Techno-economic Feasibility of Hybrid Renewable Energy System for Rural Health Centre (RHC): The Wayward for Quality Health Delivery

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***Abstract*— Role of off-grid renewable energy in extending basic healthcare services to rural villages where there is no grid extension or unreliable power supply cannot be over emphasized. This paper thus evaluated the technical and economic benefit of powering off-grid rural health clinic with renewable energy resources. The rural clinic selected as a case study in this paper is situated at Fatika rural village in northern Nigeria. Techno-economic analysis was carried out with HOMER software and the analysis found PV/diesel/battery best optimal configuration among other considered configurations. The results obtained proved greater potential of hybrid renewable energy system configuration consisting PV, diesel and battery in providing electricity to the rural health clinics far away from grid centers.**

Keywords—Hybrid Energy System; Techno-economic; Rural Health Clinic; Optimization; HOMER.

I. Introduction

Reliability of electric power supply is considered vital in rural/remote area healthcare development, the lack of which has limited its efficient delivery in many poor rural communities of the world, thereby putting lives at risks [1]. It has been reported that an estimate of 1 billion people worldwide are served with health facilities without electricity access [2]. This deficiency implies that medical equipment such as; ultra sound, autoclave, centrifuge, medical x-ray could not be used in such places. Surgery is sometimes depends on ambient light from windows or night time kerosene lamp. It was reported that women dies during pregnancy and at childbirth around the world on daily basis due to lack of proper medical care and that provision of minimum lighting and operational equipment would reduce maternal mortality by 70% if provided [3]. Modern advances in distribution of vaccines and other cold-chain dependent drugs, have presented new demands for electricity in health facilities where there is no access to reliable power supply. Operators of rural health facilities in Nigeria and other developing nations around the world are challenged with various problems, which have hindered effective delivery of healthcare to the rural populace. Challenges such as; poor medical infrastructures, even where available, unreliable power supply has hindered its functionality. For example, unreliable power supply as often rendered cold-chain activities inoperable, while a healthcare facility without means of illumination (lighting) can keep patients arriving late in the night for medical attention waiting until the following day before medical attention can be rendered.

For some of the health facilities that have resulted into the use of diesel generator (DG) to powered the facilities, none have been reported to run for long periods due to high cost of fuel, difficulty in obtaining the fuel, as well as unavailability of repair experts to carry out maintenance as at when due. Other setback of this alternative is release of CO_2 fumes into the surrounding environment, which can further deteriorate health of the patients as well as health personals working in the clinic [4]. Therefore, operators of rural health facilities need to address some of these challenges for proper delivery of the health care to the rural populace.

It is fact that conventional energy distribution has failed to be reliable and sometimes unaffordable in meeting the modest needs of rural health clinics [5]. Most rural villages in remote places are not connected to the national grid due to the distance of such locations to the grid center, and factors such as bad terrain and land topology has made it infeasible to embark on grid extension. Health and energy are closely related, in the sense that it determines the progress of rural health development [2]. Efficient energy strategy, such as the use of renewable energy resources abounding in rural areas, will be critical in improving the healthcare delivery in such areas, because these energy resources (e.g solar, wind, biomass and small hydropower) can play important role in powering healthcare infrastructures if effectively harnessed.

A solar/wind/diesel generator hybrid system can be deploy to cater for energy need of an un-electrified rural health center. It can provide means of powering lighting, mobile communication devices and certain medical equipment in an off-grid location for delivering timely and critical medical care for the rural dwellers. Hence, the need for hybrid power systems that combined conventional and renewable energy systems. Properly selected renewable power sources will considerably reduce the need for fossil fuel (diesel) as well as leading to increasing sustainability of power supply. At the same time, the conventional power sources can aid the renewable sources during varying climatic conditions, thus improving the system reliability.

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Over the years, several studies have proved the capability of renewable energy sources in delivering high quality power for rural communities need in applications such as; vaccine refrigeration [6], street lighting [7], mobile communication[8-9], clean water supplies[10] and so on. This paper thus discusses the result of techno-economic feasibility of introducing hybrid renewable energy sources in conjunction with diesel and battery energy storage to provide off-grid electricity for rural health clinic in a selected rural location in Nigeria. The analysis was carried out with HOMER (Hybrid Optimization Model for Electric Renewable), a software developed by National Renewable Energy Laboratory (NREL), United States [11]. The result obtained can be adopted in any other rural health centers of same category as the one consider in this study provided the location has similar climatic conditions.

II. METHODOLOGY OF HYBRID ENERGY SYSTEM

A. Description of Study Location

The health clinic considered in this study is located in rural village of Fatika situated in Giwa Local government area of Kaduna State, northern Nigeria with latitude (11^0 17'N) and longitude (7^0 25'E). The location is about 68km distance from existing grid. Fig. 1 shows the Map of Nigeria indicating the studied location, while Fig 2 depicts the RHC with proposed energy systems. The weather in the northern part of Nigeria is generally characterized as hot and humid. There were two major seasons, wet and dry season and each season last approximately six months. People living in this area depend largely on wood for cooking, gas lamps for lightings and electrical appliances in most cases, are powered by diesel generators. Fuel supply in this area is also difficult to come by, due to an extremely bad state of road for vehicular movement.

This healthcare facility can be classified as category 1 health clinic according to United States Agency for International Development (USAID) [5]. It consists of an emergency room, a doctor consulting room, nurse/injection room, one male ward, one female ward, a delivery room, and a laboratory. The total number of bed space in the clinic estimated at 30. In this facility, electricity is require for: (1) lighting for evening hours operations to support limited surgical procedures (such as; suturing, cesarean section etc.), as well as lighting of the surrounding environment. (2), refrigeration, in maintaining cold chain for vaccines, blood bank and other perishable medical supplies. (3), powering basic laboratory equipment including; centrifuge, microscope, incubator, hematology mixer and hand-held aspirator etc. Other appliances that can be found in the clinic are; television, VCR, and fans.

B. System Optimization Tool

HOMER, a renewable energy-based system optimization tool developed by National Renewable Energy Laboratory (NREL), was employed in modeling of the hybrid system for technical and economic feasibility [11]. It is a general-purpose system design tool for electric power systems; both stand-alone and grid-connected. Input to the software are; site load profile, renewable energy resources data, fuel price, system control parameters, constraint parameter as well as component's technical and economics details. HOMER performs numbers of hourly simulation that ensure best possible matching between the load and the supply for effective design of an optimal system. Thereafter, creating a list of feasible system sorted accordingly based on cost effectiveness and lowest net present cost (NPC).

Fig.1. Site location of Fatika Rural Health Clinic

Fig. 2: Proposed hybrid energy system for the RHC

C. Clinic Load Profile

As earlier stated, the clinic load consist of lighting load, medical diagnoses equipment load, refrigeration load, entertainment appliance load and other miscellaneous load. It is worth noting that the entire appliances are not expected to be operated at the same time, each has its specific hours operating hours daily. The load analysis computation is presented in Table 1, while Fig. 3 shows the hourly load profile of the clinic, where average energy demand per day and peak power is found to be approximately 11.5kWh and 2.75kW respectively. Major load occurs during the daytime (6am to 6pm). In reality, the size and the shape of the load profile will vary, so a day-to-day random variability of 10% and hour-to-hour random variability of 15% were specified in HOMER to take charge of the daily and hourly load variation.

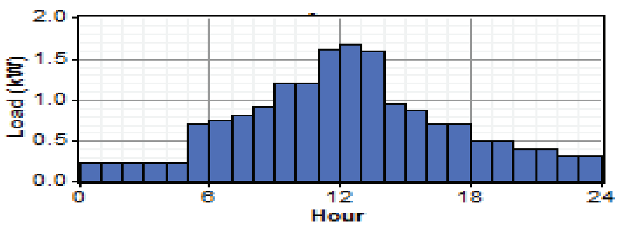

Fig. 3. Clinic daily load Profile.

TABLE 1. CLINIC LAOD ANALYSIS

Load Description	A *Quantity*	B *Power(W)*	C = AXB *Total Power (W)*	D *On-time(h/d)*	E=CXD/1000 *Total Energy (kWh/day)*
Lighting	15	10	150	10	1.50
Wall fan	10	30	300	8	2.40
Vaccine refrigerator	1	60	60	12	0.72
Small refrigerator	1	300	300	5	1.50
Centrifuge	1	575	575	1	0.575
Hematology Mixer	1	28	28	1	0.028
Microscope	2	15	30	3	0.09
Incubator	1	400	400	4	1.60
Water bath	1	1,000	1000	1	1.00
Autoclave/sterilizer	1	1500	1500	1	1.50
TV	1	80	80	6	0.48
Communication	1				
Stand-by		2	2	12	0.024
Transmitting		30	30	2	0.06
Total			4,455		11.477

D. Solar Energy Resources

The location in this study is blessed with considerable high solar irradiance due to its coordinate position; its lies within a high sunshine belt of Nigeria and hence have vast solar energy potentials. Solar radiation is well distributed with average radiation of 5.95 kWh/m^2/day and average daily sunshine of 6 hours at the site. Fig. 4 shows the monthly variation of solar radiation and clearness index in the site as obtained Nigerian Metrological Agency (NIMET) [12]. These data serves as input to software as they define the operational capacity of the PV panels throughout the year.

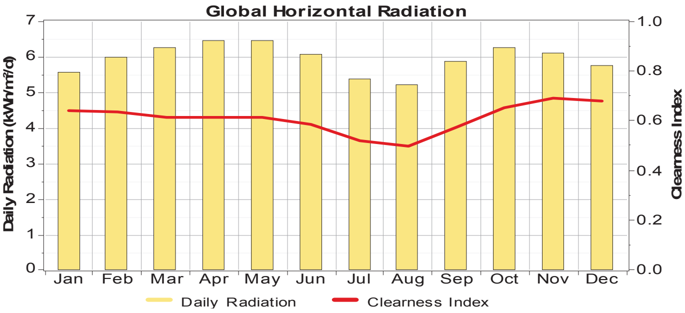

Fig. 4. Site monthly global solar radiation.

III. PROPOSED HYBRID SYSTEM CONFIGURATION

The proposed system comprise; solar PV modules, auxiliary diesel generator, batteries, converter, charge controller and its associate fittings as shown in Fig 5. Solar PV and diesel generator are combined to harness the output power of the system as well as to compensate for the unpredictable variation in solar irradiance. The converter is added to ensure energy flow between AC and DC bus, while the battery serves as backup storage to ensure uninterrupted power supply, maintain power quality at the demand point as well as to reduce the number of start/stop operation of the diesel generator at the instance of solar irradiance variation. The use of these energy sources in parallel with battery storage provides a smooth and uninterrupted output; hence make the hybrid system more reliable. Initial choice of component's size is based on the site load profile (Fig. 3).

Table 2 summarises technical and economic details of proposed the hybrid system components. The present cost of diesel in the country is 1.3$/l, and the price of the components presented in the table are estimated based on the quotation from the local distributor at present exchange rate (N199 to 1US$) [13].

TABLE 2. HYBRID SYSTEM COMPONENT'S DATA

Component Parameter	***Value***
Solar PV	
Rated Capacity	250Wp , 31.1 V
Derating factor	90%
Capital Cost	$2500/kW
Replacement Cost	$200/kW
Operational life	20 year
Diesel Generator	
Rated Power	3kW, 10.8 A
Fuel curve slop	0.33L/h/kW
Fuel curve inter.	0.05L/h/kW
Capital cost	$600
Replacement cost	$600
O & M cost	$0.5/hr
Operational life	15,000hrs
Battery	
Rating	6V , 225Ah, 11A
Round-trip Efficiency	85%
Minimum. state of charge	30%
Capital cost	$174/unit
Replacement cost	$174/unit
O &M cost	5$
Operational life	5.1years
Power Converter	
Rated Power	4kW
Efficiency	90%
Capital cost	$200/kW
Replacement cost	$200/kW
O&M cost	$10/yr
Operational lifetime	10year

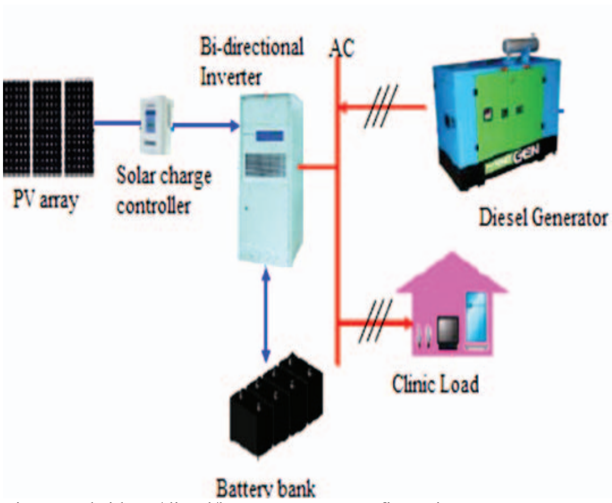

Fig. 5. Hybrid PV/diesel/battery system configuration

IV. Basic Mathematical Model of System Components

Comprehensive mathematical model of the components constituting the proposed hybrid system (Solar PV, diesel generator, batteries and converter) and the control strategy is available in literatures [9,13-17]. Nevertheless, brief summary of each mathematical models are highlighted below:

A. PV Model

A PV system employs solar panels made up of series/parallel connected solar cells to produce dc power. The power output of the PV panel is given by [14]:

$$P_{pv-out} = P_{pv-rated} \times \left(G/G_{ref}\right) \times [1 + K_T(T_c - T_{ref})] \quad (1)$$

where P_{pv-out} is output power of PV cell, $P_{pv-rated}$ is the PV rated power at reference condition, G is solar radiation (W/m^2), G_{ref} is the solar radiation at standard temperature condition (G_{ref}=1000W/m^2), T_{ref} is cell temperature at reference conditions (T_{ref}=25^{o}C), K_T is temperature coefficient of the PV module. The cell temperature $T_c = T_{amb} + (0.0256 \times G)$, where T_{amb} is ambient temperature. In this study, four different types of PV arrays are considered to obtain the optimal size (0, 2, 3, 5 and 7kW). Initial capital and replacement cost of the PV module is as presented in Table 2. Expected lifespan of PV arrays is considered as 20 years, while derating factor of each module is 90%.

B. Diesel Generator Model

Owing to intermittent nature of the proposed renewable energy resources (solar irradiance and wind speed), integrating them with conventional power sources will be a realistic approach where reliability of energy supply to the load is essential. In many hybrid system, diesel generator (DG) acts as steady source of power. The DG systems are designed to supply the load and also charges the battery, whenever the renewable energy sources along with battery are unable to meet the load demand. Proper energy balance is therefore necessary for optimum system operation as the DG fuel consumption (F_G) is proportional to the its output power as shown in (2) [15].

$$F_G = B_G \times P_{G-rated} + A_G \times P_{G-out} \quad (2)$$

where $P_{G-rated}$ is the nominal power of the diesel generator, P_{G-out} is the output power, while A_G and B_G represents the coefficients of fuel consumption curve as defined by the user (l/kWh). In this study, 0, 2.5, 3.0 and 5.5kW sizes of diesel generators were considered for simulation and maximum load ratio was set at 10% [9]. Other details on DG are provided in Table 2.

C. Battery Model

Battery energy storage is required for storing electrical energy for maximum utilization due to intermittent nature of solar irradiance as well as to reduce the number of start/stop operation of diesel generator. Modeling of batteries for real time analysis of HRES depend on parameters such as; battery state of charge, (SOC), battery storage capacity, battery rate of charge/discharge, ambient temperature as well as battery lifetime and other internal phenomenon, such as gassing, double layer effect, self-discharge, heating loss and diffusion. The battery storage capacity is given as [16];

$$C_{Wh} = (E_L \times AD)/(\eta_{inv} \times \eta_{Batt} \times DOD) \quad (3)$$

where E_L is the average daily load energy (kWh/day), AD is number of day of battery autonomy, DOD is battery depth of discharge, while η_{inv} and η_{Batt} respectively represent the inverter and battery efficiency. A Trojan T105 model battery rated 6V, 225Ah and 1.35 kWh with economic details presented in table 2 was selected in this study. In order to obtain optimal configuration, the battery bank was assumed to consist any number of batteries between 0 and 24. Each battery string comprises 8 batteries and the lifetime throughput of each is estimated 1,075 kWh.

D. Power Converter Model

The proposed hybrid system comprise both AC and DC bus, hence a bidirectional inverter (power converter) is required to provide path for power flow between the source and the load. This device can supply power in both direction; it acts as inverter whenever it provide path from DC bus to AC bus and as rectifier whenever it provides path from AC bus to DC bus to charge the batteries[17]. The rectifier and inverter mode of bidirectional inverter is respectively model by (4) and (5) [18];

$$P_{recm} = P_{G-out} * \eta_{inv} \quad (4)$$

$$P_{invm} = P_{PV-out} * \eta_{inv} \quad (5)$$

where, P_{recm} and P_{invm} are respectively the output power of bidirectional inverter in its charging mode and discharging mode, P_{G-out} is the DG output power and P_{PV-out} is the DC output power of PV module, while η_{inv} is inverter efficiency assumed to be 90% in this study. Different sizes of converters

(0, 1, 2, 3, 4 and 5 kW) are considered HOMER during analysis in order to obtain the optimal configuration.

E. System Economics

The economic evaluation of the project is based on the provided economic inputs into the software, which includes; component initial capital cost, replacement cost, operating and maintenance (O&M) cost, fuel costs, interest rate etc. In HOMER, system life-cycle cost is represented by total net present cost (NPC) given as [19];

$$C_{NPC} = \frac{TAC}{CRF\ (i,N)} \qquad (6)$$

where TAC is total annualized cost ($/year) and CRF is capital recovery factor, a function of annual interest rate (i) and project lifetime (N) given in equation (7). Also the system payback period (PBP), which represents the expected recovery time of total cash inflow on investment is calculated in HOMER by comparing each system configuration with base case system (diesel generator) using equation (8)[19];

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (7)$$

$$-Intial\ capital\ cost + \sum_{N=1}^{PBP} \frac{(Net\ cash\ inflow)}{(1+i)^N} \qquad (8)$$

The project lifetime is assumed 25 years and annual interest rate taken as 6% in this study. HOMER aim at minimizing the NPC, hence the cost of electricity (COE) while searching for the optimal system configuration. It should be noted that all economic factors considered in HOMER are calculated in constant dollar (US$) terms.

V. RESULTS AND DISCUSSION

HOMER performed hourly time series simulation for every possible system configuration on annual basis to compute the system operational characteristics including; annual electricity production, annualized cost of energy (COE), annual served, excess electricity, operating hours, renewable fraction etc. The renewable energy source and the diesel generator were evaluated to determine the feasibility of the system configuration. HOMER searched for optimum system configurations with component sizes that satisfy the load demand at minimum NPC. The simulation results are thereafter presented in terms of optimal systems and sensitivity analysis.

Table 3 shows the simulation results of the available system configurations, ordered according to lowest NPC, based on the daily noise variation in health clinic load and other parameters inputted into the software. The best optimal combination at 5.95 kWh/m^2/day average global solar radiation and 1.3$/l diesel price comprised; 3kW PV array, 2.5kW diesel generator, 16 units Trojan T-105 battery and a 3kW converter, with total NPC of $41,512, COE of $0.530/kWh and a renewable fraction of 71%. It is worth noting from the table that, the NPC and the COE of diesel-only system over the project lifetime is the highest among other hybrid configurations, due to large and frequent fuel consumption, although it has the lowest capital cost ($600).

TABLE 3. PERFORMANCE EVALUATION OF VARIOUS SYSTEM CONFIGURATIONS

Parameter	**System Configurations**		
	PV-diesel-Battery	***Diesel - Battery***	***Diesel-Only***
Component capacity			
PV panel (kW)	3	-	-
Diesel generator (kW)	2.5	2.5	3
Battery (unit.)	16	16	-
Converter (kW)	3	1	0
Economics			
Initial capital ($)	11,384	3,484	600
Annual operating cost ($)	2,257	5,043	9,357
Total NPC ($)	41,512	67,950	120,217
COE ($/kWh)	0.530	0.867	1.534
Annual fuel cost ($)	1,134	3,238	5,443
Fuel consumption (L/yr.)	872	2491	4187
DG operating hours. (hr/yr.)	1,647	3,310	8,394
Environmental (kg/year)			
Carbon dioxide (CO_2)	2,297	6,560	11,025
Carbon monoxide (CO)	567	16.2	27.2
Unburned Hydrocarbons (UHC)	0.628	1.79	3.01
Particulate Matter (PM)	0.427	1.22	2.05
Sulphur dioxide (SO_2)	4.61	13.2	22.1
Nitrogen oxides (NOx)	50.6	144	243
Electrical Production (%)			
RE penetration	71	0	0
Diesel Production	29	100	100
Excess Production	4.29	0	29.4

Addition of batteries to the existing diesel generator system may still be consider a good option, although leads to increasing capital cost, but will definitely reduce the fuel requirements of the diesel generator as energy storage during the off-peak period will optimize the fuel efficiency leading to reduction in operating cost as well as less emission. However, the NPC of this configuration is still high compare to the optimal configuration due to additional battery cost. Batteries replacement and maintenance is also a major factor need to be considered of this configuration.

On the environmental basis, the conventional diesel-only configuration produced the highest CO_2 emission (11,025kg/year), while hybrid PV/diesel/battery and diesel/battery systems produced 2,297 and 6,560 kg/yr. respectively. The inclusion of renewable energy source and energy storage can bring a total reduction of 79.2% and 40.5% in CO_2 emission respectively. Particulate emissions are also reduce proportionally, since PM contains black carbon, a short-lived climate pollutant, this represent another net gain for the climate as well as the health of the patients and staff in the clinic. Percentage reduction in pollutants emission in the power generation system is related to the level of penetration of renewable energy and energy storage device in the system. Therefore, adoption of more renewable energy options will further reduce the emission of these harmful substances to the environment.

VI. Conclusion

The analysis presented in this paper is carried out to determine techno-economic feasibility of powering rural health center with renewable energy options. The most economical and environmental friendly option for selected rural health center situated in Giwa Local government area of Kaduna State, Nigeria, having a daily load demand of 11. 5kWh comprised; 3kW PV array, 2.5kW diesel generator, 16 units Trojan T-105 battery and a 3kW converter. The analysis shows the cost of electricity generated by this configuration to be three times lower than the cost of energy generated by existing diesel alone system. In addition, the configuration is more environmental friendly as compare to diesel-only configuration, which often results in high pollutant emission, that can further leads to deterioration of patient's health as well as that of health personnel working in the facility.

The analysis presented in this case study, has demonstrated how improved energy systems can offer significant advantages in terms of economics, healthcare services, environmental health and sustainability, since the simulation results shows the optimal combination that yields multiple gains, including; lower overall cost of energy, a shift to renewable energy, and a reliable supply for the health facility energy needs.

However, government subsidies and tariff concession need to be establish in this area as well as other part of the country to boost investments in renewable energy to enhance their contribution in total energy mix, due to high initial costs of implementing the systems. This will lead to extension of operating hours of RHC with better service to patients both day and night, fuel saving and reduction in pollutant emission, safe keep of drugs and vaccine for longer period at normal temperature as a result of constant power supply to cold-chain refrigerators and many more.

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