**Comparative study of off-grid and grid-connected hybrid power system: issues, future prospects and policy framework**

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| **Article Info** |  | **ABSTRACT**  |
| ***Article history:***Received Aug 9, 2020Revised 10, 2020Accepted 25, 2020 |  | Sustainable energy system is an essential ingredient for any meaningful development in any society. Power supply in Nigeria (majorly depends on fossil fuels) is insufficient, unreliable and not sustainable. Almost half of about 200 million populations are living without electricity, with majority of them living in the rural areas. This paper proposed the use of Off-Grid (OG) Hybrid Power System (HPS) for rural electrification in remote villages and the use of Grid-Connected (GC) HPS in the urban areas. It also identified the barriers to renewable energy penetration and recommended some policy measures in ensuring sustainable energy development for the nation.To buttress the point, a techno-economic feasibility study of OG and GC Small hydropower-Solar Photovoltaic Diesel hybrid system was done using Oyan River, Abeokuta, Nigeria as a case study. The hydro solar resources data of the area were collected and analyzed using Hybrid Optimization Model for Electric Renewable (HOMER) software. The simulation results proved that the GC system is better than the OG system in technical and economic terms depending on the locations. The work will assist power sector stakeholders in making informed decisions towards HPS technology development in Nigeria. |
| ***Keywords:***Comparative studyOff-grid systemGrid-connected systemHybridpowersystem Policy framework |
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1. **INTRODUCTION**

Sustainable energy system is an essential ingredient for any meaningful development in any society. It preserves the natural resources and prevents environmental impacts that may be detrimental to the ecosystem now and in the future [1-3]. Effect of global warming and climate change as a result of long dependency on fossilized energy is now a major concern in the world [4-5].

Power supply in Nigeria (majorly depends on fossil fuels) is insufficient, unreliable and not sustainable. Almost half of about 200 million populations are living without electricity, with majority of them living in the rural areas [6-7]. Even those that are connected to the grid experience frequent outages, voltage fluctuations, blackouts (that may last for days or even weeks) and perennial load scheduling [8]. This has made so many people to buy different fossil-fuel generators of different capacities to generate their own electricity. This trend has led to loss of lives with its attendant negative impacts on the economy and ecosystem. Industrial consumers have installed generators in order to overcome the unreliable supply from the grid. Those who cannot afford the cost and maintenance of these generations have moved their businesses to the neighboring countries, leading to retarding economic growth [9].

Considering the abundant renewable energy sources (RES) in almost all parts of Nigeria, the country is in the best position to harness all these energy resources in ensuring a healthy ecosystem However, the fluctuating nature of RES especially solar PV and wind poses a great challenge, a hybrid combination of two or more RES that are complementary in nature will serve as a better option for rural electrification especially areas where it is not geographically or economically feasible for grid extension [1-4]. Renewable energy Hybrid Power System (HPS) is pollution free and environment-benign. Since it combines two or more energy sources, it captures the best features of each energy source, thereby ensuring reliable power supply in the rural setting.

 A HPS comprises of two or more RES with or without other conventional energy sources that are complementary in nature. HPS components may not also be necessarily co-located like batteries, demand side signal response and generation involving bulk power markets. Two major advantages of HPS are: project cost reduction and project market value increment [10-11]. This can be done in either as an Off-Grid (OG) energy system where power is supplied to the consumers without connection to the grid for remote locations or exist as Grid-Connected (GC) system where excess power is supplied to the grid to complement the system. The OG and GC have so many benefits peculiar to the individual methods of connection. However, some of the factors that guide the choice of either OG or GC are [12]:

* Accessibility and climate change
* Economic feasibility and load factors

Off-grid (OG) Hybrid Power System Technology (HPST) produces power without being connected to the grid. These are peculiar to remote locations, where connecting them to the grid may seemingly be impossible and economically infeasible due to scattered population. Some of the disadvantages of OG are very low capacity factor, limited storage capacity and high cost of battery. The correct sizing must be due to match the operations capacity to the demand [13].

 Grid-connected (GC) HPST can be classified into two types. The first category is where the excess power generated is fed into the grid and when there is shortage, it derives supply from the grid. The second type is to operate as a utility scale managed by private organization and the power generated is fed into the grid without supply to the rural consumers. This type is ideal for locations close to the grid. They operate at high plant load factors within improved economic viability of its operation. GC takes care of seasonal load variations and acts like battery with infinite storage capacity [12, 14].

Researches carried out on HPS, have shown its economic viability particularly in areas where it is not geographically feasible for grid-extension [15-16]. So many authors have also worked on the techno-economic feasibility of Off-Grid (OG) [2-4, 10, 14-22] and Grid-connected (GC) HPS [22-26]. The most common areas are Solar PV-Wind HPS, Solar PV-Diesel HPS, Wind-Solar PV-Diesel HPS and Solar-Wind- Biomass HPS [20, 25]. Very few authors worked on Small hydro-based hybrid combinations [2].

 Barakat et al, [23] conducted a feasibility study of hybrid-connected PV- Biomass in Beni Suef, Egypt. The study found that a grid connected PV-biomass is an effective way of emissions reduction and does not have an increase in energy system investment. Oyedepo et. al, [1] worked on effective utilization of available RES in Nigeria in electrification of the rural and urban areas that are not yet connected to the grid through energy decentralization. The study maintained that the current energy policy is not sustainable, since it still revolved around generation from conventional central generation. Gorman et al, [10] discussed the need for motivation and deployment of hybrid projects in a buck power scheme. The paper discussed the pros and cons of hybrid system with emphasis on Solar PV-battery-wind hybrid prospects.

Several works have been carried out on HPS technology; however, very few papers have been published on comparative study of OG and GC HPS especially in Nigeria [1-3, 21, 26]. This paper proposed the use of Off-Grid (OG) Hybrid Power System (HPS) for rural electrification in remote villages and the use of Grid-Connected (GC) HPS in the urban areas. It also identified the barriers to renewable energy penetration and recommended some policy measures in ensuring sustainable energy development for the nation.To buttress the point, a techno-economic feasibility study of OG and GC Small hydropower-Solar Photovoltaic Diesel hybrid system was done using Oyan River, Abeokuta, Nigeria as a case study.

**1.1 Renewable Energy Growth in Nigeria: Prospects and Barriers**

The country is abundantly blessed with vast Renewable Energy Sources (RES) which have not been fully explored [21]. The available RES potentials in Nigeria, if properly harnessed are over 68000 MW (five times the current average output of 3800 MW). Potential small hydro sites that are capable of producing electricity of about 734.2 MW in Nigeria are over 777; however 30 MW has been put to use [27].

The abundant RES in the country should be seen as an opportunity in rapid electrification of the rural areas where grid extension is infeasible. The country is gradually moving up in the area of RES utilization. There are now some handful of research centres scattered all over the country working on renewable energy technologies. Most of the research works are now targeted at improving the efficiency and reducing the energy costs. The abundant solar irradiations almost throughout the year, favors the use of solar energy-thermal and photovoltaic (PV).

 The small hydro power resources in some of the water supply dams can be used to generate electricity for rural communities. The available RES especially the solar Energy and the small hydro resources can be used to form a min-grid and grid- tied renewable hybrid power generation. Employment opportunities can be created for our young engineers through collaborative efforts in maintenance and construction of SHP. Some of the major barriers hindering RES penetration in the country are; lack of awareness, lack of technology know-how, high capital cost, few research and development centres, absence of enabling regulations and policies, high interest rates. In order to attract foreign investors and to encourage local participation in RET development. There is need to address these barriers though effective policy formulation.

**1.2**. **Nigeria’s Renewable Energy Policy Formulation**

 Energy policy is set towards enhancing efficient, reliable, sufficient, and sustainable energy system at minimum cost. It must protect the rights to access information, the rights against indiscriminate changes in price which may discourage the investors. This can be done through effective legalization, taxation, incentives to investors, guidelines, agreements and their policy ideologies [14]. Effective implementation of energy system will be successful if policies are well stated and implemented by the stakeholders-local government, private investors, international agencies, NGO’s and the consumers [12].

Some of the factors needed to be considered in RET formulation, for any meaningful development to take place in the sector are

* Policy that involves priority or target setting, conformity and a clear focus in certain issues. It targets are not set and supported with appropriate measures, it is possible to give room for non-compliance and this may discourage investors from having confidence on the policy documents
* Diversification of energy generation sources including RES and REE into the nation’s energy generation mix.

There is need for policy alignment among the stakeholders (FGN, state, local government, NGO’s, consumers) as national policy may act as a barrier to local RES development if there is no proper integration [13]. Some of the related Renewable Energy policies formulated so far and their objectives are as in

Table 1[1, 14, 22, 28]**.**

Table 1. Nigeria’s Renewable energy Policies

|  |  |
| --- | --- |
|  **Type** |  **Objectives**  |
| National Economic Empowerment & Development Strategy (NEEDS), 2004 | * It encourages privatization of government infrastructures
* It promotes the share of RES
* It creates RE agency and technologies to be funded under the National Power sector Return sector. This is significant towards the adoption of renewable in the power sector and its utilization.
 |
| Renewable Electricity Policy Guidelines (REPG),2006 | * Integration of 5% compulsory electricity generation form RE to the generation mix.
* It presents the government’s plans and policies & objectives for the promotion of renewables in power sector
 |
| Renewable Electricity Action Programme(REAP),2006  |  * It set out a roadmap for the application of REPG
 |
| Nigeria Biofuel Policy and Incentives (NBPI),2007 | * Promote the domestic fuel ethanol industry through utilization of agricultural products.
 |
| Renewable Energy Master Plan (REMP) ,2005 and 2012 | * Sets out a roadmap for increasing the role of RES in auctioning sustainable development.
* Merge
 |
| National Renewable Energy and Energy Efficiency policy (NREEEP),2014 | * Outlines the global of the policies and measures for the promotion of RES and energy efficiency.
 |

**2. MATERIALS AND RESEARCH METHOD**

A techno-economic feasibility study of Small hydropower-Solar-PV-Diesel Hybrid System was done in OG and GC modes.

**2.1 Data and Description of the Study**

Hydro and solar data for the study area for twenty five years period were collected from Osun-Ogun river Basin Development Authority (OORBDA), Abeokuta and National Aeronautical Administration Agency, web sites respectively. The load demand was obtained through administration of questionnaires. Oyan River, Nigeria, was used as a case study. It is located in latitude 7o 151 29o and N 3o 15 1 20 E. The aerial view is as in Figure 1 while the daily load demand is as in Figure 2.



 Figure 1**.** GPS Aerial View of Oyan River, Abeokuta (Google Earth, 2020)



 Figure 2**.** Daily Load Profile Chart of Abeokuta

# 2.2 Mathematical Models of the HPS Components

 The modelings of each hybrid component are as stated in the following sub-sections. The terms and meaninigs of the components used are as given in Table 2.

Table 2. Nomenclature

|  |  |  |  |
| --- | --- | --- | --- |
| **Symbol** | **Meaninig** | **Symbol** | **Meaninig** |
| $$P\_{SHP}$$ | Power output of the turbine | $$T\_{C}$$ | Cell temperature |
| $$ρ\_{water}$$ | Density of water (1000 kg/m3) | $$kT$$ | Temperature coefficient of maximum power |
| $$g$$ | Acceleration due to gravity (9.8 m/s2) | $$G$$ | Solar radiation in kW/m2 |
| $$H\_{net}$$ | Effective head | $$C\left(t-1\right)$$ | Battery capacity at previous increment |
| $$Q$$ | Water discharge expected to pass through the turbine (m3/s) | $$E\_{g}$$ | Total energy content of oil |
| $$η\_{k}$$ | Pump efficiency | $$P\_{B}(t)$$ | Battery input /output power |
| $$P\_{PV}$$ | Output power from the PV cell | $$η\_{DG}$$ | DG conversion efficiency |
| $$P\_{r-pv}$$ | Rated power at reference conditions |  |  |
| $$G\_{ref}$$ | Solar radiation (1000 W/m3) at reference |  |  |

**(a) Small Hydropower (SHP) Generator**

The SHP output power is as in (1) [29]

  (1)

(b)  **Solar Photovoltaic (PV) Model**

 The power output of the PV cell, is calculated as in $ P\_{PV}$ can be calculated as in (2) [30].

 $P\_{PV}=P\_{r-PV}\left[\frac{G}{G\_{ref}}\right]\left[1+kT(T\_{C}-T\_{ref})\right]$ (2)

**(c) Battery Bank Model**

The battery capacity, $C(t)$ at a point in time t, is calculated as in (3) [31].

.

  (3)

 $P\_{B}(t)$ is as in (4)

  (4)

**(d) Diesel Generator (DG) Model**

 DG can be described as an energy conversion system as in (5) [32-33].

 $E\_{DG}=η\_{DG}E\_{ff}$ (5)

A linear model has been assumed for the fuel consumption rate (F) in litres/hour of operation by the DG [32-33] given in (6).

  (6)

**2.3 Research Approach**

The hydro and solar resources of the area (Table 3) were collected, analyzed and converted to monthly and annual data. Sizing and costing of the hybrid components were done using the manufacturers’ sheets. The hybrid components consisting of SHP, Solar PV, BATT, DG, and inverter were modeled with and without connecting to the grid using Hybrid optimization Model for Electric Renewable (HOMER) software. Simulation was run on data fed into HOMER in order to obtain the wining configuration with the lowest levelised Cost of Energy (COE) and Net Present Cost (NPC). The living optimal hybrid system of the OG was then compared with the GC based on Economic and technical feasibility. The typical model of PV-SHP-Diesel for Abeokuta is shown in Figure. 3



 Figure 3.Solar PV-Small hydropower-diesel generator model

Table 3**.** Summary Oyan River Monthly Average Hydro and Solar Resources Data (Abeokuta)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| MONTH | HEAD(m) | DISCHARGE(L/s) | PEAK SUN HOUR(kWh/m2) | TEMPERATURE(°C) | CLEARNESS INDEX |
| JANUARY | 0.28 | 410 | 5.28 | 30.69 | 0.53 |
| FEBRUARY | 0.25 | 360 | 5.36 | 31.21 | 0.52 |
| MARCH | 0.33 | 530 | 5.29 | 30.89 | 0.50 |
| APRIL | 0.69 | 1350 | 5.32 | 30.28 | 0.52 |
| MAY | 1.10 | 4890 | 5.00 | 29.47 | 0.52 |
| JUNE | 2.27 | 7980 | 4.48 | 28.64 | 0.48 |
| JULY | 2.35 | 12730 | 4.08 | 28.15 | 0.43 |
| AUGUST | 2.93 | 14630 | 3.60 | 28.20 | 0.36 |
| SEPTEMBER | 2.33 | 12210 | 4.30 | 28.38 | 0.42 |
| OCTOBER | 1.77 | 7750 | 4.91 | 28.99 | 0.47 |
| NOVEMBER | 1.07 | 3070 | 5.31 | 29.78 | 0.53 |
| DECEMBER | 0.37 | 540 | 5.27 | 30.33 | 0.53 |
| ANNUAL AVERAGE | **1.31** | **5538** | **4.85** | **29.58** | **0.48** |

[34]

**3. RESULTS AND DISCUSSIONS**

**3.1 Evaluation of Power Production of Grid-Connected and Off-Grid Configurations**

The wining configuration is PV-DG hybrid system. The power production from each connection was compared as in Table 4. There were grid sales on the GC as compared with the OG in which excess electricity could not be sold via the grid. It will only result in waste. Grid sales on grid-connected configuration made it better than off-grid configurations technically. Thus, it makes it unfit to compete technically and economically with grid-connected configuration in Abeokuta location.

**Table 4:** Power Productions of Optimal Grid-Connected and Off-Grid Configurations.

|  |  |  |
| --- | --- | --- |
| **Topology** | **Total Power Production****(kWh/year)** | **Grid Sales (kWh/year)** |
| Grid-Connected PV-DG |  420,107,107 | 266,853.035 |
| Off-Grid PV-DG |  210,330.908 | - |

**3.2 Economic Comparison of Optimal Grid-Connected and Off-Grid Configuration**

 Economic comparison of grid-connected PV-DG with off-grid PV-DG is made based on Net Present Cost (N.P.C.), Levelised Cost of Energy (L.C.O.E), Return on Investment (R.O.I.) and Discounted Payback Period of grid-connected and off-grid PV-DG. This is as shown in Table 5. It can be seen that R.O.I. of off-grid is negative which means it is a loss. This affects other financial metrics as they indicate non-applicable (N/A). The grid-connected PV-DG discounted payback period is 5.98 years as off-grid PV-DG cannot break even. Thus, economically, grid-connected PV-DG is better than off-grid PV-DG and also the best configuration of all configurations.

**Table 5:** Economic Comparison of the Locations

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Topology** | **LCOE ($/kWh)** | **NPC ($)** | **ROI (%)** | **DISCOUNTED PAYBACK PERIOD (yr)** |
| Grid-connected  | -0.224 |  -109 M | 16.1 | 5.98 |
| Off-Grid |  0.295 |  416 M | -18.9 | N/A |

**4. CONCLUSION**

 The work carried out a techno-economic feasibility study of SHP-PV-DG hybrid system in both off-grid and on-grid modes using Abeokuta, Nigeria as a case study. The simulation results showed that the Grid–connected (GC) system is better than the Off-grid (OG) system in technical and economic terms depending on the locations. This paper therefore proposed the use of Off-Grid (OG) Hybrid Power System (HPS) for rural electrification in remote villages and the use of Grid-Connected (GC) HPS in the urban areas. The work will assist power sector stakeholders in making informed decisions towards HPS technology development in Nigeria.

Considering the harmful effects of global warming and its attendant’s environmental effects, it is imperative to shift from fossil-fuelled energy sources to environment-friendly renewable energy sources. There is need for collaborative efforts among the policy stakeholders to formulate effective energy policies towards rapid development of renewable energy hybrid system for sustainable development.

Government and private sectors should be partners in progress in establishing research centres to be able to train the youths of renewable energy technology know-how. The federal government needs to carry the state, local and even the consumers along in policy formulation. The government also needs to subsidise renewable energy components to be able to compete favourably with the fossil-fuelled power generation. This will indeed encourage local and foreign investors in power generation investments.

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