to be both the most cost-effective and environmentally sustainable. As a secondary measure, the fourth option, which integrates PV panels, battery storage, and diesel backup, was identified as a reliable contingency plan,



particularly in emergency situations. In contrast, the remaining options were marred by prohibitively high operational costs, excessive carbon emissions, or both, making them far less viable.

The study begins by analyzing the load demand distribution across day and night periods, with maximum daytime consumption recorded at 57.860 kWh and total daily usage of 509.040 kWh, while nighttime consumption peaks at 11.060 kWh with a total of 80.460 kWh. Detailed hourly consumption patterns are presented for various village components, including residential, water pumping, street lighting, medical facilities, and a supermarket, offering a granular view of energy use. To address the village's energy requirements sustainably, a photovoltaic (PV) system with a capacity of 60 kW is proposed, supplemented by a solar thermal water heating system designed to meet hot water demands efficiently.

To further refine our analysis, we developed a MATLAB Code to designed to calculate key parameters, including annual energy demand, required PV panel area, battery storage capacity, total system cost, and energy cost per kilowatt-hour (kWh). The model operated under predefined assumptions about solar radiation and daily energy consumption, ensuring accurate estimations. Additionally, it accounted for the costs associated with core components PV panels, batteries, and inverters—allowing for a precise breakdown of overall system expenditure and energy costs.

MATLAB calculations yielded illuminating insights. The village's daily energy demand was estimated at 589.50 kWh, leading to an annual requirement of 215167.50 kWh. To meet this demand, the system would necessitate 34.6 m<sup>2</sup> of PV panel area, alongside a battery storage capacity of 6900 kWh. This setup would require 72 batteries to ensure uninterrupted operation. The total system cost was estimated at \$113500, with an energy cost of \$0.671 per kWh. Furthermore, the projected annual energy output stood at 12113.29 MWh, reinforcing the feasibility of the PV-based system.

Upon reviewing these findings, it became clear that the optimal solution for cost efficiency and sustainability is a combination of PV electricity generation and solar thermal panels for hot water supply. This hybrid configuration significantly reduces maintenance demands while maximizing energy output. The estimated initial investment for such a PVT system is \$15500, providing enough hot water for the entire village alongside a power output of 7.75 kW. By supplementing this system with an additional 22.5 kW from conventional PV panels at an added cost of approximately \$23000 the overall energy production capacity can be further enhanced.

This analysis highlights the clear advantages of solar energy, particularly when compared to hybrid or diesel-based alternatives. PV systems, coupled with solar thermal technology, not only offer lower operational costs and reduced maintenance requirements but also benefit from declining initial costs. In contrast, diesel-powered solutions face mounting challenges due to rising fuel costs, transportation logistics, and their negative environmental impact.

Ultimately, these findings underscore the viability of solar energy as a clean, sustainable, and economically sound alternative. With substantial cost savings, minimal environmental impact, and long-term reliability, solar energy emerges as the ideal solution for powering rural communities, ensuring a greener and more financially sustainable future.

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**Conflicts of Interest:** The authors declare no conflict of interest.



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