# MODELING OF A RENEWABLE ENERGY BASED HYBRID ENERGY SYSTEM FOR POWER GENERATION IN SIERRA LEONE: PART II – MODEL SENSITIVITY

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## *ABSTRACT*

*In a previous study, the performance of three power generating systems (diesel Generator only, diesel generator-solar PV, and diesel generator-solar PV-battery storage), designed for an office complex in Freetown, Sierra Leone, were analyzed using HOMER software and compared in terms of their reliabilityand cost effectiveness. The simulation results indicated that the diesel generator-solar PV-battery storage system was the optimal configuration to satisfy the daily power demand of the office complex. Therefore, this system was tested under a range of parameters including primary load, diesel fuel price change, solar PV system cost and solar radiation. The sensitivity analysis showed that an increase in the primary load demand had a significant effect on the size of the major system components but a slight effect on the cost parameters. The sensitivity analysis for all the conditions investigated, especially the variation in solar radiation, validates the replication of the optimized hybrid system countrywide.*

## *KEYWORDS*

*Hybrid System, Renewable Energy, HOMER Software, Sensitivity Analysis*

## 1. INTRODUCTION

A model was developed by Bakarr et al. [1] to carry out aTechno-Economic evaluation of three competing power systems for an office complex located in Freetown, Sierra Leone. The Hybrid Optimization Model for Electric Renewables (HOMER) software [2] was used to simulate and optimize the system that closely matches the cheapest energy production with the load to ensure that the system provides more reliable and higher quality electricity at minimum costs [3, 4].The three systems analyzed included:diesel generator only, solar PV and diesel generator with no battery, and Solar PV and diesel generator with battery storage. The simulation and optimization results indicated that the Solar PV and diesel generator with battery storagehybrid system was the most feasible in terms of low cost of energy, high renewable penetration, less annual diesel consumption, less carbon dioxide emission, less unmet load and less capacity shortage.

The HOMER modelling tool takes account of any future dynamic changes resulting from fluctuations of some important input parameters such as primary load, solar radiation, priceof diesel fuel and cost of components [5, 6]. Optimal system design depends on the effect these variables have on system performance. It is therefore necessary to test the sensitivity of the system design to variations in these parameters.

### 1.1 Objective

The objective of this study is to test the sensitivity of the model to changes in primary load, solar radiation, diesel fuel price and cost of the hybrid system. The criteria used for the sensitivity analysis were the system components (solar PV, diesel generator and battery) and costs (initial or capital cost, total net present cost, and levelized cost of energy).

## 2. METHODOLOGY

### 2.1 HOMER Software

HOMER software performs three principal tasks: simulation, optimization, and sensitivity analysis. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of input assumptions to gauge the effects of uncertainty or changes in the model inputs. HOMER's optimization and sensitivity analysis algorithms make it easier to evaluate many possible system configurations [7, 8].

### 2.2 Sensitivity Analysis

Sensitivity is a measure of how the optimized system responds to variations on chosen parameters during the lifetime of the system [9, 10, 11]. HOMER software was used to perform a sensitivity analysis on the Solar PV/Diesel Generator/Battery system. The effects of stepped increase in primary load, future price change on diesel fuel, cost variation in the solar PV system and variation of solar radiation across major cities in Sierra Leone on the size of the hybrid system components, the hybrid system initial or capital cost, total net present cost (NPC), and levelized cost of energy (LCOE) were investigated.

Fourteen sensitivity cases including five values of primary load, two cases of diesel price, four cases of solar energy resource and three cases of components cost were tested close to the optimum Solar PV/Diesel Generator/Battery system condition established by Bakarr[12]as shown in Table 1.

Table 1.Base Values and Range of Variables used in the Sensitivity Analysis.

| Variable | Base | Range |
|---|---|---|
| Primary Load (kWh/day) | 387 | 423<br>465<br>503<br>553 |
| Diesel Fuel Price Change ($) | 1.05 | 1.50 |
| Solar Radiation (kWh/m$^2$/day) | 5.34 | 4.74<br>4.88<br>5.05 |
| PV Replacement Multiplier | 0.85 | 1.00<br>1.15 |

#### 2.2.1 Stepped increase in primary load.

The daily primary peak load for the office complex under study is 39 kW as shown in Figure 1, with daily energy production of 387 kWh/day.As there are possibilities that the office complex load may increase due to expansion of the business, the load was increased in increments of 10% over time up to 40% and a sensitivity analyses carried out for the load changes.

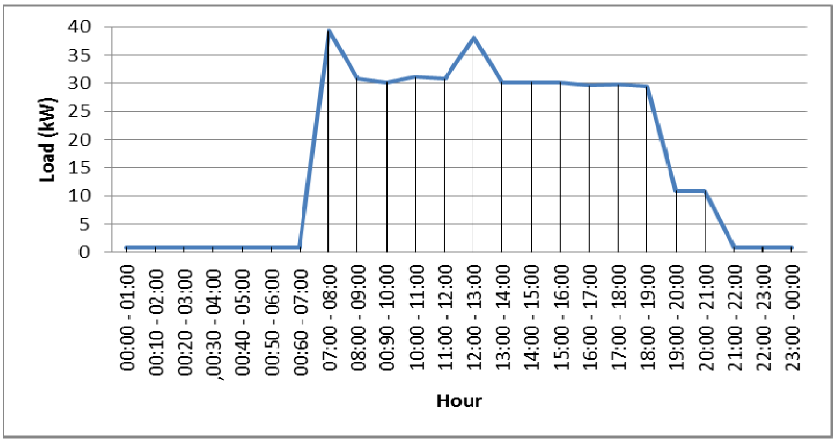


Figure 1: Office Complex Hourly Load Profile [1]

### 2.2.2 Future price change on diesel fuel.

At the time of writing this paper, diesel price was $1.05 per litre. Due to the uncertainties in global fuel costs, sensitivity analysis was carried outfor a perceived rise to $1.50 per litre.

### 2.2.3 Variation of solar radiation across major cities in Sierra Leone.

Table 2 shows the geographical coordinates of the selected site, Freetown, and the other sites of interest countrywide. These coordinates were inputs entered into the NASAwebsite[13] in the geometry information and solar resource window to output the global horizontal radiation values depicted in Table 3. The solar radiation for the other towns mentioned in Table 3 are used as variables in the sensitivity analysis to test whether the power system designed for the office complex can be applied countrywide. Table 3 indicates that the annual average daily solar radiation in the country varies from a maximum of 5.34 kWh/m$^2$/day in Freetown to a minimum of 4.74 kWh/m$^2$/day in Kenema.

Table 2. Geographical Coordinates of Selected Sites Across Sierra Leone.

| **Area** | **Freetown** | **Kabala** | **Makeni** | **Kenema** | **Port Loko** | **Bo** |
|---|---|---|---|---|---|---|
| Latitude ˚N | 8.5 | 9.5 | 8.5 | 7.5 | 8.5 | 8.5 |
| Longitude ˚E | -13.5 | -11.5 | -12.5 | -11.5 | -12.5 | -11.5 |

Table 3: Monthly Average Global Radiation kWh/m$^2$/day

| **Monthly** | **Freetown** | **Kabala** | **Makeni** | **Kenema** | **Port Loko** | **Bo** |
|---|---|---|---|---|---|---|
| J | 5.75 | 5.65 | 5.32 | 5.25 | 5.32 | 5.45 |
| F | 6.33 | 6.14 | 5.84 | 5.66 | 5.84 | 5.94 |
| M | 6.75 | 6.41 | 6.00 | 5.66 | 6.00 | 6.05 |
| A | 6.55 | 6.28 | 5.75 | 5.32 | 5.75 | 5.72 |
| M | 5.57 | 5.55 | 5.01 | 4.88 | 5.01 | 5.16 |
| J | 4.59 | 4.87 | 4.44 | 4.30 | 4.44 | 4.69 |
| J | 3.85 | 4.55 | 3.98 | 3.90 | 3.98 | 4.31 |
| A | 3.85 | 4.44 | 3.75 | 3.73 | 3.75 | 4.09 |
| S | 4.87 | 4.75 | 4.28 | 4.20 | 4.28 | 4.55 |
| O | 5.33 | 4.95 | 4.63 | 4.60 | 4.63 | 4.79 |
| N | 5.27 | 5.02 | 4.61 | 4.56 | 4.61 | 4.78 |
| D | 5.42 | 5.44 | 4.96 | 4.87 | 4.96 | 5.13 |

| Monthly | Freetown | Kabala | Makeni | Kenema | Port Loko | Bo |
|---|---|---|---|---|---|---|
| Annual Average | 5.34 | 5.34 | 4.88 | 4.74 | 4.88 | 5.05 |

### 2.2.4 Capital cost of the solar PV/diesel hybrid system.

As there can be uncertainties in the estimated installed system costs, the sensitivity analysis has been doneto address these uncertainties over a range of ± 15% over and under the estimated installed cost.

## 3. Results And Discussion

### 3.1 Stepped Increase in Primary Load

The HOMER sensitivity analyses for the base case (387 kWh/day) and four other variable loadsare summarized in Table 4.

Table 4. Sensitivities of Operational Changes due to Variable Load Increase

| COMPONENTS | PRIMARY LOAD | | | | |
|---|---|---|---|---|---|
| LOAD INCREASE | 387 | 423 | 465 | 503 | 553 |
| Percent Increase of 387 kWh/day | 0% | 10% | 20% | 30% | 40% |
| Solar PV (kW) | 150 | 150 | 200 | 200 | 200 |
| Generator (kW) | 20 | 20 | 40 | 40 | 50 |
| 6V Battery (No.) | 144 | 144 | 144 | 144 | 240 |
| Converter (kW) | 65 | 65 | 65 | 65 | 65 |
| COST PARAMETERS | | | | | |
| Initial Capital ($) | 602,800 | 602,800 | 702,800 | 702,800 | 818,000 |
| Operating Cost ($/yr) | 36,348 | 44,817 | 42,568 | 49,865 | 47,685 |
| Total NPC ($) | 955,817 | 1,038,071 | 1,116,231 | 1,187,103 | 1,281,130 |
| Levelized COE ($/kWh) | 0.697 | 0.693 | 0.677 | 0.666 | 0.653 |
| Diesel (Litres) | 9,199 | 14,208 | 11,200 | 15,535 | 12,885 |
| Generator Run Hours | 432 | 671 | 256 | 359 | 224 |

As can be seen from Table 4, the system can accept a 10% increase in primary load without changing the size of the system components. A 20% increase will require 200 kW solar PV- an additional 50 kW solar PV to the system and increase of generator rating from the base value, 20kW to 40kW- the existing generator being 45 kW. These components will remain unchanged and satisfy a 30% load increase whilst for a 40% increase in primary load, we see that the office complex will have to invest in a new 50 kW diesel generator and additional 96 batteries to meet this load.

On costs, all the cost elements rose slightly except the LCOE, which gradually reduced, from $0.697/kWh for the base case (387 kWh) to $0.653/kWh for 40% primary load increase. This indicates that the office complex can achieve up to 10% additional load and slightly improve the LCOE with the same components after which change in components costs rise towards 20% and increasing upwards.

### 3.2 Future Price Change on Diesel Fuel

From Table 5, the increase in the fuel cost from $1.05/litreto $1.5/litre has no effect on the initial capital cost but increases the system operating cost from $36,348 to $40,487 per year, the total NPC from $955,817 to $996,022 and the LCOE from $0.697to $0.726/kWh. As expected, the diesel consumption and generator running hours remained the same.

Table 5. Sensitivities of Variable Diesel Prices.

| | Diesel Price ($/L) | |
|---|---|---|
| **Diesel Price INCREASE** | 1.05 | 1.50 |
| COST PARAMETERS | | |
| Initial Capital ($) | 602,800 | 602,800 |
| Operating Cost ($/yr) | 36,348 | 40,487 |
| Total NPC ($) | 955,817 | 996,022 |
| Levelized COE ($/kWh) | 0.697 | 0.726 |

Figure 2 further reinforced the assertion that the LCOE rises with the increase in the diesel price but without any component changes, thus keeping the initial capital cost unchanged.

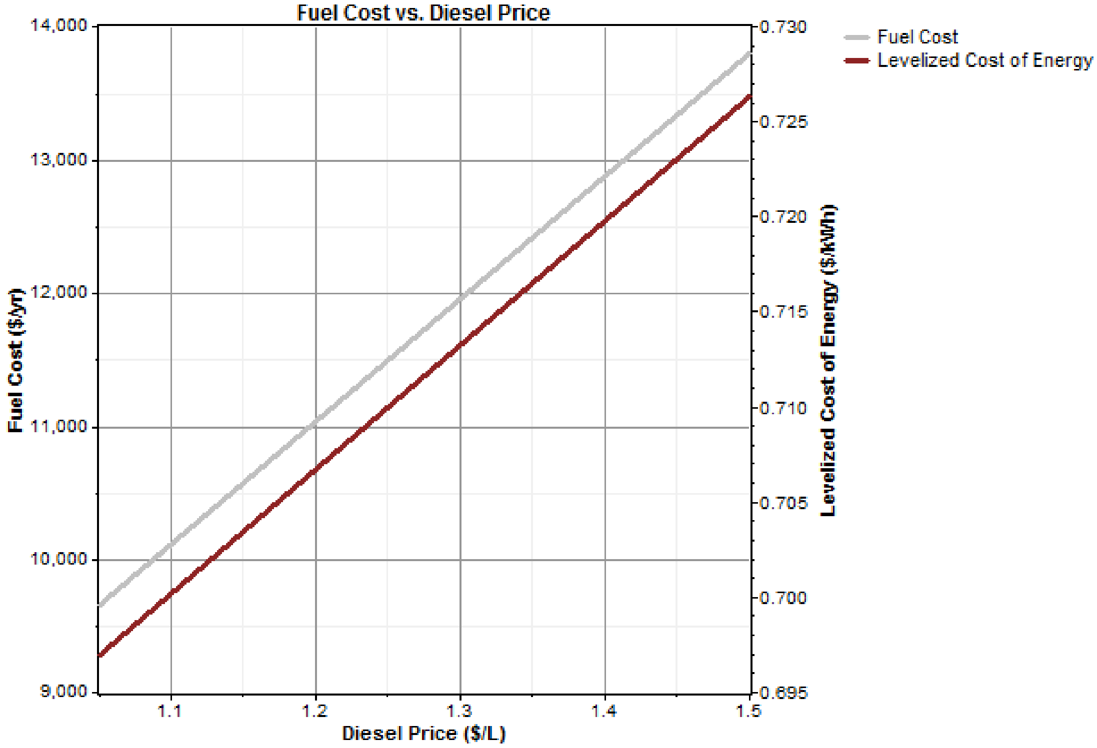


Figure 2: Fuel Cost Vs Levelized COE at Variable Diesel Prices.

### 3.3 Variation of Solar Radiation

Annual average daily solar radiation in Sierra Leone varies from a maximum of 5.34 kWh/m$^2$/day in Freetown to a minimum of 4.74 kWh/m$^2$/day in Kenema. The sensitivity analysis for this condition will test the validation for the use of the optimized hybrid system for the whole country. The HOMER generated sensitivity results are given in Table 6.A gradual reduction in solar radiation from 5.34 to 4.74 kWh/m$^2$/day resulted in a corresponding reduction in all the electrical parameters except the primary load, which is not affected. On the contrary, the cost parameters slightly increase.

Figure 3 shows how the LCOE increases with declining PV Production as a result of solar radiation varying from 4.74 kWh/m$^2$/day to 5.34 kWh/m$^2$/day. This increase in the LCOE for the said variation in solar radiation is \$0.05/kWh, which is insignificant. The sensitivity analysis has assured that the optimized solar PV-Diesel-battery hybrid system can meet similar load requirement at the office complex if similarly deployed in the main towns considered. Within the range of solar radiation, the power system will more than meet the load with excess electricity produced.

Table 6. Sensitivities of Operational Changes due to Solar Radiation Variables

| | **Solar Radiation (kWh/m$^2$/day)** | | | |
|---|---|---|---|---|
| ELECTRICAL PARAMETERS | 5.34 | 5.05 | 4.88 | 4.74 |
| Total Production (kWh/y) | 245,518 | 233,830 | 226,869 | 221,264 |
| PV Production (kWh/y) | 238,373 | 225,141 | 217,356 | 210,927 |
| Primary Load (kWh/y) | 141,197 | 141,173 | 141,187 | 141,171 |
| Excess Electricity (kWh/y) | 79,454 | 67,441 | 60,178 | 54,526 |
| COST PARAMETERS | | | | |
| Total NPC (\$) | 955,817 | 989,830 | 1,008,410 | 1,024,132 |
| Levelized COE (\$) | 0.697 | 0.722 | 0.735 | 0.747 |
| Operating Cost (\$/y) | 36,348 | 39,850 | 41,763 | 43,381 |

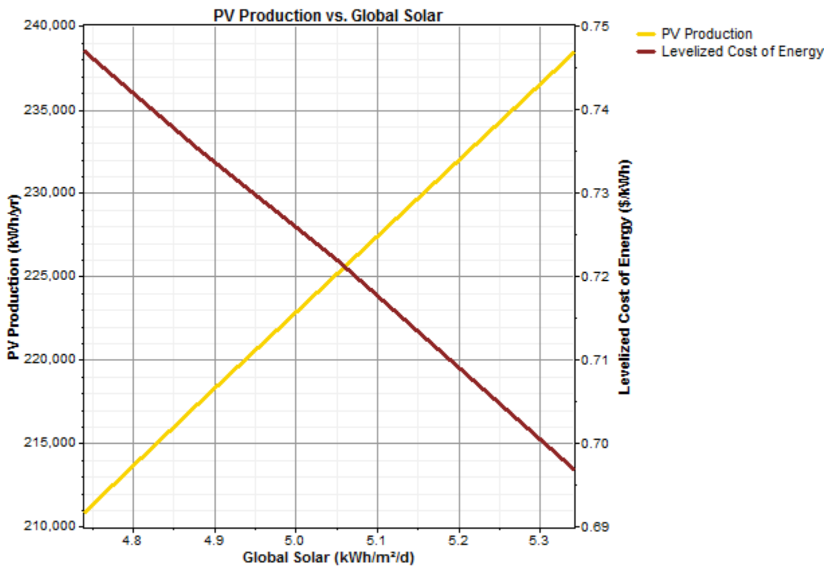


Figure 3.PV Production Vs Levelized COE at Variable Solar Radiation Values.

## 3.4 Capital Cost of the Solar PV/Diesel Hybrid System

The sensitivity analysis has been done for the system component cost uncertainties at ± 15% of the optimized system as shown inTable 7 (-15% of normal, thenormal cost and +15% of normal).The effects of uncertainties in the estimated installed system costs and changes resulting from these are given in Table 7 and depicted in Figure 4. It is seen that the Total NPC increases with the system multiplier costs and also with the LCOE across the range of the price changes. Figure 4 further reveals that at low systems cost, the LCOE is low and slightly increases as the cost multiplier increases, indicating that price volatility will have a negligible impact on the feasibility of a solar PV-based energy system. This is in agreement with the findings of other researchers [14, 15, 16].

Table 7. Effect of PV Replacement Multiplier.

| | PV Replacement Multiplier | | |
|---|---|---|---|
| | 0.85 | 1.00 | 1.15 |
| Percent Cost Variation | -15% | 1% | +15% |
| COST PARAMETERS | | | |
| Initial Capital ($) | 512,380 | 602,800 | 693,220 |
| Operating Cost ($/yr) | 34,294 | 36,348 | 38,401 |
| Total NPC ($) | 845,455 | 955,817 | 1,066,179 |
| Levelized COE ($/kWh) | 0.617 | 0.697 | 0.777 |

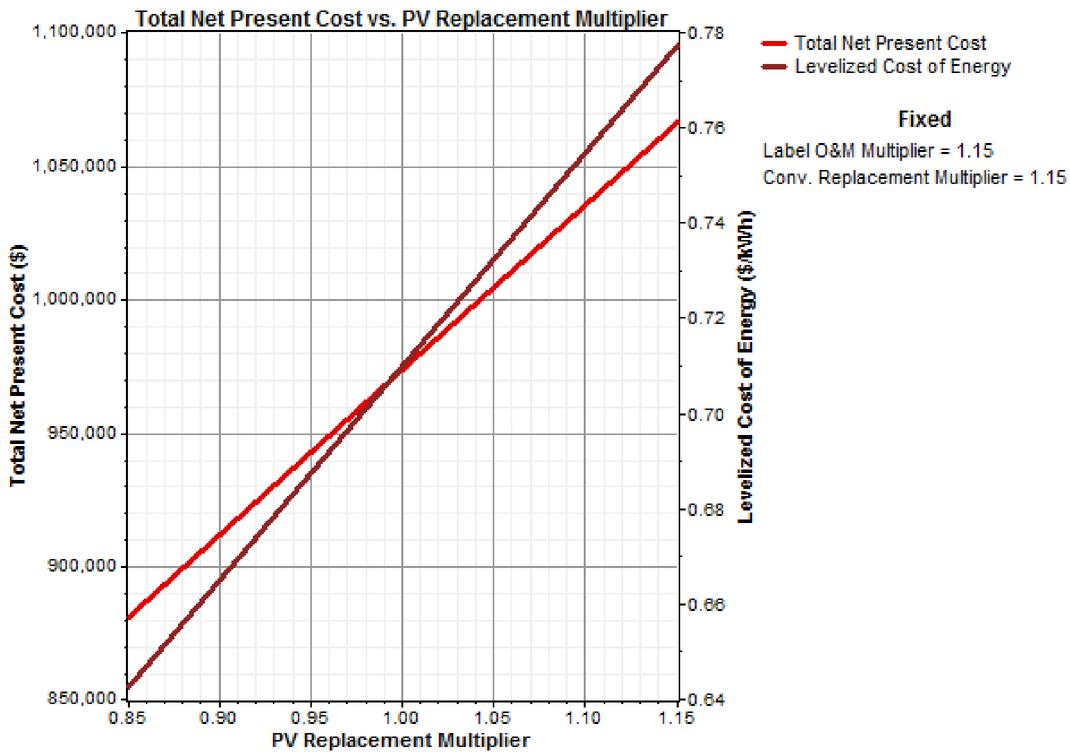


Figure 4. NPC and LCOE with Respect to PV Replacement Multiplier.

Renewable energy technologies have high initial investment and this causes the NPC to increase with cost multiplication and with it the cost of energy [17, 18]. The minimum cost of energy of $0.645/kWh occurs when the system cost is 0.85 times the base cost used in the optimum system configuration, translating to the -15% cost reduction case.Thus, the sensitivity analysis has attempted to validate the results obtained from the optimization analysis by considering the sensitivities of the input variables.

## 4. Conclusion

The HOMER Software was found to be a powerful toolfor the analysis of hybrid energy systems.A sensitivity analysis was performed for 14 input variables including 5 values of primary loads, 2 cases of diesel prices, 3 cases of component costs and 4 cases of solar radiationon the diesel generator-solar PV-battery storage hybrid system. The results revealed that the primary load has a major impact on the system components but the same system configuration was obtained except in some cases where there are quantity and size change of the componentsas a result of increased primary load.The impact of the diesel price, component cost and solar radiation on the results was found to be insignificant. Since a slight variation in the input variables can considerably influence the results, it is recommended that these variables be thoroughly investigated for any project applying a similar modeling approach.

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## Short Biography

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