Islamic University of Technology

Department of Mechanical and Production Engineering

TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF A HYBRID ENERGY SYSTEM FOR THE COMMUNITY OF ALBREDA AND JUFUREH

A Thesis by

FAKEBBA DRAMMEH

FAMARA BOJANG

Submitted in Partial Fulfillment
of the Requirements
for the Degree of
Bachelor of Science in Technical Education with a Specialization in Mechanical Engineering

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CERTIFICATE OF RESEARCH

This thesis titled "TECHNO-ECONOMIC FEASIBILITY ANALYSIS OF A HYBRID ENERGY SYSTEM FOR THE COMMUNITY OF ALBREDA AND JUFUREH" submitted by FAKEBBA DRAMMEH (190032101) and FAMARA BOJANG (190032105) has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of Bachelor of Science in Technical Education with a Specialization in Mechanical Engineering.

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DECLARATION

I hereby declare that this thesis entitled "Techno-Economic Feasibility Analysis of a Hybrid Energy System for the Community of Albreda and Jufureh" is an authentic report of our study carried out as requirement for the award of degree B.Sc.TE. (Mechanical Engineering) at Islamic University of Technology, Gazipur, Dhaka, under the supervision of Dr. Mohammad Monjurul Ehsan, Associate Professor, MPE, IUT in the year 2022

The matter embodied in this thesis has not been submitted in part or full to any other institute for award of any degree.

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ABSTRACT

A large number of rural communities in The Gambia are deprived of the basic access to a sufficient and reliable supply of electricity. Among them are those that have no access to it at all. Due to the lack of proximity of these communities to the grid, as well as their relatively low electricity consumption, it is not cost-effective to connect such communities to the only available grid network. Another major issue is the lack of the capacity to supply the electrical loads of the country. These and other factors like high fuel prices makes it necessary to deploy off-grid hybrid renewable energy systems (HRES) for electricity generation in such locations. In this paper, the Hybrid Optimization Model for Electric Renewable (HOMER) is used to model a most suitable hybrid electrical power plant to feed an electrical load of 1,795 kWh/day for the two neighboring villages of Albreda and Jufureh in the North Bank Region of The Gambia. This communities receives a daily average global solar radiation of 5.22 kWh/m^2/day and records an annual average wind speed of 4.3 m/s. The optimized system is found to be a PV-Wind-Diesel Generator-Battery system which has a renewable fraction of 0.93, an initial capital of $1,771,640 and a Total Net Present Cost (NPC) of $2,368,156 at a fuel price of $1.13/Liter. The levelized Cost of Energy (COE) is $0.406/kWh. This value is higher than the current domestic tariff of the grid electricity provider, which is $0.210/kWh. However, for a community with no access to grid electricity, this is a suitable solution. The system is built to provide an adequate and reliable electricity supply to the community for a 25-year period. It also provides an emission reduction of 91.6% compared to a conventional generator-only system. It produces an excess electricity of 323,323 kWh/h. The unmet electric load and capacity shortage are 12.4 kWh/yr and 133 kWh/yr respectively which are both approximately 0% of the total energy produced.

Keywords: Homer, Hybrid Energy System, off-grid, Solar PV, Wind Turbine

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Nomenclature

COE	Cost of Energy
D. Gen	Diesel Generator
HES	Hybrid Energy System
Homer	Hybrid Optimization Model for Electric Renewable
HRES	Hybrid Renewable Energy System
HVAC	Heating, Ventilation and Air Conditioning
NPC	Net Present Cost
O&M	Operation and Maintenance
PV	Photovoltaic
SDGs	Sustainable Development Goals
SSA	Sub-Saharan Africa
UN	United Nations
WA	West Africa
f_{PV}	Derating Factor of the PV
Y_{PV}	PV array Rated Capacity
I_T	Global Solar Radiation Received on PV Surfaces
I_S	Standard Radiation Used to Rate PV Array Capacity
α_p	Temperature Coefficient of Power
T_c	Temperature of PV cells

Chapter 1

INTRODUCTION

Access to electricity became more than a luxury for humans around the world a long time ago. It is a basic necessity that is key to the growth of individuals, communities and countries. It is a crucial component among developmental forces like the school, workplace, industry and also other public places. Today, it also acts as an important index for determining the economic status of a country as well as the wellbeing of its citizenry [1]. Electricity is applicable to almost all aspects of human activities today due to its versatility. It is necessary for the continuous use of our gadgets, electrical appliances, some vehicles and other equipment. It also helps provide comfort, storage and/or safety in our homes and industries through lightning, heating, ventilation and air conditioning (HVAC). Sufficient, reliable and cheap electricity is also a factor that investors put into consideration in making a decision to invest in a certain country. So, although the availability of modern energy is not a remedy to the social and economic problems retarding the development of developing countries, it is widely accepted that when there is in lack of energy services in an affordable and reliable manner, there becomes an obstacle to human and socio-economic development [2]. The availability of energy in our lives is so paramount that it has led the United Nations (UN) to put it among its Sustainable Development Goals (SDGs), precisely as goal number seven, which seeks to ensure that a universal access to a sustainable, reliable and affordable modern energy will be achieved by the year 2030 [3].

Despite the critical importance that the availability of a sufficient and reliable energy has to play in the wellbeing of any nation, there is still a good number of countries that cannot provide this energy to its people. The unavailability of a good access to modern energy is a main problem that still persists in Sub-Saharan Africa. In developing countries, about 1.2 billion people lack access to electricity and 53% of them dwell in Sub-Saharan Africa (SSA) [3]. Across the continent of Africa, after decades of retarded economic growth, some increase in the rate of economic development has been seen, this factor coupled with a high increase in population has led to a high demand for energy that the continent has not prepared for [4].

SSA holds more than two-thirds of the world population living in an electricity-deprived world. In 2018, North Africa achieved almost universal access while the rate of electrification in SSA was only 45% in the same year. Although the rate of electrification in SSA is slow compared to developing countries elsewhere, like those in Asia, where there is an average rate of 94%, there has been some progress. The rate of electrification for people who have never gotten connected before has increased from 9 million per year between the years of 2000 and 2013 to more than 20 million a year between the years of 2014 and 2018 [5]. In West Africa (WA), a region with one of the lowest electrification rates in the world, international attention has been received in the past years for more electrification [6].

In The Gambia, as of 2019, only about 59.92 % of people living in the country had electricity access. In the urban area, 79.80% had access but only 27.59% of those living in the provincial or rural areas had access to it [7]. It can be seen that the main sufferers from this lack of adequate capacity is the people living in the rural areas. The National Water and Electricity Company (NAWEC) is the main supplier of electricity in The Gambia. It provides electricity from fossil-fuel-fired thermal engines to the grid. Electrification of villages in most rural areas is not cost efficient due to their low energy consumption and also the energy losses incurred in the long-distance power lines. So, like most developing countries in the subregion, this reliance on a single fuel source has led to severe challenges in the electricity sector [8].

The demand for energy is always on the increase and this demand is generally met by utilizing the diminishing, ‘dirty” and limited fossil fuels [9]. These factors make it necessary for a look into alternatives approaches. The utilization of fossil fuels leads to the pollution of the biosphere and climate change [10]. The need to minimize the harmful effects caused by fossil fuel use on our environment has necessitated a shift in attention towards finding sustainable means of generating clean and cheaper energy [11]. In a world where the available deposits of fossil fuels are also dwindling, it is important to look for alternative means to providing sufficient and reliable electricity for domestic, commercial and industrial use. Fossil fuel prices rise means more expensive cost of energy for those that rely on these fuels for energy generation. The harmful effects of the use of these fossil fuels to our lives, the lives of animals and the environment is also another good reason to find alternative means.

This paper aims to design an efficient and cost-effective hybrid energy system (HES) for the purpose of generating sufficient electricity to meet the daily electrical loads of the villages of Albreda and Jufureh. This community presently is not connected to the grid supply due to its location and the insufficient capacity. The power sources selected for this project are; solar PV, wind turbine and diesel generator. It is hoped that the information generated here will serve as a and alternative option for authorities and decision makers to employ HESs to solve the electricity problems facing rural Gambia.

Chapter 2

LITERATURE REVIEW

Although there is very limited to no research on HESs and related topics in the Gambia, various studies have been done on them in countries within WA and in other places around the world.

In Sierra Leone, Konneh et al. [12] preformed a two-stage optimization method to find a more suitable way of providing electricity than using the existing diesel generator in Banana Island. Results proved that a HRES made up of a 50-kW biogas generator, a wind turbine, a 101-kW PV array, a 37.8-kW converter and 86 batteries is a better option. The results also show an NPC of \$487,247 and a COE of \$0.211/kWh while CO_2 emission was only 17.5 kg/yr. In another research, Conteh et al. [13] conducted a study to find the most reliable, economic and environmentally-friendly system for electricity generation in Lungi Town, Sierra Leone. The best system to serve the objective was found to be a wind/PV/D.Gen/battery HES. This was due to its reliability and relatively cheap O&M cost.

In Ghana, Adaramola et al. [14] performed a study to understand the techno-economic possibility of a PV-Wind-D.Gen-Battery hybrid power plant in the southern part of the country. They found that a plant consisting of an 80-kW PV system, 100-kW wind turbine, two 50-kW diesel generators and 60 batteries was more than sufficient to meet the electrical loads of remote areas of this region. The electrical load was 2,000 kWh/day and the peak power was about 83 kW. The system's COE was \$0.281/kWh which, compared to The Gambia's is almost the same as the domestic tariff. In the same part of Ghana, in Mankwadze town, Agyekum and Nutakor [15]conducted a feasibility study to see how economic a stand-alone Solar PV-Wind-D.Gen-Battery HES performs compared to a Wind-D.Gen-Battery system for large scale generation of electricity in a commercial setting. They found that, for the average load of 2,422.06 kWh/day, the COE and NPC for the former is \$0.382/kWh and \$8,649,054 respectively while the latter had \$0.396/kWh as the cost of electricity and \$8,966,700 as net present cost. Awapone A. [16] performed a feasibility analysis to find a suitable HES for electricity generation in isolated locations in northern Ghana. From the HOMER results, it was found that the most techno-economically optimal, and least-polluting system was a PV-D.Gen-Battery HES with an NPC of \$296,552 and a COE of \$0.399/kWh. The relatively high COE can be reduced by changes in capital subsides and diesel price.

In Nigeria, Bashir et al. [17] performed a techno-economic study of five different stand-alone system, which are made of both HRES and HESs, for application in Gajiram, a rural village situated in the northeastern part of the country. The five systems were a diesel generator system, a solar-PV array with battery storage, a PV-D.Gen hybrid system: one case with a battery bank and the other without a battery bank and a PV-Wind hybrid energy system with a battery bank. In this analysis, the most optimum system was realized to be the PV-D.Gen with battery storage. This system proved to be 38% cheaper than the D.Gen system and reduced emissions by 36%. A similar analysis was conducted in the same country by Salisu et al. [18] in the rural village of Moriki to serve the electrical energy needs of a secondary school. An optimal system was found based on the configuration with the lowest NPC and COE. It was found that a PV-Battery energy system with a total NPC and COE of $18,161 and $0.233/kWh was the most suitable system for this school. It was also found that changes in parameters such as discount rate, solar radiation and wind speed have effects on the total NPC and COE. This system is very much environmentally friendly because it is a 100% renewable energy system. Babatunde et al. [19] presented research on the application of a HES for electricity generation in health centers in six different rural communities in Nigeria. The found a PV-D.Gen-Battery system to be the most economical, presenting NPCs ranging from $12,779 to $13,646. The renewable fractions of the different HESs range from 0.70 to 0.80. Yimen et al. [20] embarked on a two-step analysis method to determine the overall possibility of using a PV-Wind-Battery-D.Gen HES for the purpose of electricity generation in the village of Fanisua, rural Nigeria. The proposed system was also compared to a grid supply and stand-alone D.Gen alternative to understand the techno-economic and emission implications. it was found that such systems can play an important role in bringing sustainable electricity to the doorsteps of such communities. The optimum system here was made up of a PV sub-system of 89.271 kW capacity, a 100.31-W D.Gen and a battery bank consisting of 148 batteries. The system's COE was $0.25/kWh it cuts CO_2 emissions by 85,401.80kg/yr. and 122,062.85 kg/yr. compared to the grid extension and a D.Gen supply respectively. Sofimieari et al. [21] presented a paper on the use of a PV-Wind-Diesel HES with battery storage for the electrification of rural communities in Kaduna state. The system was found to be the most economical due to its considerable COE and environmentally friendly due to its significant reduction in emissions. It recorded an NPC of $591,891 and a COE of $0.758/kWh. Each year, the PV system and wind turbine are to produce 63% and 32% of the total electrical power the D.Gen produces only 5%. They system also cuts down CO_2 emissions by 95% compared to D.Gen-only system.

Odou et al. [22] performed research on the possibility of a stand-alone hybrid energy system for application in Fouay village in Benin. A techno-economic investigation was done on the HES composed of a Solar PV array, a D.Gen, battery bank and a potential hydropower system. The results showed that for an electrical load of 679 kWh/day and peak power of 60.84 kW, a PV-D.Gen-Battery (150 kW, 50 kW, 98 3250 Ah/2V) system was the most cost-effective with a reliable electricity supply. It supplies electricity at a cost of \$0.207/kWh and has an NPC of \$555,492. It also reached a 97% CO2 emission cut when compared with a D.Gen only system due to its 96.7% renewable energy penetration and minimizes the need for a battery storage by 70% when compared with a system of only a PV array and Battery. Nsafon et al. [23] designed an optimized hybrid energy system for an electrical load of 4,876.5 kWh/day for a housing estate in Cameroon. The technical and economic feasibility results showed that for a lifetime of 25 years, the most sustainable configuration is a PV-Wind-D.Gen system with a COE of \$0.4574/kWh and an NPC of \$10,251,610. The system also emits about 1,521,310 kg less carbon dioxide yearly when compared to the D.Gen only system. In the country of Chad, a feasibility study, based on techno-economic conditions and environmental considerations, was conducted by Hassane et al. [24]. The study was based on six scenarios of hybrid configurations and included five isolated communities. It was found that, it is possible to make access to electricity a reality for these communities using different energy system configurations involving a backup D.Gen, wind turbine(s), PV panels and batteries. From the results, in terms of COE, a PV-Wind-Battery HRES at Koundoul recorded the lowest at \$0.236/kWh while a PV-Battery system recorded the highest at \$0.363/kWh. It was also recommended that the authorities subsidize diesel price to encourage the employment of such systems to make electricity accessible in such locations. Yimen et al. [25] made a technical and economic study to optimize a pumped-hydro power storage based on a HRES, a totally-renewable-energy system, to provide electricity for the Cameroonian village of Djounde. Upon simulation, using HOMER, the optimal system was found to be a PV-Biogas Generator HRES in which the PV and biogas capacities are 81.8 kW and 15kW respectively. The total NPC for the system was €370,426 and the COE was €0.25/kWh.

Salehin et al. [26] designed a PV-D.Gen system feasible for electricity generation in a locality in Char Parbotipur, northern Bangladesh. From technical and economic analysis, it was found that the system can supply electricity for an electrical load of 115 kWh/day and peak power of 16 kW at $0.461/kWh. The system had an NPC of $149,112 and emits 53.68% lower CO2 than a D.Gen only system. Almutairi et al. [27] performed a case study on the feasibility of using a stand-alone hybrid energy system to satisfy the electrical loads of buildings in Bostegan, a village in Iran. The results showed a HES system consisting of a 10-kW PV array, a 20-kW wind turbine, a D.Gen of 20 kW capacity and 20 batteries forms the most suitable configuration. The hybrid system had an NPC of $284,724 and a $1.058/kWh localized COE. This localized COE is the price at a worst-case scenario.

From these studies, it can be highly suspected that there is a potential for off-grid HES application to remedy the energy crisis in rural Gambia as proven by studies conducted in countries sharing similar weather conditions in WA. Very limited or no studies has been conducted with regards to HES application in The Gambia. The are some stand-alone or off-grid solar PV energy systems in single homes and at community levels and few research has been carried out on their application. Sakiliba et al. [28] design a stand-alone solar PV system to meet the electrical load of a typical household in Banjul. Sowe et al. [29] assessed the practicability between crystalline Silicon and thin-film solar PV arrays in a 1 MW solar PV plant in the town of Farafenni. From techno-economic analysis, the thin film PV modules were found to be a more reasonable technology.

Chapter 3

MATERIALS AND METHODOLOGY

3.1 Research Area

This HES is design for the community of Albreda and Jufureh which are neighboring villages in Upper Nuimi District in Northern Gambia. Albreda is situated on latitude 13.3378° N and longitude 16.3861° W while Jufureh sits on latitude 13.3497° N and longitude 16.3648° W. The combined number of households in this community is taken to be 203, taken data from the 2013 census conducted by The Gambia Bureau of Statistics [30] and making projections. There is no electricity supply to this community except for those households that might have small diesel generators or solar panels to serve mainly lighting loads at night. Some households use battery-powered lamps or candles during the darkness of the night. Biomass in the form of wood or charcoal is the main fuel used in cooking in this community. The community also has a Lower Basic School, a junior and senior secondary school in one campus, a mosque and a community garden with a pump-irrigation system.

3.2 Energy Resources

This community, by virtue of its location receives enough solar radiation and sunshine hours to produces a great deal of electricity from a solar PV array. Assuming the solar plant will be in Albreda, there is a scaled annual average solar radiation of 5.220 kWh/m2/day and a 0.536 clearness index available for utilization. As shown in Figure 1, the highest monthly solar radiation value is experienced in April, 6.138 kWh/m^2/day, at a clearness index of 0.582. The months of March, April and May experience high solar radiations which are very favorable for solar PV power production. The lowest monthly solar radiation is experienced in August which is most likely due to the frequent rains during this month. This solar radiation data was obtained by Homer from the National Aeronautics and Space Administration (NASA).

Figure 2 shows the average monthly wins speeds. The annual average wind speed in the community is not very promising as it is only 4.3 m/s. In the months of July to November, the monthly average wind speeds range from about 2.952 m/s to 3.926 m/s which are very low. This will be a period of low wind power production for the system. During the remaining months, average wind speeds range from 4.380 m/s to 5.556 m/s. The highest wind speed recorded was 5.556 m/s in March while the lowest was 2.952 m/s, recorded in September. This wind resource data was obtained from “renewables.ninja” [31] and the data was from 2019.

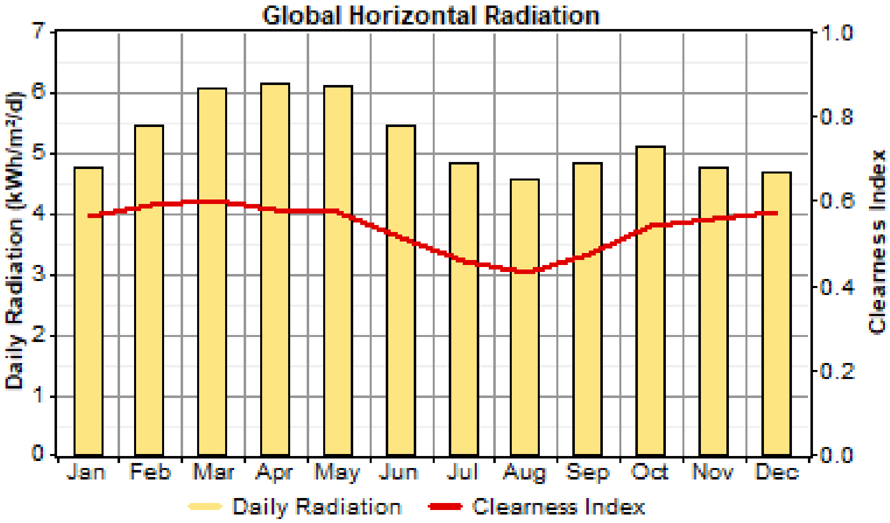


Figure 1: Average Monthly Solar Radiation at the site

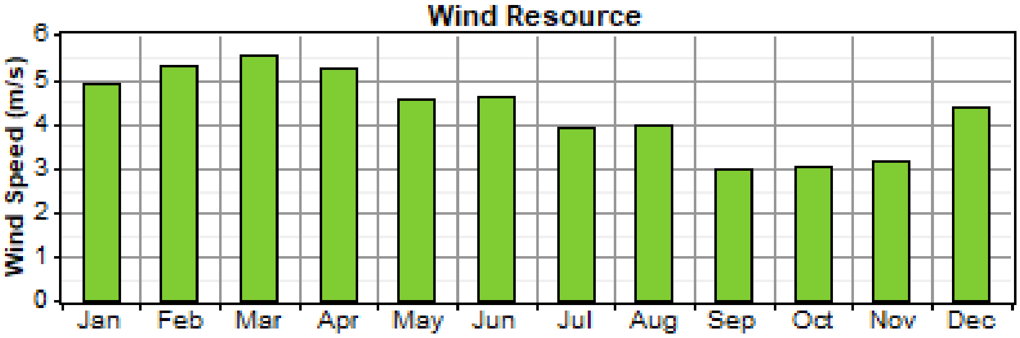


Figure 2: Average Monthly Wind Speeds at the site

3.3 Load Profile

The load demand of this community was assessed based on different categories of load (Table 1). The primary load includes the household, the school and the mosque load. The deferrable load comes from the water pump in the community garden. The average primary load is 1,759 kWh/day at a peak power of 282 kW while the deferrable load is 0.746 kWh/day. As shown in Figure 3, during summer and winter days, the peak load period happens from 6 pm to 9 pm while the period of lowest load demand falls between 8 am and 10 am in the morning. Figure 4 shows the seasonal load profile in which the maximum loads range from 180 to 190 kW during the months from February to November, which is summer. In the winter months (January and December), the peak load is 180 kW during the month of January and 175 kW in December. Figure 5 shows the yearly load profile. It shows that the highest load demands across the year are experienced around 6 pm to 9 pm during the summer while the least load demands happen during winter, between 8:00 am to 10 am. The deferrable load, as shown in Figure 6 is constant across the year. However, it is not as time restrictive as the primary load since it can be fed anytime time within a specified time period.

For a more inclusive analysis, simulation was also done for a what is considered the standard load. This load considers the effect of extra loads, which are refrigerators and electric kettles. For this setting, the average primary load is 4,032 kWh/day at a peak power of 571 kW.

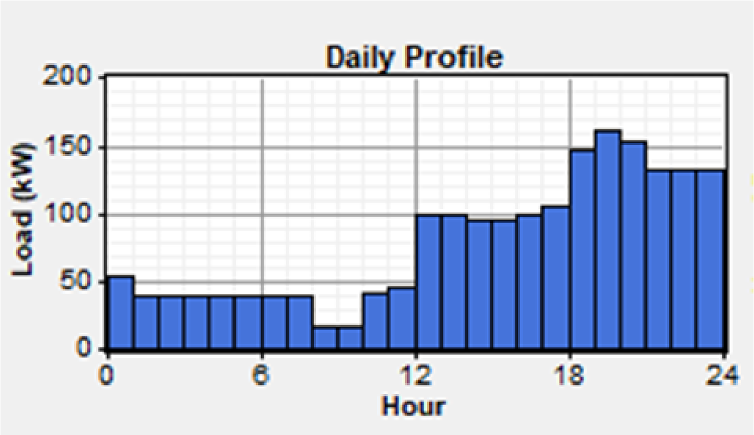
Table 1

Daily Electrical Load

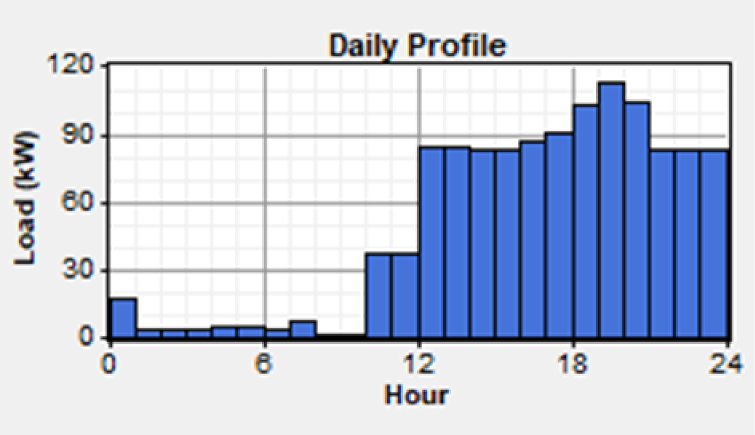
Load Category	Summer Load (kWh)		Winter Load (kWh)	
	Weekday	Weekend	Weekday	Weekend
Household	3,843.05	3,843.05	2,358.67	2,358.67
School	33.21	6.725	13.365	3.14
Mosque	3.9	3.9	1.45	1.45
Garden	2.45	2.45	2.45	2.45

3.4 System Modelling/ Simulation

For this analysis, the Hybrid Optimization Model for Electric Renewable (HOMER) is used to simulate and find the most optimal configuration of PV array, wind turbine(s), D.Gen and battery storage. HOMER is a computer software designed by the National Renewable Energy Laboratory (NREL) [32]. It performs technical, as well as economic analysis of on-grid and off-grid power systems to show their physical behavior with regards to varying conditions as well as their life cycle cost over the project lifespan.



(a)



(b)

Figure 3: Load Profile of a Typical Weekday: (a) Summer, (b) Winter

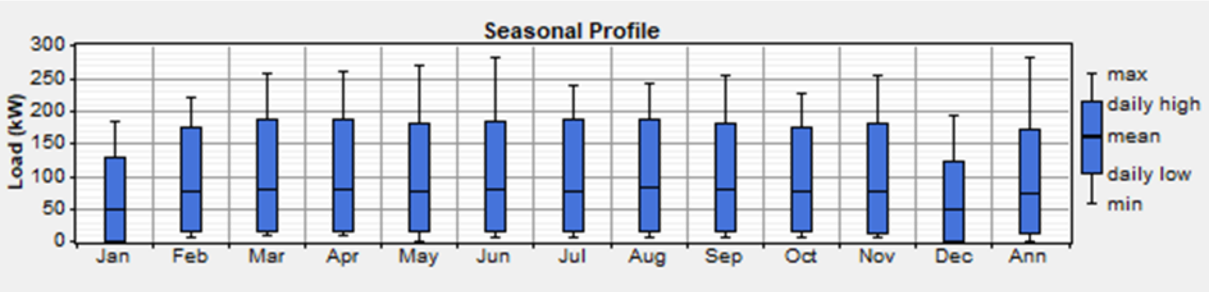


Figure 4: Seasonal Load Profile

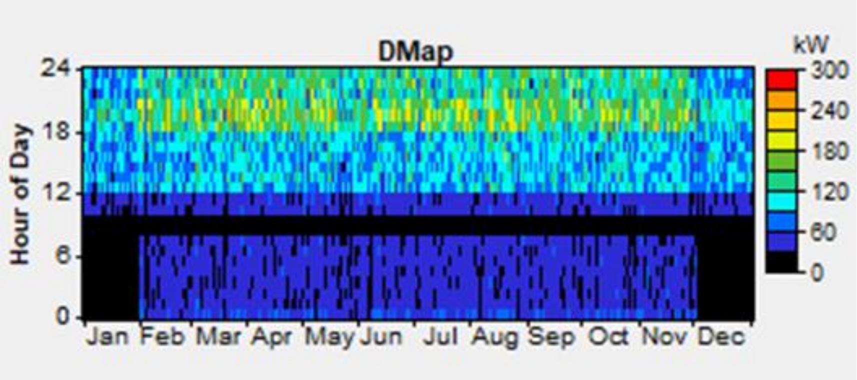


Figure 5: Yearly Load Profile

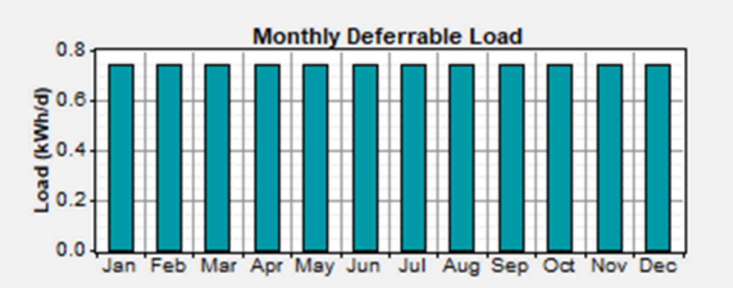


Figure 6: Deferrable Load Profile

Chapter 4

SYSTEM DESCRIPTION AND OPTIMIZATION

4.1 PV Array

PV panels are made of photovoltaic cells. These cells are devices that produce electricity through an electric reaction phenomenon to the sun's incident light rays [33]. A generic solar PV array was chosen for this project. During simulation, the PV sizes considered from 0 to 2000kW. Techno-economic details of the chosen PV panel are shown in Table 2.

The power output by the PV array is calculated by HOMER from the equation [32]:

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_S} \tag{1}$$

Where f_{PV} is the derating factor of the PV, Y_{PV} the PV array rated capacity, I_T the global solar radiation received on the PV surfaces and I_S the standard radiation used to rate PV array capacity, which is 1 kW/m^2.

When the effect of temperature on the PV array's performance is considered, the output power can be derived from [14]:

$$P_{output} = f_{PV} Y_{PV} \left(\frac{\bar{G}_T}{G_{T,STC}} \right) [1 + \alpha_p (T_c - T_{c,STC})] \tag{2}$$

Where $\bar{G}_T$ is solar radiation received on the PV surfaces, $G_{T,STC}$ the incident radiation at standard test conditions, which is 1 kW/m^2, α_p the temperature coefficient of power, T_c the temperature of the PV cell and $T_{c,STC}$ temperature, at standard test conditions, of the PV cells.

The effect of temperature varies with brand of PV panel. Since a generic case is what is chosen here, the effect of temperature is not considered.

Also, there is no tracking system involved in the solar array.

Table 2

Techno-economic details of the PV panel

Description	Value	Reference
Panel type	Generic flat plate	
Lifetime (years)	24	[34]
Derating factor	90%	[27]
Ground reflectance	20%	[27]
Capital cost (\$/kW)	1378	[34]
Replacement cost (\$/kW)	1378	[34]
O&M (\$/kW)	10	[35]

4.2 Wind Turbine

A Hummer H25.0-200kW wind turbine was chosen for this research. This selection was based mainly on its low cut-in wind speed, 2.5 m/s, so there is a power production capability at even low wind speeds. Techno-economic details of this turbine are shown in Table 3.

The equation for the power produced by the wind turbine can be denoted as [27]:

$$P(\upsilon) = \frac{1}{2} C_p A \rho \upsilon^3 \tag{3}$$

where C_p is the wind turbine's power coefficient, A the swept area of the turbine and υ the wind speed.

The power curve of a wind turbine can be written as [27]:

$$P(\upsilon) = P_r \begin{cases} 0 & \upsilon < \upsilon_c \\ P_n(\upsilon) & \upsilon_c \leq \upsilon < \upsilon_r \\ 1 & \upsilon_r \leq \upsilon \leq \upsilon_f \\ 0 & \upsilon < \upsilon_f \end{cases} \tag{4}$$

P_r is the rated power. υ_f is the wind speed beyond which the wind turbine gets shut down to prevent it from getting damaged.

The power curve of the Hummer H25.0-200kW wind turbine is shown in Figure 7.

Table 3

Techno-economic details of the wind turbine

Description	Value	Reference
Manufacturer	Anhui Hummer Dynamo Co. Ltd.	
Rated capacity (kW AC)	200	
Lifetime (years)	25	
Rotor diameter (m)	25	
Hub height (m)	Site specific (50m)	
Capital cost ($/kW)	1489	[34]
Replacement cost ($/kW)	1489	[34]
O&M ($/year)	30	[23]

4.3 Diesel Generator

A significant component of this hybrid energy system is the diesel generator. It is a backup source of power that produces electricity to feed the loads or charge the battery when the PV system cannot due to nightfall, clouds and or when the wind turbine cannot due to low wind speeds. It can also run along with the PV system and wind turbine during high load demands that the renewable systems cannot sufficiently meet.

Table 4

Techno-economic details of the diesel generator

Description	Value	Reference
Type	Generic	
Lifetime (years)	25	[34]
Operational hours	15000	[35]
Minimum load ratio (%)	30	[35]
Capital cost ($/kW)	1200	[34]
Replacement cost ($/kW)	1200	[34]
O&M ($/hr)	0.010	[35]

A generic diesel generator is considered for this study. The sizes considered is from 0 to 350 kW. Techno-economic details of the generator are shown in Table 4. The price of diesel fuel in The Gambia, at the time of this simulation, rose to 61 Dalasis per liter (D61.00/L) which is equivalent to $1.13/L.

The fuel consumed by the diesel generator is calculated by HOMER using the expression [32]:

$$F = F_0 Y_{gen} + F_1 P_{gen} \tag{5}$$

Where F_0 is the coefficient of fuel curve intercept, Y_{gen} the generator's rated capacity in kW, F_1 the slope of the fuel curve and P_{gen} the generator's electrical output in kW.

The diesel generator's fuel efficiency curve is shown in Figure 8.

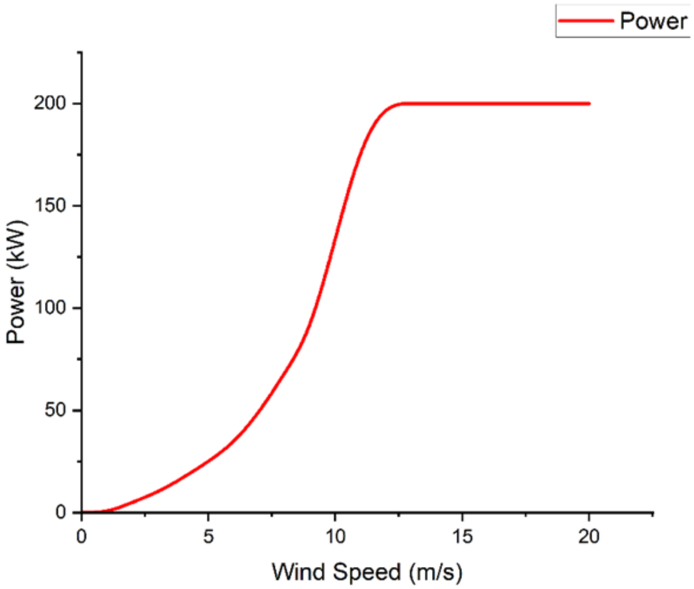


Figure 7: Power curve of Hummer H25.0-200kW wind turbine

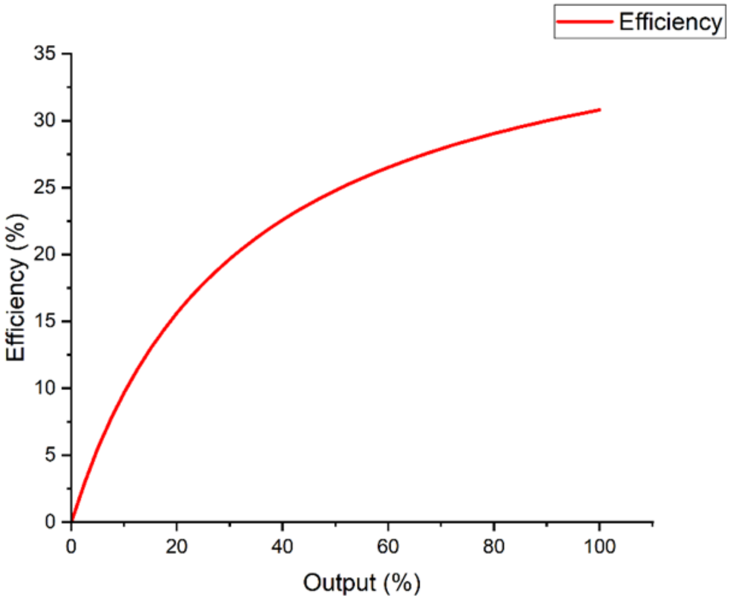


Figure 8: Generator fuel efficiency curve

4.4 Battery

A battery bank functions as an electricity storage device for the continuous supply of power to meet load demands especially during nights, cloudy weather and the event of power failures [36]. A Surrette 4KS25P battery is chosen for this study. The Surrette 4KS25P capacity curve is shown in Figure 9 while its lifetime curve is illustrated in Figure 10. Techno-economic details of the battery are listed in Table 5.

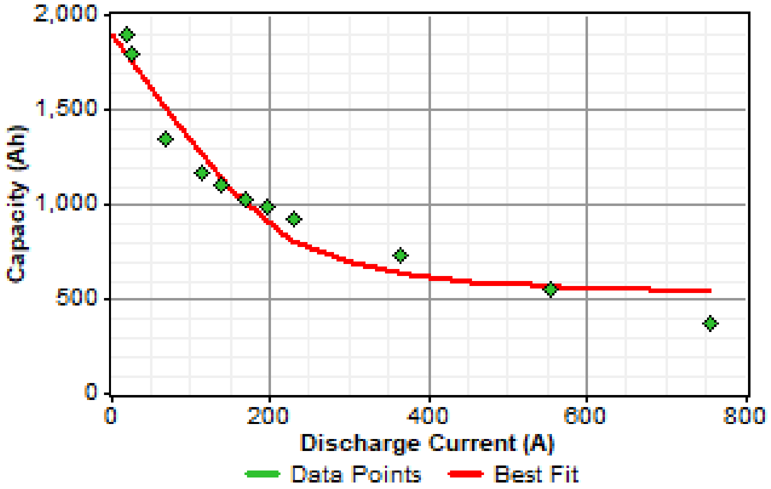


Figure 9: Capacity Curve of the Selected Battery (Surrette 4KS25P)

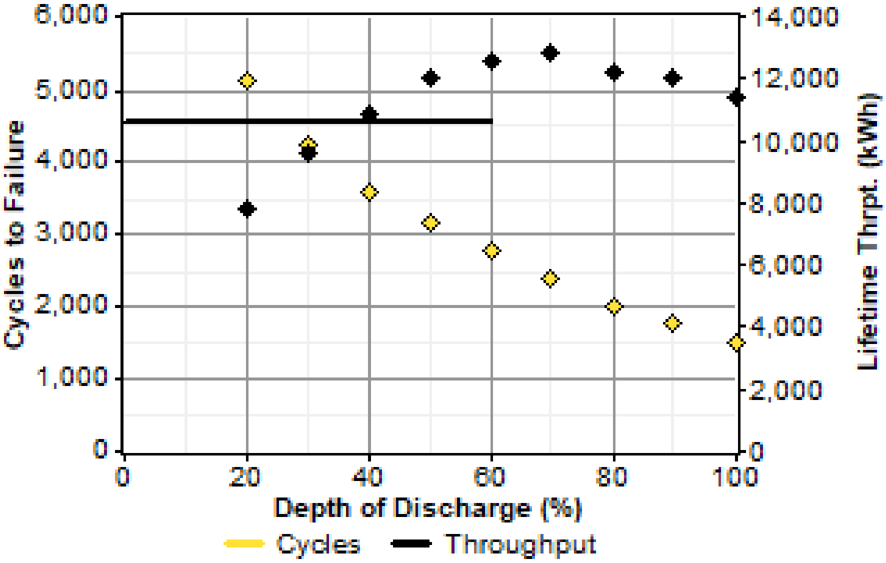


Figure 10: Lifetime curve of the Selected Battery (Surrette 4KS25P)

Table 5

Techno-economic details of the battery

Description	Value	Reference
Type	Surrette 4KS25P	
Nominal capacity (Ah)	1900	
Nominal voltage (V)	4	
Max. charge current (A)	67.5	
Lifetime throughput (kWh)	10,569	
Capital cost ($/kW)	1259	[37]
Replacement cost ($/kW)	1100	[37]
O&M ($/year)	5	[37]

4.5 Converter

A generic converter with efficiency and lifespan of 95% and 15 years respectively is selected for this study. Sizes 0 to 350 kW were considered for this converter. The costs associated with this component is taken from a case study in Ghana, a country within the same sub region as Gambia. Techno-economic details of the converter are shown in Table 6.

Table 6

Techno-economic details of the converter

Description	Value	Reference
Type	Generic	
Lifetime (years)	15	[38]
Efficiency (%)	95	[38]
Capital cost ($/kW)	347	[38]
Replacement cost ($/kW)	315	[38]
O&M ($/year)	7	[38]

4.6 The Hybrid System

The total system is made up of a PV array, wind turbine(s), a backup diesel generator, a battery storage and a converter. This makes it a hybrid system. A HES is one of the most promising applications of renewable energy technologies in areas where grid connection is not cost-effective and the price of fuel also increases rapidly [39]. The configuration was done through HOMER to give the best possible combination to cater for the total load demand while making provision for an operating reserve too. An operating reserve is an extra power capacity that is utilized in times of imbalance between load demand and power generated [40]. A ‘load following’ charging method is used for the battery bank, this means that, the excess electricity is what charges the batteries, therefore there is no cost associated with charging. Shown in Figure 11 is the system schematic.

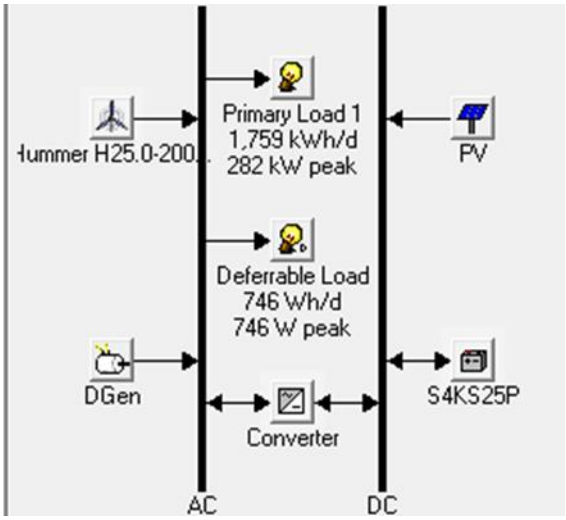


Figure 11: Schematic diagram of hybrid energy system

The lifetime of this project is 25 years. The interest rate in The Gambia, as of February 2022, was 10% [41]. The cost-effectiveness of this project was based on the total net present cost (NPC) and levelized cost of energy (COE) of the system. The NPC represents the overall cost incurred over the project lifetime while the COE is the average cost of electricity per kilowatt-hour.

The NPC is calculated by the following equation [32]:

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i,R_{proj})} \qquad (6)$$

Where $C_{ann,tot}$ is the total annualized cost, CRF the capital recovery factor, i the annual real interest rate and R_{proj} the lifetime of the project.

The COE is calculated by the equation [32]:

$$COE = \frac{C_{ann,tot}}{E_{prim}+E_{def}+E_{grid,sales}} \tag{7}$$

Where $C_{ann,tot}$ is the total annualized cost and E_{prim}, E_{def} and $E_{grid,sales}$ are the total amount of primary load, total amount of deferrable load and the amount of energy sold to the grid respectively.

Chapter 5

RESULTS AND DISCUSSION

The results discussed here are for a PV-Wind-D.Gen-Battery HES designed to supply electricity for the daily load demand of Albreda and Jufureh. HOMER optimized a suitable configuration of the components best suited to supply enough power for a daily load of 1,759 kWh/day and a deferrable load of 746Wh/day.

5.1 The Optimum System

From the HOMER simulation results, at a scaled annual average solar radiation of 5.22 kWh/m^2/day, a scaled annual average wind speed of 4.297 m/s and a fuel price of $1.13/L, the optimum system consist of a 300 kW PV array, two (2) Hummer H25.0 200-kW wind turbines, a 200-kW diesel generator, a battery bank consisting of 360 Surrette 4KS25P batteries and a 200-kW converter.

The PV array produces a mean power output of 60kW at a capacity factor of 20.1% while producing a mean energy output of 1,445 kWh/day. It operates 4,369 hours in a year at a levelized cost of $0.093/kWh and has a penetration of 82.2%. Figure 12 shows the PV power output across the year. It can be seen that the PV system starts to produces power at around 8 am to 9 am morning and stops at around 6 pm evening with the most power being produced at around 12 pm to 3 pm. This is the period of sunshine.

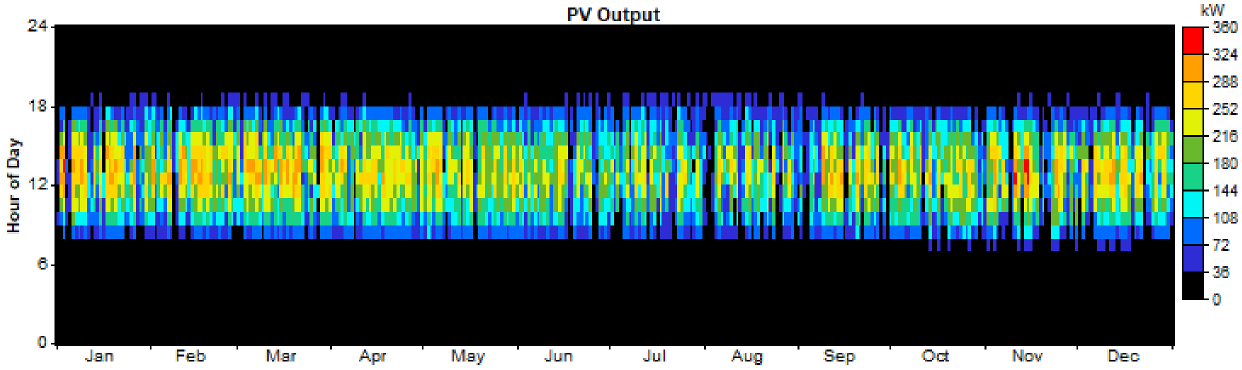


Figure 12: PV Annual Power Output in a Year

The wind turbines, with a total capacity of 400 kW, have a mean power output of 51 kW at a capacity factor of 12.6%. They generate a mean energy output of 442,968 kWh/yr, have a penetration of 69.0% and operates 8,458 hours in a year at a levelized cost of $0.148/kWh. Most of the power generated by the wind turbines occurs around 9 am to 8 pm from mid-January to mid-June. Figure 13 shows the annual wind turbine power output.

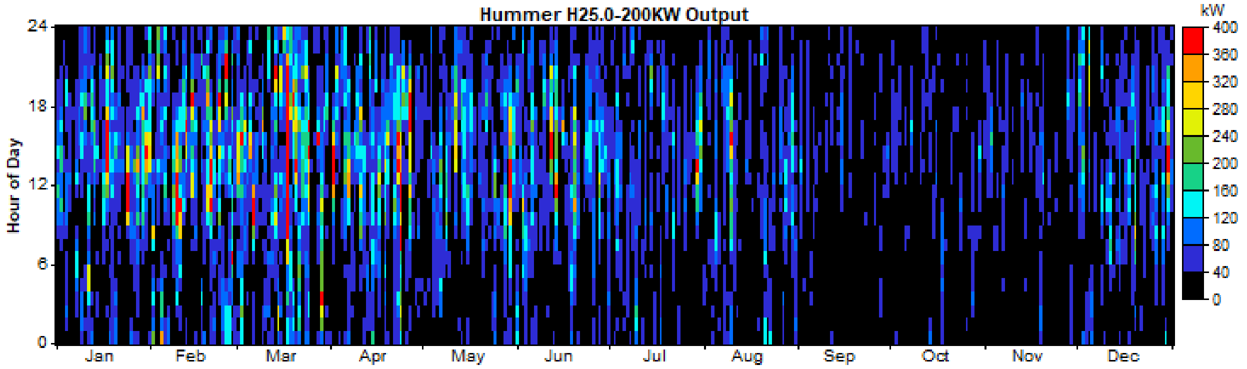


Figure 13: Wind Turbine Annual Power Output

The diesel generator runs for 936 hours per year consuming 32,067 liters of diesel in a year. It produces 68,366 kWh of electrical energy per year at a mean electrical power output of 73.0 kW, a capacity factor of 3.90% and a mean electrical efficiency of 21.7%. It has a fixed generation cost of $36.1/hr. It produces most of its power from around 6 pm to 7 am during the months from August to November which coincides with low power production of the wind turbines. Figure 14 shows the diesel generator power output in a year.

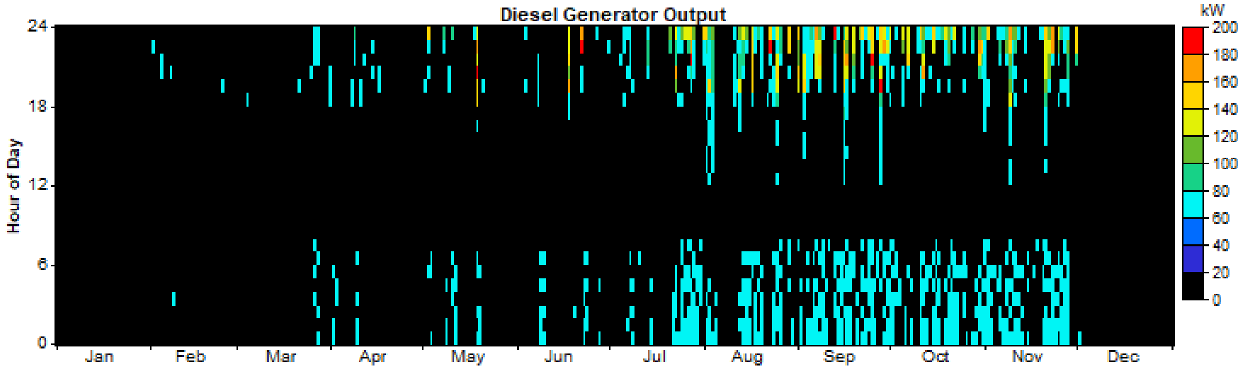


Figure 14: Diesel Generator Annual Power Output

The 360 Surrette 4KS25P batteries are connected in six (6) strings of sixty (60) batteries each and have a nominal capacity of 2,736 kWh. They have an annual throughput of 224,079 kWh per year and an expected life of 12 years. It incurs 49,061 kWh of losses per year. The batteries attain 100% charge throughout the winter. The batteries have zero cost of energy. Figure 15 shows the battery bank state of charge.

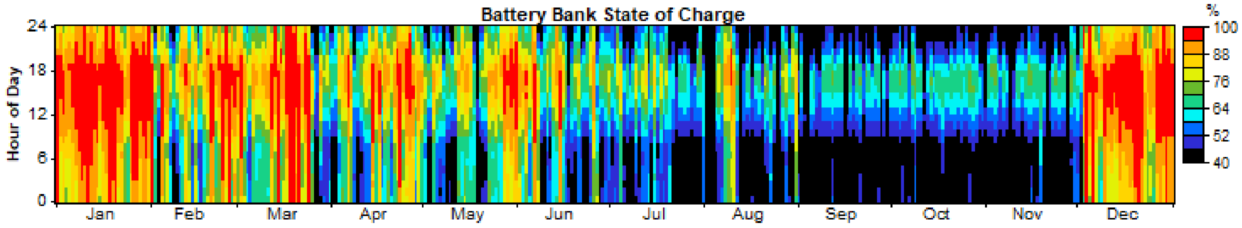


Figure 15: Battery Bank State of Charge Across the Year

5.1.1 Economic Analysis

The total NPC of the system is $2,368,156 and the COE is $0.406/kWh. Among the capital costs, the cost of the two wind turbines, equaling an amount of $595,600 is the highest followed by the battery bank, then the PV array and the diesel generator while the least cost is $69,400 by the converter. However, in the total NPC, the highest cost was for the diesel generator which recorded $628,266, followed by the battery bank, the wind turbines, the PV array and finally the converter which recorded a cost of $95,251. For the overall different costs, the capital cost recorded the highest with a sum of $1,771,640, followed by a cost of fuel of $328,917, then a replacement costs of $275,538 and the least is an operation and maintenance (O&M) cost of $73,814. This low cost for O&M is due to the fact that most of the power produced, 93.4%, is generated by renewable energy sources which have relatively very low O&M costs. Table 7 shows the cost summary of the optimum system while Figure 16 shows the cash flow diagram by cost type for the 25-year period.

5.1.2 Electrical Power Production

Figure 17 shows the monthly average electrical power production for the optimum HES. This is for an average global solar radiation of 5.22 kWh/m2/day, an average wind speed of 4.3 m/s and a diesel price of $1.13/L. The solar PV array generates the most power in a year, accounting for 51% of the total power produced. This power is produced across the twelve (12) months of the year but especially in the month from January to May and most especially the month of March when the average solar radiation is 6.055 kWh/m2/day and the clearness index is 0.602. The wind turbines generate the second highest percentage, recording 43% of the total power produced annually. The least power is produced by the diesel generator, 7%, which happens mostly in the months from July to November when the average wind speeds are at their lowest. The primary load consumes 642,024 kWh/yr of the electricity produced while the deferrable load consumes only 272 kWh/yr. The excess electricity from the optimum configuration is 323,323 kWh/yr which is 31.1% of the total energy produced. The unmet electric load and capacity shortage are 12.4 kWh/yr and 133 kWh/yr respectively which are both approximately 0% of the total energy produced. The total electricity produced per year is 1,038,841 kWh with a renewable fraction of 0.934.

Table 7

Cost summary of the optimum system

Component	Capital($)	Replacement ($)	O&M($)	Fuel ($)	Salvage($)	Total ($)
PV	413,400	41,971	27,231	0	-36,565	446,036
H25.0-200KW	595,600	0	545	0	0	596,145
Diesel	240,000	52,103	16,992	328,91	-9,746	628,266
Surret4KS25P	453,240	166,382	16,339	0	-33,503	602,457
Converter	69,400	15,082	12,708	0	-1,938	95,251
System	1,771,640	275,538	73,814	328,917	-81,753	2,368,156

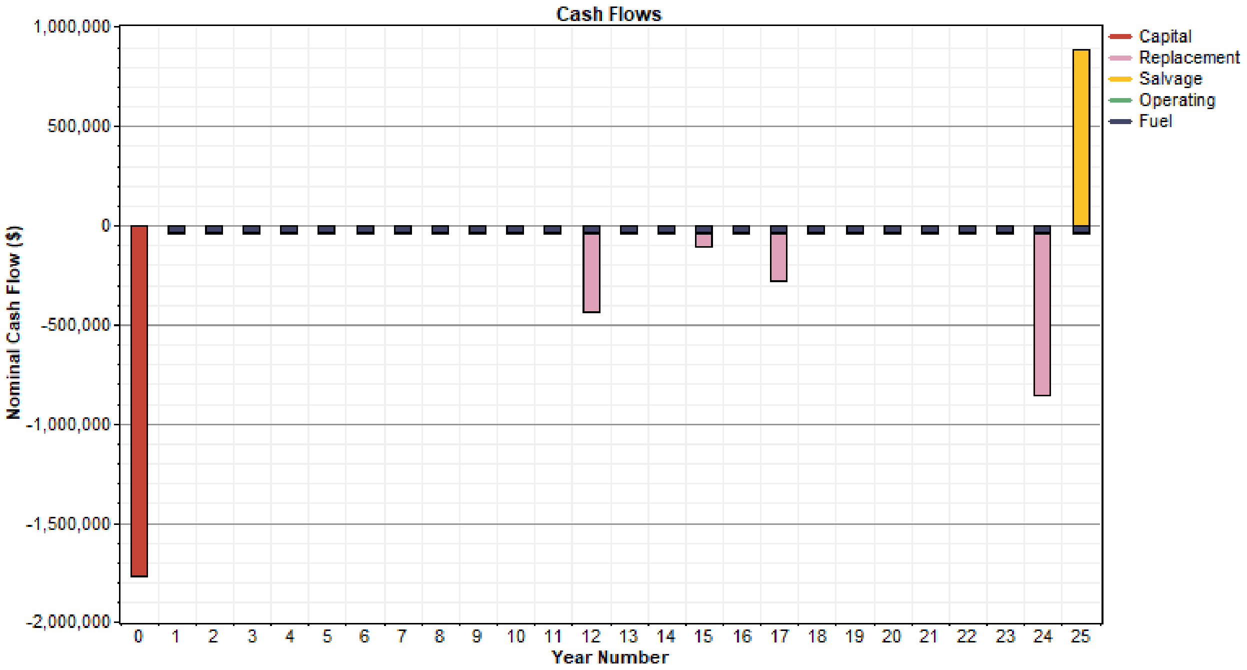


Figure 16: Cash Flow Diagram by Cost Type for the 25-year Period

5.1.3 Effects on the Environment

The PV-Wind-D.Gen-Battery hybrid energy system has a total emission of 86,720.8 kg of pollutants per year. This includes an 84,444 kg/yr of carbon dioxide, 208 kg/yr of carbon monoxide, 23.1 kg/yr of unburned hydrocarbons, 15.7 kg/yr of particulate matter, 170 kg/yr of sulfur dioxide and 1,860 kg/yr of nitrogen oxide. In comparison to other configurations, a Wind-D.Gen-Battery hybrid energy system has a lower emission rate with a PV-D.Gen-Battery hybrid energy system having an even lower emission rate. A PV-Wind-Battery hybrid energy system produces zero (0) emissions because it is a 100% renewable energy system. The diesel generator-only system produces 1,035,243 kg/yr of pollutants which is really high compared to the emission rate of the optimum system. In fact, the optimum system produces 948,523 kg/yr less emission than the diesel generator-only system which is a 91.6% reduction in emission rate. So, this optimum system offers a far more environmentally friendlier power generation means than a conventional system. Figure 18 shows the optimum system's rate of emissions per year.

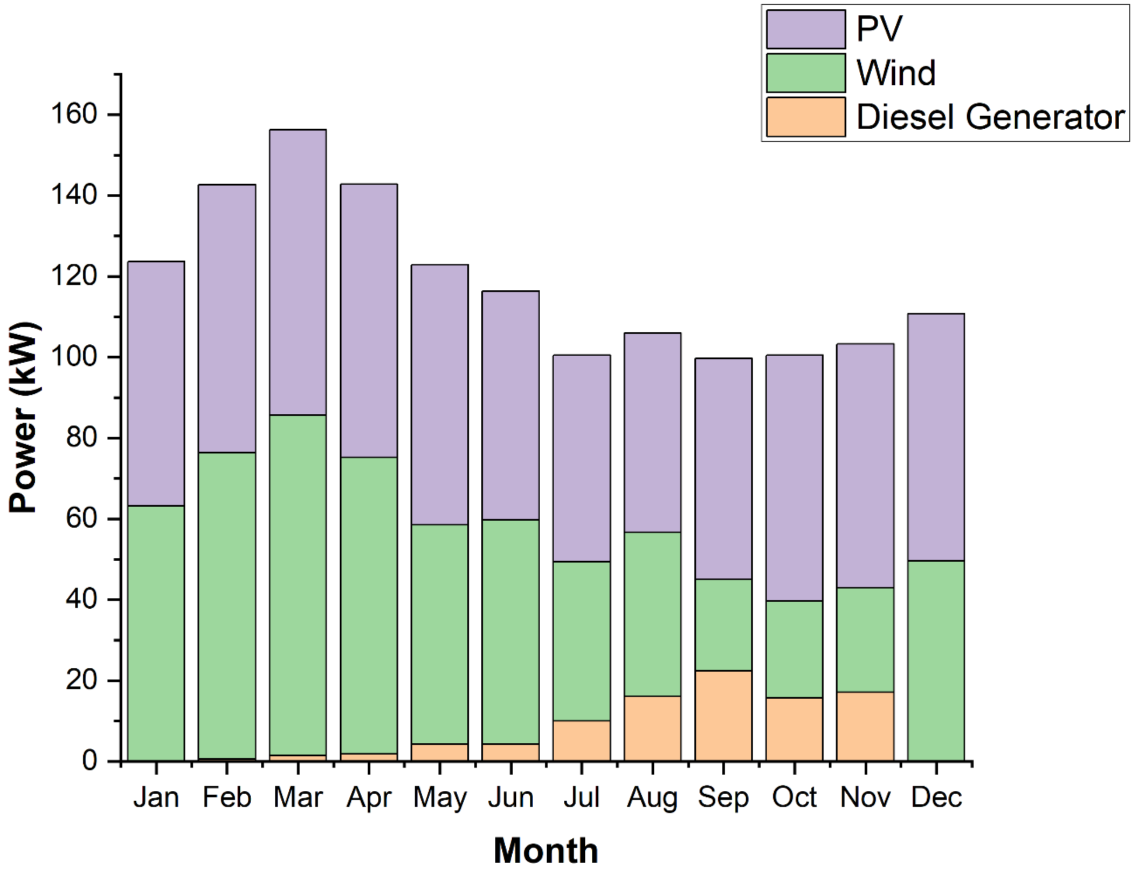


Figure 17: Monthly Average Electrical Power Production

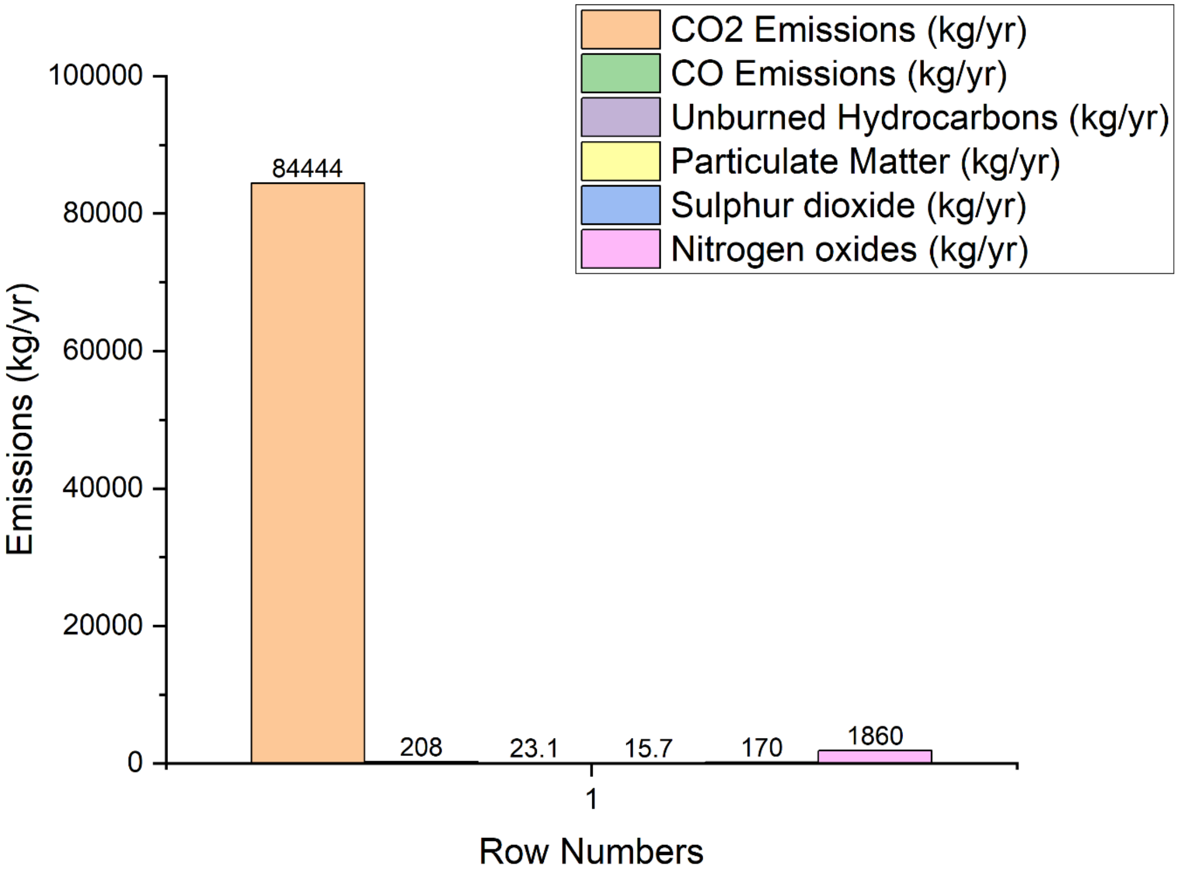


Figure 18: Number of pollutants and amount emitted per year

5.1.4 Sensitivity Analysis

For a techno-economic analysis, the effects of variability of certain variables such as the wind speed, solar radiation and fuel price on the optimum system are analyzed. From Figure 19, it can be seen that at a fixed diesel price of $1.30/L the optimum configuration becomes a PV-D.Gen-Battery system for wind speed values below 3.15 m/s. From a wind speed of 3.15 to 3.4m/s, the optimum system changes to a PV-Wind-D.Gen-Battery system as the solar radiation decreases from 6.15 to 5.55 kWh/m2/day. The optimum system always involves the wind turbine for wind speeds above 3.4 m/s while always involving a PV array and a diesel generator irrespective of the variations. The COE values also vary with solar irradiation and wind speed. The cheapest COE is achieved at the highest values for both solar radiation and wind speed while the most expensive one is at the lowest solar radiation and wind speed values.

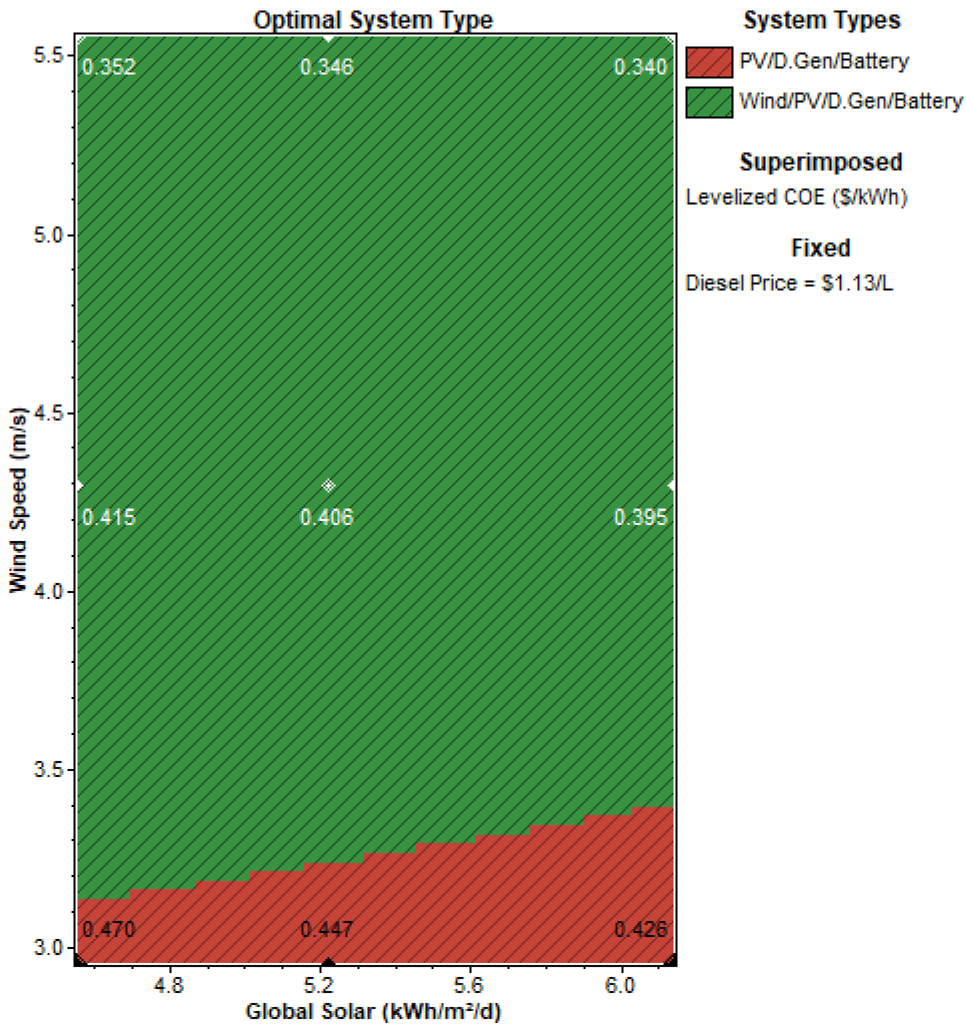


Figure 19: Optimal system showing COE for different wind speed and solar radiation values.

5.1.4.1 Effect of Solar Radiation

Solar radiation in this study areas vary from 6.138 kWh/m2/day in April to 4.549 kWh/m2/day in August. At the highest radiation rate, a wind speed of 4.3 m/s and a diesel price of $1.13/L, the PV array generates optimum system generates 55% of the total electrical power produced reducing the values of Total Capital Cost, total NPC and COE to $1,771,640, $2,302,663 and $0.395/kWh respectively. At the same wind speed and diesel price and at a solar radiation rate of 4.549 kWh/m2/day, the Total Capital Cost, total NPC and COE values rise to $1,780,560, $2,418,799 and $0.415/kWh and the PV array's power production reduces to only 29% of the total power produced. So, the solar radiation has a considerable effect on the technical and economic configuration of the optimum system. Shown in Figure 20 is the effect of solar radiation on the COE, NPC, Total Capital Cost and PV production.

5.1.4.2 Effect of Wind Speed

The average monthly wind speed values range from 5.556 m/s in March to 2.952 m/s in the month of September with 4.297 m/s being the average. At a wind speed of 5.556 m/s, solar radiation of 5.220 kWh/m2/day and a diesel price of $1.13/L, the wind turbines generate 65% of the total electricity produced and the optimum system achieves a Total Capital Cost of $1,482,760, total NPC of $2,018,109 and a COE of $0.346/kWh. At the same values of solar radiation and fuel price and at a wind speed of 2.95 m/s, which is the lowest average monthly value, the wind turbines generate zero (0) electricity and the Total Capital Cost, total NPC and COE values rise to $1,891,600, $2,608,441 and $0.447/kWh respectively for the optimum system. Therefore, the wind speed also has a significant effect on the technical and economic configuration of the optimum system. Figure 21 shows the effect of wind speed on the COE, NPC, Total Capital Cost and wind production.

5.1.4.3 Effect of Diesel Price

Fuel precises are mostly rising with time. The price of diesel per liter also has technical and economic effects on the optimum system. At an increased diesel price of $1.330/L and at an average solar radiation and a wind speed of 5.22 kWh/m2/day and 4.3 m/s respectively, the electrical power production by system components remains the same as the optimum system. However, the total NPC and COE values change to $2,426,371 and $0.416/kWh respectively while the Total Capital Cost also remain the same, $1,771,640. By decreasing the diesel price to $0.930/L and keeping the average solar radiation and wind speed the same, the optimum system produces 50% of its electrical power from the PV array, 42% of it from the wind turbines and 8% from the diesel generator. The Total Capital Cost, total NPC and COE values change to $1,696,100, $2,300,572 and $0.395/kWh respectively. It is observed that the diesel price has a huge economic impact on the optimum system while having only little technical effects. Figure 22 shows the effect of diesel price on the COE, NPC, Total Capital Cost and diesel generator production.

5.2 A Standard Community Load

For the standard load, the optimum power generation configuration is also a HES consisting of a PV array, wind turbines, battery bank and a converter. At an average global solar radiation of 5.22 kWh/m2/day, an average wind speed of 4.3 m/s and a diesel price of $1.13/L, the PV system produces 53% of the total electrical power produced, the wind turbines produce 38% while the diesel generator produces 9%. The total NPC of the system is $5,829,450 while the COE is $0.436/kWh.

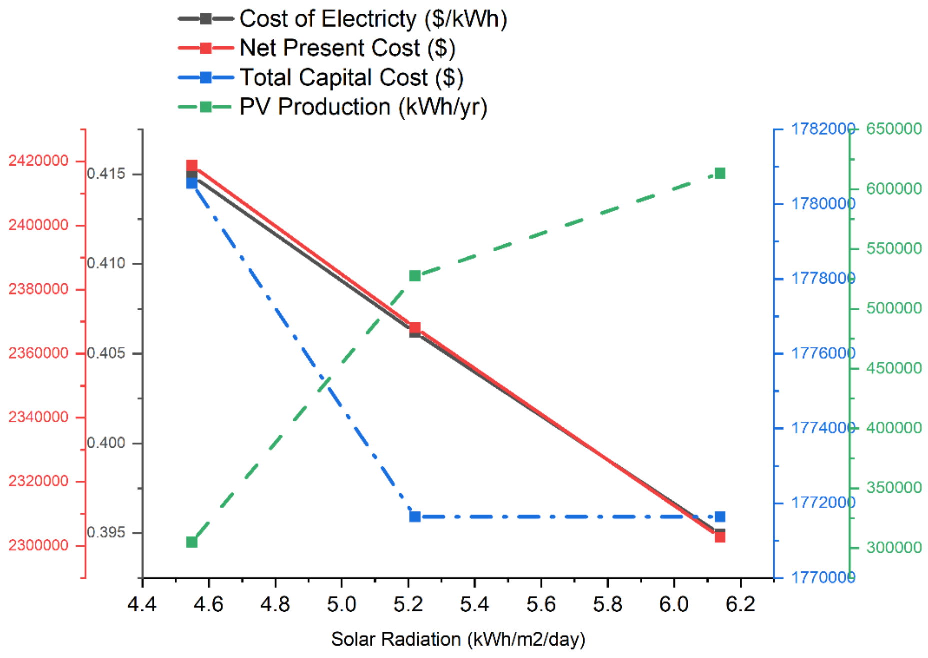


Figure 20: Effect of Solar Radiation

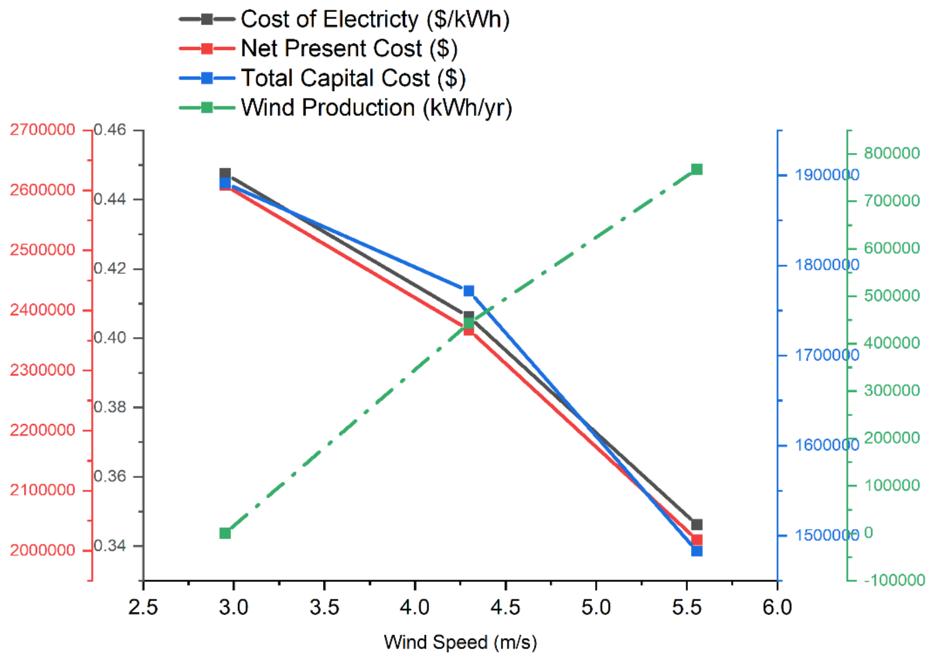


Figure 21: Effect of Wind Speed

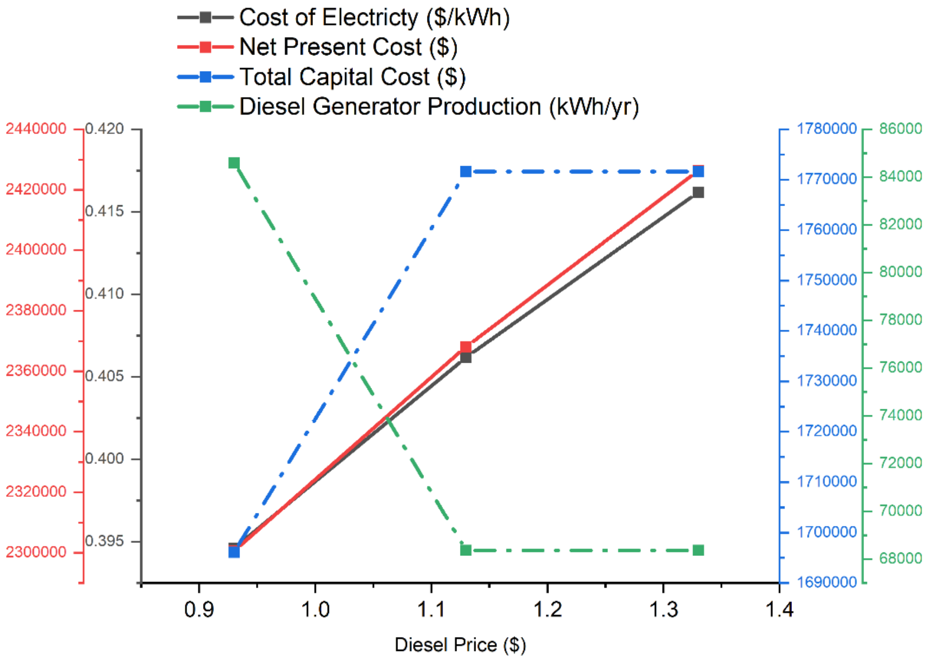


Figure 22: Effect of Diesel Price

Chapter 6

CONCLUSION AND RECOMMENDATION

In an effort to build an economical and environmentally friendly electricity generating plant for the community of Albreda and Jufureh, a technical and economic analysis was performed using HOMER. The result produced an optimized system, based on NPC and COE criteria, consisting of a 300 kW PV array, two (2) Hummer H25.0 200-kW wind turbines, a 200-kW diesel generator, a battery bank consisting of 360 Surrette S4KS25P batteries and a 200-kW converter. The following conclusions are made from the results.

- The optimum configuration is a PV-Wind-D.Gen-Battery hybrid energy system with a total NPC of \$2,368,156 and a COE of \$0.406/kWh. The system is made up of 93% renewable energy and emits 86,720.8 kg of pollutants every year.
- A diesel generator-only system is the most expensive system with a total NPC of \$5,926,387 and a COE of \$1.017/kWh and emits 1,035,243 kg of pollutants each year.
- Solar radiation and wind speeds have great technical and economic influences on the optimum system. At high solar radiations and wind speeds of 6.14 kWh/m^2/day and 5.56 m/s respectively, the optimum system produces 95% of its total electrical power from solar and wind resources while recording a total NPC of \$1,979,425 and a COE of \$0.340/kWh
- Another simulation was done on a standard case which consist of refrigerators and electric kettles as extra loads in which the total NPC and the COE of the system are \$5,829,450 and \$0.436/kWh respectively.

In further research, researchers can use this method or similar ones to find efficient, reliable and environmentally friendly HESs to cater for the electricity needs of electricity-deprived communities around the world. More extensive considerations including the cost of transmission and distribution as well as the cost of construction of the power plant can be included to give a more detailed understanding of the real economic aspect involved in establishing such facilities.

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