JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

DESIGN AND IMPLEMENTATION OF A SOLAR PHOTOVOLTAIC-WIND HYBRID SYSTEM FOR IRRIGATION AND ELECTRIFICATION IN RURAL SIERRA LEONE

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***Abstract*:** With less than 36% electricity access and 2% access in rural and farming communities, low food production and lack of viable options to irrigate, farmers in Sierra Leona face huge challenges. The solar PV-wind hybrid system designed in this study aims to improve this situation by providing a low-cost solution for irrigation and low-scale electrification and enabling year-around crop production on a plot of land in Fonima village, Northern Sierra Leone. The hybrid energy system comprises a 400 W solar PV system, 600 W wind turbine, a shared inverter, a shared charge controller and a shared battery bank. The wind turbine was fabricated using locally available materials and integrated with the solar PV system. The designed solar PV-wind hybrid system is now supplying power to a standalone drip irrigation system, indoor and outdoor light bulbs, and a mobile phone charging station in Fonima village, Northern Sierra Leone. This pilot project is expected to form a replicable model that can be used throughout all the villages of Sierra Leone. It is also expected to be a useful guideline in making investment decisions in hybrid irrigation and electrification systems.

***Index Terms* -** Fonima Village, Hybrid system, Irrigation, Solar Energy, Wind Energy.

INTRODUCTION

For decades, despite fluctuations in output, labor-intensive subsistence agriculture has maintained its dominant role in the economy of Sierra Leone, contributing 40 to 50% of the Gross Domestic Product and about 10% of exports [1]. Agricultural activity is carried out by nearly two thirds of the population in mainly small, family farms (with women as the predominant labour force), which use traditional methods with few inputs and a low degree of mechanization [2, 3]. Whilst agricultural growth has significant poverty reduction effects, the sector is characterized largely by smallholders, practicing mainly subsistence agriculture. Many technologies that have the potential to boost rural incomes require electricity, and only 2 per cent of the rural population has access to electricity compared to 51% for urban areas [4]. However, even in communities connected to the national grid, the quality and reliability of the electricity supplied is poor, leading to long and frequent power outages and/or poor quality of access.

The integration of renewable energy and irrigation systems can directly advance energy and food security. This can be achieved by meeting the current and future demand for both food and energy in a clean, environmentally sustainable, and inclusive manner, while contributing to climate resilience and adaptation. Renewable energy-based solar Photovoltaic (PV) and wind energy can play a vital role in meeting the energy essentials of agri-food systems in Sierra Leone. Sierra Leone has abundant potential for exploiting solar energy and the wind speed in most of the regions of the country is well-suited to produce power.

Solar PV and Wind turbine hybrid systems have not yet been implemented in Sierra Leone and the literature revealed that such systems can be more cost effective than solar PV-alone or Wind-alone systems [5, 6, 7, 8, 9] by reducing the energy storage requirements. This paper attempts to investigate the possibility of providing electricity from a Solar PV - Wind hybrid power system for irrigation and low-scale electrification in rural Sierra Leone.

METHODOLOGY

Study Area

The name of the project site selected for the implementation of the solar PV-wind hybrid power system is Fonima Village, located in the Sambaya Chiefdom, Tonkolili District, Northern Sierra Leone (latitude = 9.0792 N and longitude = 11.621 W with an elevation = 562 m above the mean sea level) as shown in Figure 1.

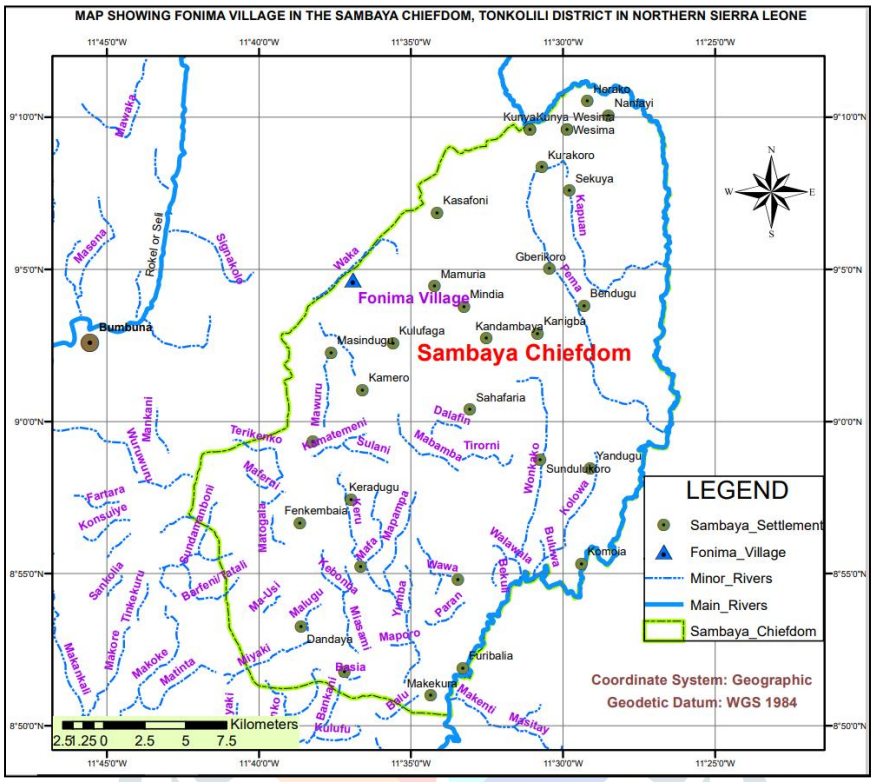


Figure 1: Location of Fonima Village.

Fonima village consists of 15 thatched houses and about 80 inhabitants. Most of the inhabitants are smallholder farmers, where agriculture and livestock constitute the primary economic activities in the village. Others work as labourers in nearby small mining companies. A drone imagery of the village is depicted in Figure 2.



Figure 2: Drone imagery of Fonima Village.

The access to Fonima village is by bulldozed dirt-roads and the residents have never had any access to electricity. Energy sources such as candles, kerosene lamps and dry cell battery powered torchlights are used for lighting. Residents have no television sets and therefore have limited access to entertainment and news broadcasts. For their cooking and heating demands, the inhabitants use the nearby vegetation (forest) either directly as firewood or as charcoal as shown in Figure 3. This is an indication of extreme energy poverty in this village. The inhabitants reported eye irritation, coughing, nasal problems and fire hazards associated with the use of kerosene lamps. The disposal of used dry cell batteries in open dumps or as litter is a common practice in Fonima village. Since this area lacks programmes for solid waste management, soil and water sources can be contaminated with toxins, including mercury. Another danger is the fact that children use them as toys.



Figure 3: Food Preparation using firewood and charcoal in Fonima Village.

Design Method

The solar PV-Wind turbine power plant design was carried out based on the site characteristics and the total desired energy demand. Using these data, a detailed estimation of the nominal capacity of the Solar PV plant and the wind turbine, selection of appropriate technology, sizing of different components such as Solar PV module (panel), wind turbine, inverter, storage battery bank and charge controller with their required technical specifications was carried out.

Site Assessment

To assess the feasibility of the solar PV-wind power plant and to ensure proper sizing of the hybrid system, the study site was visited to collect site-specific information. Critical information including geographic location, topography and land characteristics were collected and analyzed as they have a major impact on the design and performance of the system. The most suitable locations for the solar PV and wind turbine installations in the village were determined during the site visit and local persons with requisite basic understanding of electrical technology were identified and trained to maintain the hybrid system during and after the installation exercises.

Prior to the commencement of the site assessment, a consultative meeting was held with the relevant stakeholders including the local chief and his subjects, women and youth in the project location to discuss important issues pertinent to the timely achievement of the project milestones and obtain permission for the researcher to access the site as traditional laws and culture demand.

Solar Radiation and Wind Resource Assessment

An important step in the planning and design of a solar PV-wind hybrid system is to acquire the solar and wind resource data for the site because the amount of electrical energy that can be generated depends on the radiation and wind intensity throughout the year [10]. The solar insolation and wind speed data for the study location were obtained from the NASA Surface Meteorological and Solar Energy website [11]. Data related to the environment such as temperature pattern, relative humidity and atmospheric pressure were also collected from the NASA website by introducing the site coordinates.

Energy Demand Assessment

Professional solar PV-wind system design requires a detailed inventory of all loads and their consumption patterns. The load assessment includes a listing of the quantity, power and daily operational hours of the loads. This information is evaluated to find the total power and energy consumption of all loads to be supplied by the hybrid system.

Reference System Specification Rating

In this design, the specifications of the major components of the solar PV system are selected as reference in the sizing of the system.

Design and Sizing of the Solar PV-Wind hybrid System

The following steps/procedures were followed to design the solar PV-wind hybrid system [5, 12]:

1. Sizing of the solar PV array
2. Sizing of the wind turbine
3. Sizing of the battery bank
4. Sizing of the inverter
5. Sizing of the charge controller

1) Sizing of the Solar PV Array: The solar PV array, a combination of solar PV modules, is the main component of a solar PV system. Before sizing the solar PV array, the following vital information should be known: the daily energy demand, the DC voltage of the system and the average sun hours of the installation site per day. The total energy required from the solar PV array will be the daily energy demand of the site and compensation factor for the system losses, which is generally taken as 1.5 [13]. To form an array, modules are connected in series to increase the nominal voltage of the PV system, while the parallel connection of modules results in a higher current in the PV system.

2) Sizing of the Wind Turbine: The small, five bladed wind turbine designed for this study is based on the vertical axis wind turbine (VAWT) technology that are usually installed in isolated, off-grid and remote areas where there is no power connected to the national grid as the case for Fonima village. The VAWT is omnidirectional and, therefore, can receive wind from all directions. Since Fonima village winds are from all directions, VAWT was considered to be the best option to be designed. It can generally start to produce power at very low wind speeds, unlike other wind turbine technologies [14, 15].

3) Sizing of the Battery Bank: The role of the battery bank in a standalone PV system is to store electric energy for nighttime supply or when there is no sunlight during the day. The total storage capacity of the battery bank (C_{tb}) can be calculated based on the number of continuous cloudy days (days of autonomy), battery efficiency, battery depth of discharge and nominal battery voltage to cover the total energy required [16, 17]. The Depth of Discharge of the battery is the percentage of the battery that is allowed to deplete before recharging. The battery bank comprises batteries that are connected in series and in parallel according to the system requirements.

4) Sizing of the Inverter: An inverter converts DC electricity into AC electricity. To size the inverter, the total power to be used by the appliances running simultaneously is increased by 25 - 30% [16].

5) Sizing of the Charge Controller: The primary function of a charge controller is to maintain the battery at the highest possible state of charge while protecting it from overcharge by the power source(s) and from over discharge by the loads. According to standard practice, the sizing of the charge controller can be obtained by dividing the total wattage of the solar array and the wind turbine by the voltage of the battery bank.

RESULTS AND DISCUSSION

The results of the design and implementation of the solar-wind hybrid system are presented and discussed in this section.

Site Assessment

The case study location, Fonima Village, Sambaya Chiefdom, Tonkolili District, Northern Sierra Leone, is located around 9.0792° N latitude; 11.621° W longitude at an Elevation of 562 m as shown in Table 1.

Table 1. Relevant Information for the Study Location.

Item	Observed Data
Latitude	9.0792°N
Longitude	11.621°W
Elevation	562 m
Vegetation cover/shading	None

Based on observations during the site assessment, the study site has adequate sunshine and moderate wind speeds. Since land use and land cover were the key factors in finding the optimal location for the solar PV power plant and the fact that the inhabitants of the village cultivate the lands up to close to their houses, rooftop installation of the solar panels was considered as the most appropriate option. This will also avoid shading of the panels from trees. The 30 m tower for the wind turbine was installed in a location clear of trees to ensure free flow of wind.

Solar Radiation and Wind Resource Assessment

Solar radiation on a horizontal surface, wind speed and related data obtained from the NASA Surface Meteorology and Solar Energy database for Fonima village location using exact coordinate (Latitude: 9.0792°N; Longitude: 11.621°W) are presented in Table 2. The annual average solar radiation and wind speed of 4.56 kWh/m^2/day and 3.17 m/s, respectively indicate sufficient potential for solar and wind power plants installation. The wind turbine, mounted at hub height of 30 meters, was designed to be strong enough to survive extreme wind speeds of up to 20 m/s.

Energy Demand Assessment

As indicated in Table 3, the Fonima village total load demand is estimated as 410 W and the total energy demand is estimated as 3000 Wh/day. In addition to the weather data, these load and energy demands are used in the sizing of the solar PV-Wind hybrid system to power the irrigation electric pump and light bulbs. The electric pump is designed to operate for three hours a day to irrigate a portion of pepper plantation and the light bulbs will provide lighting at night for six hours daily.

Table 2. Solar Radiation, Wind Speed and Other Weather Data for Fonima Village.

Month	Air Temperature (ºC)	Atmospheric Pressure (kPa)	Relative Humidity (%)	Wind Speed (m/s)	Daily Solar Radiation - horizontal (kWh/m²/d)
January	23.5	96.7	33.7	3.41	5.92
February	26.6	96.5	26.4	3.41	4.74
March	29.8	96.3	36.6	3.42	4.09
April	28.7	96.4	64.0	4.30	4.17
May	27.6	96.5	74.8	3.44	4.26
June	26.0	96.6	81.8	3.34	3.73
July	24.7	96.5	84.1	3.22	2.96
August	24.5	96.5	83.2	3.68	2.74
September	24.4	96.6	85.0	2.55	2.81
October	26.0	96.5	73.0	2.16	5.35
November	25.9	96.5	53.9	2.65	7.09
December	26.3	96.4	37.5	2.47	6.91
Annual Average	**26.2**	**96.5**	**61.2**	**3.17**	**4.56**

Table 3. Energy Demand of Fonima Village for Irrigation And Electrification.

Appliance	No. of Units	Total Load (W)	Operating Hours/day	Total Demand (Wh/day)
Electric Pump	1	400	3	1200
Bulb	30	10	6	1800
Total		**410**		**3000**

Reference System Specification Rating

The specifications of the solar module (panel), solar charge controller, battery and inverter selected as reference in the sizing of the solar PV component of the hybrid system system are given in Table 4.

Table 4. Specifications of Selected Solar PV System Components

Item	Value	Source
Solar Panel - Suntech Monocrystalline STP250S		
• Peak Power (P_{max})	200 W	[18]
• Open Circuit Voltage (V_{oc})	44.3 V	
• Short Circuit Current (I_{sc})	7.78 A	
• Voltage at Maximum Power (V_{mp})	34.8 V	
• Current at Maximum Power (I_{mp})	7.18 A	
• Panel Efficiency	12.9%	
Solar battery – Trojan Deep Cycle		
• Voltage	12 VDC	[19]
• Capacity	410 Ah	
• Depth of discharge	80%	
• Efficiency	85%	
Inverter – Shenzhen Pure Sine Wave off-Grid		
• Rated Capacity	1000 W	[20]
• Output rated voltage	220/240 VAC	
• Frequency	50/60 Hz	
Charge Controller - Steca Power Tarom 2140		
• Load Current	45 A	[21]
• Voltage	24 VDC	

Sizing of the Solar PV Array

The first step in the sizing of the solar PV array is to oversize the energy requirement from the array by multiplying the total daily energy required, which has been estimated as 3000 Wh/day (Table 3) by a factor of 1.5 to compensate for the system losses [22]:

$$E_r = Daily\ Energy\ Demand, E_d \times System\ Losses\ Compensation\ Factor = 3000 \times 1.5 = 4500\ Wh \quad (1)$$

The required energy from the modules (E_r) is then divided by the average sun hours per day, which is assumed to be 11 for the study location to obtain the peak power rating of the array:

$$P_{PV\ Array\ Required} = \frac{Daily\ Energy\ Requirement, E_r}{Peak\ Sun\ Hours\ per\ Day, T_{sh}} = \frac{4500}{11} = 409.1\ W \quad (2)$$

The total current required from the PV array is calculated by dividing the peak power by the DC-voltage of the system as follows:

$$I_{PV} = \frac{Peak\ Power,\ P_{PV\ Array\ Required}}{System\ DC\ Voltage, V_{DC}} = \frac{409.1}{24} = 17.05\ A \quad (3)$$

The number of solar panels required for the hybrid system is obtained from:

$$Number\ of\ solar\ panels, N_s = \frac{I_{PV}}{Short\ circuit\ current\ of\ the\ selected\ solar\ panel} = \frac{17.05\ A}{7.78\ A} = 2.19 \approx 2 \quad (4)$$

Sizing of the Wind Turbine

The daily energy required of a wind turbine in amperes per hour can be obtained using the following Equation [10]:

$$P_{Ah} = \frac{P_{load}}{V_{system}} = \frac{4500}{24} = 187.5\ Ah^{-1} \quad (5)$$

Calculating Design Parameters for the Wind Turbine: The annual average wind speed at Fonima village measured at 10 m height is 3.17 m/s. This wind speed value is increased to a value at 30 m height, the approximate height of the wind turbine hub, by the following Hellman equation [15]:

$$V = V_o \left(\frac{h}{h_o}\right)^{\propto} \quad (6)$$

Where: V = speed to the height h, Vo is speed to the height ho (frequently referred to as 10 m height) and $\propto$ is the friction coefficient or Hellman exponent. This coefficient is frequently assumed as a value of 1/7 for open land as in the case of the study site.

Hence, the wind speed at 30 m height is estimated as follows:

$$V = 3.17 \left(\frac{30}{10}\right)^{\frac{1}{7}} = 3.7\ m/s \quad (7)$$

The Annual energy requirement was obtained from the calculated energy requirement (P_{Load} = 4500 Wh/d) as follows:

$$\left(\frac{4500\ Wh/d}{1000} \times 365\ days\right) = 1643\ kWh \quad (8)$$

The size of the wind turbine that is required to be installed to meet the energy demand or requirement was determined based on the following assumptions.

1. Coefficient of performance = 0.4.
2. Density of air = 1.225 kg/m^3.
3. Capacity factor (Cp) of 0.30 (this means that 30% of the time wind turbine is producing energy at rated power).
4. Alternator losses of 0.9.
5. Number of operational hours per year = 8760.

- *Wind Power density:* The power density (PD) of moving air is given by Equation 9 (Saxena and Kao, 2016).

  $$WPD = \frac{1}{2}\rho V^3 \quad (9)$$

  Where: WPD is the wind power density, ρ is the air density and V is the wind speed.

  $$WPD = 0.5 \times 1.225 \times (3.7)^3 = 31 m/s \quad (10)$$

- *Actual wind power density to be converted to useful energy:* The actual power density as shown in Equation 11 is a product of wind power density, capacity factor, transmission and generator losses [23].

  $$Actual\ WPD = WPD \times C_p \times Transmission\ loss \times Alternator\ loss \quad (11)$$

  $$Actual\ WPD = 31 \times 0.4 \times 0.9 \times 0.9 = 10\ m/s^2$$

- *Annual useful energy density:* The annual useful wind energy density was obtained as a product of wind power density and total operational hours per year as shown in Equation 12.

  $$Annual\ useful\ energy\ density = Actual\ WPD \times number\ of\ years\ per\ year = 10 \times 8760 = 88\ kWh/m \quad (12)$$

- *The rotor size and turbine rating estimation:* A wind turbine rotor is the organ that transforms the kinetic energy of wind to mechanical energy. For this reason, it is very important for wind turbines. As shown in Equation 13, the rotor size was determined from the swept area of the turbine.

$$Swept\ Area = \frac{\text{Total annual energy required}}{Annual\ useful\ energy\ density} \quad (13)$$

$$Swept\ Area = \frac{1643}{88} = 18.7\ m^2$$

- *Power rating of the turbine:* The output of a wind turbine depends on the turbine's size and the wind speed through the rotor [24]. The turbine rated power as shown in Equation 14 was obtained.

$$Power\ rating = Actual\ power\ density \times rotor\ swept\ area \quad (14)$$

$$Power\ rating = 10 \times 18.7 = 187\ W = 0.187\ kW$$

- *Actual rated power of the turbine rating:* The capacity factor is defined as the actual power output over a certain period of time as a proportion of a wind turbine/facility's maximum capacity [24]. Equation 15 was then used to estimate the actual rated power and a capacity factor C_P of 0.30 was selected for the study.

$$Actual\ rated\ power = \frac{Power\ rating}{Capacity\ factor} = \frac{0.187}{0.30} = 0.6\ kW = 600\ W \quad (15)$$

Thus, a 600 W rated power wind turbine was designed and fabricated to provide the desired annual energy under the given situation. This power rating is based on the assumption that the average Fonima village wind speed of 3.7 m/s at 30 m height will be available throughout the year, 8760 hours, which is not the case, and that is why we have taken the capacity factor into account.

Sizing of the Battery Bank

The battery capacity with its voltage level was designed considering 2 days of battery autonomy. The maximum depth of discharge is restricted to 80% to ensure long lifetime of the storage and the efficiency of charging/discharging of the battery is taken to be 85% [17]. With these analyzes, the capacity of the battery bank required is estimated using the equation suggested by [16] as follows:

$$C_{tb} = \frac{Total\ Watt{-}hours\ per\ day\ used\ by\ the\ appliances \times Days\ of\ Autonomy}{Battery\ Efficiency \times Depth\ of\ Discharge \times Nominal\ Battery\ Voltage} = \frac{3000{\times}2}{0.85{\times}0.80{\times}12} = 735\ Ah \quad (16)$$

Based on the Trojan 12V/410Ah battery selected, the number of batteries required is:

$$N_{tb} = \frac{Total\ capacity\ of\ battery\ bank,\ \ C_{tb}}{Capacity\ of\ one\ battery,\ \ C_b} = \frac{735}{410} = 1.8\ \approx 2$$

Sizing of the Inverter

To size the inverter, increase the power to be used by the loads running simultaneously (Table 3) by a factor of 1.25 to allow room for expansion of the system if need be (Leonics, 2013). The input rating of the inverter is then estimated as shown in Equation 17.

$$P_{Inverter} = 410 \times 1.25 = 513\ W \quad (17)$$

The inverter to be used for this system should be able to handle about 513 W and voltage of 48 VDC. Assuming that the irrigation pump would draw excess current at start-up, a 1000 W pure sine wave inverter with high surge power up to 150% load for 10 seconds was selected.

Sizing of the Charge Controller

Dividing the total power produced by the solar PV array and the wind turbine by the voltage of the battery bank, the charge controller rating is calculated as:

$$I_{Rated} = \frac{1000}{24} = 41.67\ A \quad (18)$$

Based on the selected charge controller (Steca Power Tarom 2140, 45A), the number of charge controllers is estimated by dividing the rated current by the selected current of the charge controller (Equation 19).

$$N_{CC} = \frac{41.67}{45} = 0.926 \cong 1 \quad (19)$$

One 45A charge controller is needed.

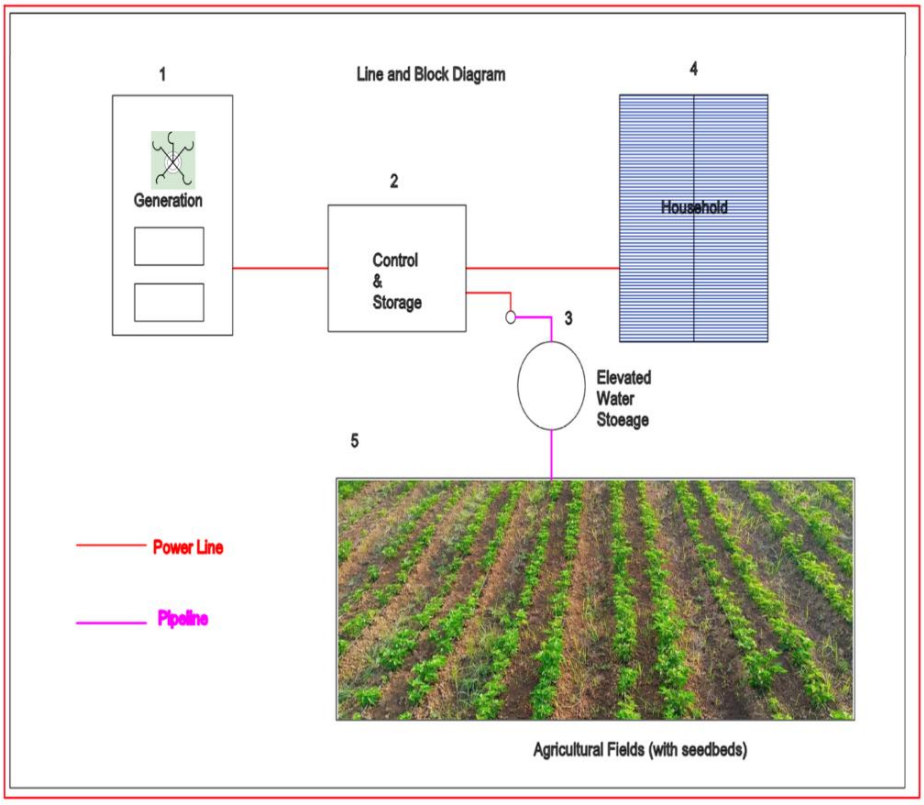
Technical Specifications of the Solar PV-Wind Hybrid System

As per the calculations above, a solar PV-wind turbine system was designed with the specifications given in Table 5.

Table 5. Designed and Fabricated solar PV-wind turbine Parameters.

Component	Quantity	Specification
Solar PV panel	2	200 Wp Each
Battery	2	410 Ah/12 V Each
Inverter	1	1000 W
Charge Controller	1	45 A
Alternator	1	600 W/24 VDC
Drip Irrigation Kit	1	Set
Pump	1	400 W
Water Tank	1	200 L
Cable	Assorted	1.5, 2.5, 4, 6 and 25 mm^2

Figure 4 shows the configuration of the designed solar PV-wind hybrid system including the water tank and plot to be irrigated. This hybrid system is constituted by a 400 W solar PV branch and a 600 W wind power branch. The solar PV power branch is composed of two panels, a shared battery tank, a shared inverter and a shared charge controller. On the other hand, the wind power branch is composed of an alternator, a rectifier, a shared battery tank, a shared inverter and a shared charge controller.



1: Wind turbine and Solar PV 2: Control Room 3: Water Tank 4: Homes in Fonima village 5: Irrigated plot

Figure 4: Configuration of the solar PV-wind hybrid system.

The designed and installed solar PV-wind hybrid system shown in Figure 5 is now supplying power to a standalone drip irrigation system and light bulbs in Fonima village.

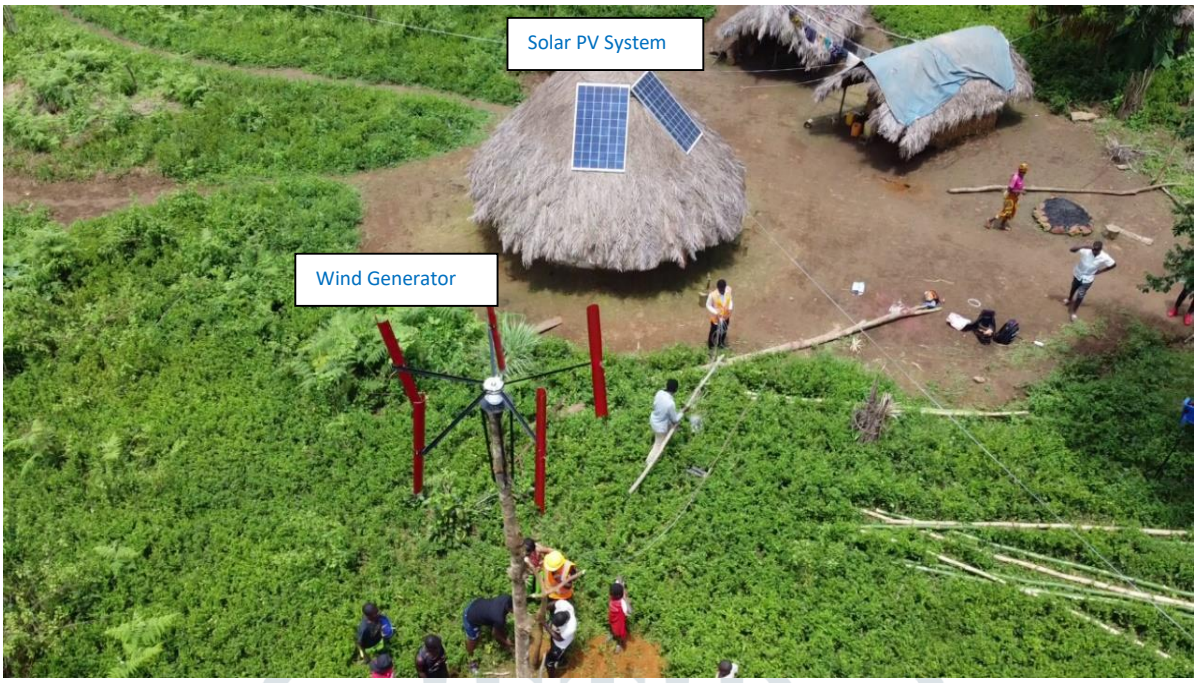


Figure 5: Drone Imagery of the solar PV-Wind hybrid system.

The hybrid system design focused on simplicity, reliable operation and the use of high-quality components to maximize their life in order to minimize the high cost of component replacement in remote areas like Fonima village.

CONCLUSION

The design, sizing and installation of a solar PV-wind hybrid system was successfully completed and now providing power for residential electrification and irrigation in Fonima village, Northern Sierra Leone. Fonima village was selected for the implementation of the project because of its total dependence on traditional fuels of its inhabitants to meet their energy needs, due to the absence of a power grid extension.

This project is expected to lead to several encouraging social outcomes/impacts in Fonima village. The kerosene lamps used earlier caused respiratory and eye problems. Children can do their school homework and study in the evenings, which may result in better marks in school examinations. Available electric light will help women to cook food in the evening, not during the day as previously. The evening meals served are thus 'straight from the pot' meaning better quality 'fresher' food. The lights make it easier to spot insects inside the house at night. Streetlights have made walking outdoor after dark safer and reduction in the incidence of snake bites. As electricity has enabled pumping of water, women and girls do not have to walk long distances to collect water to irrigate their plots. The residents of the village were happy to receive access to electricity and expected to benefit from the improvement in socioeconomic conditions that electricity services could bring about.

ACKNOWLEDGEMENT

The financial assistance provided by the Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ) GmbH through Fourah Bay College, University of Sierra Leone to undertake this work is gratefully acknowledged. Special thanks go to Ms. Mallence Bart Williams, the Chief Executive Officer of Light Salon Initiation Group for her exemplary leadership in the planning and execution of the project activities.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest regarding the publication of this paper.

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