International Journal of Research Publication and Reviews

Journal homepage: www.ijrpr.com ISSN 2582-7421

Overview of Energy Generation and Conversion Schemes in Sub-Saharan Settlement

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DOI: https://doi.org/10.55248/gengpi.4.723.48276

ABSTRACT

Africa is among sub-Saharan region with low electrification, and efforts to improve it by individual administration has been hampered by financial limitations and lack of technological sophistication. The effectiveness of integrated electricity generation schemes involves solar PV (photovoltaic) and wind technologies which were therefore evaluated, with focus on their plausibility, environmental and socioeconomic impact assessments, intra-technological variations, climate parameters, and elevation. This study concentrates on assessing income generation with the view toward sustainability by advancing our understanding of how to better mitigate climate change, limit deforestation and carbon sequestration, and ease adaptation. This study will ultimately increase the population's willingness to pay for efficient electricity generation systems in sub-Saharan Africa through cooperative consumption and community ownership.

Keywords: Electricity, Photovoltaic, sub-Saharan, Renewable, Wind

1. Introduction

Energy is a basic need for the development of socio-economic and enhancement of people's living standard. As the people becomes more developed then the energy consumption also increases but the conventional energy have a negative impact in our environment and it is also in the way of exhaustion. Getting an access to electrical energy is one of the basic needs for the civilized world. But many villagers in developing nations have no access to electricity [1]. At the present time 2 to 3 billion people in the world have no access to electricity and this will continue until 2030 due to population growth. Among 70% of population living in rural area of sub-Saharan Africa region, only less than 10% of these populations have access to electricity [2]. The conventional electricity system for rural electrification is not succeeded in satisfying the electricity consumption of the rural population because rural villages are most of the time far from the main grid lines. The planners (corporations who is responsible for the distribution of electricity) do not give a priority for rural electrification since it does not directly lead to economic regeneration or increased productivity [3].Due to the increased energy demand, and the problem of environment such as global warming leads to a growth interest of renewable energies which are environmentally friendly. Solar energy is one of the main renewable resources which can curb the negative impact of fossil fuels. These areas usually have a low population density. Because of this, there are not attractive economic benefits for private investors or electricity supply utilities to offer electricity services to these villages [4]. In addition, because the transmission and distribution systems have not reached all the populated areas in the country, it is more economical to electrify gradually from the urban centers out than to extend the grid to reach all the remote villages in rural areas. This leaves the vast majority of the population in Nigeria without electricity access. There exist low expectations of grid infrastructure expansion to rural villages anytime soon.

2.0 Selection elements of system design

2.1 Electrical load

An estimation of family user daily consumption has been realized based on the information in the questionnaire and the beneficiaries needs regarding the electricity. The estimated daily demand and all the appliances which may be used in communities are shown in Table 1.

Table 1. Estimated total daily consumption/family				
Applications	**# Quantity**	**Power (Watt)**	**h/day**	**W.h/day**
PL lamp	2	11	4	88
TV	1	120	5	600
Radio	1	20	5	100
Mobile charger	1	10	1	10
Small refrigerator	1	200	5	1,000
Highly efficient washing machine	1	180	2	360
			Total =	2,158

2.2 Sizing PV generator

In selecting a suitable PV module when designing a PV solar system to cover the average load energy demand of 2,158 Wh/day, PV array size can be determined, using equation (1).

$$P_{PV-array} = \frac{E_L}{\eta_V * \eta_R * P_{SH} * S_f} \qquad (1)$$

E_L: Estimated average daily load energy consumption in Wh/day (2,158 Wh/day)

P_{SH}: Peak Sun Hours (5.4 h) [5]

η_V: Efficiency of inverter (95%)

η_R: Efficiency of wire losses (97%)

S_f: Safety factor (1.15)

$P_{PV-array}$ = 377 watt

Using PV module of 135 W the number of modules in system (Nm) is determined by equation (2).

$$N_M = \frac{P_{PV-array}}{P} \qquad (2)$$

Nm = 2.7933 ≈ 3 modules

2.3 System voltage selection

Selecting the operating DC voltage of standalone PV system is based on system requirements, so the selected system voltage is 48 V.

According to system voltage, the number of modules in series (Nm) is calculated according to this Equation [6].

Nm = PPV − array/P selected module = 48/17.6 = 2.72 ≈ 3moduleinseriesNm = PPV −array / P selected module = 48/17.6 = 2.72 ≈ 3 module in series (3)

The PV array is composed of 36 PV modules on galvanized steel metallic support and distributed by three sub-array of 4 string, and each string has 3 modules (3 modules * 4 string * 3 sub-array = 36 modules), and the array capacity is 4.86 KWp of 135 Wp

PV module and also with approximate area of 38.88 m^2.

So, the modules of the system were installed in series, and as a result, Voc array = 22×3 = 66V VIS.C. array = 8.19×4=32.76A Isc array = 8.19×4=32.76A

2.4 Sizing of battery bank

The battery is the most important part in a stand-alone PV system, so we consider that the battery will cover the needs of beneficiaries at night and cloudy day which required a highly efficient battery.

The capacity of the battery (C_{A-H}) is measured in Ampere-hours, as in Equation [8]

CA−H= Nc× EL/VB× DOD×ηv× ηRCA−H= Nc× EL/VB× DOD×ηv× ηR (4)

N_c: Numbers of days of autonomy (1.5–3 days)

V_B: Operating voltage for system (48 V)

DOD: Maximum depth of discharge (0.6–0.75)

$C_{A\text{-}H}$ = 1,045 A.HCWH= CA−H× VB...CWH= CA−H× VB... (5)

C_{WH} = 1,000 Ah × 48 V = 48 kWh

2.5 Sizing of charge controller

The basic function of charge controller is to extract as energy as possible from PV array in order to maintain a high state of charge of the battery and avoid its complete discharge, so it controls the cycle of charge and discharge avoiding overcharge and deep discharge.

When we selected the charge controller, we consider that the unit has the following characteristics:

- Highly efficient charge controller with low self-consumption
- Maximum power point tracker (MPPT) to get the maximum power of PV array
- Possibility to maintain the batteries at floating voltage to compensate the losses in case of full charge
- Advanced algorithm of charge and discharge control

The size of the charge controller will be selected according to [9].

P = VB× IP=VB× I (6)

4,860 = 48 × I × 1.15

I = 88 A × S_{f2}

I = 110 A

S_{f2}: Safety factor (1.25); in special conditions, the panel produces more power than it's rated (about 25–30%). For example, sunlight reflects from snow and water.

So, we used MPPT-150 A and peak efficiency of 97.5%.

2.6 Sizing of inverter

When we select the inverter which will be used in the project, we consider the system voltage, output voltage 230 V/50 Hz, low self-consumption with efficiency, maximum charge current >15 A and the input of inverter has to be matched with the battery bank voltage as in electric grid as follows :

Rating inverter = PV rating = 135 Wp × 36 = 4,860 W

The input energy of inverter = PV rating × PSH × η_R

= 4,860 × 5.4 × 0.97 = 25,456 Wh

The output energy of inverter = input energy of inverter × η_V

= 25,456 × 0.95 = 22,974 Wh

We selected inverter with a highly efficient sinusoidal bidirectional generator with self-consumption less than 10 W, the working voltage is 48 Vdc, and the output voltage is 220 V/50 Hz, with capacity 5 kW [10].

Total energy generated by PV power plant

The system was monitored using the data logger, and the data were collected and stored each hour, so we can obtain total produced energy on monthly and annual basis, using

Equation 7.Et=Σ (Em1+Em2………. Em12) Et =Σ Em1+Em2………. Em12 (7)

where $m1$ = January, …, $m12$= December

Em: Actual energy production by plant in month (kWh)

Et: Annual energy production by plant (kWh)

For the estimated energy generated by PV plant, in order to inspect the performance of PV power plant in reference to global and technical factor, we have to calculate the estimation energy that may produce using this PV plant, using

Equation8.Ee=H∗A∗Ee=H∗A∗ (8)

Ee: Estimated energy generated by PV plant (KWh)

H: Irradiation (kWh/m^2)

A: Net plant area (m^2)

Ŋ: Efficiency of photovoltaic module in operating condition

Estimation energy output and the load consumption in both villages.

Figure 2: Array of Solar PV system

3.0 Wind Energy

The wind turbine captures the wind's kinetic energy in a rotor of two or more blades mechanically coupled to an electrical generator. The turbine is mounted on a tall tower to enhance the energy capture. Numerous wind turbines are installed at one site to build a wind farm of the desired power generation capacity. Obviously, sites with steady high wind produce more energy over the year [11].

3.1 Speed and Power Relations

The Kinetic energy in air of mass m moving with speed V is given by the following in joules:

Kinetic energy = $^1/_2$ mV^2

The power in moving air is the flow rate of kinetic energy per second in watts:

Power = $^1/_2$ (mass flow per second) V^2

If

P = mechanical power in the moving air (watts)

ρ = air density (kg/m^2)

A = area swept by the rotor blades (m^2)

V = velocity of the air (m/sec),

3.2 Power extracted from the wind

Two potential wind in sites are compared in terms of the specific wind power expressed in watts per square meter of area swept by the rotating blades. It is also referred to as the power density of the site, and is given by the following expression in watts per square meter of the rotor-swept area:

Specific power of the site = $^1/_2\, \rho\, V^3$

This is the power in the upstream wind. It varies linearly with the density of the air sweeping the blades and with the cube of the wind speed.

Mass flow rate = $\rho A\ \frac{V+V_o}{2}$

The mechanical power extracted by the rotor, which drives the electrical generator, is therefore:

$$P_o = \frac{1}{2}[\rho A\ \frac{V+V_o}{2}](V^2 - V_o^2)$$

In this design of wind turbine 2- Bucket wind turbine was considered due to low wind rate in the southern part of Nigeria. This type can accommodate low flow rate to produce required energy.

Figure 3: A 2- Bucket wind turbine

4.0 Metering

Metering is a vital device that quantifies the energy consumption of respective user and determines the cost of consumption based on the tariff system applied. This is the most important aspect of the system because it determines the sustainability of the whole system. In this work Arduino-based prepaid energy meter using GSM technology was employed [12].

Benefits of the metering system

(i) Pay according to your load usage

(ii) Reduction in power consuming

(iii) No billing errors

(iv) No debt money

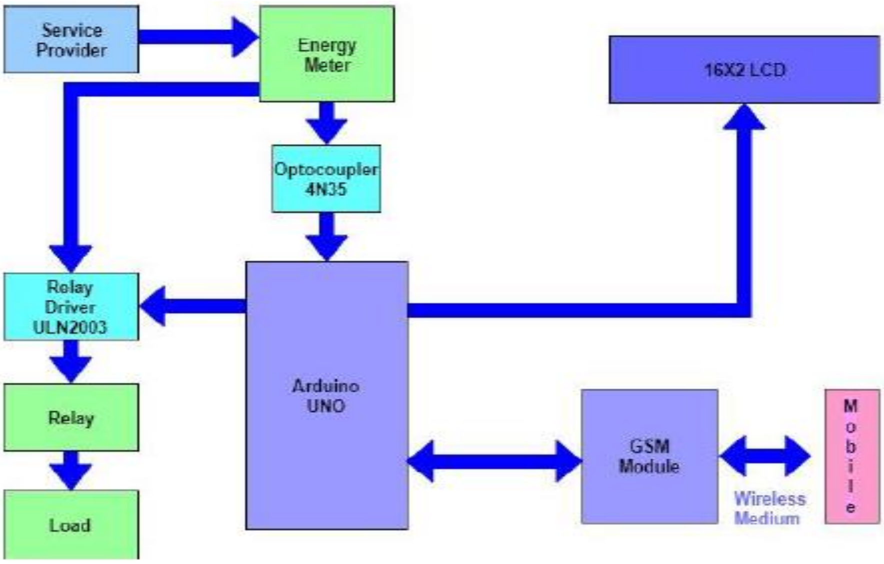

Figure 4: Layout of prepaid energy meter

5.0 Measurement system

5.1 Meteorological data

The measurement system consists of two parts; the metrological measurements and the measurements of system parameters. The solar radiation is measured with a pyranometer CMP 3. The wind set from Campbell Scientific consists of an anemometer and wind vane to measure the wind speed and wind direction. The meteorological data that were included in the paper (irradiance, wind speed, wind direction and air temperature) were obtained over a period of one year through Automatic weather station (AWS). Figure 5 and 6 respectively shows the monthly mean variation of wind speed, ambient temperature and solar radiation taken from the data acquisition.

It is observed that during summer months the solar mean daily radiation and ambient temperature reach the maximum values as expected, G_{max} = 555.06 Wm^{-2} and T_{am-max} = 32.69ºC respectively. From the outer hand, monthly wind speeds are higher during winter, Vmax = 4.44 ms^{-1}, as opposed to low wind speeds during other seasons. It was discovered from the readings that solar and wind power sources are complementary over a year. The summer provides good solar irradiance but poor wind conditions, while a relatively effective wind speeds but poor solar radiation occurs in the winter. The combination of two energy sources can provide a better utilization factor for the energy demand. The wind turbine and photovoltaic provide a load with electricity through controller, battery and inverter.

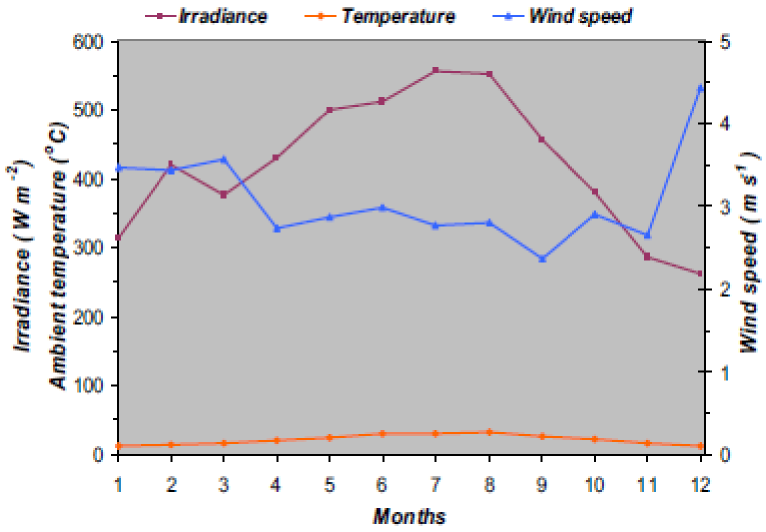

Figure 5: Monthly mean wind speed, ambient temperature and irradiance

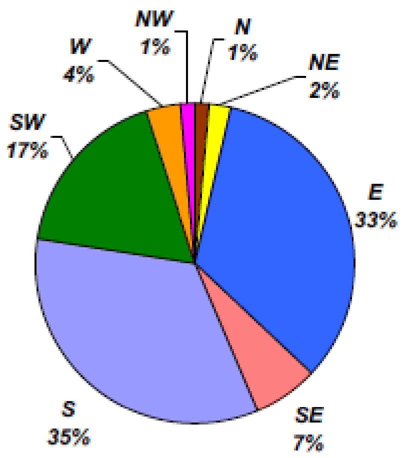

Figure 6: Annual frequencies for each cardinal coordinate

5.2 System performance

The performance of the system was evaluated for a time period of one year (January-December). The highest value of irradiance was in July with 55.06 Wm^{-2} and the lower was in December was 262.79 Wm^{-2}. The total yearly generated power from PV modules was 194.60 kWh, while the total amount of solar energy in-plane of photovoltaic modules was 3187.87 KWh and the mean ambient temperature was 21.55^{o}C. In addition, the overall efficiency of the PV subsystem was 6.1%

The amount of electrical energy generation from the wind turbine for same time period, was 37.08 kWh while the total amount of wind energy that flowed through the rotor of the WT was 620.82 kWh. The mean conversion efficiency was 5.7%. In fig. 5 we present the monthly generated energy from PV modules (Fig. 5a) and wind turbine (Fig. 5b) versus the available solar and wind energy.

The calculation of the generated energy of the solar collector is a complicated procedure due the dependence of performance of collector from the mean water temperature, the ambient temperature and the solar radiation. For the calculation of useful energy of collector we assume that the mean daily temperature of thermal system operation is T_{mean} = 40^{0}C. From the equation (1) and taking into account the measured meteorological data, the energy produced was 1686.04 kWh, while the energy input to the aperture of solar collector was 3120.58 kWh, resulting to a mean yearly thermal efficiency of 54%.

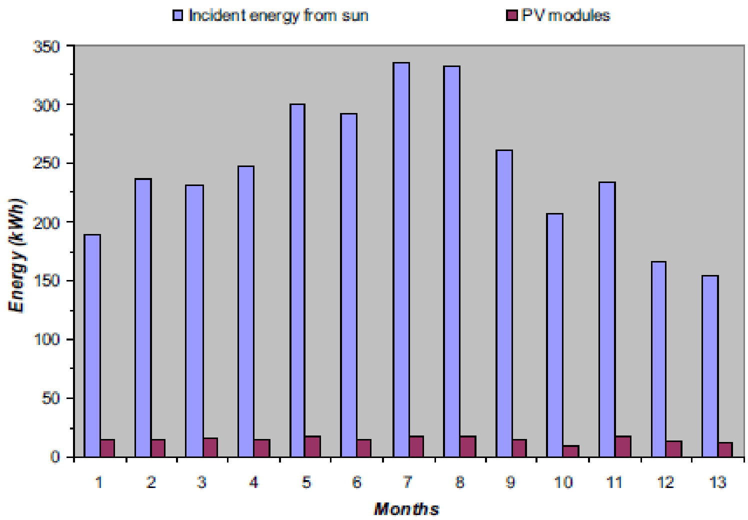

FIGURE 7: Total generated energy from PV module

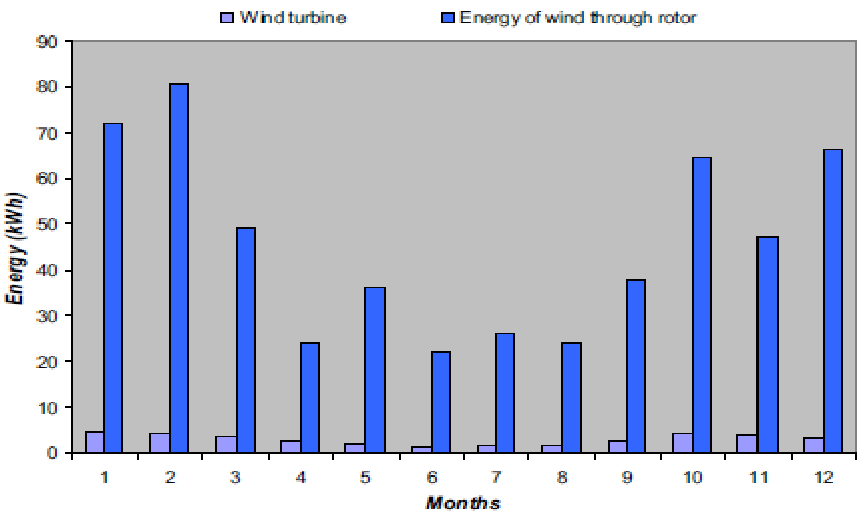

FIGURE 8: Total generated energy from wind turbine

6.0 CONCLUSIONS

PV, thermal collectors and wind turbines can be combined to cover energy needs in rural settlement. A system with PV modules, wind turbine. The generated energy from PV modules was 194.6 kWh with overall conversion efficiency 6.1%. At the same time the output energy from the wind turbine was 37.08 kWh while the conversion efficiency reach the value 5.7%. For the sustenance of the energy generation the metering was included and the rating was done as energy used.

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