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DESIGN AND SIMULATION OF A 17 KWH STANDALONE SOLAR POWER SYSTEM FOR A RURAL HEALTH CENTRE IN KEBBI

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ABSTRACT

A standalone solar power system of 17 kWh for a rural health centre in Kebbi has been designed and simulated. HOMER was used to perform the simulation and optimization procedure using the solar radiation data, clinic load profile, sensitivity variable and other design variables which served as input parameters. Kebbi lies on latitude 12°27'14" N and longitude 4°11'51" E, and altitude of 225 m. The solar resource data used were obtained from the NASA Surface meteorology and Solar Energy/HOMER Data for a ten year period (2005 – 2014). The least economical system is the generator-battery configuration with a total initial cost, net present cost, and electricity cost of US$ 11,613, US$62,746, and US$0.765, respectively. The optimal system is made of 40PV modules of 200 W, 20 solar batteries of 12 V, 205 Ah and a converter of 3 kW.

INTRODUCTION

Although, the United Nations (UN) has identified energy as an enabler of universal access to health, little attention has been paid to energy as an important contributor to health care delivery in health facilities. Hundreds of health facilities across many developing countries lack basic modern energy services needed for lighting during child delivery, emergency night-time care, refrigeration for blood and vaccines, sterilization facilities, and electricity for simple medical devices, (Karen and Lu, 2012; WHO, 2015). Most grid-connected hospitals in developing countries suffer prolonged power blackout during periods of peak demand, and hence resort to expensive backup generators or stay without power. On the other hand, hospitals in remote location depend diesel-powered generators for energy supply. These generators are usually expensive to operate due to high cost of fuel and equipment maintenance. Another problem with the use of generators is that they produce pollutants, (WHO, 2015). The use of renewable sources of energy can serve as a viable alternative to solve this problem.

Different authors have studied the use of renewable energy resources to meet electricity demand. Olatomiwa (2016), assessed optimal configurations of hybrid renewable system for health clinic with mean total daily energy consumption of 15.5 kWh and 2.75 kW peak demand in three rural villages in Nigeria. Using the HOMER software, Ali and Kazmerski (2010) found that the best system for a remote health clinic in southern Iraq having a daily load of 31.6 kW h is composed of 6-kW PV panels comprising 210 W modules, 80 batteries of 6-V, 225-Ah capacity and a 3-kW inverter. Getachew and Gelma (2012), proposed the design of a solar – wind hybrid renewable energy system for a model community in rural Ethiopia. According to a report by Nigeria Demographic and Health Survey (NDHS) for North Western Nigeria, Kebbi

State is one of the States with high incidence of infant and maternal mortality rate, (NDHS, 2013). Malaria contributes to an estimated 11% of maternal mortality in Nigeria. It has high prevalence of about 50%, in children age 6-59 months in the North West region, (US Embassy Nigeria, 2011). Yauri Local Government Area of Kebbi State is a remote area with high incidence of maternal and infant death. The majority of these deaths, according to UNICEF occur within the first week of life, mainly due to complications during pregnancy and delivery, (UNICEF, 2014). Kebbi State enjoys abundant supply of solar radiation. This huge amount of solar radiation which is capable of supplying clean reliable electricity, remains mainly untapped (Gana *et al.*, 2014). The aim of this study is to design and simulation a 17 kWh standalone solar power system for a rural health centre in Kebbi, Nigeria.

Theory

Sizing of stand-alone systems require a fine balance between cost, energy supply and demand. The use of simulation tools such as Hybrid Optimization of Multiple Energy Resources (HOMER) help in overcoming the challenge of setting the balance between cost, energy supply and demand. HOMER is to model and simulate the performance of the solar power system configuration to determine its technical feasibility as well as the system's life-cycle cost. Life cycle cost (LCC) is the sum of all the cost associated with an energy delivery system over its lifetime or over a selected period of analysis and takes into account the time value of money. In lifecycle cost analysis, all anticipated future costs are discounted back to present cost by calculating how much would have to be invested at a market discount rate to have the funds available when they will be needed, (Duffie and Beckman, 2013). The simulation procedure determines how power system would behave with variations in design input parameters over a specified period of time, and hence search for best system configuration. The optimization process determines the best possible system configuration. Its purpose is to determine the optimal value of each decision variable that interests the modeler, (Felix and Simoes, 2006; Sharma, Singh and Khemariya, 2013). A decision variable is a variable over which the system designer has control and for which HOMER can consider multiple possible values in its optimization process.

The PV array is the primary element that converts solar irradiation into direct current, DC. The power output from a solar panel depends on amount of radiation incident on the tilted module surface and the ambient temperature. The power output from the array, P_{PV} can be calculated according to the following equations (Said *et al.*, 2007):

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{\bar{G}_T}{\bar{G}_{T,STC}} \right) [1 + \alpha_P (T_c - T_{c,STC})] \quad (1)$$

where Y_{PV} is the rated capacity of the PV array, meaning its power output under standard test conditions [kW], f_{PV} is the PV derating factor (%), $\bar{G}_T$ is the solar radiation incident on the PV array in the current time step (kW/m^2), $\bar{G}_{T,STC}$ is the incident radiation at standard test conditions (1 kW/m^2), α_P is the temperature coefficient of power (%/°C), T_c is the PV cell temperature in the current time step (°C) and $T_{c,STC}$ is the PV cell temperature under standard test conditions (25 °C). According to (Lambert *et al.*, 2016), the diesel generator is modelled on the basis of its fuel consumption rate which in turn is a function of power output given as:

$$F = F_0 \times Y_{gen} + F_1 \times P_{gen} \quad (2)$$

where F is fuel consumption rate, F_0 is generator fuel curve intercept coefficient, that is the no-load fuel consumption of the generator divided by its rated capacity, F_1 is generator fuel curve slope, Y_{gen} is rated capacity of the generator and P_{gen} is power output of the generator at any instant.

The battery bank serves as means of storage for energy produced from the solar panels and delivers the energy on demand. The capacity of the battery bank is modelled as (Kamjoo *et al.*, 2013):

$$N_{Bat} = \frac{E_L \times S_D}{C_{Bat} \times V_{Bat} \times DOD_{max} \times \eta_{Bat}} \quad (3)$$

where E_L is the load in *(Wh)*, S_D is the battery autonomy, C_{Bat} is the battery bank nominal capacity in *(Ah)*, V_{Bat} is the battery bank voltage in *(V)*, DOD_{max} is the maximum depth of discharge and η_{Bat} is the battery efficiency.
During HOMER's simulation and optimization processes, the system is operated so as to minimize total net present cost, such that it searches for the system configuration with the lowest total net present cost and the lowest energy cost, (Said *et al.*, 2007). HOMER compares the economics of a wide range of system configurations made up of different sources of renewable and non-renewable energy. The total net present cost, NPC, is used to represent the system life-cycle cost and given as (Said *et al*., 2007):

$$C_{NPC} = \frac{C_{ann.tot}}{CRF(i,N)} \quad (4)$$

where $C_{ann.tot}$ is total annualized cost ($/yr), i the annual interest rate, N is project life span (yr), and CRF (i, N) is the system's capital recovery factor. The capital recovery factor, CFR is a ratio used to calculate the present value of an annuity (a series of equal annual cash flows). It is given by (Said *et al.*, 2007) as:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (5)$$

The levelised cost of energy (COE) which is the average cost per kWh of useful electrical energy produced by the power system, is calculated by dividing the annualized cost of producing electricity (the total annualized cost minus the cost of serving the thermal load) by the total electric load served using the following equation (Lambert *et al*., 2010):

$$COE = \frac{C_{ann.tot} - C_{boiler} H_{served}}{E_{served}} \quad (6)$$

The second term in the numerator is the portion of the annualized cost that results from serving the thermal load. In systems with no thermal load to serve ($H_{served} = 0$), this term will equal zero, where C_{boiler} is boiler marginal cost ($/kWh), H_{served} is the total thermal load served (kWh/yr) and E_{served} is total electrical load served (kWh/yr).

Materials and Methods

The clinic building comprises the following rooms: one administration room, one doctor's room, one nurses' room, one waiting room, one treatment room, one pharmacy room, and two rest rooms. The medical equipment, lighting, and other devices used in this clinic are: refrigerator (80 W), freezer (80 W), electric sterilizer (1500 W), water pump (100 W), colour TV set (130 W), 13 fluorescent lamps (20 W each), and five ceiling fans (60 W each). The proposed hybrid renewable energy system is composed of 40 photovoltaic (PV) modules of 200 W each, one inverter of 3 kW, one diesel generator, and 20 solar batteries of 12 V, 205 Ah for back-up power supply, one charge controller 12 V, and the rest of the balance-of-systems, wiring, fuses, and other system safety devices.. A schematic of the proposed system is shown in Fig. 1.

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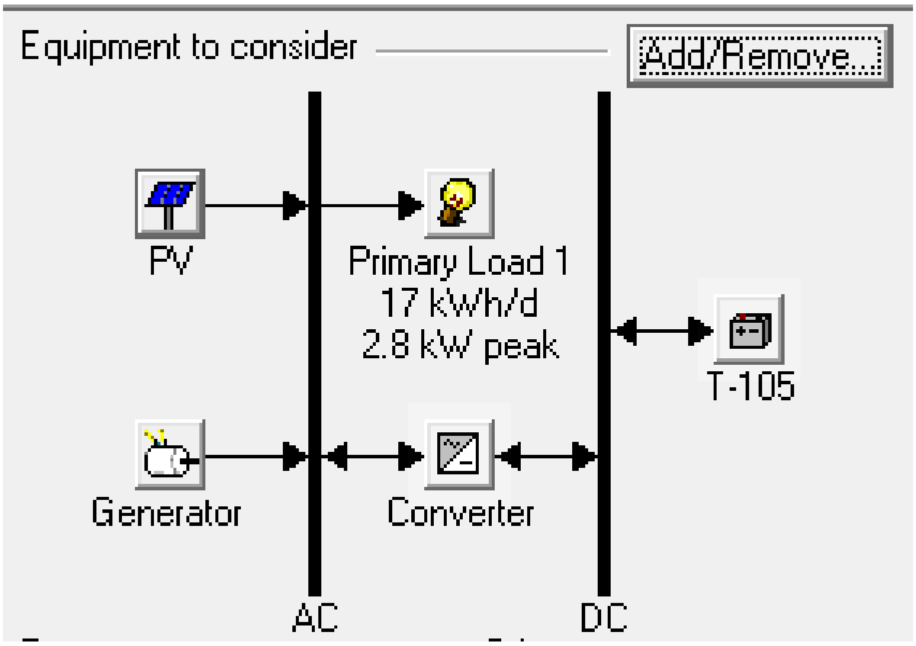

Fig. 1: Proposed System Architecture for the Clinic showing System Components

The prices for the PV system devices were taken from the manufacturer's web site. The estimated daily working hours of the medical equipment and other devices are as follows: fluorescent lamps (exteriors and interiors), 12 h/day; TV set, 12 h/day; refrigerator and freezers, 14 h/day; ceiling fans, 12 h/day; electric sterilizer, 3 h/day; and water pump, 6 h/day. The system is designed to work for 7 days a week, and the weighted average operating time is calculated, this together with the total load capacity of the clinic are used to size the battery bank. The load analysis is shown in Table 1 and the hourly load profile of the Clinic is presented in Fig. 2.

Table 1: Daily average electric AC load profile of the Clinic

Individual load	Qty	V (V)	I (A)	P (W) (AC)	Usage (h/d)	Usage (d/wk)	P (Wh) (AC)	P (kWh)
Lamps	10	220	0.1	220	12	7	2640	2.64
Lamps (out)	3	220	0.1	66	12	7	792	0.792
Refrigerator	1	220	0.364	80	14	7	1120	1.12
Freezer	1	220	0.36	80	14	7	1120	1.12
Elec. sterilizer	1	220	6.82	1500	3	7	4500	4.5
Water pump	1	220	0.45	99	6	7	594	0.594
Ceiling fan	5	220	0.27	297	12	7	3564	3.564
TV set	1	220	0.6	132	12	7	1584	1.584
TOTAL				2474			15914	15.914

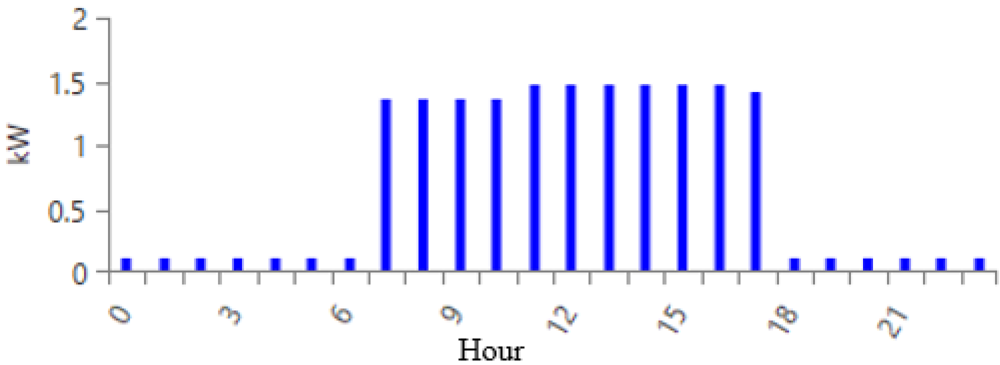

Figure 2: Hourly Load Profile of Clinic

Kebbi lies on latitude 12°27'14" N and longitude 4°11'51" E, and altitude of 225 m. The ten years period (2005 – 2014) solar resource data used for the site were obtained from the NASA Surface meteorology and Solar Energy/HOMER Data. The PV panels produced direct-current (DC) electricity in direct proportion to the global solar radiation incident upon it (Ali and Kazmerski, 2010). Table 2 and Fig. 3 show the monthly averages of global solar radiation and the monthly clearness index for Kebbi. The annual average solar radiation is 5.65 kW h/m^2/day. Equations (1-6) were used to obtain the power output from the PV array and other design parameters of the stand-alone power system. The monthly mean global horizontal solar irradiation and clearness index data for Kebbi is shown in Table 2. Table 3 shows the cost summary of system component.

Table 2: Monthly mean global horizontal solar irradiation and clearness index data for Kebbi

Month	Clearness Index	Daily Radiation (kWh/m^2/day)
January	0.642	5.645
February	0.633	6.011
March	0.611	6.23
April	0.597	6.286
May	0.581	6.081
June	0.532	5.496
July	0.475	4.919
August	0.451	4.707
September	0.507	5.199
October	0.588	5.679
November	0.65	5.798
December	0.672	5.734

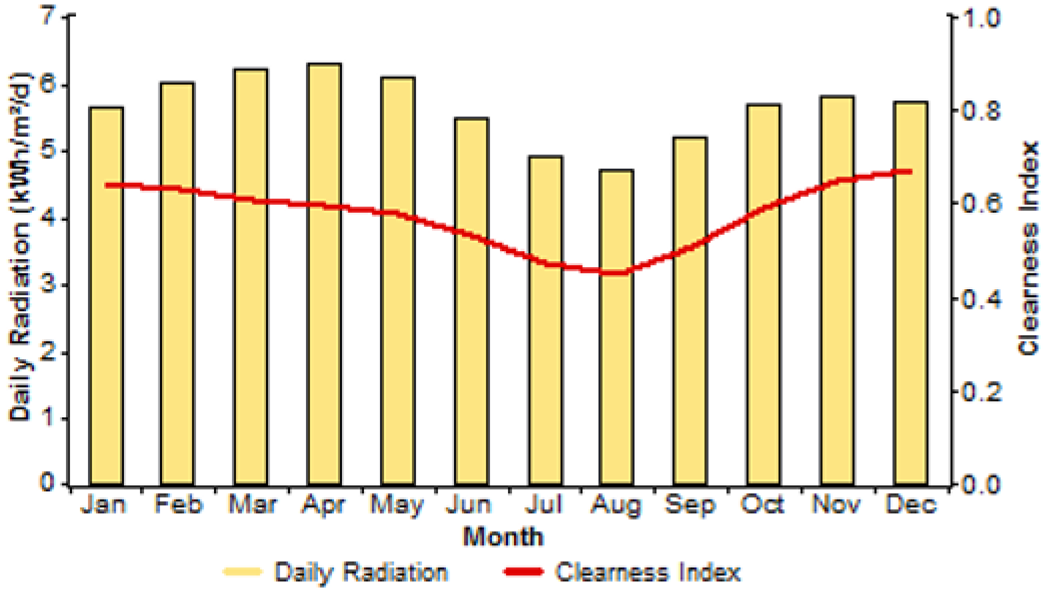

Figure 3: Solar Radiation Profile for Kebbi

Table 3: System components and estimated prices

Components Parameter	Value/Price
PV array	
Model	Solar World Sun module Plus SW 200 Poly
Capital cost	$711
Replacement cost	$711
Maintenance cost	$15/year
Sizes consideration	0, 1, 2, 3, 4, 5, 6, 7, 8, and 10 kW
Lifetime	20 years
De-rating factor	90%
Battery	
Model	Trojan SAGM 12 205
Capacity	12V, 205 Ah / 20Hr Rate
Capital cost	$542
Replacement cost	$542
Maintenance cost	$7/year
Unit consideration	0, 20, 30, 50, 70, 80, and 100
Converter	
Model	Universal
Capital cost	$206
Replacement cost	$206
Sizes considered	0, 2, 3, 4, 5, 6, and 10 kW
Lifetime	15 years
Diesel generator	

Model	Sumec Firman
Rating	2.5 kVA
Capital cost	$157
Replacement cost	$157
Maintenance cost	$0.6/h
Fuel cost	$0.59/L
Sizes considered	0, 1, 2, 3, 5, 8, and 10 kW
Lifetime	15,000 h
System Economics	
Interest rate	14%
Discount rate	14 %
Inflation	15.13%

RESULTS AND DISCUSSION

HOMER performed the simulation and optimization procedure using the solar radiation data, clinic load profile, sensitivity variable and other design variables which served as input parameters. Table 4 presents the HOMER (HOMER determines the emissions factor (kg of pollutant emitted per unit of fuel consumed) for each pollutant. After the simulation, it calculates the annual emissions of that pollutant by multiplying the emissions factor by the total annual fuel consumption) simulation results with the diesel price, discount rate, and inflation rate are US$0.57, $12.5, and $10.5 respectively. Table 3 shows that the most optimal configuration is 8-kW PV modules, 20 batteries, and a 3-kW inverter. This system gives the cheapest configuration with a total initial and net present cost of US$ 13,630 and US$ 30,842 respectively. The electricity cost is US$ 0.438/kW h.

Furthermore, the result of the simulation shows that the next optimal system is for PV-Gen battery configuration composed of 10-kW PV modules, 20 batteries, and a 3-kW inverter, and a 2.5-kW generator. The total initial cost, net present cost (NPC), and electricity cost of this system are US$18,929, US$41,123, and US$0.501, respectively. The least economical system is the generator-battery configuration. This system has a total initial cost, NPC, and electricity cost of US$ 11,613, US$62,746, and US$0.765, respectively. The summary of the optimisation result and amount of emissions prevented by using a photovoltaic system instead of diesel generator are respectively presented in Table 4 and Table 5. A summary of the cost estimates for the optimal system is presented in Table 6.

Table 4: Summary of Optimisation Result

System configuration	PV (kW)	Gen (kW)	Batt.	Conv. (kW)	Initial capital ($)	Total NPC ($)	COE ($/kWh)	Ren. Fraction
PV-Batt.	8	-	20	3	13,630	30,842	0.438	1.00
PV-Gen-Batt.	10	2.5	20	3	18,929	41,123	0.501	0.60
Gen-Batt.	-	3	20	2	11,613	62,746	0.765	0

Table 5: Amount of emissions prevented by using PV system instead of diesel generator.

Type of emission	Emissions (kg/yr)
Carbon dioxide (CO_2)	10,918.0
Carbon monoxide (CO)	26.9
Unburned hydrocarbons (HC)	3.0
Particulate matter	2.0
Sulfur dioxide (SO_2)	21.9
Nitrogen oxides (NO_x)	240.9

Table 6: Summary of optimal system and cost estimates

System component	Specification	Qty	Cost ($)
PV	200 W	40	145
Battery	12V, 205 Ah	20	542
Converter	3 kW	1	206
TOTAL			**16 846**

CONCLUSION

The design and simulation of a 17 kWh standalone solar power system for a Rural Health Centre in Kebbi has been carried out. The most optimal PV system for a rural health clinic in Kebbi has been determined using HOMER computer model. The advantages of deploying this PV system in remote rural community with good all year round high solar radiation are highlighted. Analysis of the systems shows that the price of electricity produced from the generator-battery configuration is over 70% greater than that produced from the PV system. The analysis also shows that using PV system instead of a diesel generator can prevent the release of substances which are toxic to human health and the environment.

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