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Article

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Cost Optimization of Micro grids Using Homer: A Case Study in Botswana

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ABSTRACT

Fast dwindling fossil fuels and its impact on carbon footprint, encourage the use of renewable energy sources as an alternative power source. Renewable energy resources are now playing a pivotal role in gradually adding to the development of community and country. This paper focuses on optimal sizing and design, planning and operation of a micro grid solution for Botswana and demonstrate the usage through three different scenarios while taking into account cost factors, environmental emissions, economics, etc. The three modeling includes a combination of Solar PV's, generators, grid. The simulations are carried out using well-known modeling software HOMER. The paper accommodates sensitivity analysis to perceive the impact of solar insolation, investment costs of PV, converters, and fuel price on the optimum result. The results also positively encourage the use of renewable energy as a source to reduce greenhouse gases and reduce carbon footprint as per Kyoto protocol.

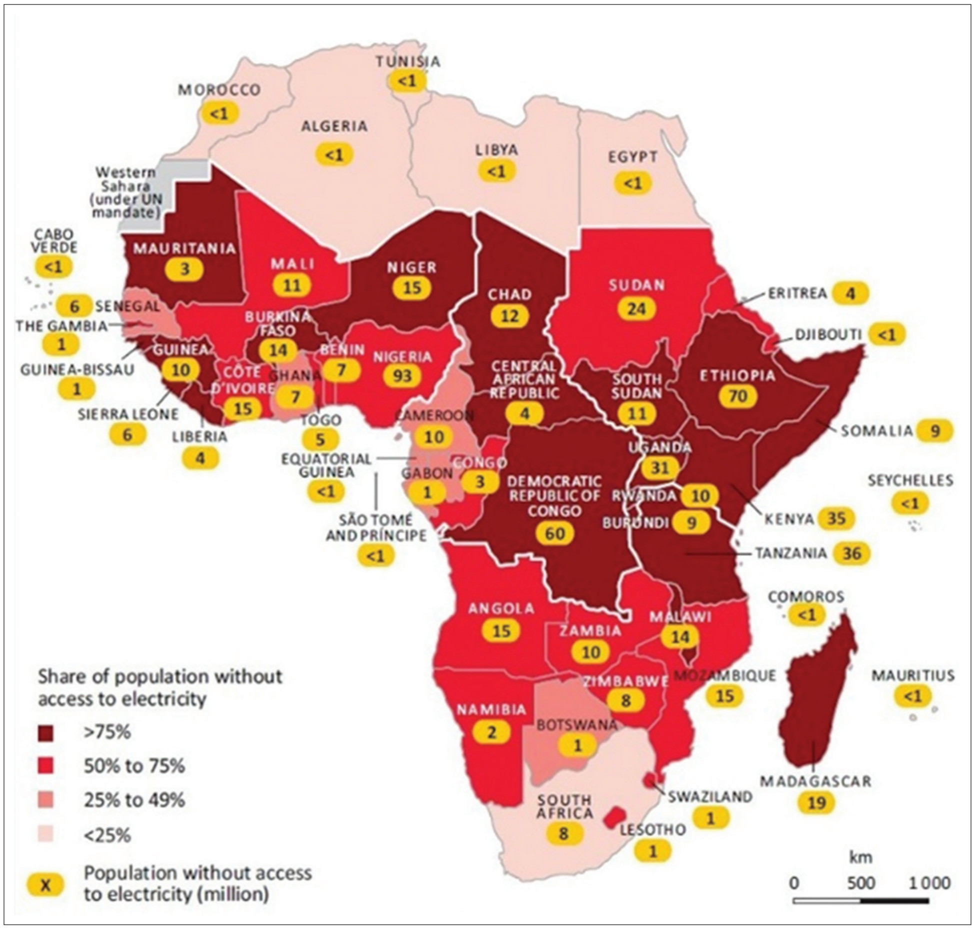
Keywords: Levelized Cost, O&M, Unmet Electricity Load, Annualized Cost
JEL Classifications: A1-19

1. INTRODUCTION

Energy is key for the future. It plays a major role in the socio and economic development of a country. With the depleting fossil fuels, it is crucial that the developing countries utilize other renewable sources and tap the potential for its development. "Earth's population has become abundant, but world inhabitants living in cities have not surpassed those people residing in the countryside until recent years" Therefore, the demand for energy is expected to grow significantly and considering the limited resources, it becomes a major bottleneck on the fossil resources and depleting natural resources. It is therefore essential to tap the renewable and alternative energy resources to lower the impact on the planet. Jesús Rodríguez-Molina et al. (2014) thus, it can safely be assumed that renewable resources act as a catalyst to increase and improve energy access in remote rural areas (Maiga et al., 2008). Rapidly increasing energy demands, the need to mitigate global warming and mounting pressure to reduce carbon footprint and pollution, has resulted in many governments encouraging renewable energy generation by providing subsidies and incentives. As of 2016, over 5 million people across the globe have been living without electricity, and this poses a major challenge to many developing nations. Access to energy in rural areas in developing countries is paramount as a means of increasing standard of living and sustainability and tops the agenda in any developing country (Karekezi and Ranja, 1997; Karekezi and Waeni, 2003; Karekezi and Waeni, 2002; Djiby-Racine, 2010).

The entire region of Sub-Saharan insurmountable challenges in the form energy and climate change and the socio-economic growth of the region lies in its ability to harness energy, which is critical to its growth. As indicated in Figure 1, lack of access to critical commodity, 'electricity' is a major determinant of poverty in Sub-Saharan Africa. Uwe et al. (2011). According to world energy outlook report 2014, Sub-Saharan Africa has more than 620 million people that is nearly half of global total figure living without electricity and is rising day by day due to rapid population growth, out of which 37 Nations in the Sub-Saharan Africa rose 100 million people though the overall access to electricity rate for the region has improved to 23% in 2012 (IEA, 2014). IEA (2014) the grid infrastructure across many countries still operate in the same manner, and not much has changed in its outlook. The same holds good for the generation part of the energy. One of the primary reason for the above is the inability of the Governments to focus

Figure 1: Population without access to electricity



Source: (IEA, 2014) (IEA, 2014)

on advanced technologies. Fangxing et al. (2010) Clement, Kevin (n.d.). According to WHO, global health observatory, (WHO, Global Health Observatory).

Virtual power plant or micro grids is a cluster of distributed generators with controllable loads and systems. It is unique in the sense that power plant can be a combination of the fossil generators, renewable energy sources. The cluster of generators are connected to a centralized energy management system by mutual coupling and is bi-directional. Microgrids were first developed by consortium for electric reliability technology solutions. Hina and Palanisamy (2015). The advent of artificial intelligence has contributed hugely to the development of critical infrastructures, and research has paved the way for advancement in VPPs application (Wu and Huang, 2012), thus enabling to break down complex structures into simpler and efficient way. The virtual grid plays a relevant role in the process of optimization in a virtual power plant. The challenges in the virtual power plant are enormous because it is a combination of units like PV, Wind Turbines, Geothermal, Hydro, Wave, etc. Due to this fluctuating nature of the energy resources, it is not easy to achieve the same. In a virtual power plant, each unit of DG's is connected either directly or indirectly through the grid to the centralized management systems. It is therefore imperative to provide information about the actual participant in the cluster, and therefore communication becomes a critical aspect of the plant. Several components need to be taken into account when communication becomes the focus. Some of the components are grid security; grid data flow exchange; speed/delays, etc. Since the system is networked it is essential that the system is fast, reliable, provide minimum delay and expandable in terms of adding new devices. Pio et al. (2009). It is essential that the combined production of electrical energy in a virtual power plant be managed efficiently with respect to network constraints (Roberto et al. 2004).

This paper provides an insight into various techniques used in optimization and analyzes the possibility to develop simple micro ON grid model utilizing local renewable energy. The optimization is conducted using HOMER software. The paper is organized into five sections. The first section is an introduction; the second provides insight into various methods used in optimization, the third section describes the system configuration of the proposed model and development using homer mode, the fourth section presents the case study for University, results, and discussion and the last (fifth) section concludes the research paper.

2. INSIGHT INTO OPTIMIZATION TECHNIQUES

In mathematics, optimization may be defined as a problem to find the most optimal solution. Optimization techniques may be applied in energy grid to obtain best optima. Optimization is to determine either the maximum or minimum of a real function using selected inputs. In power systems optimization the main objective is to minimize unwanted input like energy loss, errors, etc. and to maximize desirable elements like profit, quality, efficiency, etc. Heuristics includes trial and error solution but feasible solutions within time limits. Various optimization techniques have been studied and applied to solve many complex power system problems since 1950&60's by different authors. Kothari and Ahmad (1998); Kothari (1988); Sen and Kothari (1988); Mamoh et al. (1999); Mamoh et al. (1999); Sachdev et al. (1977). Optimization can either aim at minimizing energy production costs and maximizing profits or maximizing reliability, power quality, etc., in short, generation side, control side, operational side, and distribution side. In a virtual power plant, it is essential to minimize generation costs and maximize profits. There are several optimizing techniques applied successfully in Energy. Muis et al. demonstrate optimal planning of renewable energy systems using mixed integer linear programming (MILP) for Malaysia to reduce the carbon dioxide emission by 50% from current emission level. They use integrated gasification combined cycle, natural gas combined cycle and biomass from landfill gas and palm oil resources (Muis et al., 2010; Omar and Kankar, 2012) Nazir et al. proposed a micro-grid model that integrates the power plants driven by employing micro hydro (MHP) and photovoltaic system (PV) connected to grid system and analyze the possibility to develop the simple micro-grid model optimizing the utilization of local renewable energy for on-grid area by using HOMER and MATLAB simulation (Nazir et al., 2014). Thiam studies feasibility analysis in remote areas of Senegal on off-grid stand-alone renewable energy technology systems to compare the electricity costs with normal grid operations and shows that cost of renewable energy technology is lower than the cost of energy generated from the grid. Djiby-Racine (2010) Aris and Yannis studies PSO algorithm for optimal sizing of Photovoltaic grid connected systems Aris and Yannis (2010). Eberhart and Kennedy study stochastic based Particle Swarm Optimization, which based on the population of birds flocking social behavior. A randomly selected population initializes the system and searches for optima by updating generations and has no crossover and mutation. Eberhart and Kennedy (1995). Nayar et al. successfully implemented the hybrid system in three remote islands of Maldives (Nayar et al., 2008). Mizani et al. propose a mathematical model and optimization algorithm to identify the optimal micro grid configuration and obtained results for an optimal selection of renewable energy in conjunction with an optimal dispatch strategy in a grid-connected microgrid. Shervin and Amirnaser (2009); Omar and Kankar (2012); Salmani et al. propose a nonlinear profit maximization using General Algebraic Modeling system with constraints for the supply of electric energy for all loads in a VPP (Salmani et al., 2009) Zhao et al. analyses and suggests optimization model considering the battery life costs, operation, maintenance cost, fuel cost including lifetime characteristics of lead-acid batteries. They propose a multi-objective optimization model to minimize power generation cost and to maximize the life of lead acid batteries using a nondominated sorting genetic algorithm (NSGA-II) Zhao (2013). Many meta heuristic algorithms have been studied and applied. An insight into some of the optimization algorithms observed is presented in Table 9.

2.1. Solar Resources in Distributed Grids/VPP

A distributed grid or VPP can have multiple sources of inputs to the grid. It can be a combination of PV Systems, Bio Gas Generators, Diesel Generators, Wind, Wave, etc. This paper mainly focuses on two sources of input Solar and Diesel generators. Since virtual power plant is a combination of resources where small individual DG's make up a combined power unit, the total electricity generated can be combined as follows:

$$P_{grid\_total} = P_{Chp} + P_{Gen} + P_{wind} + P_{wave} \quad (1)$$

P_{Chp} = Combined heat power
P_{Gen} = Bio gas generators
P_{wind} = Wind turbine
P_{wave} = Wave.

Where Pgrid_total is the summation of all the power units generated in the VPP system.

The PV system comprises of a photovoltaic array made of silicon semiconductor crystalline materials which capture the light photons and converts it to electrons. The generated output is non-sinusoidal or DC current and is converted to AC using converters. Therefore specific MPPT system, an essential component for optimal absorption of solar energy, is employed to maximize the energy from the sun by tilting the angle of the PV's or tracking the sun. As solar insolation varies with the direction of the sun, the MPPT system adjusts itself to maximize its capture of solar radiation to generate maximum real power at a constant voltage. Efficiency in solar panels is measured by the ability to convert sunlight into energy and is a significant factor in choosing the correct panel for PV system.

The output of PV depends on many factors like temperature, irradiance, type of material, etc. Its efficiency can be represented and expressed as follows:

$$R = \frac{Pmax}{F(rf)*A} \quad (2)$$

Where
R = Maximum efficiency,
rf = Incident radiation flux in W/m^2 or solar irradiation,
A = Area in Sq.mt.

Or

$$Ppv = Pstc\frac{Gc}{Gstc}[1 + k(Tc - Tstc) \ \text{(Zhao, 2013)} \quad (3)$$

Ppv = The output power,
STC = Standard test condition (solar irradiance Gstc is 1000 W/m^2, PV temperature Tstc = 25°C.

Relative atmospheric optical quality is AM 1.5 condition.
Gc = Irradiance of operating point,
K = Power temperature coefficient in deg kelvin,
Pstc = Rated output power under STC,
PV = PV temperature of operating point.

Energy can be represented by the formula.

$$E = A*R*h*pr \tag{4}$$

Where,
E = Energy in Kwh
A = Total area of solar panel
R = Efficiency of solar panel
H = Annual solar radiation on tilted panels
Pr = Performance ration, coefficient for losses (range between 0.5 and 0.9; default value = 0.75).

2.2. Diesel Generators

Diesel generators are mostly used as backup resources. In the event of the solar PV's failing to supply the required load, the generators kick in to meet the required load. Factors that influence diesel generators include fuel costs, maintenance and running costs, transportation costs, load, etc. Alexis et al. (2012). Generators efficiency is determined by the total power or load in the circuit and the total watts produced by the generator. It is expressed in percentage, and the losses include transformers, copper windings, magnetizing losses in the core and rotational friction of the generator. Normally generators on full load are more efficient and economical. In simple words, generator efficiency is expressed as:

$$Ntot = nbt \times Ng \text{ (Hina and Palanisamy, 2015)} \tag{5}$$

Where
Ntot = Overall
Nbt = Brake thermal
Ng = Generator.

2.3. Economics in Power Generation

Different components in electricity generation influence the costs and these costs can be calculated at grid or at the point of connection to a load. The costs are in kWh or MWh, and it typically includes capital, discount rates, subsidies, operational costs like fuel, maintenance, etc. Since, electrical generation connected to the grid is from many sources like hydro, PV, nuclear, etc., the costs of these need to be standardized or levelized. Levelized cost is the measure which attempts to compare different methods of electricity generation on a constant basis, in short, it is averaging the total cost to build and operate a power generating equipment. LCOE can be termed as the minimum cost at which electricity must be sold to end users to achieve break even over the lifetime of a project (Wikipedia, 2017; Matthew, 2015).

The elements influencing the total cost of the system is net cost and cost of energy. The following equation is used for calculating total net cost.

$$CTot = \frac{CAnnual}{F(interest, years)} + \frac{CAnnual}{Ei+Eg} \tag{6}$$

Where
CTot = Total net cost,
CAnnual = Annualized cost,
F = Capital recovery factor,
interest = Annual interest rate,
years = No of years.
Ei = Electrical energy that microgrid serves,
Eg = Amount of electricity sold to the grid by micro grid.

Levelized cost can be calculated by using the following formula:

$$LCOE = \frac{\text{Sum of costs}}{\text{Sum of electrical energy produced}} \text{ (Matthew, 2015)} \tag{7}$$

$$LCOE = \frac{\sum_{t=1}^{n} \frac{It+Mt+Ft}{(1+r2)}}{\sum_{t=1}^{n} \frac{Et}{(1+r2)}} \tag{8}$$

It = Yearly investment expenditure
Mt = Yearly maintenance and operations expenditure
Ft = Yearly fuel expenditure
Et = Yearly electricity generated
r = Discount rate
n = Lifetime expectancy of the system or power station.

3. SYSTEM CONFIGURATION, DESCRIPTION AND CASE STUDY

3.1. Case Study: University, Private

Botswana is a landlocked country with coordinates Latitude 24.40 S, Longitude 025.55E (Gaborone) and situated at 999 meters elevation. The total population is about 2.265 million. World Bank (2017). The country is sparsely populated and distributed among villages, thus making it difficult for the government to provide and meet energy demands. As of 2016 (Figure 1), 1 million people still live without electricity in Botswana. IEA (2014) estimating the right type of renewable energy system requires detailed study of the area, climate profile, and demographics. In a country like Botswana, due to its sparse and distributed population, makes it difficult to provide electricity at a nominal cost, thus making it ideal for studying distributed generation systems. Due to this rural profile, renewable energy is seen as increasingly viable generation source and also aid in sustainable livelihood for its citizens. Several solar power projects have been taken up in the recent past as study in Botswana. However, no study or research has been done in the area of distributed generation in Botswana.

Botswana is hot and receives abundance of sunshine as shown in Table 1. Botswana receives approximately 3,200 hrs of the sunshine per year and has high insulation on a horizontal surface of $21MJ/M^2$. The average day length and the average sunshine hours is about 9.9 hrs and 8.2 h in winter. Base (n.d.) this amounts to one of the highest insulation rates in the world, and this abundant sunshine can be used for generating electric

Table 1: Climate data of Botswana (Wikipedia, 2017; Anon., n.d.; Anon, 2017)

Climate data for Gaborone (Sir Seretse Khama Airport, 1981-2010)													
Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
Record high °C (°F)	39	40	39	37	33	29	28	33	39	38	40	39	40
	−103	−104	−102	−98	−91	−84	−83	−91	−103	−100	−104	−103	−104
Average high °C (°F)	32.7	32.1	30.8	28.4	25.6	23.1	22.9	26.2	30	32	32.3	32.5	29.1
	−90.9	−89.8	−87.4	−83.1	−78.1	−73.6	−73.2	−79.2	−86	−89.6	−90.1	−90.5	−84.4
Daily mean °C (°F)	25.7	25.2	23.7	20.6	16.8	13.7	13.5	16.9	21.2	24	24.7	25.3	20.9
	−78.3	−77.4	−74.7	−69.1	−62.2	−56.7	−56.3	−62.4	−70.2	−75.2	−76.5	−77.5	−69.6
Average low °C (°F)	19.7	19.3	17.4	13.5	8.3	5	4.4	7.5	12.3	16.3	17.7	18.8	13.4
	−67.5	−66.7	−63.3	−56.3	−46.9	−41	−39.9	−45.5	−54.1	−61.3	−63.9	−65.8	−56.1
Record low °C (°F)	14	13	11	0	−1	−1	−2	0	5	7	8	11	−2
	−57	−55	−52	−32	−30	−30	−28	−32	−41	−45	−46	−52	−28
Average precipitation	32.5	30.2	20.9	12.9	8.4	10.2	0.4	4.8	6.1	13.1	17.3	32.9	189.7
mm (inches)	−1.28	−1.189	−0.823	−0.508	−0.331	−0.402	−0.016	−0.189	−0.24	−0.516	−0.681	−1.3	−7.469
Average precipitation days	6	5	5	3	2	1	1	1	2	4	5	6	41
Average Sunshine hours	9	10	9	9	9	9	9	11	11	11	11	11	9.9

power. Global solar radiation (GSR) is expressed as the total amount of solar energy received by earth at any given point of time. In other words, GSR is the sum of direct, diffuse and reflected solar radiation. Direct solar radiation passes directly through the atmosphere to the Earth's surface, while diffused solar radiation is scattered in the atmosphere, and reflected solar radiation reaches a surface and is reflected adjacent surface (Licor.com, n.d.). Figure 2 shows the direct and GSR across Botswana as captured by Solar GIS (Solar GIS, n.d.) and Figure 3 shows the global irradiance data from HOMER. The GSR (H_i) may be represented by the following expression (Duffie and Beckman, 2013).

$$Hi = Ki \times Hj \tag{9}$$

Where Ki is the clearness index, and Hj is the extraterrestrial solar radiation on a horizontal surface which is a function of latitude and is independent of other location specific parameters. The clearness index can be written as Ki = Hi/Hj, namely, as the ratio of daily global radiation on horizontal surface to daily extraterrestrial radiation on horizontal surface.

Numerous models have been developed for predicting average GSR, the popular being Angstrom regression model developed in 1924 (Angstrom, 1924):

$$\frac{Hi}{Hj}=a+b\left(\frac{S}{So}\right) \tag{10}$$

Where Hi is the monthly average daily global radiation on horizontal surface represented in M_J/m^2, Hj is the monthly average extraterrestrial radiation, S is the average number of hours of sunshine, and S_o is the length of day in hrs.

The extraterrestrial solar radiation on a horizontal surface is calculated from the following equation (Duffie and Beckman, 2013).

$$Hj = \frac{(24*3600*Gsc)}{\pi} \times \{1+0.033\cos\left[\frac{360\,x\,n}{365}\right] \cos\varnothing\,\cos\partial\sin w\} + w\sin\varnothing\sin\partial \tag{11}$$

Where Gsc is solar constant represented as 1367 Wm^2, ϕ is latitude of the location, n is the Julian day number, w is the sunset hour angle, ∂ is declination angle which is given by the following (Duffie and Beckman, 2013).

$$\partial = 23.45\,\mathrm{Sin}\,(360\times\frac{284+n}{365}) \tag{12}$$

And w=Cos-1 (−tan∅ tan∂)

The maximum possible sunshine duration So is given by (Duffie and Beckman, 2013).

$$So=\left(\frac{2}{15}\right)w \tag{13}$$

Botswana's energy challenges include rapidly growing demands for electricity, untapped solar potential, etc. The Energy sector in Botswana comprises both conventional and non-conventional energy sources. The conventional energy sector is dominated by electricity, petroleum products, and coal, whereas the non-conventional comprises of mainly biomass in the form of wood. Other forms of non-conventional energy sources like solar, wind, geothermal, etc. largely remains untapped.

The study site is a private University in Botswana. The university has five buildings. The electricity requirement is met by Botswana Power Corporation utility feeder grid through a transformer. The campus also houses two stand by 500 kva generators of Scania make.

HOMER is a product developed by the U.S. National Renewable Energy Laboratory to assist simulation, planning, and design of renewable energy systems and is predominantly used for designing smart grids, microgrids, VPP, etc. and to overcome the challenges in analysis and design of microgrids. The system allows to simulate both off-grid and on-grid scenarios and can be used for remote areas, rural areas for simulating loads, estimating costs and optimizing the system. The system also helps in considering various factors influencing the system like sensitivity analysis, future fuel prices, etc. In HOMER the cost of the system is total cost comprising of capital cost, replacement and maintenance

Figure 2: Global horizontal irradiation (Solar GIS, n.d.)

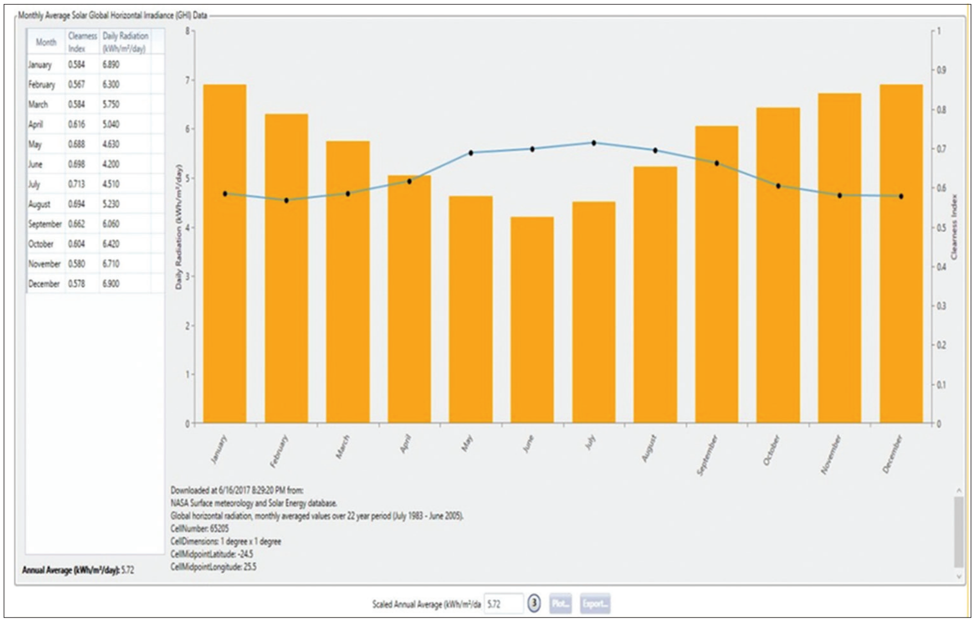


Figure 3: Global horizontal irradiance (Botswana)

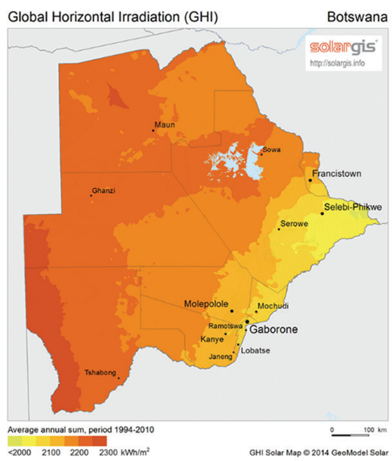
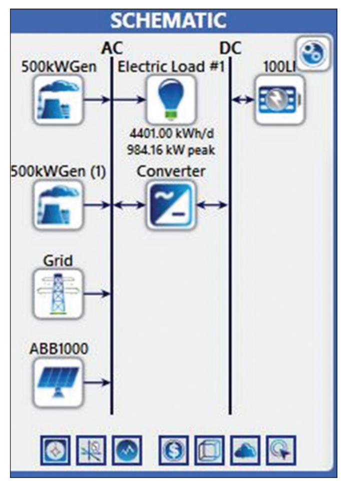


Figure 4: Schematic model



cost, operation cost, fuel consumption costs, miscellaneous costs. The system also includes costs for pollution tax, emission costs, grid costs, etc. The difference between the interest rates and the inflation rate is equal to real interest rate is also accommodated and needs to be entered by the programmer (Farret et al., 2006; Lambert and Gilman, n.d.).

3.2. Model Inputs and Assumptions

Figure 4 illustrates the available energy supply options and schematic microgrid system for the University. Under consideration, are PV's (array) and Diesel Generators, Battery bank, converters. The method proposed is ON grid. A 3 phase transformer feeds the university. The average load consumed is three thousand to five thousand kW/h/day.

3.3. Electrical Load Profile for University

3-year power consumption data from 2014 to 2016, as shown in Appendix I and II, Tables 7 and 8, was used for calculating the load profile for the university. The period during the late hours in the evening and the night is assumed at constant values. 15% daily noise and 20% hourly noise is considered for the study. The HOMER profile for daily profile and seasonal profile is as shown in Figure 5.

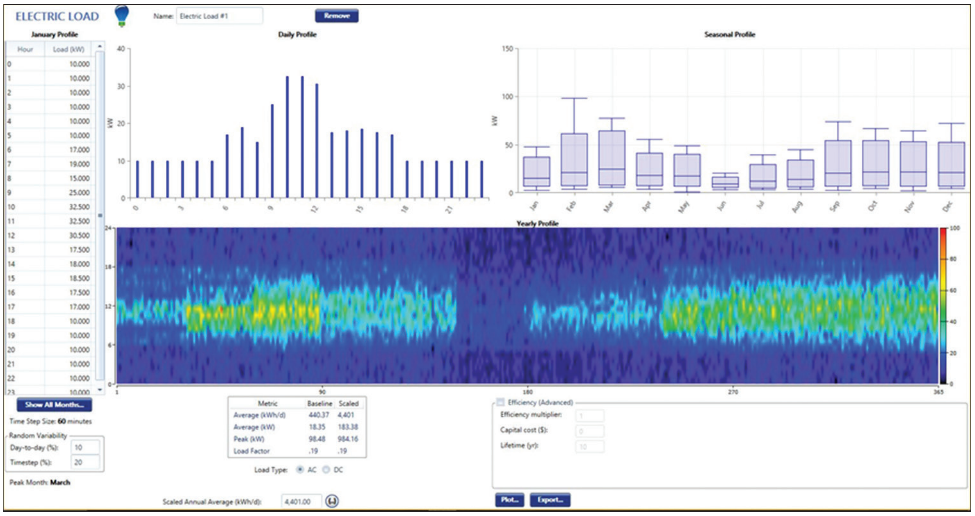
3.4. Components Selected

The design consists of two Scania 500 KVA Generators PV system, Battery, Converter and grid profile. The generators are used as standby power resource in the university. Three design model inputs were provided as follows:

a. Model 1 – PV + generator + grid
b. Model 2 – PV + grid
c. Model 3 – PV.

The fuel curve intercept is about 7 L/h. The specifications of the generators are shown in Figure 6. The PV system is ABB 315 Kw with an efficiency of 17.30%. The battery pack is 100KVA Li-ion each.

Figure 5: Daily profile and season profile of electric load



3.5. Diesel Price

The study includes a sensitivity analysis on the price of diesel, which can vary considerably based on region, transportation costs, and current market price. Diesel prices of 0.90-1.50 $/L are evaluated, with an emission density of 13.56 g/L, the carbon content of 88% and a sulfur content of 0.40%.

3.6. Economics

The annual real interest rate considered is 0.7%. The real interest rate is equal to the nominal interest rate minus the inflation rate. The project lifetime is 25 years. The model constraints include maximum annual capacity shortage, varying from 0% to 10% (Givler and Lilienthal, 2005).

3.7. PV Selection

The PV power generation out is determined by the following equation.

Power in PV (P) = Derating factor of PV * rated capacity (solar irradiance/standard radiance) and can be expressed as:

$$P = f^{*}r\left(\frac{Ir}{Is}\right) \quad (14)$$

Where P is power in kW, f is derating factor of PV, r is rated capacity of PV in kW, Ir is solar radiation in kW/m^2, Is is the standard amount of radiation in kW/m^2.

The PV module selected is ABB PVS800-1000, and the specifications are shown in Figure 7. The inverter selection is 3 phase grid tied inverter. The capital cost is computed at 4400$/kW including the cost of purchasing solar panels, mounting panels, control systems, wiring, and installation. Based on the specifications the age of the module is fixed at 25 years, and the calculation is for 25 years. The default derating factor of 96 is maintained for the proposed system.

3.8. Battery and Converter Model

100 KVA Li-ion battery is provided to improve the system performance of the micro grid as shown in Figure 8. The device is used in the event of short time disturbances and climate variations and also to act backup power. The number is adjusted to suit the capacity of the PV generation. The capital cost and replacement cost is assumed at 50,000$. A DC to AC converter system is also provided to manage the flow of the electrical power in both the directions. The cost for the converter is included as a part of the ABB PV system.

Figure 6: Generator specification

Name: **Scania Genset 500 KW**

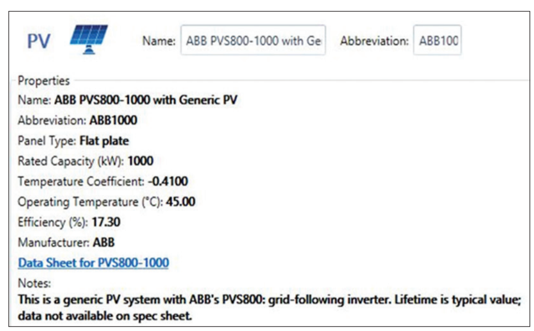
Capacity: **500.00 kW**

Fuel: **Diesel**
Fuel curve intercept: 7.00 L /hr
Fuel curve slope: 0.244 L /hr/kW

Emissions
CO (g/L fuel): 13.566
Unburned HC (g/L fuel): 0.72
Particulates (g/L fuel): 0.116
Fuel Sulfur to PM (%): 2.2
NOx (g/L fuel): 2.60

Fuel Properties
Lower Heating Value (MJ/kg): 43.2
Density (kg/m3): 820
Carbon Content (%): 88
Sulfur Content (%): 0.4

Figure 7: Spec sheet for ABB PVS800-1000



3.9. Utility Grid Operations

The current laws in Botswana do not allow selling of electricity back to the grid. However new laws are being enacted to accommodate the above.

3.10. Simulation and Optimization

Homer analyses the technical feasibility and life cycle costs of the micro grid for each year and tests the input components over the given period. The simulation capability is long term for HOMER. The optimization and sensitivity analysis is performed to determine the simulation capability with the configurations defined by the user. The minimum cost of microgrid depends on the total net cost. The optimization is carried out based on these inputs and results tabulated. While doing the optimization, HOMER takes into consideration the profile of each generator based on the user specifications.

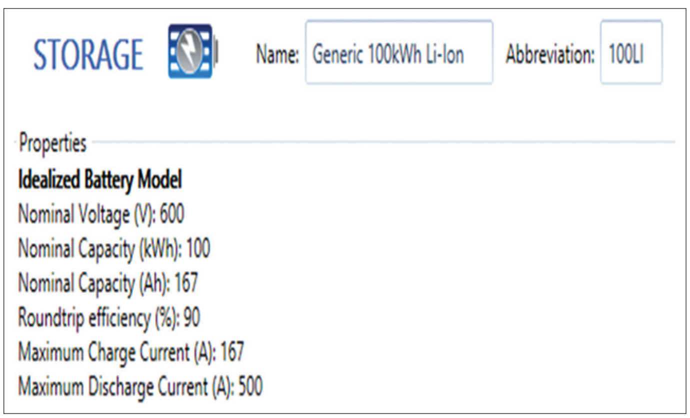
3.11. Sensitivity Analysis

Homer can analyze the effects of parameter variations to find out optimal values for the different sizes and quantities. The model is scaled to accommodate the increase in diesel fuel price; Solar scaled average (kWh/m^2/day) and nominal discount rates.

4. RESULTS AND DISCUSSION

The current model depicts the usage of existing 2 × 500 KVA generators connected to the load. However running costs are expensive due to the high cost of fuel, maintenance, emissions, etc. The model also depicts connection of PV solar system, practically, free from many of the factors above. The model was optimized using HOMER. The optimal grid design considers various optimization reports obtained from HOMER using the input parameters as detailed in Table 2. Two case components are studied in the design. Wind generators were not added to the model, due to climate profile of Botswana. Botswana is a landlocked country hence micro-hydro, hydro, etc. were not a part of the profile as depicted in summary of cases studied (Table 3). The grid rates included the peak demand rates and unit rates and were converted from Pula to USD at 1:12. The discount rates at 0.75%, Annual shortage capacity at 5% and project life at 25 years are used as base components.

Figure 8: Battery specs



4.1. Electrical Components

The simulation is aimed at finding least cost and best utilization of resources available locally. In the first model (Table 4 and Figure 9), model 1, it is seen that both the generators are put to use and the load generated is evenly distributed among all the three components with a grid purchase of about 1.59%. In the second case scenario, model 2, (Figure 10) the PV is put to the maximum generation of about 85.2% and a grid purchase of about 14.8%. Since both the generators are in operation, the fuel consumption used in a generation is about 0.259 L/kWh, and the electricity production is about 2667955 kWh/year with about 5559 h of operation per year. In the third case scenario, 100% renewable energy is used to supply and meet the demand.

4.2. Annualized Cost Summary

While comparing the costs between the Models 1-3, it is noticed from the Table 5, cost summary, the capital investment in case of opting for Model 1, will require reduced investment for the PV while incurring a cost of replacement for generators. In case of opting for Model 2, the initial investment cost is substantially high. However the cost of replacement remains $0 in the cases for PV. The levelized cost of energy for model one is $10.76 which is higher due to significantly large fuel usage, than the cost for Model 2 at $4.23, while the PV stands at $0.399, It is noticed that the largest cost components case are those of O&M and fuel costs. Figures 11 and 12 presents the cash flows

Table 2: Input parameters

Input components and costs					
Model	**Components**	**Capital cost**	**Replacement cost**	**O&M cost**	**Fuel/Lit**
HOMER	Solar (1 kW)	$4,400.00	$4,400.00	$15.00	
	Generators (existing) (per Hr)	$85000	$85000	$15.00	$0.90
	Converter (per kW)	$300.00	$300.00	$15.00	
	Battery (100 kW)	$70,000.00	$56,000.00	$15.00	
	Grid extension (Km)	$8,000.00	$8,000.00	$15.00	

Table 3: Summary of cases studied

Components studied using 3-year consumption data			
Model	**Components**	**Description**	**Test case**
HOMER	Grid	Grid connected	
	Generators	2×500 KVA Generators (existing). The university currently uses the generators as backup	Diesel dependent microgrid (base case)
	PV	ABB PV 800-1000 inverter with Tata BP 315kp used	Renewable based using PV, battery, converter
	Battery	Li-ion 100K	

Figure 9: Simulated electrical component model 1

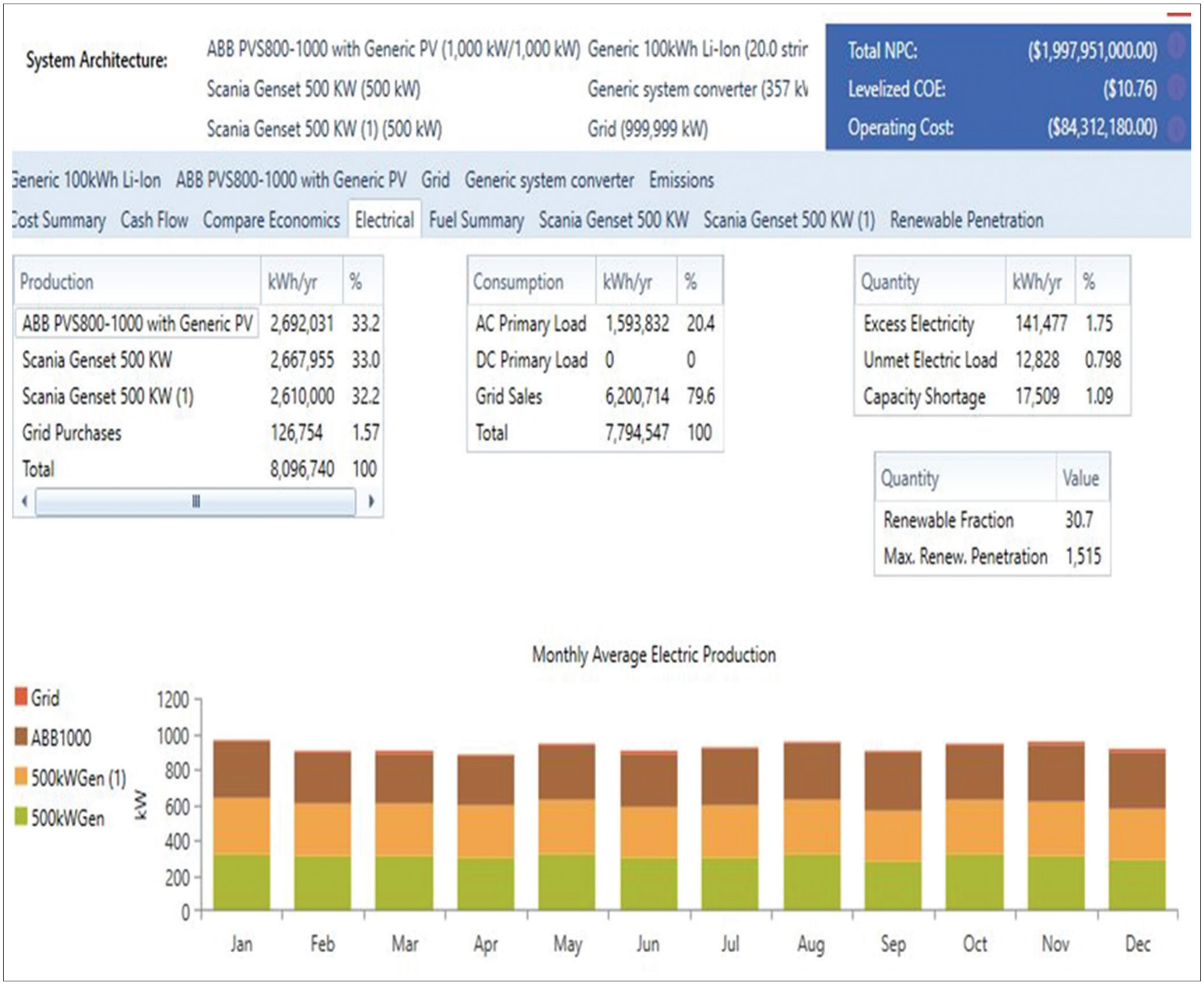


Figure 10: Simulated electrical component model 2

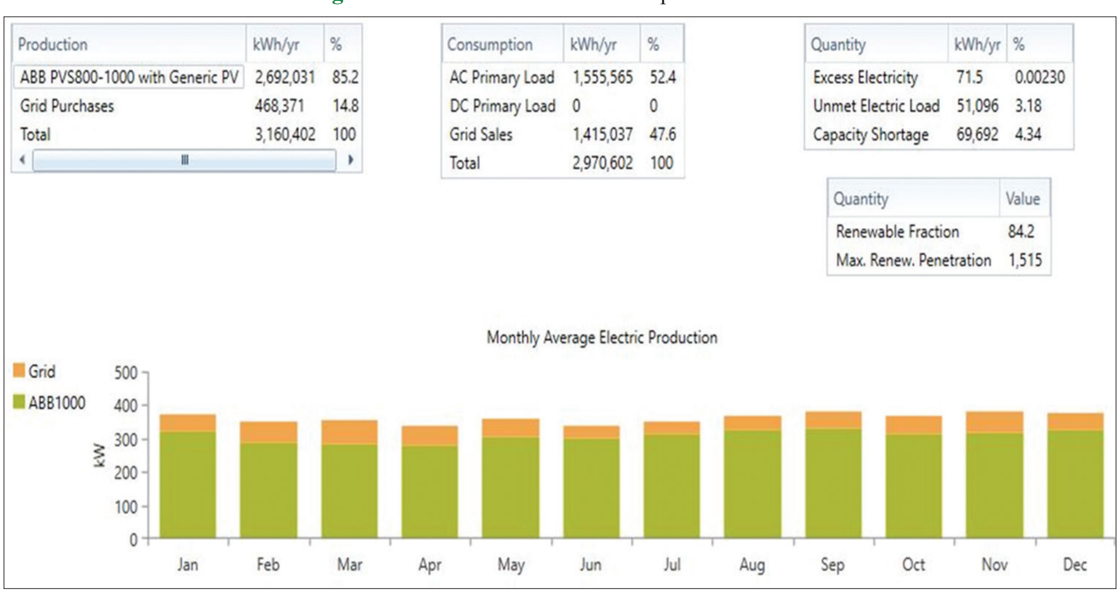


Table 4: Optimal simulated electrical component

Component	Model 1 (generator+PV) (%)		Model 2 (PV+grid) (%)		Model 3		Model 1 (generator+PV +)		Model 2 (PV)		Model 3	
Architecture												
Excess electricity quantity (value)	141,477	2	71.5	0	10,07,575	37.40						
Unmet electric quantity load (value)	12,828	1	51,096	3	60,757	3.78						
ABB PVS800-1000 with generic PV	26,92,031	33	26,92,031	85	26,92,031	100						
Scania Genset 500 kW	26,67,955	32										
Scania Genset 500 kW (1)	26,10,000	32										
Grid purchases	126,754	2	4,68,371	15								
AC primary load							15,93,832	20	15,55,565	52	15,45,904	100
Grid sales							62,12,897	80	14,15,037	48		
Total	80,96,740	100	80,79,857	100			78,06,730	100	29,70,602	100	15,45,904	100

respectively. In model 1, the generators incur replacement cost for every 2.7 years due to their operating life in addition to incurring maintenance costs. On the other hand Model 2, incurs only an initial investment cost while the replacement cost is sporadically distributed over its lifetime of 25 years. The full tables computed for 25 years, the nominal cash flow and discounted cash flow is not given here. However, it is readily available with the authors for reference.

4.3. Emissions

The usage of both the generators in Model 1, contributes substantially to carbon dioxide emissions, while in the case of PV dependability alone decreases the emissions. As mentioned above, the primary aim of this research is to reduce emissions and carbon footprint. The emission portfolio is presented in Table 6.

4.4. Grid Components

Since the model is ON grid model, it is possible to feed back the excess electricity generated by the models back into the grid. The ratio for each of the models will vary due to factors influencing them (Figure 13).

4.5. Sensitivity Analysis

The effect of shortage in capacity on the grid is examined by the unmet electric load. A small fraction of the annual load is allowed to remain in the micro-grid. Two scenarios are obtained, one with a 5% of unmet load and second with a 10% maximum allowable unmet load as seen from Table 4.

5. CONCLUSION

This research paper presents a comprehensive summary of how renewable energy potential can be tapped in Botswana with an optimal design and comparative studies with real-time data consumed by the university. It compares three models and how it can be beneficial to the university to accommodate frequent power cuts and disruptions and also to encourage the use of renewable energy resources in the country. Analysis revealed that diesel-renewable-grid model has the lowest net present cost but has a larger impact on carbon footprint when compared to other two models. It is observed that microgrid, when connected to the grid, is economically favourable. However, it is noticed that the peak load demand needs to be met from the grid. The third model uses 100% renewable energy and is completely dependent on the PV system to supply the needs, and the model has nil emission rate as compared to the other two models. It is to be taken note that there is much research work to be carried out in the renewable energy systems due to its initial capital and replacement costs. However, on a positive note it needs to be appreciated that due to subsidies by government agencies and with advancement in technologies and efficiency in operations of the PV, the cost of PV/watt has come down significantly.

When comparing with diesel versus solar systems, the decision on solar comes to high upfront costs and low long-term operating expenses. As Botswana's demographic profile, is sparsely populated and dispersed across, it poses significant challenges in providing electricity supply through the grid across various

Figure 11: Simulated electrical model 3

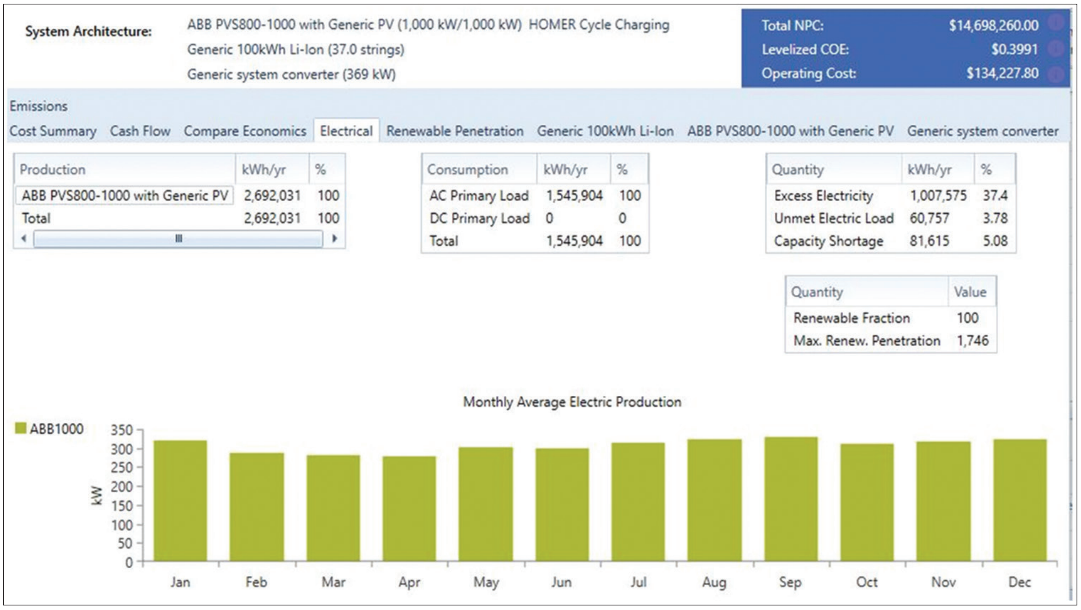
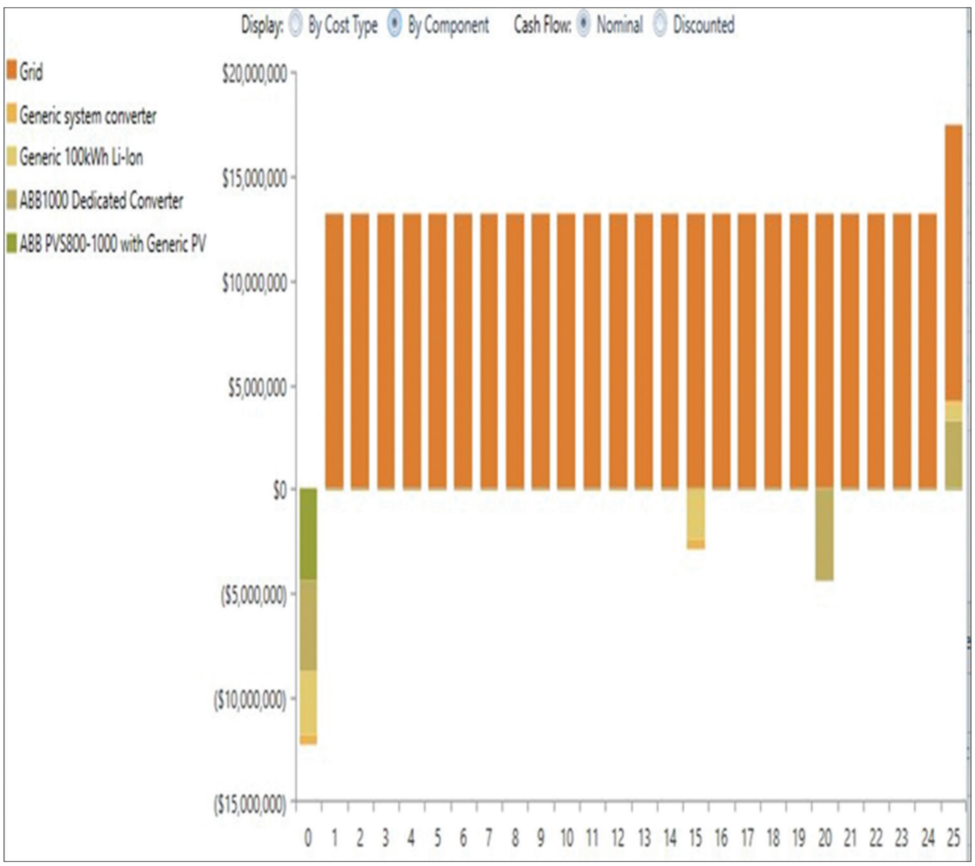


Figure 12: Cash flow (Without generator component)



communities and this provides encouragement and opportunities for the distributed model. With its climate profile, there is significant potential to develop on the solar segment. Botswana's contributes significantly to biomass as well due to its abundant cattle and animal population. This area largely remains untapped, and this profile encourages the use of biomass generators. It is critical to understand that a combination of PV or biomass or diesel can be a successful model for Botswana. The reason that could be is due to poor battery or system performance of PV, in particular on a long overcast day, so installing a hybrid system could aid the development of village electricity profile. HOMER can be used to analyze different combinations of hybrid models and is a beneficial tool to calculate costs and in the planning of micro grids or distributed grids. With proper planning and sizing, it is possible to provide electricity to the deprived community in Botswana.

Figure 13: Cash flow (With generator component)

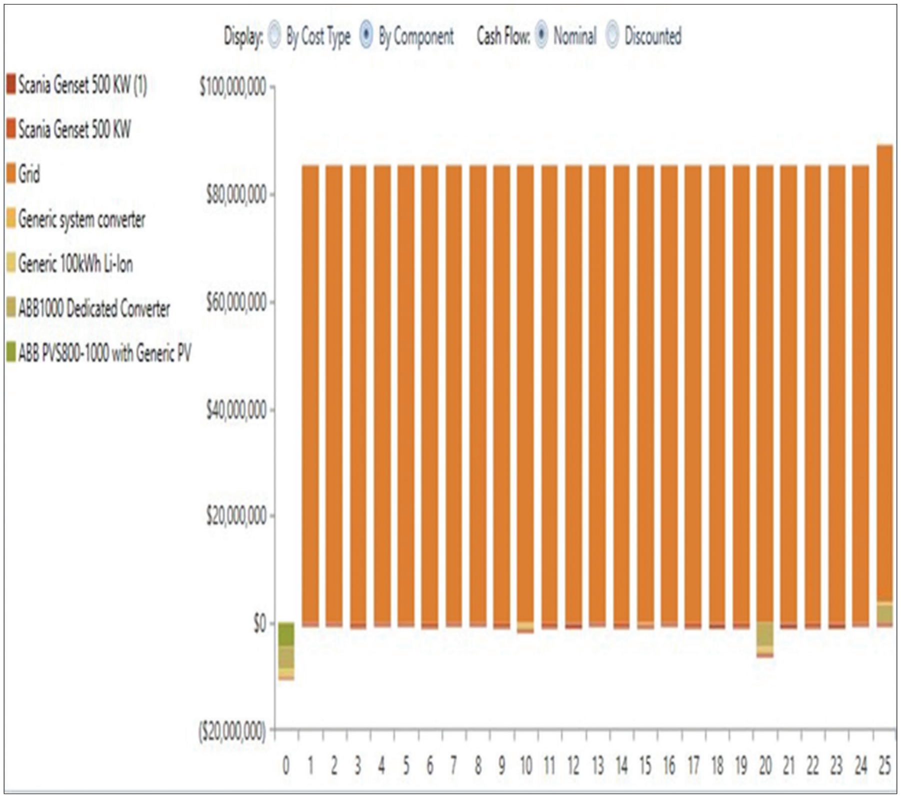


Table 5: Annualized cash flow

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
Model 1 (generator+PV)						
ABB PVS800-1000 with generic PV	$184,708.44	$0.00	$15,000.00	$0.00	$0.00	$199,708.44
ABB1000 dedicated converter	$184,708.44	$171,386.09	$15,000.00	$0.00	$126,156.33	$244,938.20
Generic 100kWh Li-Ion	$58,770.87	$88,941.62	$100.00	$0.00	$20,829.78	$126,982.71
Generic system converter	$4,502.09	$4,256.29	$0.00	$0.00	$1,366.64	$7,391.74
Grid	$0.00	$0.00	$85,288,058.40	$0.00	$0.00	$85,288,058.40
Scania Genset 500 kW	$3,568.23	$30,543.00	$83,385.00	$310,452.28	$2,388.37	$425,560.14
Scania Genset 500 kW (1)	$3,568.23	$27,205.37	$78,300.00	$303,021.00	$974.84	$411,119.76
System	$439,826.30	$322,332.38	$85,096,273.40	$613,473.28	$151,715.96	$83,872,357.41
Model 2 (PV+grid)						
ABB PVS800-1000 with generic PV	$184,708.44	$0.00	$15,000.00	$0.00	$0.00	$199,708.44
ABB1000 dedicated converter	$184,708.44	$171,386.09	$15,000.00	$0.00	$126,156.33	$244,938.20
Generic 100kWh Li-Ion	$126,357.36	$95,566.83	$215.00	$0.00	$30,685.30	$191,453.90
Generic system converter	$17,264.43	$16,321.83	$0.00	$0.00	$5,240.73	$28,345.53
Grid	$0.00	$0.00	$13,231,941.73	$0.00	$0.00	$13,231,941.73
System	$513,038.68	$283,274.75	$13,201,726.73	$0.00	$162,082.36	$12,567,495.67
Model 3 (PV)						
ABB PVS800-1000 with generic PV	$4,400,000.00	$0.00	$357,319.89	$0.00	$0.00	$4,757,319.89
ABB1000 dedicated converter	$4,400,000.00	$4,082,643.99	$357,319.89	$0.00	$3,005,211.09	$5,834,752.79
Generic 100kWh Li-Ion	$2,590,000.00	$1,958,873.44	$4,406.95	$0.00	$628,969.43	$3,924,310.95
Generic system converter	$110,775.00	$104,726.93	$0.00	$0.00	$33,626.49	$181,875.44
System	$11,500,775.00	$6,146,244.36	$719,046.73	$0.00	$3,667,807.01	$14,698,259.08

Table 6: Emissions

Component	Model 1	Model 2	Model 3
	Value Kg/year	Value Kg/year	Value Kg/year
Carbon monoxide	18,494	0	0
Unburned hydrocarbons	982	0	0
Particulate matter	158	0	0
Sulfur dioxide	−7904	−2594	0
Nitrogen oxides	−4595	−1269	0

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APPENDIX

Appendix Table 7: Energy consumed by university during the last 3 years

Utility consumption, energy costs																
Meter reading date	Units consumed	Days between readings	Average daily consumption	Total energy consumption	Average monthly consumption/KWH	Watts/Pm	Watts/day	Maximum demand charge	Electricity charge	Electricity charge/unit	Standing charge	Sub total	VAT @12%	National Standard cost levy	Total	K/F
18-6-2014	425	33	3090.91	102000.03	123400.33	4,25,000	12878.78788	61762.94	43837.35	103.1467059	59.4	105659.69	12679.1628	5100	123438.8528	0.116339149
18-7-2014	391	30	3128	93840	122293.25	3,91,000	13033.33333	61762.94	40330.36	103.1467008	59.4	102152.7	12258.324	4692	119103.024	0.116339155
18-8-2014	448	31	3468.39	107520.09	108218.91	4,48,000	14451.6129	61762.94	46209.72	103.1466964	59.4	108032.06	12963.8472	5376	126371.9072	0.11633916
18-9-2014	552	31	4273.55	132480.05	104065.25	5,52,000	17806.45161	61762.94	56936.98	103.1467029	59.4	118759.32	14251.1184	6624	139634.4384	0.116339153
17-10-2014	638	29	5280	153120	113665.57	6,38,000	22000	70143.06	65807.6	103.1467085	59.4	136010.06	16321.2072	7656	159987.2672	0.116339146
18-11-2014	682	32	5115	163680	121393.55	6,82,000	21312.5	72486.95	70346.05	103.1467009	59.4	142892.4	17147.088	8184	168223.488	0.116339155
18-12-2014	555	30	4440	133200	128498.36	5,55,000	18500	61161.05	57246.42	103.1467027	59.4	118466.87	14216.0244	6660	139342.8944	0.116339153
	527.285714					527285.7143	17140.38368									
16-01-2015	454	29	3757.24	108959.96	131624.38	4,54,000	15655.17241	58128.46	46828.6	103.146696	59.4	105016.46	12601.9752	5448	123066.4352	0.11633916
18-02-2015	719	33	5229.09	172559.97	140946.17	7,19,000	21787.87879	72226.52	74162.48	103.1467038	59.4	146448.4	17573.808	8628	172650.208	0.116339152
18-3-2015	665	28	5700	159600	147781.1	6,65,000	23750	63661.2	68592.56	103.1467068	59.4	132313.16	15877.5792	7980	156170.7392	0.116339148
17-4-2015	552	30	4416	132480	143406.92	5,52,000	18400	64821.62	62583.23	113.3754167	59.4	127464.25	15295.71	6624	149383.96	0.105843051
18-5-2015	570.4	31	4416	136896	139916.42	5,70,400	18400	69293.77	69130.98	121.1973703	59.4	138484.15	16618.098	6844.8	161947.048	0.099012049
18-06-2015	291.6	31	2257.55	69984.05	128579.9	2,91,600	9406.451613	68137.74	35341.15	121.1973594	59.4	103538.29	12424.5948	3499.2	119462.0848	0.099012058
17-07-2015	362	29	2995.86	86879.94	124942.34	3,62,000	12482.75862	68137.74	43873.45	121.1973757	59.4	112070.59	13448.4708	4344	129863.0608	0.099012045
18-08-2015	442	32	3315	106080	114746.27	4,42,000	13812.5	68137.74	53569.24	121.1973756	59.4	121766.38	14611.9656	5304	141682.3456	0.099012045
18-09-2015	626	31	4846.45	150239.95	111347.47	6,26,000	20193.54839	68137.74	75869.56	121.1973802	59.4	144066.7	17288.004	7512	168866.704	0.099012041
16-10-2015	617	28	5288.57	148079.96	115018.12	6,17,000	22035.71429	92278.35	74778.78	121.1973744	59.4	167116.53	20053.9836	7404	194574.5136	0.099012046
18-11-2015	748	33	5440	179520	120845.68	7,48,000	22666.66667	99928.55	90655.64	121.1973797	59.4	190643.59	22877.2308	8976	222496.8208	0.099012042
18-12-2015	645	30	5160	154800	135344.26	6,45,000	21500	85308.18	78172.31	121.1973798	59.4	163539.89	19624.7868	7740	190904.6768	0.099012041
	557.666667	30.41666667	4401.81333	133839.986	129541.5858	557666.6667	18340.8909	73183.13417	64463.17	116.032877	59.4	137705.699	16524.684	6692	160922.383	0.10391307
18-01-2016	580			0		5,80,000	#DIV/0!	85580.18	70294.48	121.1973793	59.4	155934.06	18712.0872	6960	181606.1472	0.099012042
18-02-2016	804	31	6224.52	157389.89		8,04,000	25935.48387	83336.12	97442.69	121.1973756	59.4	180838.21	21700.5852	9648	212186.7952	0.099012045
18-03-2016	792	29	6554.48	190079.92	165509.06	7,92,000	27310.34483	98908.52	95988.32	121.1973737	59.4	194956.24	23394.7488	9504	227854.9888	0.099012046
18-04-2016	575	31	4451.61	137999.91	161192.87	5,75,000	18548.3871	79942.84	69688.49	121.1973739	59.4	149690.73	17962.8876	6900	174553.6176	0.099012046
18-05-2016	521	30	4168	125040		5,21,000	17366.66667	79942.84	63143.83	121.1973704	59.4	143146.07	17177.5284	6252	166575.5984	0.099012049
18-06-2016	361	31	2794.84	86640.04	142937.71	3,61,000	11645.16129	79942.84	43752.25	121.1973684	59.4	123754.49	14850.5388	4332	142937.0288	0.099012051
17-07-2016	362	29	2995.86	86879.94	124942.34	3,62,000	12482.75862	68137.74	43873.45	121.1973757	59.4	112070.59	13448.4708	4344	129863.0608	0.099012045
18-08-2016	425	34	3000	102000	120474.47	4,25,000	12500	79942.84	51508.88	121.1973647	59.4	131511.12	15781.3344	5100	152392.4544	0.099012054
18-09-2016	626	31	4846.45	150239.95	111347.47	6,26,000	20193.54839	68137.74	75869.56	121.1973802	59.4	144066.7	17288.004	7512	168866.704	0.099012041
16-10-2016	617	28	5288.57	148079.96	115018.12	6,17,000	22035.71429	92278.35	74778.78	121.1973744	59.4	167116.53	20053.9836	7404	194574.5136	0.099012046
18-11-2016	748	33	5440	179520	120845.68	7,48,000	22666.66667	99928.55	90655.64	121.1973797	59.4	190643.59	22877.2308	8976	222496.8208	0.099012042
18-12-2016	645	30	5160	154800	135344.26	6,45,000	21500	85308.18	78172.31	121.1973798	59.4	163539.89	19624.7868	7740	190904.6768	0.099012041
	588					5,88,000	17574.83561									
18-02-2017	624	31	4830.97	149760.07	128613.38	6,24,000	20129.03226	81126.07	75627.16	121.1973718	59.4	156812.63	18817.5156	7488	183118.1456	0.099012048
21-3-2017	440	28	4830.97	128875.62	128613.38	4,40,000	15714.28571	79126.82	53326.84	121.1973636	59.4	132513.06	15901.5672	5280	153694.6272	0.099012055
25-04-2017	574	31	4830.97	129303.13	128613.38	5,74,000	18516.12903	80448.24	74818.51	130.3458362	63.88	155330.63	18639.6756	6888	180858.3056	0.09206278
22-05-2017	377	31	4830.97	129303.13	128613.38	3,77,000	12161.29032	84526.16	51631.29	136.9530239	67.12	136224.57	16346.9484	4524	157095.5184	0.087621285
	503.75					5,03,750	16630.18433									

Appendix Table 8: Hourly load profile in KW

Hourly load profile											
Janruary	**Febuary**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**
10	11	11	10	10.3	7	7	8	8.5	10	10	9
10	11	11	10	10.3	7	7	8	8.5	10	10	9
10	11	11	10	10.3	7	7	8	8.5	10	10	9
10	11	11	10	10.3	7	7	8	8.5	10	10	9
10	11	11	10	10.3	7	7	8	10	10	10	9
10	13.5	16.63	13.5	13.5	10.63	10.31	11.31	13.5	17.3	19.3	19.3
17	18.5	22.5	18.5	18.5	11.89	12.43	13.46	19.32	22.5	24.12	24.12
19	25.5	29.82	23.3	23.3	12.45	16.76	17.32	26.31	27.32	28.7	26.13
15	43.2	37.79	27.4	27.4	12.36	20.64	21.38	41.2	34.01	37.09	34.76
25	45.5	49.32	32.1	32.1	12.8	23.31	25.31	44.21	41.32	43.36	38.16
32.5	56.5	55.5	33.4	33.4	12.91	27.27	29.78	44.89	45.67	44.07	43.12
32.5	56.6	53.3	34.1	34.1	12.78	25.19	25.19	44.56	47.18	48.13	47.17
30.5	30.5	45.3	34.6	34.6	11.7	21.2	23.21	39.12	44.67	45.01	43.78
17.5	24.3	38.4	30.3	30.3	11.3	17.5	21.67	27.8	39.31	38.19	41.13
18	25.6	32.28	24.3	24.3	11.2	15.1	17.87	25.52	33.98	34.98	35.87
18.5	19.45	27.31	19.3	19.3	9.8	12.2	14.56	20.45	26.53	24.36	24.41
17.5	21.5	21.45	18.6	18.6	9.12	10.1	11.28	19.6	20.45	22.37	22.18
17	19.63	16	17.7	16.3	8.79	9.6	10.65	18.79	14.41	16.66	14.76
10	13	13.56	16.2	13	8	7.98	8.67	12.95	13.45	15.98	13.11
10	11	12	10	10.3	7	7	8	8.5	10.8	11.13	8.91
10	11	11	10	10.3	7	7	8	8.5	10	10	9
10	11	11	10	10.3	7	7	8	8.5	10	10	9
10	11	11	10	10.3	7	7	8	8.5	10	10	9
10	11	11	10	10.3	7	7	8	8.5	10	10	9
15.83333	21.80333	23.75667	18.47083	18.40417	9.405417	12.48292	13.81917	20.19667	22.0375	22.64375	21.57958

Appendix Table 9: Review of optimization methods and algorithms used in power sector

Optimization algorithm	Objectives	Title	Publication reference
Modified additive increase multiplicative decrease algorithm	Optimize cost of generation with application to a virtual power plant - additive increase and multiplicative Decrease algorithm, which is already used for optimization in microgrids is improved further and is presented as modified Additive increase multiplicative decrease algorithm and is applied in the second stage of the algorithm for optimization	A two stage increase-decrease algorithm to optimize distributed generation in a virtual power plant	Kumar (2015)
HOMER	Micro-grid model in optimizing the utilization of local renewable energy for on-grid area	Renewable energy sources optimization: a micro-grid model design	Nazir et al. (2014)
Nonlinear mixed-integer programming; inter-temporal constraints and is solved by the fruit fly algorithm	The optimal dispatch strategy of a virtual power plant, based on a unified electricity market combining day-ahead trading with real-time trading	Optimal dispatch strategy of a virtual power plant containing battery switch stations in a unified electricity market	Hao et al. (2015)
Meta-heuristic algorithms hill climber and GRASP	Optimal dispatch strategy for VPP	Heuristic optimization for the discrete virtual power plant dispatch problem	Petersen et al. (2014)
MILP; GAMS	In order to reduce the CO_2 emissions by 50% from current CO_2 emission level, the optimizer selected a scheme which includes IGCC, NGCC, nuclear and biomass from landfill gas and palm oil residues	Optimal planning of renewable energy-integrated electricity generation schemes with CO_2 reduction target	Muis et al. (2010)
Multi-objective (NSGA-II)	Optimization problem is solved using the NSGA-II	Operation optimization of standalone microgrids considering lifetime characteristics of battery energy storage system	Zhao (2013)
PSO	Locate the optimal number of system devices and the optimal values of the PV module installation details, such that the total net economic benefit achieved during the system operational lifetime period is maximized	Contribution for optimal sizing of grid-connected PV-systems using PSO	Aris and Yannis, 2010
PSO and fuzzy logic (two stage optimization)	Improving the forecasting effectiveness of electricity price from the perspective of reducing the volatility of data with satisfactory accuracy	A hybrid multi-step model for forecasting day-ahead electricity price based on optimization, fuzzy logic and model selection	Ping et al. (2016)
ANN	Find the market price for a given period, with a certain confidence level	Forecasting electricity prices with historical statistical information using neural networks and clustering techniques	Filipe and Zita (2006)
ANN - EBFO	To optimize and set the MPF parameters to enhance and tune the micro grid dynamic response	Enhanced microgrid dynamic performance using a modulated power filter based on enhanced bacterial foraging optimization	Ahmed and Hossam (2017)
ANN	Intraday session models for price forecasts (ISMPF models) for hourly price forecasting in the six intraday sessions of the Iberian electricity market (MIBEL) and the analysis of MAPEs obtained with suitable combinations of their input variables in order to find the best ISMPF models	Short-term price forecasting models based on artificial neural networks for intraday sessions in the Iberian electricity market	Claudio et al. (2016)
Stochastic programming	Day ahead electricity market prices -forecasting of the electricity price through ARIMA models; and construction of a portfolio of ARIMA models per hour using stochastic programming	Portfolio decision of short-term electricity forecasted prices through stochastic programming	Sánchez and de la Nieta (2016)

GRASP: Greedy randomized adaptive search procedure, GAMS: General algebraic modeling system, NSGA: Non-dominated sorting genetic algorithm, EBFO: Enhanced bacterial foraging optimization, MAPEs: Mean absolute percentage errors, ARIMA: Autoregressive integrated moving average, PSO: Particle swarm optimization