MODELING OF A RENEWABLE ENERGY BASED HYBRID ENERGY SYSTEM FOR POWER GENERATION IN SIERRA LEONE: PART I – MODEL SIMULATION AND OPTIMIZATION

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ABSTRACT

Energy is in short supply in Sierra Leone as the generation entities struggle to satisfy consumption, causing businesses, households and institutions to look for alternative power supply. This paper depicts one such venture wherein an office complex in Freetown seeks the most feasible configuration of a solar PV system with diesel generator as back up for its power supply. HOMER software was used to compare the technical and economic feasibility of three competing power systems, with equal capacity and serving the same load. The three investigated systems include a diesel generator only, diesel generator and solar PV system, and diesel generator and solar PV with battery storage. The simulation results indicate that the diesel generator and solar PV with battery storage system has the highest renewable energy penetration of 95%, the lowest total net present cost of $955,817 and prevents 739,040 kg/yr of CO_2 *from entering into the atmosphere.*

KEYWORDS

Hybrid System, Renewable Energy, HOMER Software, Sensitivity Analysis, Simulation and Optimization.

1. INTRODUCTION

Poor generation, transmission and distribution characterize the power supply in Sierra Leone. Where the central grid exists, it is overloaded and unbalanced to the extent that consumers may find comfort, albeit expensive, in running their self-generating diesel plants rather than depending on the grid, whose unstable voltage may cause damage to appliances and equipment [1, 2].

Large-scale power infrastructure is expensive, let alone grid extension, and Governments or International Organizations are finding it difficult to fund the capital cost of an electrification project [3]. Even when the project will have been instituted, recurring costs such as operational, fuel, repairs and other related costs comprising the net present cost (NPC) over the life cycle of the system can be as large as or larger than the initial capital costs [3, 4].

In Sierra Leone, power generation is predominantly by fossil fuel engines and hydroelectric plants. The cost of electricity (COE) at $0.32/kWh is one of the highest in the region [5]. Transmission and commercial lossesestimated at 40% [5, 6]have made it impossible to reduce the COE from the central power authority. With all these uncertainties, it is a challenge for an electrification project to sustain itself within a community at such high COE. Consequently, the electric utility regularly finds it difficult to operate and meet all its obligations without government intervention.

Hybrid power systems that combine two or more electricity generation methods, like diesel generators and solar photovoltaic (PV) systems, into a single plant has the ability to provide affordable electricity access into remote communities or for areas with weak grid infrastructure [6, 7, 8]. Despite the benefits that hybrid systems can bring to off-grid power systems, there are relatively few commercially installed systems, primarily due to the paucity of cost benefit comparative studies of this technology and the high initial costs required for their deployment. Hybrid Optimization Model for Electric Renewables (HOMER) is used to 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 [9].

1.1. Objective

The main objective of this paper is to design an off-grid hybrid renewable energy system comprising solar PV, diesel generator and battery storage that can generate and provide cost effective electricity to a specific office complex located in Freetown, Sierra Leone. The decision to incorporate solar PV into the generation mix for the office complex came out of the desire to reduce both maintenance costs and diesel consumption.

2. METHODOLOGY

2.1. Model Development

The Hybrid Optimization Model for Electric Renewables (HOMER) program used to model the system design is an energy-modeling tool for designing and analyzing hybrid power systems. This is done by creating a model of the system including electrical loads, energy resources, equipment and several economic inputs, then simulating the system based on each possible configuration, resource and load scenario. Sensitivity values can also be attached to many of the model inputs in order to analyze the response of the model to varying input values, which can be valuable if input data quality is questionable or the results may be replicated [10].

The HOMER model is composed of four major elements; loads, resources, equipment components, and economic factors. Loads and resources are completely site-dependent. The equipment tobe considered and economic factors are defined primarily by the project boundaries such as budget limitations, project scale and lifetime, technical capacity, and available materials. Once the boundaries are defined, a model can be created and the input data entered for loads, resources, equipment and other factors, as well as any sensitivity input values. A simulation can then be run which computes a set of output values for every scenario possible within the boundaries of the model, as well as for each sensitivity value defined in the model. The resulting output values include both optimization results, which give a set of values for every possible system configuration, and sensitivity results, which demonstrate the impact of changing input values on the resulting output values.

2.2. Project Research Location

The project research location is an office complex in central Freetown. The work carried out in this office is engineering consultancy, which means that the dominant loading will be coming from general office-type alternating current (A/C) electrical equipment.

The proposed energy system should meet the load demand of the office complex. The main renewable source of energy considered in this hybrid system is solar PV. The diesel generator, previously used as the main power supply system, will now be used as backup and a battery bank will be used as energy storage system due to the intermittency of the renewable source. This study considers the following power system configurations:

Option 1: Diesel generator only (base case, as existing)
Option 2: Diesel generator, solar PV system and converter (no battery)
Option 3: Diesel generator, solar PV system, converter and battery bank.
Figure 1 depicts the components of option 3.

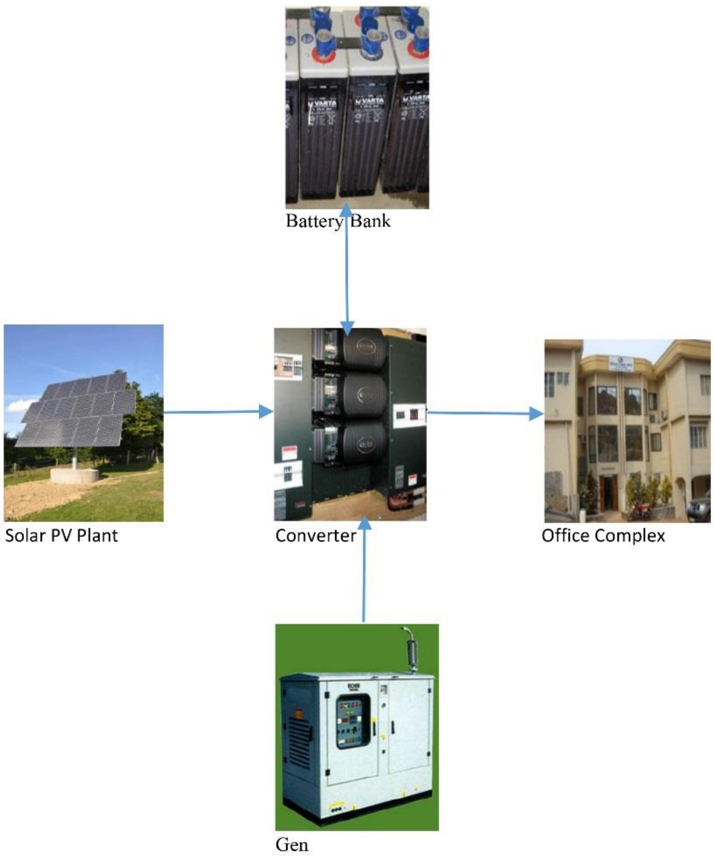

Figure 1. Diagram of the proposed Solar PV/Diesel Hybrid System for the Office Complex.

2.2.1.Estimation of Primary Load

The primary load is the load that should be met when required, by the power system providing the office complex with energy. This includes lighting, air-conditioning, refrigeration, computers, printers, photocopiers, plotters, and others as listed in Table 1. The pattern of the power required does not change during weekdays except for weekends. The electricity load estimation is made by carrying out EXCEL software calculations of the total power for all equipment with their hours of operation to get the total kWh/day. The EXCEL software generated hourly electricity load (24 hours data) in kilowatt (kW) is the first to be entered into the screen output of the HOMER hybrid system chosen. HOMER software then modelled the system to produce the daily load profile depicted in Figure 2.

Table 1. Daily Primary Load of the Office Complex.

Load	Quantity	Rated Power (W)	Total Power (kW)	Hrs/day	kWh/day Actual
Lights	2	60	0.12	10	1.20
Lights	11	40	0.44	16	7.04
Lights	55	36	1.98	10	19.80
Air Conditioner 12000 Btu	8	1190	9.52	10	95.20
Air Conditioner 9000 Btu	2	867	1.734	10	17.34
Air Conditioner 18000 Btu	3	1667	5.001	10	50.01
Air Conditioner 24000 Btu	3	2230	6.69	10	66.90
Laptop Computer	36	65	2.34	10	23.40
Standing Fan	6	65	0.39	10	3.90
Fridge	7	100	0.7	24	16.80
Desktop Computer	10	108	1.08	10	10.80
Printer	5	1200	6	1	6.00
Photocopier	1	648	0.648	2	1.30
Plotter	1	150	0.15	0.25	0.04
Microwave	1	900	0.9	0.25	0.23
Hot Water Kettle	2	900	1.8	0.25	0.45
Modem, Chargers, etc	1	40	0.04	4	0.16

The office peak demand occurs during the period around 07:00 hours at the commencement of the day's work and at 13:00 hours at the commencement of the afternoon session.

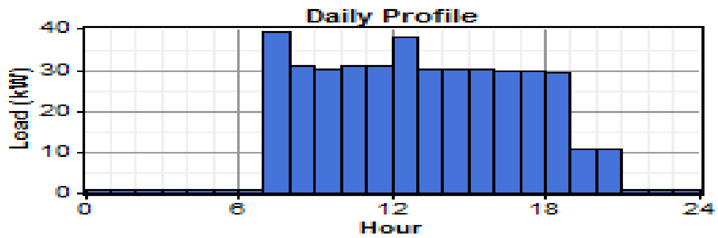

Figure 2. Office Complex Daily Load Profile Simulated in HOMER

2.3. Solar Energy Resource

The solar resource data input into the software was obtained from the NASA Surface Meteorology and Solar Energy website [11] for the geographical coordinates of Freetown (8.5N; -13.5E).The solar radiation data were used in HOMER simulation to compute energy potential for any photovoltaic array to be considered.

Table 2 shows a comparison between solar radiation and clearness index for Freetown as generated by the HOMER simulator and from work done by Redwood-Sawyerr and Coulson [12]. The global radiation figures and clearness index values reported by Redwood-Sawyerr and Coulson are statistical estimates using regression models. These are lower by 8.4% and 7.1%, respectively when compared to the HOMER simulator generated values. There are no recent data on these parameters after the study by Redwood-Sawyerr and Coulson. Since this project was limited to the HOMER values for the design, it was considered out of scope to do comparative design. However, because solar radiation profile is vital to solar PV/generator hybrid system design, future studies emanating from this project may consider redesigning the system using the Redwood-Sawyerr and Coulson values to determine the level of tolerance that might be needed for the HOMER simulator.

Table 2. Comparative Solar Radiation and Clearness Index for Freetown.

	Monthly Averaged Global Solar Radiation (kWh/d/m^2)		**Clearness Index**	
Month	**HOMER Generated**	**Redwood-Sawyerr and Coulson (1999)**	**HOMER Generated**	**Redwood-Sawyerr and Coulson (1999)**
January	5.75	4.99	0.633	0.556
February	6.33	5.48	0.652	0.570
March	6.75	5.59	0.656	0.549
April	6.55	5.52	0.624	0.532
May	5.57	5.10	0.54	0.499
June	4.59	4.75	0.453	0.473
July	3.85	4.21	0.378	0.417
August	3.85	4.17	0.372	0.407
September	4.87	4.65	0.473	0.457
October	5.33	4.91	0.542	0.504
November	5.27	4.80	0.574	0.528
December	5.42	4.50	0.613	0.515
Average	**5.34**	**4.89**	**0.539**	**0.501**

2.4 System Components

Table 3 depicts the component sizes and prices used in performing the HOMER simulations.

Table 3.Component Size and Price Inputs to Homer Software for the Site.

	Solar PV Reliance	**Diesel Generator** Perkins	**Battery** Surrette 6CS 25P	**Converter** Sunny Island 4548
Size (kW)	1	45	1,156 Ah/6.94 kWh	1
Capital Cost ($)	2,000/kW	0	1200	2,000
Replacement Cost ($)	1,800/kW	2,000	1000	2,000
O & M Cost ($/y)	100	0.65	12	100
Sizes to consider (kW)	0, 20, 40, 50, 75, 100, 120, 150, 200, 250	0, 20, 40, 45, 50	0, 1, 2, 3, 5	5, 8, 12, 16, 20, 65, 70
Lifetime	25 Years	15000 Hours	9,645 kWh	15 Years

2.4.1. Solar PV

Different sources and studies have come up with varied prices for PV modules. A USAID study carried out by Alliance for Rural Electrification in 2011 [13] on Hybrid Mini-Grids quoted listed price at $2822/kW. More recently, reports [14, 15, 16] have quoted initial system cost, replacement cost and O&M cost as $2000/kW, $1800/kW and $100/kW, respectively. The PV modules envisaged in the project were Polycrystalline Photovoltaic Modules with 150 kW maximum power, a derating factor of 80% and a ground reflectance of 20%. It will have a slope of 15^{o} and a lifetime of 25 years. Sizes considered as inputs range from 0 - 250 kW in staggered steps.

2.4.2. Diesel Generator

The office complex already has a 45 kVA Perkins Diesel Generator to handle the load. Therefore, the price of the generator was taken as zero. The estimated replacement cost and O&M cost are $2000/kW and $0.65/kW, respectively. Its lifetime is assumed to be 15000 hours and 0, 20, 40, 45 and 50 kW were the sizes considered in this analysis.

2.4.3. Batteries

The price references quoted under solar PV above were used to arrive at a price for the storage batteries and the characteristics were obtained from the HOMER battery listings. The Surrette 6CS25P was chosen, and the quoted initial system cost, replacement cost and O&M cost as $1200/kW, $1000/kW and $12/kW, respectively. Its lifetime is considered to be 9,645 kWh of throughput per battery. The sizes considered in this analysis were 0, 1, 2, 3, and 5 kW.

2.4.4. Converter

A power converter is a device that converts electric power from *DC* to *AC* in a process called inversion and from *AC* to *DC* in a process called rectification. The price of the Sunny Island converter used is $2000 and its lifetime is up to 15 years. Converters of various sizes (5, 8, 12, 16, 20, 65 and 70 kW) were considered. Sunny Island inverters offer flexibility in terms of combination with other equipment, which means that the system can be configured precisely to meet the applicable power requirements. The Sunny Island 4548 used in this study is an off-grid inverter boasting an impressive 96% maximum efficiency and is a complete power system capable of handling critical loads as well as intelligently managing the batteries [17].

2.4.5. Other Inputs

The project lifetime of the power system is based on 15 years and the annual real interest rate was taken as 6%. Simulation time steps of 60 minutes, cycle charging with 80% set point state of charge were used.

The equipment and loads are displayed in HOMER as shown in Figure 3. The model is now complete and the simulation can be carried out. The figure indicates that the annual primary peak load for the complex is 39 kW, with daily energy production of 387 kWh/day.

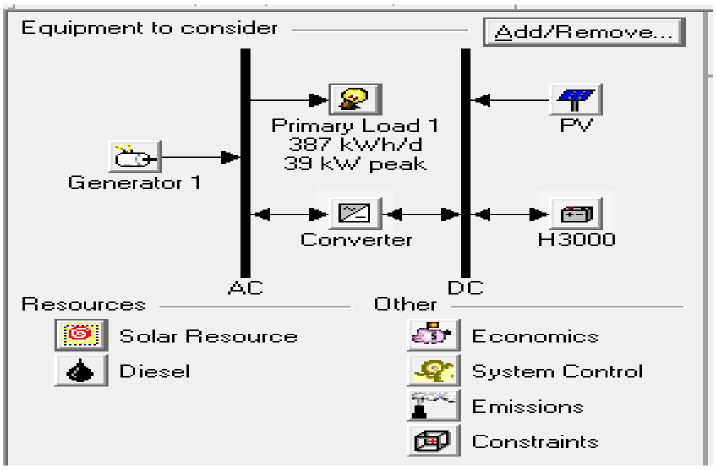

Figure 3.Network Architecture for the HOMER Simulator.

3. Results and Discussion

3.1. Categorized Results

The optimum hybrid system is the one, which can supply electricity at the lowest total net present value, whilst at the same time supplying the electricity at the required level of demand. Three different scenarios (1: Diesel generator only; 2: Diesel generator, solar PV and converter (no battery) and 3: Diesel generator, solar PV, converter and battery bank) are proposed for comparison and to find the most optimized system. Power systems with less NPC, less COE, higher renewable fraction, less capacity shortage, smaller excess electricity and minimum fuel consumption would be suggested as the optimum system. The categorized results of all three scenarios are shown in Table 4.

Table 4.System Configurations.

Scenario	**PV (kW)**	**Generator (kW)**	**Battery (Unit)**	**Converter (kW)**	**Initial Capital ($)**	**Operating Cost ($/year)**	**Total Net Present Cost,NPC ($)**	**Cost of Electricity COE ($/kWh)**	**Renewable Fraction**
1	-	45	-	-	0	572,479	5,560,062	4.053	0.00
2	250	40	-	65	630,000	301,089	3,554,250	2.581	0.63
3	150	20	144	65	602,800	36,348	955,817	0.657	0.95

The system based on diesel generator only (Scenario 1) has an operating cost of $572,479/year, total net present cost of $5,560,062 with cost of electricity at $4.053/kWh. Initial cost here is $0 because the diesel generator already exists. For this scenario, the major costs are for fuel and operations, thereby elevating the levelized cost of energy to $4.05/kWh.

In the diesel generator, PV array and converter with no battery system (Scenario 2), the solar PV provides the major component of electricity supply, while the diesel generator provides the additional energy supply on demand. This scenario becomes economically attractive, as the additional cost of batteries will be excluded. However, the increased size of solar PV may also bring a new cost dimension to the system. The optimal system design comprises ofa 40 kW diesel generator and 250 kW solar PV, at an initial system cost of $630,000, a total net present cost of $301,089 and a system-levelized cost of energy of $2.6/kWh.

In Scenario 3 (Diesel Generator, Solar PV, Converter, and Battery Bank), the power supply for the office complex main load is from the solar PV while the diesel generator acts as a secondary power supply. The use of the generator is necessary to fill up the intermittency gap in solar PV electricity production as it allows power to be stored in the batteries for use on demand. The optimal design comprises of a 150 kW solar PV, 20 kW diesel generator, and a 3-string battery bank with 48 batteries (rated at 9.645 kWh per battery) per string, and a 65 kW converter. The initial cost of this system ($602,800) is lower than scenario 2 ($630,000) because the system modeled 150 kW solar PV for scenario 3 whilst for scenario 2, without battery storage, 250 kW solar PV was modeled. Battery replacement cost is a major cost component. This system offers the lowest life cycle costs compared to the first two scenarios, with COE at $0.657/kWh and is therefore selected for the office complex.

3.1.1 Analyses of the Optimized Hybrid System

The optimized system configuration of the final system (scenario 3) is shown in Table 5.

Table 5. Optimized System Configuration.

PV system capacity	150 kW
Generator capacity	20 kW
Battery bank	48 batteries, 144 kWh
Converter capacity	65 kW
Renewable fraction	0.95

Reproduced below are reports extracted from the HOMER simulation of Scenario 3 together with brief discussions of their relevance. Figure 4 indicates that monthly electrical production is predominantly from solar PV except in the months of May to September (rainy season) when the diesel generator will supplement the power system. This makes the renewable fraction contribution to the power system very high, at 95%. Reduced generator hours with less diesel usage will be realised in this scenario. Figure 4 further reveals that the system produces 32.4% excess electricity over the total power demand, which allows for some additional load to be accommodated. The other interesting feature of Scenario 3 is that HOMER modelled a 20 kW generator for this system, which will consume less fuel over its life cycle compared to the existing 45 kW generator.

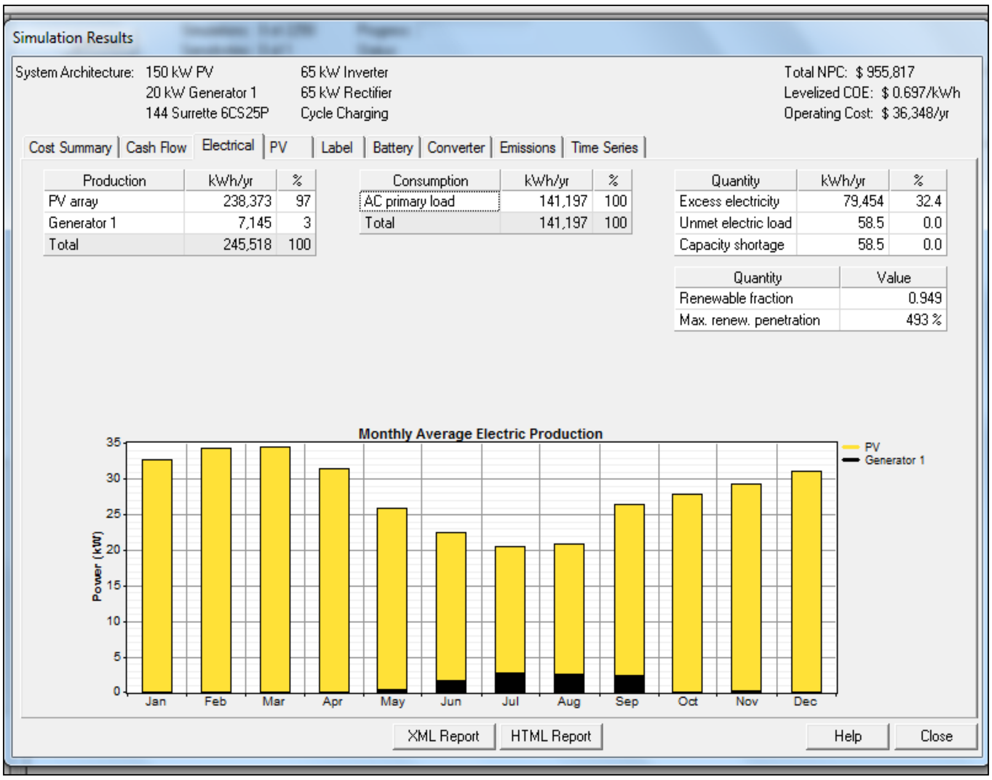

Figure 4. HOMER Generated Electrical Data for Scenario 3.

Form the cash flow results shown in Figure 5, it is seen that the highest cost is for the solar PV whilst the lowest cost is for generator operation, maintenance and fuel.

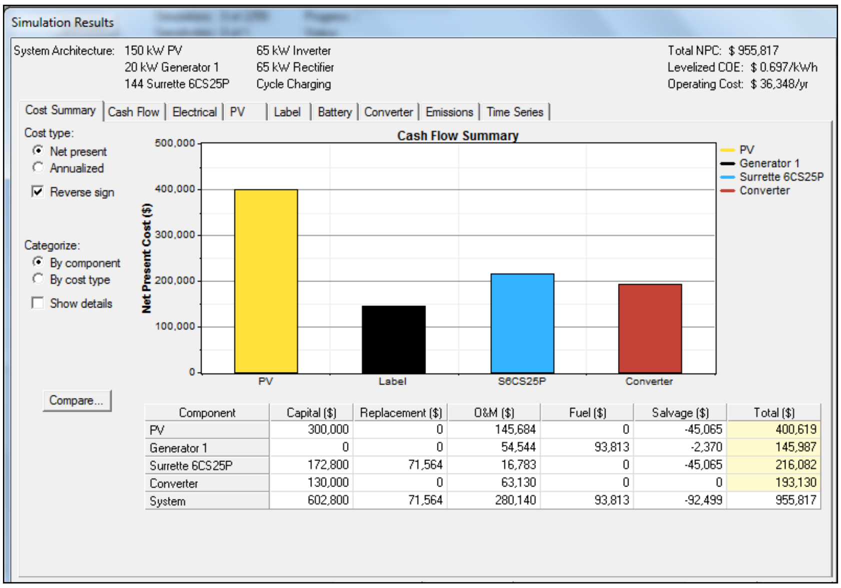

Figure 5. Cash Flow and Component Cost Summary for Scenario 3.

The cash flow of the project throughout its lifetime of 15 years for Scenario 3 is shown in Figure6. Battery replacement occurs after 12 years whereas the diesel generator replacement does not occur within the 15 years lifetime of the project as the generator will operate for only 432 hours during a year or 6480 hours in 15 years which is far less than the lifetime operating hours of the generator (15000 hours). This is because 95% of the energy supplied is from the renewable energy system and the generator is seldom used.

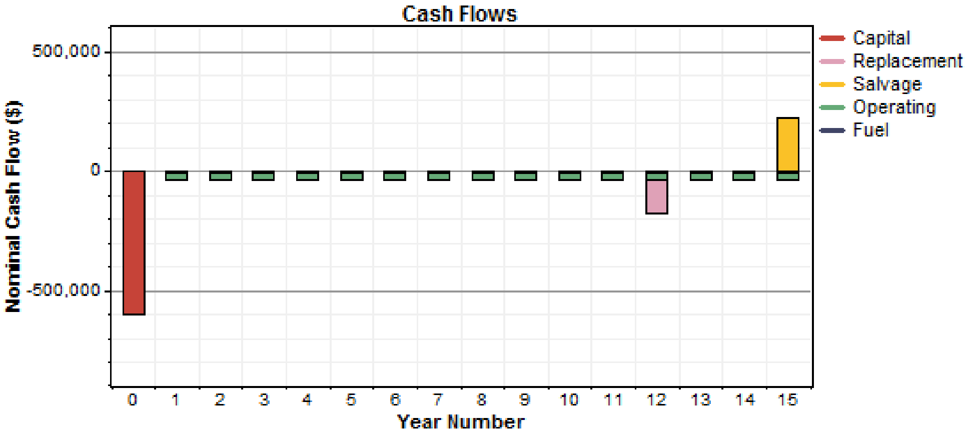

Figure 6: Scenario 3 Cash Flow Analysis.

3.2. Environmental Impact

The most important environmental indices are fuel consumption and pollutant emissions. Comparing the emission figures for Scenario 1 with generator running for 8,760 hours/year and consuming 298,848 litres/year, with Scenario 3 where generator utilization is 432 hours/year and consuming 9,199 litres/year, we can see that Scenario 3 will greatly reduce the environmental impact caused by the operation.

Table 6 shows the relative figures on pollutant gas emissions from the three scenarios. It clearly indicates that Scenario 3 has comparatively lower levels of emissions and further supporting the latter scenario system chosen.

Table 6. Homer Simulated Emission Levels.

Scenario	**Generator**	**Generator + Solar PV (no battery)**	**Generator + Solar PV + Battery Storage**	**Reduction in Quantity of Scenario 3 relative to Scenario 1**
Scenario	1	2	3	(# 1 Minus # 3)
Pollutant	Emissions (Kg/yr)			
Carbon dioxide	763,265	325,354	24,225	739,040
Carbon monoxide	1,884	803	60	1,824
Unburned hydrocarbons	209	89	6.62	202.38
Particulate matter	142	60.5	4.51	137.49
Sulfur dioxide	1,553	653	48.6	1504.44
Nitrogen oxides	16,811	7,166	534	16,277

The reductions in the quantity of different air pollutants compared to that of the diesel-only option are shown in the last column of Table 6, and as can be seen they are more compelling reasons to switch to a solar PV/diesel hybrid system from the environmental point of view.

4. CONCLUSION

Our search for a technically feasible and economically viable hybrid solution for power supply to an office complex in Freetown, Sierra Leone resulted in a least cost combination of solar PV, diesel generator and batteries that can meet the demand in a reliable manner at a cost of $0.657/kWh. With the project site receiving an annual average solar radiation of 5.34 kWh/m^2/day, most of the electricity coming from the optimal solution comes from the solar PV plant and it provides a cheap source of power to the office complex as well. The simulation results support the hypothesis that the hybrid power system offers a better economic and system performance compared to the diesel only system. This is because of the resulting reduction in operating costs, greenhouse gases and particulate matter emitted into the environment and consequently a reduction in diesel consumption and costs.

ACKNOWLEDGEMENTS

The authors would like to thank the staff and Management of CEMATTS Group Sierra Leone Ltd for the use of their office complex as a case study. Fourah Bay College, University of Sierra Leone is also acknowledged for the support and facilities that made this research possible.

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