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Techno-Economic Viability Analysis of a Hybrid Renewable Energy System for Katsira Village

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Abstract

Off-Grid rural electrification with the help of Renewable Energy Sources (RES) has become a cost-effective and convenient option for areas where grid connection is neither available nor feasible in the near future. This paper focuses on creating a model for electricity generation from a mix of renewable energy resources to satisfy the electrical needs of an off-grid remote village of Katsira, located in north western state of Sokoto in Nigeria. The selected solution is based on the system cost and the availability of the renewable energy resource at the location. The monthly average daily global solar radiation for the village is about 5.919 kWh. With an estimated primary energy demand of 189KWh/day and 33kW peak load demand for the village, an economic feasibility and assessment of a proposed hybrid system to supply this requirement was carried out. The simulation using NREL's Homer software indicate that for the proposed hybrid system comprising of PV, Diesel and Small Hydro Power (SHP), the cost of generating energy (COE) is 0.045$/kWh. This cost is 40% lower than that of the public utility supply company in Nigeria. The optimized hybrid system realized has a Net Price Cost of $39,828.00 and no storage battery is necessary.

Keywords: *Small Hydro Power, Cost of Energy, Net Price Cost, Renewable Energy, hybrid system*

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Background to the Study

There exists abundant evidence that climate change (CC) is a severe threat to economic development and can substantially affect a nation's GDP, as it affects water, forest, sanitation, food security, industrial development, housing, energy , health and air we breathe. Fossil fuels have been a major cause of adverse environmental and social consequences such as climate change, air pollution and mining accidents. Up to date, fossil fuels (coal, oil and natural gas) have been the main source of energy, meeting three-quarters of total world energy needs. However, rising concerns about the security of energy supplies have led to a global search for alternative energy sources. Sustainability is a key factor influencing the long-term viability of any energy resource, and it comes as no surprise that it is at the forefront of the global campaign to abandon the use of fossil fuels (Lambert et al, 2005). In view of this, renewable energy sources are being increasingly exploited to meet the energy needs (Simon & Guido, 2011).

The World Commission on Environment and Development (WCED) called for renewable energy resources as the foundation of the global energy structure during the 21st century (WCED 1987)(John &Akinbami,2001) but the National Energy Policy acknowledges that despite the abundant energy resources available in Nigeria, they have not been properly managed to satisfy the nation's energy needs. The Nigerian economy is predominantly oil-driven, but the contribution of oil to the nation's GDP is very small indeed (Mustafa &Dilşad, 2012).

Reliable access to electricity is a basic precondition for improving people's lives in rural areas, for enhanced healthcare, education and for growth within local economies. At present, more than 1.5 billion people worldwide do not have access to electricity in their homes (Energy, 2011); in many cases, utility grid extension is impractical owing to dispersed population or rugged terrain (Simon & Guido,2011). An estimated 80% of these people live in rural areas; most have scant prospects of gaining access to electricity in the near future (Energy, 2011). By 2030 there will still be 1.2 billion people without access to electricity. The number of people without electricity will even rise in Sub-Saharan Africa.

In the rapidly growing economies of the developing countries the demand for electricity is constantly increasing. Electricity is one of the driving forces in a growing economy and increasing demand puts incredible pressure on the countries' energy infrastructure to match that demand (Mustafa &Dilşad, 2012). The generation of electrical energy through an alternative sources such as wind and solar, has become more attractive and is widely used for substituting fossil fuels in the process of electrical power energy since 1970s because of the crisis in oil. Nevertheless, such alternative energy sources have a slow development and the transition into a new phase of evolution in the electrical power generation sector appears to be a complex task (Nouniet al, 2008).

Village electrification is a vital step for improving the socio-economic conditions of rural areas and crucial for the country's overall development. The villages' welfare is one of the main aims of the rural electrification program. Enormous benefits can be achieved in irrigation, food preservation, crop processing, agriculture and rural small-scale industries. It creates employment opportunities for the villages' youth and promotes a better standard of life (Kaundinya et al, 2009 & Nwosuet al, 2008). Therefore, availability of electricity removes poverty and helps economic development by fulfilling health, education, water supply (for drinking and irrigation) needs of the rural population (Chaureyet al, 2004).

Rural electrification is relatively costly compared to electrification of urban areas. At any off-grid location, the delivered energy cost from the grid depends on four factors: -

a. Cost of energy (COE) generation from the central power plant.
b. Cost of transmission and distribution through the new network lines.
c. Transmission and distribution loss. (Technical and non-technical)
d. Load factor (Nwosuet al, 2008)

This study addresses those rural communities for whom off-grids are the most suitable solution and under-lines the benefits of using a mix of technologies based on renewable energies, battery storage, and fossil fuels. It focuses on rural communities isolated from public grids and without any prospect of connection in the next 15-20 years; having a certain load demand and serving a concentrated group of 15 or more households.

Study Area

The selected off-grid location for this paper is Katsira village in Goronyo local government of Sokoto State, in the north-west geo-political zone of Nigeria. The location of Goronyo on Latitude: 13° 45'N and Longitude:5° 41'E; the area of interest (i.e. Katsira village) is about 16km away from the main local government headquarter, Goronyo. Therefore, the daily radiation for Katsira is assumed to be the same as that of Goronyo due to their proximity. The village is nowhere near the national grid network and there no indication as to when it will be connected.

Electrical Loads

The demand for electricity in each area is different and therefore depends on numerous equipment factors, such as the price of equipment for electricity, the weather conditions, the time of day, the type of day and the season. Furthermore, even the level of affluence and lifestyle of the people in the community has an effect on the energy demand. The load profile describes the variation of the electricity demand with time. The hourly load profile provides crucial information on how electricity is used, and thus on where and what demand side management strategies could be potentially effective. Demand side management is the process of managing the consumption of energy to optimize available and planned generation resources (Nouniet al, 2008). Thus in this study the primary energy demand of Katsira village is 189Kwh/day and 33kw peak. Figs. 1a and 1bshow the daily profile and the seasonal profile of electricity demand for the village respectively.

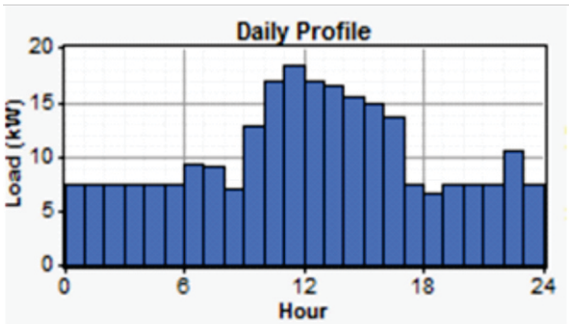

Fig.1a, Daily Profile of Electricity Demand

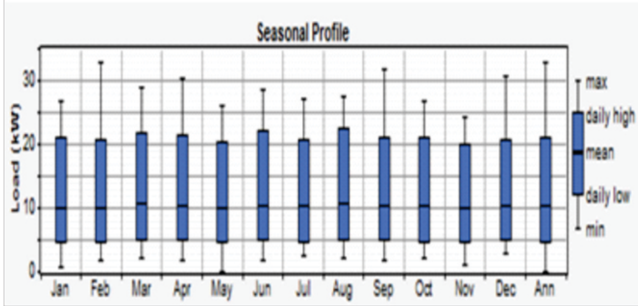

Fig.1b, Seasonal Profile of Electricity Demand

Methodology

Careful studies of different approaches were carried out for an optimal result. The methodology is based on the followings;

Hybrid Power System

A hybrid energy system generally consists of a primary renewable source working in parallel with a standby secondary non-renewable module or grid and storage units (Nouniet al, 2008). In this case the proposed system is comprised of PV modules, diesel generatorand small hydropower (SHP) system. Description of these components is given in the following sections. In the system also is included a storage battery and a DC/AC inverter.

Fig. 2 shows the hybrid system for the study.

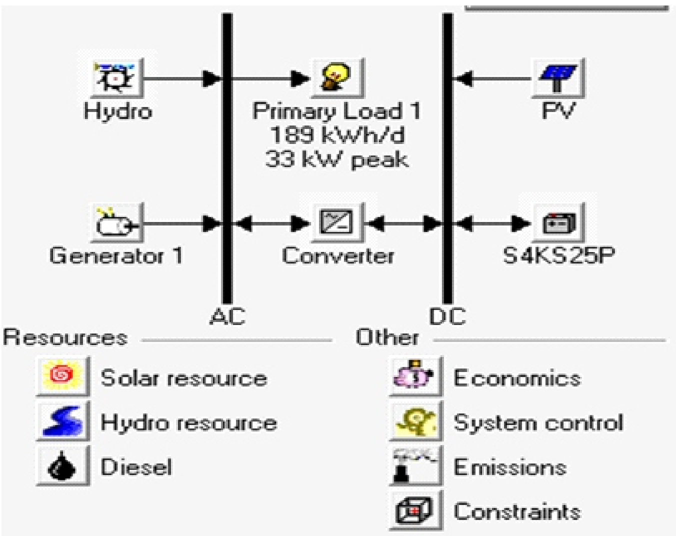

Fig. 2 Model of Hybrid Energy Systems (HOMER)

Solar Radiation Resource

Renewable energy sources are intermittent and naturally available.Due to these factors our first choice to meet the household electric energy demand will be solar energy. Weather data are important factor for pre-feasibility study of PV based hybrid energy system for any particular site (Kaldelliset al, 2000). For the selected location, the monthly average solar radiation, the global radiation and clearness index are indicated in fig.3.

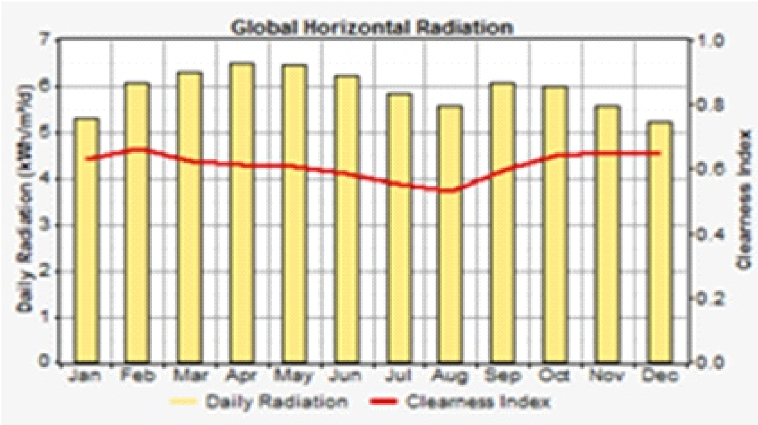

Fig. 3 Monthly average daily radiation, global radiation and clearness index of Katsira.

Diesel Generator

The off-grid diesel-based system is the most expensive solution over the whole lifetime of the project. The fuel costs of diesel, the running costs, and the replacement cost of the generating set every 3-4 years (25000 operating hours) offset the low initial investments. For the 20kW generator size considered, HOMER uses the following equation to determine fuel consumption:

$$F = F_0\, Y_{gen} + F_1\, P_{gen}$$

F_0 = is the fuel curve intercept coefficient

F_1 is the fuel curve slope

Y_{gen} is the Rated Capacity in kW

p_{gen} is the electric output in kW

It also uses the following equation to determine a generator's fixed cost of energy:

$$C_{fixed} = C_{O\&M} + \frac{C_{replacecost}}{lifetime\ (hrs)} + F_0\, Y_{gen}\, C_{fuel}$$

$C_{O\&M}$, and C_{fuel} are the operation and maintenance cost and fuel price in U.S. Dollars, respectively

F_0= is the fuel curve intercept coefficient

Y_{gen} is the rated capacity in kW

In terms of the fuel price and the fuel curve slope, HOMER determines a generator's marginal cost; an additional cost for every KWh generator produces using the following expression

$$C_{marginal} = F_1 \ C_{fuel}$$

Small-Hydro Power

The electrical power generated by the small-hydro unit is given by:

$$P_h = \eta_{hyd} \rho_{water} . g . H_{net} . Q$$

Where η_{hyd} is the hydro efficiency as obtained from the quadratic fit to the manufacturers' data, ρ_{water} is the density of water, *g* is the acceleration due to gravity, H_{net} is the effective head, and Q is the flow rate (Chaureyet al, 2004). Figs.4a and 4b show the average discharge of Goronyo dam from 1996-2005 and the cumulative average discharge of Goronyo dam from 1996-2005 respectively (Umar, 2005).

Month	Stream Flow (L/s)
January	269,300.0
February	273,960.0
March	297,850.0
April	358,400.0
May	328,400.0
June	742,600.0
July	1,471,100.0
August	444,880.0
September	616,970.0
October	110,980.0
November	355,250.0
December	284,550.0

Annual average: 163,826.9

Scaled annual average (L/s) 463827

Fig. 4a Average Discharge of Goronyo Dam1996-2005(Umar,2005).

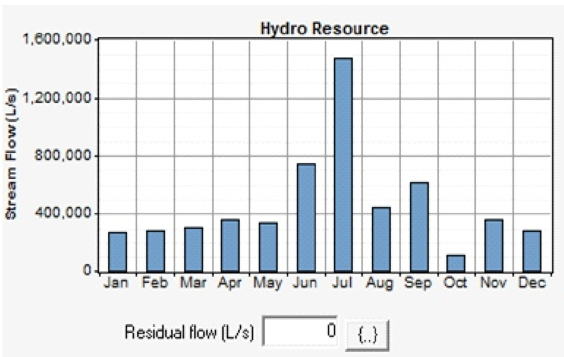

Fig. 4b, Cumulative average discharge of Goronyo Dam 1996-2005 (Umar,2005)

Converter

A converter is an electronic power device that is required in a hybrid system to maintain the energy flow between AC and DC electrical components. It has an inverter and a rectifier to do the conversions from DC to AC and vice versa (Chaureyet al, 2004).

Battery Power

Battery is used as a backup system which maintains constant voltage across the load during peak loads or a shortfall in generation capacity (Nouniet al, 2008). The state of charge of battery can be calculated from the following equations:

A. Battery discharging

$$P_b(t)=P_b(t-1)(1-\sigma)-\left[\frac{P_h(t)}{\eta_i}-P_i(t)\right]$$

B. Battery charging

$$P_b(t)=P_b(t-1)(1-\sigma)+\left[\frac{P_h(t)-P_L(t)}{\eta_i}\right]$$

Where $P_b(t-1)$ and $P_b(t)$ are the battery energy at the beginning and the end of interval t, respectively, $P_l(t)$ is the load demand at the time t, $P_h(t)$ is the total energy generated by micro-hydro unit and wind generators at the time t, σ is the self-discharge factor and ηb and ηi are the battery and inverter efficiency, respectively, as obtained from the manufacturers' data (Chaureyet al, 2004).

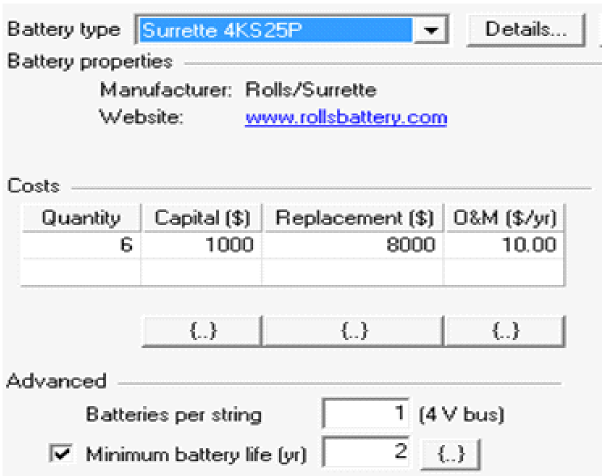

Fig.5, Surrette Battery's technical & cost parameters

The battery chosen for this study is Surrette 4KS25P as shown in fig 5. It is a 4V battery with a nominal capacity of 1,900Ah. It has a lifetime throughput of 10,569 kWh. The capital cost, replacement cost and O&M costs for one unit of this battery were considered as $1000, $800, and $10/year respectively.

Sensitivity Results | Optimization Results

Tabular | Graphic

Double click on a system below for optimization results.

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Hydro Head (m)		PV (kW)	Hydro (kW)	Label (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)	Batt. Lf. (yr)
2		20.0	5.52	5.0	12	30	$ 23,933	2,291	$ 53,219	0.060	1.00	136	121	12.0
3		15.0	11.04	5.0	3	30	$ 21,216	1,756	$ 43,659	0.050	1.00	128	157	12.0
1		20.0	3.68	15.0	12	30	$ 27,255	5,549	$ 98,192	0.111	0.92	3,016	1,167	12.0
5		5.0	18.39	5.0		30	$ 18,281	1,478	$ 37,178	0.042	1.00	65	79	
4		10.0	14.72	5.0		30	$ 19,498	1,590	$ 39,828	0.045	1.00	149	175	

Fig 6, Sensitivity Analysis Details

Simulation

Simulations were conducted using HOMER software; a product of National Renewable Energy Lab, a division of the U.S. Department of Energy (Bernal & Dufo, 2009)&(John & Akinbami, 2001). HOMER specializes in modeling and comparing different power generation systems based on electric and/or thermal loads. HOMER facilitates finding the optimum solution in terms of a system's installation and recurrent costs over a specific life span. The software executes three major tasks; simulation, optimization, and sensitivity analysis. A model is simulated at every hour of the year to assess its efficiency, viability, and cost effectiveness. Optimization analyzes different system's combination in search for the most cost-effective solution while meeting technical feasibility. Sensitivity analysis analyzes the effect of different input assumptions (such as cost of fuel and average wind speed) on a system (Shaahid & El-Amin, 2008). Figure 1 represents HOMER's schematic representation of the hybrid system.

Results and Discussion

HOMER performs the simulation for a number of prospective designed configurations. After examining every design, it selects the best that meets the load with the system constraints at the least LCC. HOMER performs its optimization and sensitivity analysis across all mentioned components and their resources, technical and cost parameters, system constraints and sensitivity data over a range of exogenous variables. Results for the hybrid system options are compared regarding the least-cost scenario (Okbaet al, 2012).

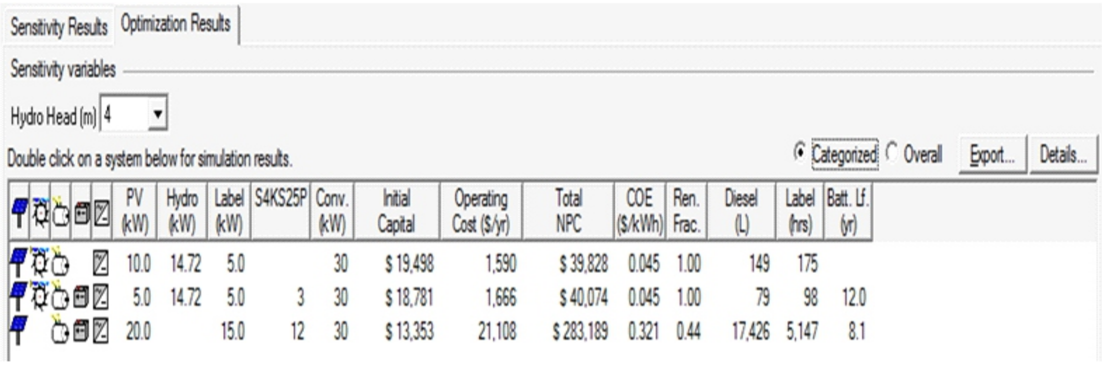
Sensitivity Result

Sensitivity analysis eliminates all infeasible combinations and ranks the feasible combinations taking into account uncertainty parameters. HOMER allows taking into account future developments, such as increasing or decreasing load demand as well as changes regarding the resources, for example fluctuations in the river's water flow rate, wind speed variations or the biodiesel prices (Okbaet al, 2012). Here, the various sensitive variables are considered to select the best suited combination for the hybrid system to serve the load demand of Katsira village. Fig. 6 below shows the sensitivity analysis detail.

It can be observed that with change in the sensitive variables, the configuration of the system changes. Even in this analysis, HOMER ranks the configurations in descending order of their total NPC.

Optimization Results

For the off-grid electrification of Katsira, various combinations have been obtained for hybrid systems with SPV, SHP, Diesel plant batteries and converters from the HOMER Optimization simulation. This is shown in fig.7.


Sensitivity Results | Optimization Results

Sensitivity variables

Hydro Head (m) 4

Double click on a system below for simulation results. Categorized Overall Export... Details...

PV (kW)	Hydro (kW)	Label (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)	Batt. Lf. (yr)
10.0	14.72	5.0		30	$ 19,498	1,590	$ 39,828	0.045	1.00	149	175	
5.0	14.72	5.0	3	30	$ 18,781	1,666	$ 40,074	0.045	1.00	79	98	12.0
20.0		15.0	12	30	$ 13,353	21,108	$ 283,189	0.321	0.44	17,426	5,147	8.1

Fig. 7 Optimization Result Details

According to the optimization results, the optimal combination of RET system components are a10kW PV-Array, 14.72kW SHP, 5kW diesel plant, 30kW Inverter. By this result it can be seen that there is no need for storage batteries. The implication of this is that when there is no energy supplied from the PV system (i.e. in the night), the load requirement will be met by the combination of SHP and the diesel generating set. Detail optimization results are shown in fig.7. The total Net Present Cost (NPC) was found to be $39,828, Capital cost as $19,498 and Cost of Energy (COE) as $0.045. As per the results obtained, the COE of $0.045/kWh from this hybrid system is cheaper than that of $0.075/kWh obtainable from PHCN. Assuming exchange rate of $1 to N160, the COE will translate to N7.20/unit which is less than N12.00/unit charged by PHCN. Thus, the optimized system is 40% cheaper than that of PHCN. Therefore there is no need for a grid extension to meet up the village load. But, if the cost of electricity from the PHCN falls below $0.045/kWh, grid extension becomes viable. It should be noted that, the second and third optimized options have far less capital outlay when compared with the first option. However, but their operating costs are $1,666; $21,108 and total NPC are $40, 07; $283,189 respectively are higher than the corresponding values for the first optimum choice.

Conclusion and Recommendation

The analysis presented in this paper validates the possibility of guaranteeing continuous availability feature of firm power at Katsira village by means of hybrid power option consisting of SPV, SHP, Diesel plant, Surrette Batteries and inverter. This combination has been identified as the cheapest and most dependable solution with a COE of $0.045/kWh; total NPC of $39.828 and initial cost of $19.498.The simulation results obtained indicate that, the COE of $0.045/kWh from this hybrid system is cheaper than that of $0.075/kWh obtainable from PHCN, thus it is by 40% cheaper than that of PHCN.

The observations of this study can be employed as a benchmark in designing hybrid systems for other locations having similar climatic and load conditions so as to avoid over dependence on fossil which has detrimental impact on human life and climate. In other to achieve this, the government, cooperate bodies, and cooperative societies will avail themselves of this opportunity to generate "all-green" power and save our environment from the global warming caused by greenhouse gases.

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