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# Sizing and Analysis of an Off-Grid Photovoltaic System for a House in Remote Nigeria

**Japhet C. Ozogbuda[1*], M. Tariq Iqbal[2]**

[1, 2] Department of Electrical and Computer Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, Newfoundland, Canada
E-mail: jcozogbuda@mun.ca

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***Abstract—*** This paper presents the design and modeling of an off-grid hybrid stand-alone system for fulfilling the load requirements of an off-grid household located in remote Benin City, Edo State in Nigeria. Using a 48 V DC bus, the system was sized using Homer Pro software. Optimization results - which presents various systems' designs – show that the most cost effective and efficient system is the hybrid system consisting of a 1.23 kW photovoltaic (PV) array, four 12 V batteries, 1.6 kW inverter and a 4.8 kW diesel generator. Moreover, the hybrid system is found to be a better solution in terms of its techno-economic performance compared to the diesel generator only system. Sensitivity analysis is carried out to test the adaptability of the hybrid system to a load variation of 20%, and Solar PV input variation of 10%. Results unveil that the lowest cost investment (i.e., investment in the PV-battery system) may not give the best returns. This supports the selection of the aforesaid hybrid configuration to satisfy the household's load.

***Keywords—*** Stand-alone hybrid system; Photovoltaics; Sensitivity analysis; Homer Pro; System optimization; Economic analysis.

## 1. INTRODUCTION

Renewable energy is a term used to refer to forms of energy that are naturally obtained from the environment and from sources that can be replenished naturally. It includes solar energy, hydro power, geothermal energy, wind energy and biomass. It is abundantly available in our world with a very low running and maintenance cost [1]. Renewable energy emits little or no waste into the environment, it does not deplete. A large majority of population; mostly those living in rural or remote areas are geographically isolated from the grid [2]. Greater population of Nigerians do not have access to electricity, as the installed power capacity is 12.5 MW for a population of over 200 million, as compared to other nations of the world (for example, Brazil with a population of 210 million with installed power capacity of 150 GW). Hence, the need to salvage for this inadequate supply makes solar renewable energy technology a suitable solution.

Nigeria, located on the Gulf of Guinea, is a developing country with the largest production of oil in Africa and eleventh largest production in the world. Brazil has a similar population but produces twenty-four times Nigeria's amount of energy. The energy in Nigeria is also very unstable. Half of the population do not have access to energy while the other half experiences long blackouts for up to seven hours a day. Because of this, many people choose to benefit from oil-based generators, which are dangerous and very unstable, and their poor maintenance has resulted in oil spills and flaming of natural gases. The government has launched a program called renewable energy program. Its objective is to decrease greenhouse gas emissions to 50% by 2030 and to provide both reliable energy for the

* Corresponding author
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entire population and alternatives to cooking with coal and firewood in rural parts of the country. The program is also working on ensuring that houses are also energy efficient. The ideal tools to utilize in order to achieve the aforesaid objectives of the renewable energy program are solar panels, windmills and hydroelectric power plants.

Various households in Nigeria have remote communities that are cut out from the utility grid and thus, integrating these areas to the grid could be capital intensive. Hence, in remote areas in Nigeria, the best alternative is the use of photovoltaic (PV) solar energy for powering domestic appliances in those communities. Due to the geographical location of Nigeria, solar energy is readily available which makes it the best option for remote locations. Egbon designed a standalone PV-based system which was implemented in the northern part of Nigeria. Results showed that system - comprised of 4 kW PV array, 24 (12 V, 500 Ah) batteries and 48V inverter built in with charge controller - is sufficient to meet the load demand of a typical household in the remote areas of Kano State, Nigeria. The system was found to be reliable and cost effective with the capability of producing power for a period of 3 days in a rainy day using the backup batteries [3].

Numerous researches in renewable energy resources in Nigeria have been carried out with the objective of determining their feasibility in the country**.** Onyebuchi carried out an estimate of solar energy potential in the country with a device conversion efficiency of 5%. It resulted in $15 \times 10^{14}$ kJ of useful energy in a year, which equates to 258.62 million barrels of oil which, in its turn amounts to $4.2 \times 10^5$ GWh of annual electricity production [4]. Chineke and Igwiro revealed the abundance of solar energy resources that can be harnessed in Nigeria. They found that the country has an average solar irradiance of 5.25 kWh/m$^2$/day at the northern area. It has been estimated that the average sunshine hours in Nigeria is 6.5 h. This produces an average solar intensity of about 1,934.5 kWh/m$^2$/year. In the span of one year, an average of 1770 TWh of solar energy hits the surface of the land area in Nigeria. This amounts to 120,000 times the annual electric energy generated by the national electricity company known as Power Holding Company of Nigeria (PHCN) [5].

One of the cleanest sources of energy which produces DC power is the PV. Use of the PV system can reduce losses resulting from the conversion of AC to DC by a factor of 30% [6]. Due to the unpredictable changes in solar irradiation and load, Kumar proposed a control algorithm for proper operation of the PV system in household application [7]. Shimomachi carried out an - analysis using Electrical Transient Analyser Program (ETAP) - to determine AC and DC distribution of power in a residential capacity, considering factors such as architecture of residence and distribution of loads. In the analysis, a comparison was made for an AC voltage of 220 V with several DC voltages using a typical size of 4 wire gauge. The results revealed that the 48 V DC has an efficiency of about 4% and 9% more than a 380 V DC and 220 V AC, respectively. Hence, a 48 V DC is the best option for an isolated residence [8].

Studies carried out for sizing a PV hybrid system in remote areas, showed the reduction of both life cycle cost (LCC) and $CO_2$ emissions and dumped energy when compared to kerosene use or diesel generators [9, 10]. Al-Rashed carried out economic analysis for a PV hybrid system for a house in remote Jordan with a load demand of 37.5 kWh/day and peak load of 6.98 kW. The system was optimized using HOMER PRO software, and the optimal configuration was found to consist of 12.1 kW PV, 7.7 kW diesel generator, 36 kWh battery and 4.82 kW converter. The system showed a minimum net present cost (NPC) of 66,012 $, cost of energy (COE) of 0.338 $/kWh and lower gas emission in comparison to other solutions [11].

This paper aims to present an efficient stand-alone PV hybrid system for remote residence to meet the challenges of inaccessibility to the electrical grid in Edo State, Nigeria. A 48 V DC bus along with a 1.6 kW inverter with an output of 220 V AC was deployed for supply and also to increase the efficiency of the standalone system. The objective of this research is the sizing and designing the system of the aforesaid system. The rest of paper is divided into the following: section 2 shows the structure of the design and sizing. Section 3 gives detailed economic analysis. Section 4 provides the sensitivity analysis and results. Lastly, section 5 presents the conclusions.

## 2. SYSTEM SIZING

### 2.1. Site Selection and Electrical Loads

The investigated household is located at Benin-Asaba highway in Edo State, Nigeria. It is an off-grid two-bedroom bungalow residence with no access to the utility grid as depicted in Fig. 1. It is located on the following co-ordinates on Google maps: 6°17'22.2"N latitude and 5°59'31.8"E longitude (see Fig. 2). The primary source of power is a diesel generator.

Fig. 1. The off-grid household.

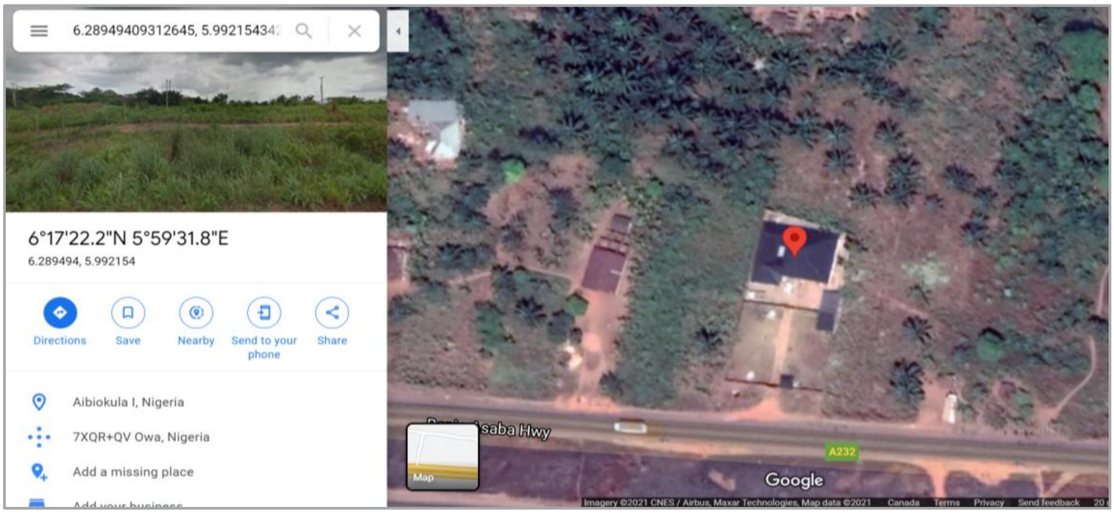


Fig. 2. Location of the household on Google maps.

In determining the load, Table 1 is used. It exhibits the daily energy consumption for the household and shows the appliances used in the residence, their power rating, energy consumption and duration of usage per day using the diesel generator.

Table 1. Daily energy consumption of the off-grid household.

| Appliance | Quantity | Power rating [W] | Total wattage [W] | Duration [Hours] | Total energy [kWh] |
|---|---|---|---|---|---|
| Ceiling fans | 2 | 60 | 120 | 7 | 0.84 |
| Television | 1 | 50 | 50 | 5 | 0.25 |
| Deep chest freezer | 1 | 140 | 140 | 10 | 1.4 |
| Water pump | 1 | 750 | 750 | 0.2 | 0.15 |
| LED bulb | 7 | 8 | 56 | 6 | 0.34 |
| Double arm streetlight | 2 | 70 | 140 | 3 | 0.42 |
| Total load | | | 1260 | | 3.4 |

### *2.1.1. Design Calculation*

With typical house load = $3.4kWh/day$ ; 5 days backup = $5 \times 3.4 = 17kWh$ . Using a 48 V bus:

Battery bank Ahr = $\frac{17,000}{48} = 354.1667 Ahr$ (100% depth of discharge).

If each battery = 350Ahr, 12V; Strings of Battery = 17,000 /48V/ 350 = 1.01 = 1 string.

For a 48 V bus, four 12 V battery will be connected in series to make 48 V. Since 100% depth of discharge will reduce battery life, it is, not allowed. Therefore, we use 50% depth of discharge which requires 8 batteries.

Efficiency of PV, $\eta_{pv}$ = 16.94%

Solar irradiance = 4.66 kWh/m$^2$/day

Available energy = $\frac{4.66kWh}{m^2 - day} \times 0.1694 \times 4.3m^2 = 3.4kWh/day$

In a year, $3.4 \times 365 = 1,241kWh/year$ .

### *2.1.2. Generator Specification and Maintenance/Operating Cost*

If the solar resources are not available, some of the load demand will be mitigated (some from the battery and some from the generator). Therefore, a small generator is added to the configuration. Generator's specifications are listed in Table 2.

Table 2. Generator's specifications.

| Specification | Value |
|---|---|
| Model | Elemax SH2900DX(Gen50) |
| Maximum output power | 4.8 kW |
| DC output | 12 V/8.3 A |
| Fuel tank capacity | 15 L |
| Double arm streetlight | 2 |
| Cost of generator | 350 $ |
| Maintenance cost/month | 20 $ |
| Fuel cost/month | 102 $ - 117 $ |
| Total average cost of maintenance/month | 130 $ |

The generator is fuelled with 7 to 8 liters of fuel daily, which is approximately 210 to 240 liters per month (note that 1 liter of fuel in Nigeria costs 1.51$). The household is completely off the grid and runs on generator mostly from 8pm to 6am daily.

### 2.2. Solar Radiation

Solar irradiance is a crucial factor of consideration in the design of a PV system. The Homer Pro software is a very useful tool that gathers data from around the world. Data such as: wind resources, temperature, solar resources, and hydro resources. The solar radiation and the clearness index at the site - obtained from Homer Pro - are depicted in Fig. 3. It shows that the annual average solar irradiation at the location is 4.66 kWh/m²/day.

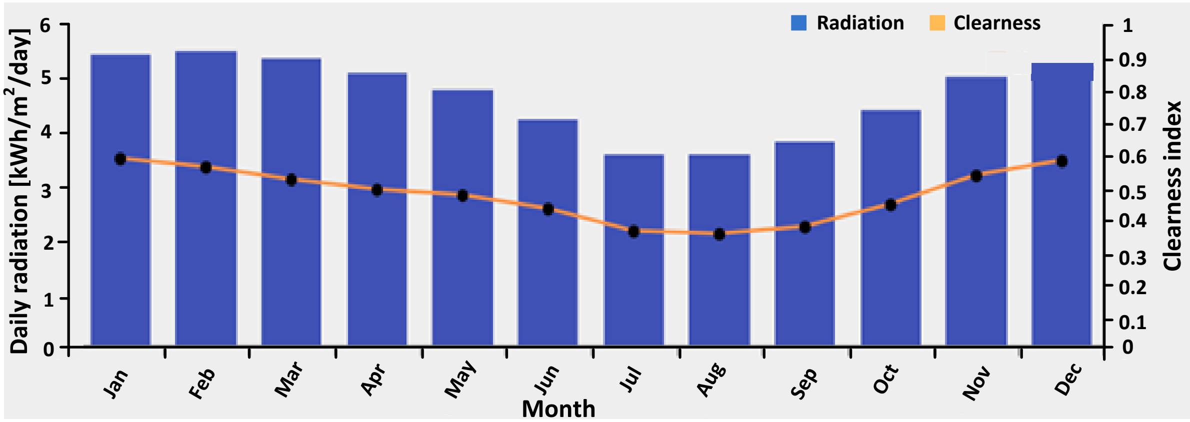


Fig. 3. Average monthly solar irradiance at selected location.

### 2.3. System Components and Electrical Output

Block diagram of the designed system is provided in Fig. 4, and its schematic in Homer Pro - used to perform its sizing - is depicted in Fig. 5. The system consists of a 48 V DC bus with DC load, CS6X-325P solar PV, 12 V battery, 4.8 kW generator and 1.6 kW inverter.

After simulation of the system, the optimization results showed the NPC, operating cost, initial capital cost, power rating of components, renewable fraction , and other important parameters with possible configurations that would yield a cost effective and efficient system. The electrical output of the PV-battery hybrid system in shown in Fig. 6.

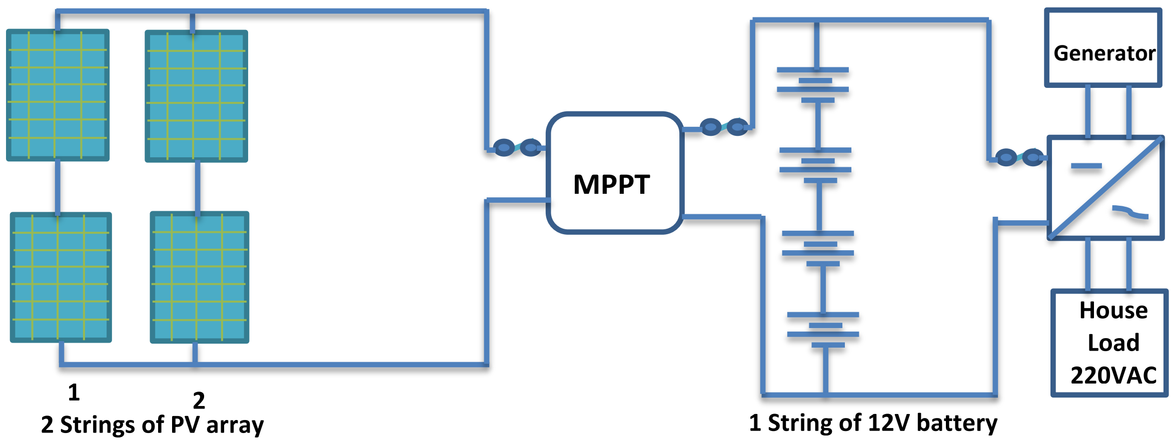


Fig. 4. Block diagram of the utilized hybrid system.

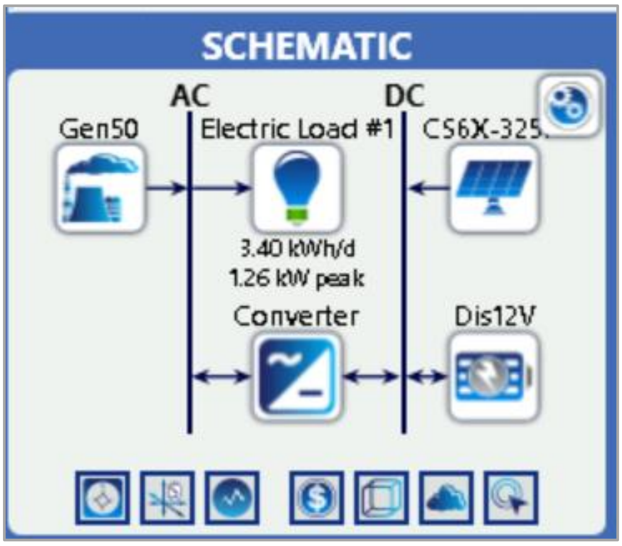


Fig. 5. Schematic diagram of the utilized hybrid system in Homer Pro.

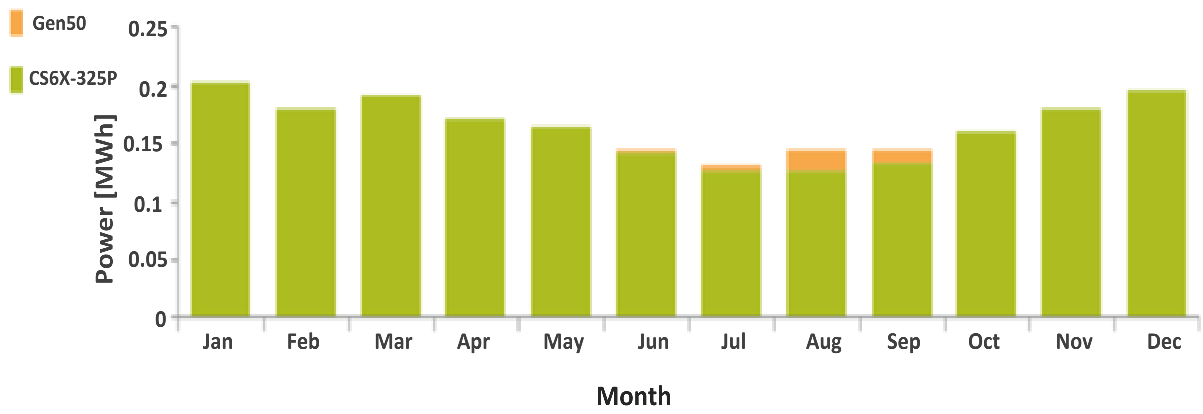


Fig. 6. Electrical output of the PV-battery hybrid system.

## 3. ECONOMIC ANALYSIS

Homer Pro software makes a comparison between the possible configurations obtained from the optimized results to determine the most cost-efficient and reliable system to be adopted for a specific load. In our case, looking at NPC of the base system (the generator only system) and the proposed system (the system comprised of the PV array, generator, battery, and inverter), we see that the proposed system is more cost-effective compared to the base system. Fig. 7 exhibits the economic comparison between these two systems; NPC of the generator only system is 10,785$ while for the hybrid system NPC equals 4,146$. It also shows that the present worth of investment is 6,639 $, annual worth of investment relative to diesel case equals 514 $, as well as the return of investment which equals 79.1%, etc.

Homer Pro is a great tool not just for finding the low-cost systems but for doing investment analysis. Homer Pro can determine payback period and internal rate of return by comparing a particular simulation to another base simulation. In this research, the base case/business as a usual case (the system that might be designed if one is not doing an incremental investment in renewables or storage) would be just the generator, since it is the traditional way of supplying power in remote areas. By selecting a base case, Homer Pro will calculate the payback period for all the systems within each optimization result. In the selected system architecture, Homer Pro has calculated the simple payback as one year and showed a 74% internal rate of return. Value calculated for other systems are shown in Fig. 8 that includes the payback period and internal rate of return (IRR) of all the systems. With a 97.1% renewable fraction, the system would cost 2,977$ to install, 90.42 $ for annual operating cost and an NPC of 4,146 $, which is more economical in comparison to the diesel only case that has an NPC of 10,785 $.

| | Architecture | | | | Cost | |
|---|---|---|---|---|---|---|
| | CS6X-325P (kW) | Gen50 (kW) | Dis12V | Converter (kW) | NPC ($) | Initial capital ($) |
| Base system | | 4.80 | 4 | 1.60 | $10,785 | $2,277 |
| Current system | 1.23 | 4.80 | 4 | 1.60 | $4,146 | $2,977 |

| Metric | Value |
|---|---|
| Present worth ($) | $6,639 |
| Annual worth ($/yr) | $514 |
| Return on investment (%) | 79.1 |
| Internal rate of return (%) | 73.6 |
| Simple payback (yr) | 1.36 |
| Discounted payback (yr) | 1.47 |

Fig. 7. Economics of the base and hybrid systems.

| Architecture | | | | | Cost | | | | System | | Compare Economics | | Gen50 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CS6X-325P (kW) | Gen50 (kW) | Dis12V | Converter (kW) | Dispatch | NPC ($) | COE ($) | Operating cost ($/yr) | Initial capital ($) | Ren Frac (%) | Total Fuel (L/yr) | IRR (%) | Simple Payback (yr) | Hours | Productio (kWh) |
| 1.77 | | 4 | 1.60 | CC | $4,003 | $0.250 | $93.12 | $2,799 | 100 | 0 | 99 | 1.0 | | |
| 1.23 | 4.80 | 4 | 1.60 | LF | $4,146 | $0.258 | $90.42 | $2,977 | 97.1 | 12.2 | 74 | 1.4 | 15.0 | 36.0 |
| | 4.80 | 4 | 1.60 | LF | $10,785 | $0.672 | $658.11 | $2,277 | 0 | 654 | | | 804 | 1,930 |
| 7.51 | 4.80 | | 1.60 | CC | $51,093 | $3.18 | $3,572 | $4,911 | 0 | 3,984 | | | 4,897 | 11,753 |

Fig. 8. Payback period and IRR.

In the cash flow summary shown in Fig. 9, the selected hybrid design reveals a large capital outlay and relatively modest operational cost as compared to the diesel system where a relatively smaller capital outlay is present but with significantly higher operational cost.

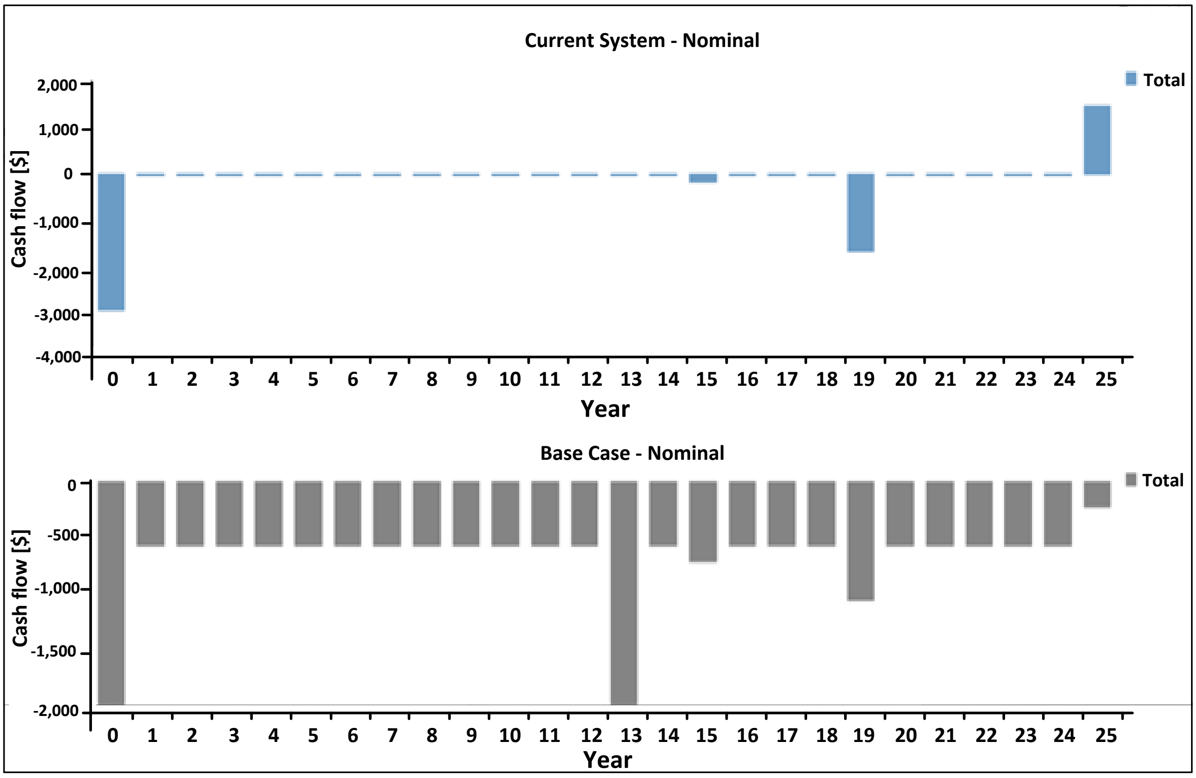

Fig. 9. Cash flow summary for the base and the hybrid systems.

## 4. SENSITIVITY ANALYSIS

At the most fundamental level, the simulation layer in Homer Pro tells us what it costs to operate a system, the fuel it will use, the energy that will cycle through the batteries which determine how long it will last before needing to be replaced. The real heart of Homer Pro is the optimization algorithm that tells us what system is the best. If you only do one optimization, you only know what system is the best for one scenario. So, sensitivity analysis tells us what happens if - for example - prices change, the load grows or the technology improves, and how that system design could be adapted for different markets.

In this model, we are performing a sensitivity analysis on the load and solar PV. We have a range of load variation from 2.18 kW up to 3.4 kW (20%) and a range of solar PV input variation from 80% up to 100% (10%); indicating that sometimes PV modules are clean or dusty.

The simulated results of sensitivity analysis in are depicted in Table 3, whereas the optimization results are exhibited in Table 4. In the sensitivity case table, i.e., Table 3 there are several entries. For each sensitivity case, Homer Pro displayed the lowest cost design, which means that each of the systems have the lowest NPC after comparing all various design options. For example, for the case of 80% CS6X-325P solar PV and 3.4 kWh of average electric load per day, the system design with the lowest cost was found to be comprised of 1.48 kW of PV, 4 of the 12 V lead acid batteries, a 1.6 kW inverter and a 4.8 kW generator. By selecting this system, it changes the optimization result table, i.e., Table 4. The optimization result updates to show how all the different systems simulated, all the different design options performed at the selected sensitivity case (i.e., the 80% CS6X-325P Solar PV derating factor and 3.4 kW of average electric load per day). In the optimization table, it is noticed that the lowest NPC system is always at the top of the table. It is all ranked according to the NPC.

 

The top system in the sensitivity table is the same system as selected in the sensitivity case table. It is also seen that the overall winner at this sensitivity case costs 3,118 $ to install, and on average it costs about 92.29 $ to operate each year. The operating cost may vary from year to year but 92.29 $ is the average operating cost. Together, the initial capital cost and the annualized operating cost can be used to calculate the NPC that is used to compare systems.

Table 3. Sensitivity cases of PV hybrid system.

| CS6X-325P Derating [%] | Electric load [kWh/d] | CS6X-325P [kW] | Generator [kW] | Battery 12 V | Inverter [kW] | NPC [$] | Operating cost [$/yr] | Initial capital [$] | Renewable fraction [%] | IRR [%] | Simple payback [yr] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 2.18 | 0.895 | - | 4 | 1.60 | $3,274 | $75.41 | $2,299 | 100 | - | 0.063 |
| 80 | 2.18 | 1.12 | - | 4 | 1.60 | $3,449 | $78.91 | $2,429 | 100 | 231 | 0.43 |
| 90 | 2.18 | 0.994 | - | 4 | 1.60 | $3,351 | $76.95 | $2,356 | 100 | 447 | 0.22 |
| 100 | 2.72 | 1.22 | - | 4 | 1.60 | $3,523 | $80.40 | $2,484 | 100 | 208 | 0.48 |
| 80 | 3.40 | 1.48 | 4.80 | 4 | 1.60 | $4,375 | $97.29 | $3,118 | 96.3 | 61 | 1.7 |

Table 4. Optimization results of the selected cases.

| CS6X-325P [kW] | Generator [kW] | No of batteries | Inverter [kW] | NPC [$] | Operating cost [$/yr] | Initial capital [$] | Renewable fraction [%] | IRR [%] | Simple payback [Yr] |
|---|---|---|---|---|---|---|---|---|---|
| 1.48 | 4.80 | 4 | 1.60 | $4,375 | $92.29 | $3,118 | 96.3 | 61 | 1.7 |
| 1.61 | - | 8 | 1.60 | $6,213 | $144.14 | $4,349 | 100 | 24 | 4.3 |
| - | - | 4 | 1.60 | $10,785 | $658.11 | $2,277 | 0 | - | - |
| 8.70 | 4.80 | - | 1.60 | $52,513 | $3,630 | $5,589 | 0 | - | - |

## 5. CONCLUSIONS

This study involved the sizing a hybrid renewable system for satisfying the load of a residence in remote Edo State in Nigeria having an average load of 1.26 kW and energy consumption of 3.4 kWh. Using a 48 V DC bus, Homer Pro was used to determine the most optimal system for the off-grid residence in terms of both system design and economic feasibility. From the optimization result, and looking at the NPC, it was seen that of all the possible systems, the hybrid system comprised of the PV array, inverter, and battery is a better option compared to the diesel only base system. Sensitivity analysis was also carried out for a solar PV input variation of 10% and load input variation of 20% to determine the adaptation of the system. From sensitivity case analysis, it is interesting to note that the lowest cost investment is not the one of the best returns. The best option was found to be that one with 100% renewable fraction, i.e., the system comprised of 1.77 kW PV array, four 12V batteries and 1.6 kW inverter.

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## REFERENCES


[1] J. Sterling, J. Mclaren, "Treatment of solar generation in electric utility resouce planning," *IEEE Transaction on Electron Devices*, vol. 11, no. 1, pp. 34–39, 2013.

[2] S. Shezan, S. Julai, M. Kibria, K. Ullah, R. Saidur, W. Chong, R. Akikur, "Performance analysis of an off-grid wind-PV (photovoltaic)-diesel-battery hybrid energy system feasible for remote areas," *Journal of Cleaner Production*, vol. 125, pp. 121-132, 2016.

[3] C. Egbon, "Design of stand alone photovoltaic system in developing countries: a case study of Kano, Nigeria,"*Preceedings of IEEE Australasian Universities Power Engineering Conference*, pp. 1-6, 2018.

[4] E. Onyebuchi, "Alternative energy strategies for the developing world's domestic use: a case study of Nigeria household's final use patterns and preferences," *The Energy Journal*, vol. 10, no. 3, pp. 121-138, 1989.

[5] T. Chineke, E. Igwiro, "Urban and rural electrification: enhancing the energy sector in Nigeria using photovoltaic technology,"*African Journal Science and Tech,* vol. 9, no. 1, pp. 102-108, 2008.

[6] Y. Dabas, T. Iqbal, "Sizing and analysis of a DC stand-alone photovoltaic battery system for a house in Libya," *Jordan Journal of Electrical Engineering*, vol. 7, no. 2, pp. 84-95, 2021.

[7] B. Kumar, M. Ramalingaraju, "Stand-alone PV hybrid system for residential applications," *Proceedings of IEEE Interntional Conference on Electrical, Electronics, and Optimization Techniques*, pp. 2035-2040, 2016.

[8] K. Shimomachi, R. Hara, H. Kita, "Comparison between DC and AC microgrid systems considering ratio of DC loads," *Preceedings of IEEE PES Asia-Pacific Power and Energy Engineering Conference,* pp. 1-4, 2015.

[9] A. Ogunjuyigbe, T. Ayodele, O. Akinola, "Optimal allocation and sizing of PV/wind/split-diesel/battery hybrid energy system for minimizing life cycle cost carbon emission and dump energy of remote residential building," *Applied Energy*, vol. 171, pp. 153-171, 2016.

[10] S. Mandal, B. Das, N. Hoque, "Optimum sizing of a stand-alone hybrid energy system for rural electrification in Bangladesh," *Journal of Cleaner Production*, vol. 200, pp. 12-27, 2018.

[11] R. Al-Rashed, T. Faza', O. Ayadi, "Potential of using off-grid PV/wind/diesel battery hybrid energy system in Jordan," *12th International Renewable Engineering Conference*, pp. 1-7, 2021.