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# Design of a Sustainable Energy System for an Eco-Village: A Case Study of Bulindo Village

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***Authors' contributions***

*This work was carried out by collaboration between all authors. Author TM initiated the idea, developed it, selected the materials and methods for the study and participated in writing the manuscript. Authors SBK and AS assisted in providing information sources, data collection as well as giving technical guidance during the study. Author JBK assisted in the development of the manuscript as well as English revision of the final draft. All the authors read and approved the final manuscript.*

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## ABSTRACT

**Aims:** To plan and design Bulindo eco village to accommodate 10,000 residents with the main emphasis on the sustainable energy system that meets the energy demand under available constraints i.e. maximum annual capacity shortage, allowable emissions, operating reserve and the minimum renewable energy fraction
**Study Design:** The planning and design was accomplished by ascertaining the current state of Bulindo village as well as determining the energy requirements of this village and the available resource potential in the area. Using the above data as input to computer simulation model using HOMER software an energy system configuration that meets the energy demand for this village

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was obtained.
**Place and Duration of Study:** The study was done in the School of Engineering under the College of Engineering, Design, Art and Technology of Makerere University, Kampala-Uganda from January 2013 to May 2013.
**Methodology:** After gathering the relevant information for the study i.e. energy demand of the village using a field survey and the primary energy resource potential at Bulindo got from a climate file for Wakiso district provided by Meteonorm software, HOMER was used to model, simulate and optimize the energy system that meets the energy requirements of the village under available constraints. HOMER also assisted in determining both the technical and economic feasibility of the designed system.
**Results:** From computer modeling and simulation, it was found that Bulindo has an overall electrical energy demand of 49 MWh/day. The demand is maximum from 18:00-22:00hrs with a peak of 4.6 MW. The fresh water supply system for the village which was modeled as a deferrable load had an energy demand of 680 kWh/day. The demand is highest during the dry season i.e. from January to March and from June to September with a peak demand of 170 kW. The designed energy system consisted of a PV array, a wind generator, the grid, battery bank, a converter and a biomass generator which acts as backup. This system can meet up to 95% of the annual energy demand while the remaining 5% will be supplied by the national grid. The unit cost of the electricity is $0.028 and the project life is 50 years.
**Conclusion:** The sustainable energy system for Bulindo eco village to be moved in by 2025 has been designed. The designed system is believed to offer a better performance due to its sustainability as well as its ability to meet all the energy requirements of the village i.e. both energy and fresh water demand. Simulation results demonstrate that using green energy sources such as solar PV and wind generators will reduce the operating costs, greenhouse gas emissions and particulate matter. In addition, the system also supplies fresh water for residential, commercial and industrial usage. The amount of energy produced by the system is 63,658,616 kWh/year at a unit cost of $0.028 /kWh. 76% of the generated energy is consumed by the system i.e. AC primary load and the deferrable load while the surplus (24%) is sold to the national grid which earns crucial revenue to the village for better management of the system hence guaranteeing sustainability. However, the challenge will be getting the human resource to maintain and manage this system.

*Keywords: Design; sustainable; energy system; eco village; Bulindo.*

## ABBREVIATIONS

*HOMER: Hybrid Optimization Model for Electric Renewables; PV: Photovoltaic; AC: Alternating Current; DC: Direct Current; NWSC: National Water and Sewerage Corporation; NEMA: National Environment Management Authority; KCCA: Kampala Capital City Authority; KTC: Kira Town Council; MEMD: Ministry of Energy and Mineral Development; GIS: Geographical Information Systems; GPS: Global Positioning System, NPV: Net Present Value; NOMA: Norwegian Programme for Master Studies; TV: Television UAE: United Arab Emirates.*

## 1. INTRODUCTION

Urbanization began with the Industrial Revolution in the 18$^{th}$ century, and has only been on the rise since then. It is believed that half of the world's population lives in urban areas, and this is expected to increase to 60% by 2030 [1]. Cities have lured people for various reasons, the basic one being the hope for a better life. People are drawn to the cities for the comforts they offer, the opportunities they hold and the sleek lifestyle they promise. While cities occupy only 2% of the world's land mass, they account for 75% of the energy consumption and are responsible for emitting 80% of the greenhouse gases [2,3,4].

An eco-city is an ecosystem where ecologically healthy human settlements are modeled on self-sustaining resilient structures and function of natural eco-systems and living organisms. An eco-city builds on the synergy and interdependence of ecological and economic sustainability as well as their fundamental ability to reinforce each other in an urban context. This is demonstrated through the ability to enhance resource efficiency while simultaneously reducing pollution and unnecessary waste and by so doing, improving the quality of life of their citizens, enhance their economic competitiveness and resilience, strengthen their fiscal capacity and create an enduring culture of sustainability [5].

Uganda has one of the fastest growing populations and the rate of urbanization is also on the increase. Approximately, 13.1% of the population lives in urban areas and this is also on the increase [6]. This increase in urbanization has put pressure on available services such as municipal solid waste management, increased demand for health care, water supply and energy. The demand for electricity has been increasing at an average rate of 8% since 2007 and this is expected to increase with the current levels of industrialization and urbanization [7]. Currently, the energy demand is being met by thermal and hydropower plants. In 2005, the country experienced an energy crisis that led to the introduction of thermal power in the energy mix. This on top of being environmentally unfriendly has also led to almost double the power tariffs [8].

Kampala, the capital city is located on the northern shores of Lake Victoria and covers an area of 195 $km^2$. Situated at an average altitude of 1120 m above sea level it sits on 24 low flat topped hills that are surrounded by wetland valleys. The city 'region' of Kampala covers an estimated land area of 1895 $km^2$ engulfing the satellite towns of Entebbe, Bombo, Wakiso, Mukono, Lugazi and Gayaza. As a rapidly expanding city, Kampala is beset by growing social, economic and environmental challenges that largely affect the poor urban population. The urban poor live in the most risk prone valley bottom areas of the city faced with flooding, poor sanitation and water borne diseases due to accumulation of municipal solid waste among others. Unconventional methods of waste disposal which include pits within the backyard where it is regularly burnt, collection of the waste in polythene bags and dumping it in streams, water drainage channels, roadsides and unattended plots have emerged [9,10]. This has led to blockage of water drainage channels and streams, causing flooding in the low lying areas during the rainy season, unpleasant odors and loss of recreation potential as well as ecological services of regulation and provisioning.

Kampala generates an estimated 30,000 tons of waste per month, with a composition of food and yard waste 90.64, paper 1.67%, plastic 1.77%, metals 0.15%, glass and porcelain 1.16%, textiles and miscellaneous 1.03% [11]. The average per capita solid waste generation rate is 0.6kg/per person/per day with a high organic content. Solid waste management therefore is one of the serious problems in Kampala that has undermined the Authority's capacity for proper management and efficient disposal [12]. Huge amounts of municipal solid waste is generated most of which is never collected and disposed of properly. The city generates about 1200 tons of this waste daily but only 40% is collected and land filled with no energy recovery with the rest either burnt or left to decay posing a danger to the environment and health [7,12]. In order to meet the energy demand and future needs of Kampala in a sustainable and low cost manner, there is need to explore the different renewable energy options available in the country as stipulated in the country's energy policy.

This study sought to turn some of the burdens into livelihood benefits through profitable waste management, and contributing to poor policy reforms that promote shared visions for sustainable urban development. The study aimed at expanding Kampala city to a new part called Bulindo eco village ready to move in by 2025. It is within this area that a number of sustainability factors have to be met including sustainable urban functions, ecological environment, energy utilization, water resources management, solid waste disposal, green traffic and building design. The new town district has been planned for 10,000 residents of which 25% work inside the system. However, the biggest challenge will be energy use minimization while maintaining or improving the service level of society.

Bulindo village is a neighborhood in Kira municipality in Wakiso district. Bulindo is bordered by Nakweero to the north, Kitukutwe to the northeast, Kigulu to the east, Malawa to the south, Kitikifumba to the southwest and Kazinga to the west. This location lies approximately 21 km by road, northeast of Kampala city center. The coordinates of Bulindo are (Latitude: 0.42500, Longitude: 32.645833). Bulindo was a residential and farming village and in 2001, a law was passed incorporating the village into Kira municipality which is the second largest urban center in Uganda with an estimated population of about 180,000 in 2011. During the 21st century, Bulindo has developed into a middle class residential neighborhood with planned housing developments, large private farms and ranches.

Bulindo is connected to the national grid and to the water pipeline of NWSC.

## 2. MATERIALS, INSTRUMENTATION AND METHODS

### 2.1 Materials

The materials used in the study included; a questionnaire for collecting data about the energy demand for the system as well as the present land use type in the system, GIS used to determine the present land use and contour map of the system; Meteonorm software used to provide information about the primary energy sources and HOMER software used for modeling, simulation and optimization of the energy system.

### 2.2 Instrumentation

#### 2.2.1 Global positioning system

A GPS was used to determine the coordinates of Bulindo village as well as getting the elevation data within the system which data was used to come up with the map showing the present land use in the system and a contour map for Bulindo village using GIS software.

### 2.3 Methods

#### 2.3.1 Information sources

Information related to the project was collected from various sources such as the internet, relevant textbooks and brochures. The relevant authorities like KCCA, KTC, NEMA, MEMD and NWSC among others were consulted as well.

#### 2.3.2 Detailed load and resource assessment at Bulindo

First and foremost, there was need to define the system boundaries showing exchange of energy between the system and its surroundings; the main system coincides with the boundaries of Bulindo village. The system has been defined to cater for tourists and residents whose number is expected to be 10,000 by 2025 while putting into consideration the general economic growth of the village and variations in energy demand over the year. The system also considered the travel of people to or from the village, energy generated and used in the system as well as energy imported and exported. The average energy consumption per household in the eco-village was obtained through a field survey in Bulindo with the help of a questionnaire. Also, information was obtained from the authorities like KCCA and KTC and the energy requirement took into consideration both electrical and thermal energy. The system has several primary energy resources that can be harnessed i.e. solar with an average insolation of 5.426 kWh/m$^2$/day, wind with an average wind speed of 4.06m/s and biomass with an average tonnage of 27.67 tons/day. The choice of the energy resource to be used depended on the technical and economic feasibility. A detailed assessment of the energy potential at the proposed site was carried out with the help of climatic data for the area provided by the climate file for Wakiso district downloaded from Meteonorm software. The data used in the design included; average wind speed, solar insolation and available biomass. Also, the population at the proposed site and the different economic activities carried out were ascertained in order to determine the power requirement at this site. From literature, although the average energy requirement per capita is 0.24 kW [13], a field survey using a questionnaire was used to provide a realistic forecast for the energy demand as shown in Table 1.

Since the eco-village is to be planned for 10,000 residents, this translates into an average energy demand of 49MWh/day with a peak of 4.6 MW. In order to provide fresh water supply for the village, a water pumping system is to be installed as a deferrable load. This system should be able to supply 1000 m$^3$/day of fresh water while operating for 8 hours a day. Such a system would require 680 kWh/day of energy with storage of 2 days giving a storage capacity of 1360 kWh and a peak demand of 85 kW.

The transportation system was subdivided into two, i.e., transport while in the city and transport to and from the city. Emissions from a person moving in and out of the city were assumed to be shared by the system and its environment making the analysis to be based on a single route i.e. to or from the eco-city. Transport to or from the eco-city was incorporated in the analysis for transport while in the city. For transport across the system boundary, there is no air and water travel. The only acceptable means of transport across the system boundary is road and this will be used mainly by commuters and visitors. To abate $CO_2$ emissions in the transport sector, there will be need for intervention measures in form of more efficient fuel engines as well as emissions penalties. It was therefore considered to be an environment to the system since it has an effect on the system but little can be done to counteract it. There should be buses moving around the city to transport commuters and visitors. The sector should be public with the road network designed to accommodate pedestrians, cyclists and public transport. Fig. 1 shows a summary of the proposed energy production and usage system for Bulindo village.

#### 2.3.3 Development, simulation and optimization of a computer model of the energy system for Bulindo eco-village

After establishing the energy use for the eco-village with regard to the population, transportation, industrial activities, etc., a model that was able to calculate the demand for energy carriers for all activities on an hourly basis was developed. From a field survey, energy consumption per household was ascertained and the energy demand for the rest of the activities was established by emphasizing use of renewable energies, energy efficient technologies as well as conservation of energy. After determining the average energy requirement for the village and using the climatic file for Wakiso, HOMER software was used to simulate the energy production and usage system for Bulindo.

During modeling and optimization of the energy system for Bulindo village, the task was complicated by the sporadic nature of the renewable energy supplies, load demand, non-linearity of the system components and the interdependency of the sizing and operational strategies. This therefore called for optimization of the system with an objective of minimizing the lifecycle cost while guaranteeing a reliable system operation. As component sizes and operation are interdependent, different sets of component configuration were analyzed for each hybrid combination to obtain an optimal hybrid system.

Numerical iterative algorithm was used for unit sizing of the hybrid energy system, which minimized the capital cost for $2^n$-1 combination of renewable sources. Timely availability of energy sources, load demand and supply balance as well as minimum and maximum operating limits of the units were the major constraints. Since the energy density of a wind turbine is greater than for the other sources, the number of wind turbines is fixed as one and the number of PV modules and biomass generators incremented until the system is balanced; the optimal operating strategy and annual lifecycle costs of this configuration was determined. These steps were then repeated with the number of PV modules in incremental steps. In a similar manner, the whole procedure was repeated for all the combinations and the best combination based on lowest cost, minimal use of generator and service reliability was selected as the optimal one. The battery bank is sized with a capacity equal to the difference between positive and negative peaks of the energy curve. The unit sizing of this system was to minimize the total capital cost $C_c$ given by;

$$C_C = \sum_{s=1}^{N_s} C_s + \sum_{w=1}^{N_w} C_w + \sum_{g=1}^{N_g} C_g + \sum_{b=1}^{N_b} C_b \quad \text{…. (1)}$$

Where $N_s$, $N_w$, $N_g$ and $N_b$ are the total number of solar, wind, biomass generators and battery units respectively and $C_s$, $C_w$, $C_g$ and $C_b$ are the corresponding capital costs.

The wind turbine power output is given by;

$$P_w = \eta_t.\eta_g.0.5.\rho_a.C_p.A.V^3 \quad \text{………………….. (2)}$$

Where V is the wind velocity, $\rho_a$, the air density, $C_p$ the power coefficient of the wind turbine and A the swept area of the rotor, $\eta_t$ and $\eta_g$ are the wind turbine and wind generator efficiencies respectively.

The output power of a solar PV array per hour is given by;

$$P_{pv} = \eta_{pv}.N_{pvs}.N_{pvp}.V_{pv}.I_{pv} \quad \text{…………………. (3)}$$

Where $\eta_{pv}$ is the conversion efficiency of a PV module, $V_{pv}$ is the module operating voltage, $I_{pv}$ the module operating current, $N_{pvp}$, $N_{pvs}$, the number of parallel and series solar cells respectively. The biomass generator and battery model were important to ensure supply continuity and energy storage respectively. In a given interval, the rate of fuel F consumed by the generator delivering the power P is generally expressed as;

$$F = aP^2 + bP + C \quad \text{………………...(4)}$$

**Table 1. Summary of the electric energy demand by load**

| Load | Number per household | Rating (kW) | Time of use(h) | Consumption(kWh) |
|---|---|---|---|---|
| Computer | 2 | 0.05 | 5 | 0.50 |
| Cooker | 1 | 10.00 | 4 | 40.00 |
| Electric kettle | 1 | 2.00 | 0.5 | 1.00 |
| Home theater | 1 | 0.30 | 3 | 0.90 |
| Iron | 1 | 1.20 | 0.5 | 0.60 |
| Lights | 13 | 0.06 | 6 | 4.68 |
| Refrigerator | 1 | 0.50 | 8 | 4.00 |
| Toaster | 1 | 0.80 | 0.2 | 0.16 |
| TV | 1 | 0.15 | 8 | 1.20 |
| Vacuum cleaner | 1 | 0.50 | 0.25 | 0.125 |
| Washing machine | 1 | 0.50 | 1 | 0.50 |
| **Total** | | | | **53.665** |

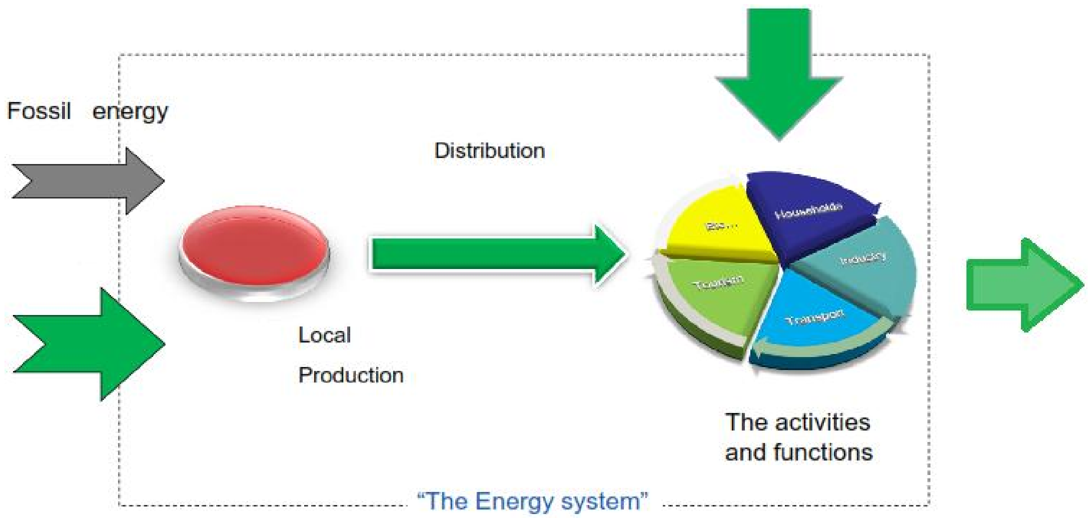


**Fig. 1. The energy system for Bulindo**

Where a, b and c are coefficients of the generator as given by the manufacturer's data.

The state of charge of the battery can be calculated from the following equations;

Battery discharging;

$$P_b(t) = P_b(t-1).(1-\sigma) - [P_h(t)/\eta_i - P_l(t)] \quad (5)$$

Battery charging;

$$P_b(t) = P_b(t-1).(1-\sigma) + [P_h(t) - P_l(t)/\eta_i].\eta_b \quad (6)$$

Where $P_b$(t-1) and $P_b$(t) are the battery energy at the beginning and end of interval t respectively, $P_l$(t) is the load demand at the time t, $P_h$(t) is the total energy generated by the system at time t, σ the self-discharge factor and $\eta_b$, $\eta_i$ the battery charging and inverter efficiency respectively as obtained from the manufacturer. As a recommended practice to ensure sufficient lifetime, batteries are cycled between a minimum and maximum level of rated capacity. The grid was not modeled since it was considered external to the system. The power generated by the system at any time is given by;

$$P(t) = \sum_{s=1}^{N_s} P_s + \sum_{w=1}^{N_w} P_w + \sum_{g=1}^{N_g} P_g \quad (7)$$

Optimal dispatch strategy of a hybrid system is to obtain the most economical schedule for different combinations of renewable generators with a generator and battery as back up to the system that satisfies load balance, resource availability and equipment constraints. The dispatch strategy was such that the battery charges if the energy generated by the renewable generators is in excess and discharges if the load exceeds the renewable energy being generated. The biomass generator and the grid serve as a part of the system that responds to emergency conditions where renewable generation and stored energy are insufficient to meet the load requirements. The optimal operation strategy for a solar/wind combination so as to minimize the annual operating cost $C_o$ computed basing on the operating cost for the interval t in a day are as below;

$$C_{ot} = \sum_{i=1}^{365} \left\{ \sum_{t=1}^{24} (C_{og}(t) + C_{ow}(t) + C_{os}(t) + C_{ob}(t)) \right\} \quad (8)$$

Subjected to the constraints expressed in equations 2-6. $C_{og}$ (t), $C_{ow}$ (t), $C_{os}$ (t) and $C_{ob}$ (t) are the operational costs of the solar PV, wind turbine, generator and battery units for the hourly interval t (t=1-24) respectively. The operational costs were calculated on the basis of component characteristics, size and efficiency. The total annualized lifecycle cost of the system incorporating components of both capital and operating costs is given by;

$$C_{an} = \left[ C_c.CRF + C_{ot} \right] \quad (9)$$

The unit cost of energy by the system is given by;

$$C_{oe} = \frac{C_{an}}{E_l} \quad (10)$$

Where $E_l$ is the load served (kWh/yr) and CRF is the capital recovery factor for the system with expected discount rate.

From the simulated model, the maximum electrical capacity needed was determined. This was followed by selection of energy sources for internal use, energy carriers flowing over the system boundary, the need for storage so that peak demand can be met, estimating the cost of energy services within the system as well as determining the best location for co-generation, wind and solar basing on prevailing wind direction and topography. This was followed by suggesting an organizational form for the energy business to implement the changes and run the new system. The economic analysis was performed by HOMER software using the NPV criteria. The optimization algorithm for the energy system of Bulindo village is as shown in Fig. 2.

## 3. RESULTS AND DISCUSSION

### 3.1 Detailed Load and Resource Assessment of Bulindo Village

#### 3.1.1 Load assessment

The energy consumption per household of the eco village was ascertained through a field survey of Bulindo .It was estimated that Bulindo eco-village has an overall energy demand of 49 MWh per day resulting into 490 GWh per annum. Figs. 3-6 show the daily, monthly and seasonal electrical energy demand variation for the eco-village as well as the monthly deferrable load respectively;

According to the models developed, the peak capacity was estimated at 170 kW for the deferrable load and 4.6 MW for electricity.

From Figs. 3-6, it can be seen that during early morning hours i.e. 00:00 to 06:00 hrs, there is less energy demand as most of the residents are asleep. The only demand for electricity will be in form of street lighting and outdoor security lighting at homes. Between 06:00 and 09:00 hrs, energy demand is high as most workers and school going children are awake and preparing to go to their workplaces and schools respectively. This is because, during this period, both outdoor and street lights are being switched off but more energy consuming devices such as water heaters, cookers, electric kettles, electric irons, radios and TV sets are being switched on.

Between 09:00 and 12:00hrs, there is a slight drop in demand as most people have left their homes for work and school and the major contribution to the energy demand is the commercial and industrial sector. Between 12:00 and 15:00hrs, the electrical demand increases as school going children are back home (kindergarten and lower primary level) and will start using electronic gadgets such as TV and computers for entertainment. Also, this is the time when homesteads are preparing their lunch using heating devices like electric cookers and electric kettles. From 15:00 to 18:00 hrs, there is a decrease in the electricity demand as most homes have finished having their lunch and are taking a rest; most of the energy demand is attributed to the commercial and industrial sector.

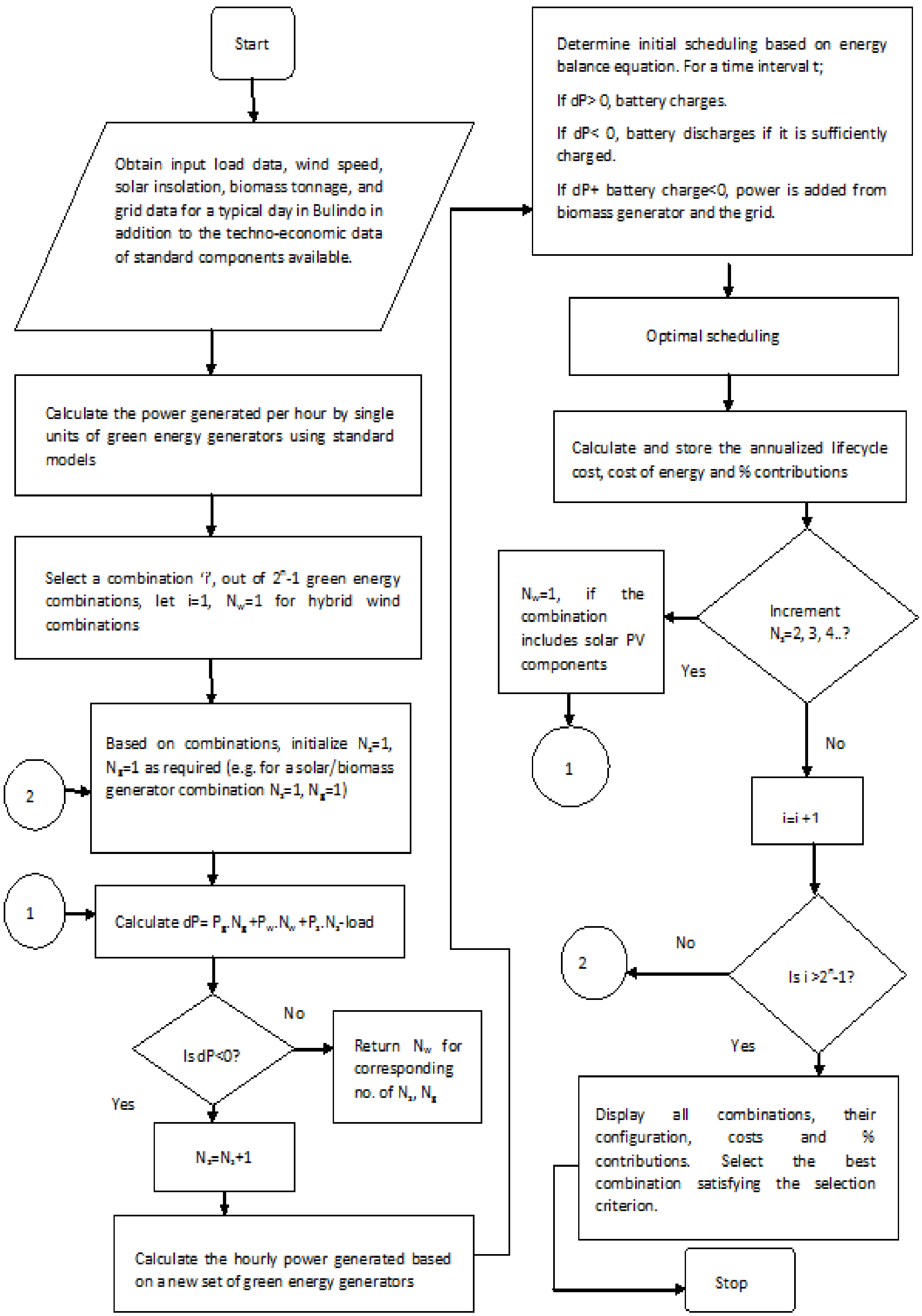


**Fig. 2. Optimization algorithm for the energy system**

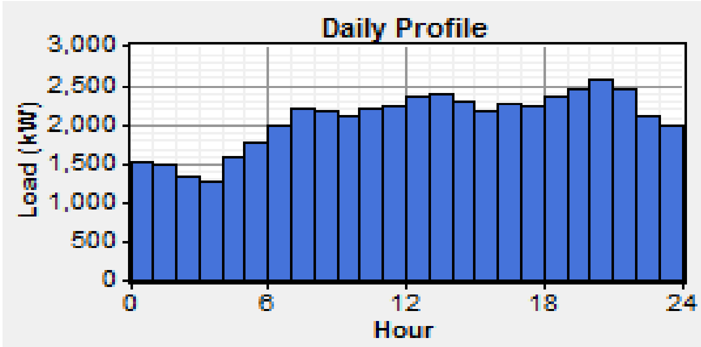


**Fig. 3. Daily load profile for Bulindo eco village**

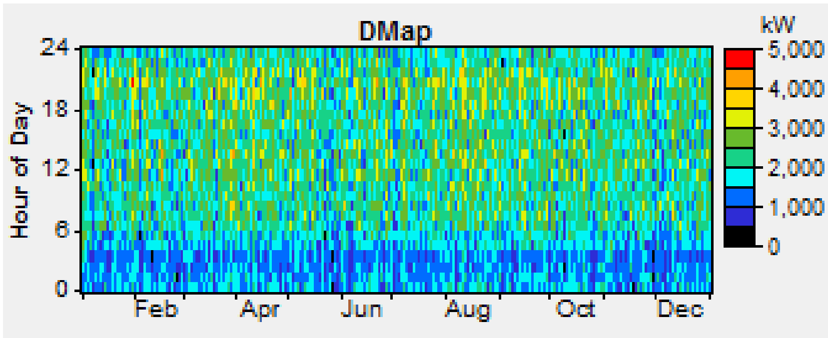


**Fig. 4. Variation of hourly load profile throughout the year**

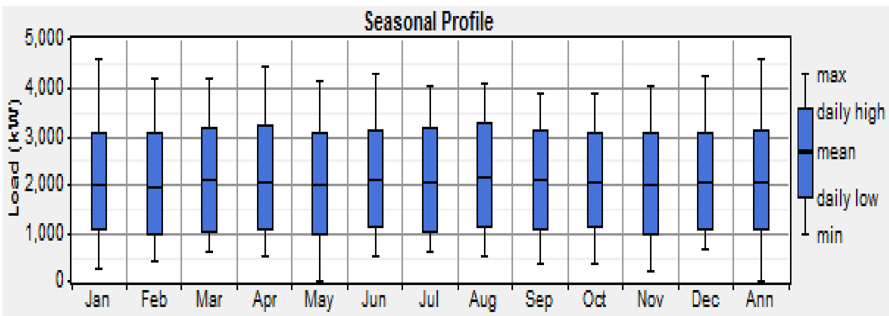


**Fig. 5. Monthly variation of seasonal load profile**

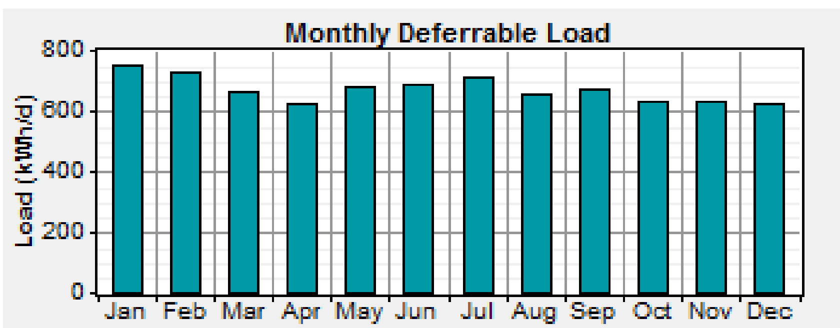


**Fig. 6. Monthly variation of the deferrable load**

The energy demand is highest from 18:00 to 22:00hrs because during this time, school going children (upper primary, high school and University) as well as workers have left for their homes and both indoor and outdoor lights are being switched on, electronic equipment and appliances are being used for entertainment and preparation of dinner. The demand reduces significantly after 22:00 hrs as residents have finished having dinner and are switching off their indoor lights and appliances to start going to bed.

On the other hand, the deferrable load (water supply system) consumes most energy during the dry season i.e. January to March and June to September. This is because during this period, there is no harvesting of rain water and the village is relying entirely on piped water that has to be pumped. The demand is lowest during the wet seasons as homes now supplement piped water with what has been harnessed from their roofs. The harvested rain water can be used for bathing, laundry, car washing, cooking and dish washing.

#### 3.1.2 Resource assessment

The eco village has various energy resources that can be harnessed. These resources include solar, wind and biomass. The choice of the energy resource to be used depended on the technical and economic feasibility. Below is the available resource potential for the eco village;

*3.1.2.1 Solar resource*

The average solar insolation for Bulindo village is 5.426 kWh/m$^2$/day. This translates to an average clearness index of 0.542. It can be seen from the insolation data that February is the month with the highest insolation while December has the least insolation. The annual variation of solar insolation is as shown in Fig. 7.

*3.1.2.2 Wind resource*

The average wind speed for the village is 4.06 m/s. Which is slightly lower than the 6 m/s considered being the speed that defines a good wind site. The wind speed is maximum in the month of February and lowest in December. The relatively low wind speeds mean that the village has a limited potential for wind power generation. The variation of wind speed throughout the year is as shown in Fig. 8.

*3.1.2.3 Biomass resource*

The average daily tonnage for biomass resource at Bulindo village is 27.676 tons/day. March is the month with the highest biomass resource availability while July has the least resource availability. This can be attributed to the fact that human metabolism increases with a decrease in ambient temperature and reduces with an increase in ambient temperature. The biomass resource variation throughout the year is as shown in the Fig. 9.

### 3.2 Development, Simulation and optimization a Computer Model of the Energy System for Bulindo Eco-Village

To design a hybrid energy system for Bulindo eco-village, there was need to provide some data such as the load profile that should be met by the system, solar radiation, wind speed, capital cost of each component in the system, annual interest rate and project lifetime. HOMER software was used to model, simulate and optimize the performance of the system as well as its configuration. The average daily solar radiation for Bulindo village is 5.26 kWh/m$^2$/day, the average monthly wind speed is 4.06 m/s and the average daily tonnage for biomass is 27.7 tons/ day. The capital cost for the wind turbine is $200,000, the PV array costs $300,000, the battery costs $200,000, the converter costs $100,000, and the biogas generator costs $200,000 while the cost of energy from the national grid is $0.10 /kWh with an interest rate of 6.56% per annum.

The average energy consumption per household in Bulindo is 53.665 kWh. Since the eco-village is to be designed for 10,000 residents, this translates into an average energy demand of 49MWh/day with a peak of 4.6 MW. In order to provide fresh water supply for the village, a water pumping system is installed as a deferrable load. This system should be able to supply 1000 m$^3$/day of fresh water while operating for 8 hours a day. Such a system would require 680 kWh/day of energy with storage of 2 days giving a storage capacity of 1360 kWh and a peak demand of 85 kW.

Basing on the energy requirements of Bulindo village and the availability of primary energy sources, it was decided to design a sustainable hybrid energy system for the village using resources such as solar PV, wind, grid and a biogas generator as back up. The system is connected to the national grid where energy generated within the system is exported to the national grid during the period of high resource potential and minimal load (off peak) and energy can be imported from the grid during period of low resource potential and maximum load (peak). The system configuration is as shown in the Fig. 10.

The designed energy system is shown in Fig. 10. The system configuration is composed of a solar PV array, a wind generator, a biomass generator, the grid, the battery set for energy storage during periods of low demand and making it available during periods of high demand (peak) and also when there is no sunshine/wind, i.e., at night. The converter acts both as an inverter and as a rectifier. The system configuration also consists of both AC and DC bus bars where the generated energy can be tapped from. The modeled energy system was then simulated and the feasible solutions obtained which have been ranked according to the lowest NPV as shown in Fig. 11. From the results, it can be seen that the most feasible solution consists of the national grid, PV array, wind generator, the battery and the converter.

In the designed system, renewable energy sources account for 95% of the annual electricity production in the system with the remaining 5% to be met by the national grid. Solar PV and the wind turbine generate 76% and 19% respectively of the electricity in the eco village. This is because the energy generated by these sources is cheap and its generation is associated with minimal environmental impact. The total energy generated by the PV array is 48,602,612 kWh/yr, the wind turbine generates 12,043,562 kWh/yr and the grid contributes 3,012,442 kWh/yr. The biomass generator will be used during periods of sporadic sunshine and low wind speeds and will mainly serve as a backup. Figs. 12 and 13 give a summary of the electricity production from the energy system.

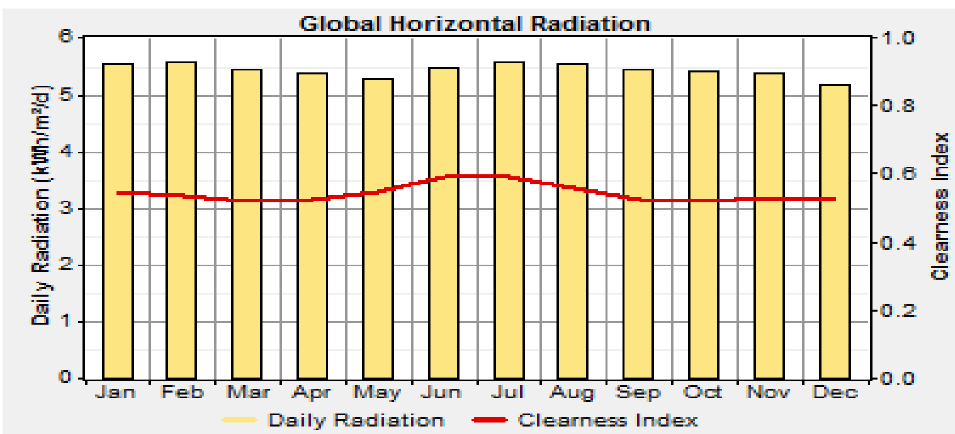


**Fig. 7. Monthly variation of solar radiation**

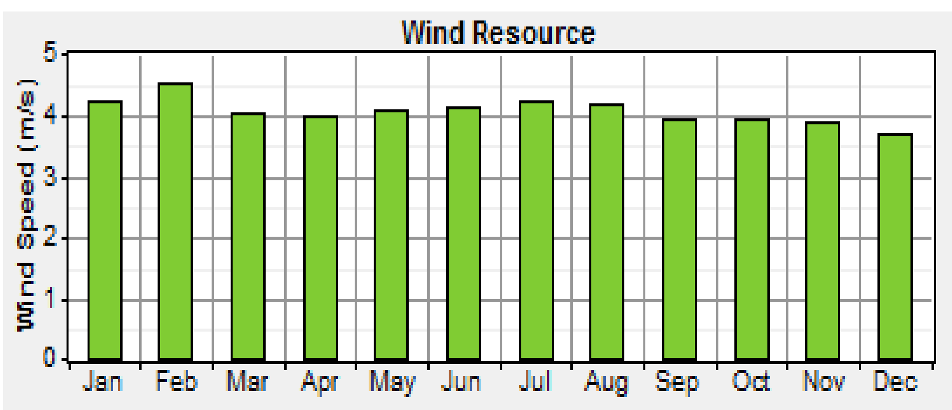


**Fig. 8. Monthly variation of wind speed**

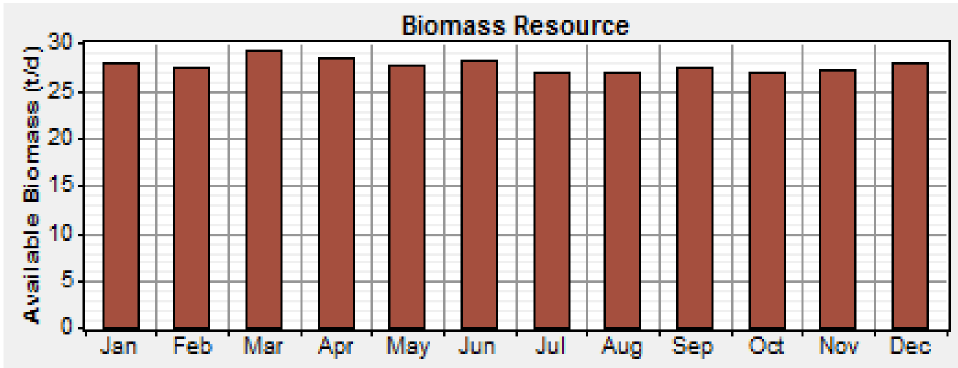


**Fig. 9. Monthly variation of biomass tonnage**

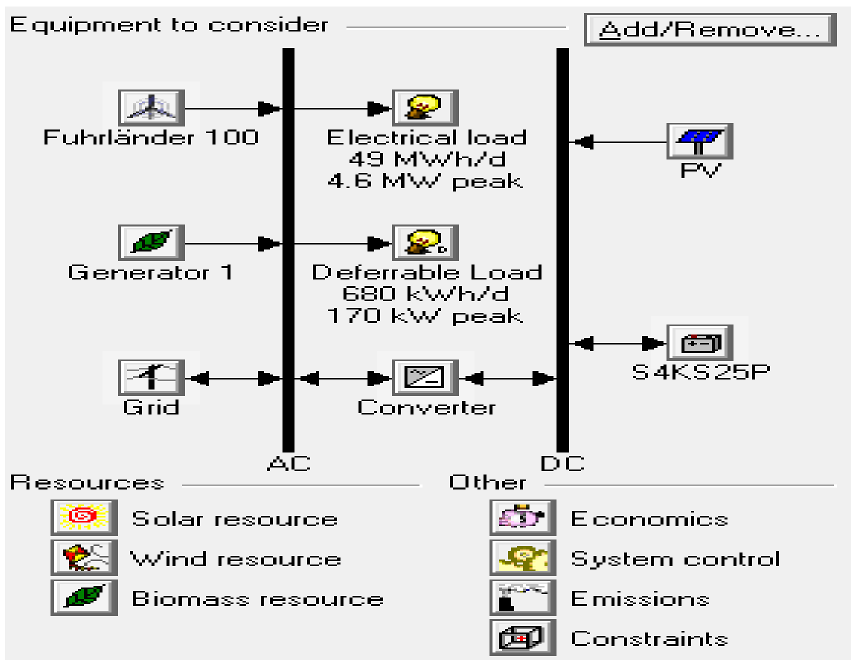


**Fig. 10. Designed energy production and usage system for Bulindo Eco-Village**

| PV (kW) | FL100 | Label (kW) | S4KS25P | Conv. (kW) | Grid (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Capacity Shortage | Biomass (t) | Label (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 500... | 100 | | 3392 | 5000 | 1000 | $ 3,995,634 | 192,876 | $ 6,813,167 | 0.028 | 0.95 | 0.12 | | |
| 100... | | | 3392 | 5000 | 1000 | $ 3,495,633 | 289,734 | $ 7,728,064 | 0.034 | 0.96 | 0.19 | | |
| 500... | 100 | 10 | 3392 | 5000 | 1000 | $ 3,999,634 | 277,645 | $ 8,055,478 | 0.033 | 0.95 | 0.10 | 26 | 7,273 |
| 500... | 100 | | | 5000 | 1000 | $ 4,000,000 | 299,905 | $ 8,381,008 | 0.037 | 0.94 | 1.00 | | |
| 100... | | 10 | 3392 | 5000 | 1000 | $ 3,499,633 | 383,943 | $ 9,108,280 | 0.040 | 0.96 | 0.17 | 32 | 8,756 |
| 500... | 100 | 10 | | 5000 | 1000 | $ 4,004,000 | 388,345 | $ 9,676,947 | 0.042 | 0.94 | 1.00 | 31 | 8,760 |

**Fig. 11. Feasible system solutions after simulation**

Fig. 14 shows the electricity consumption of Bulindo eco village energy system. The AC primary load consumes 75% of the generated energy; the water supply system (deferrable load) consumes 1% while the surplus is sold to the national grid.

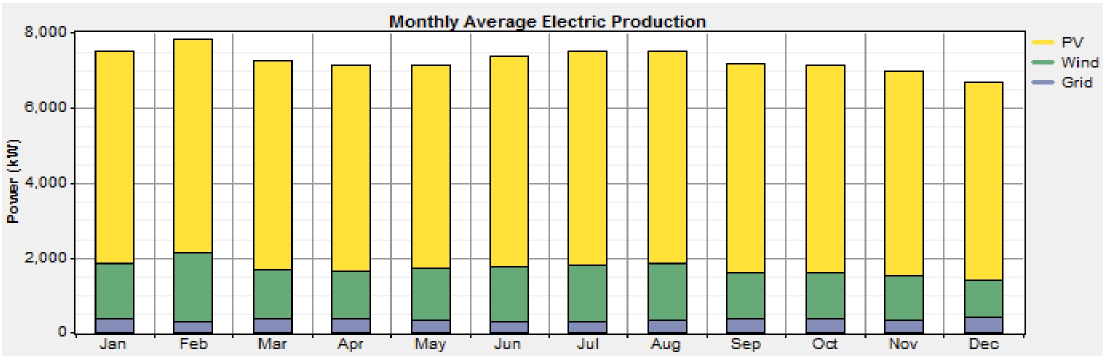


**Fig. 12. Monthly average electricity production by the system**

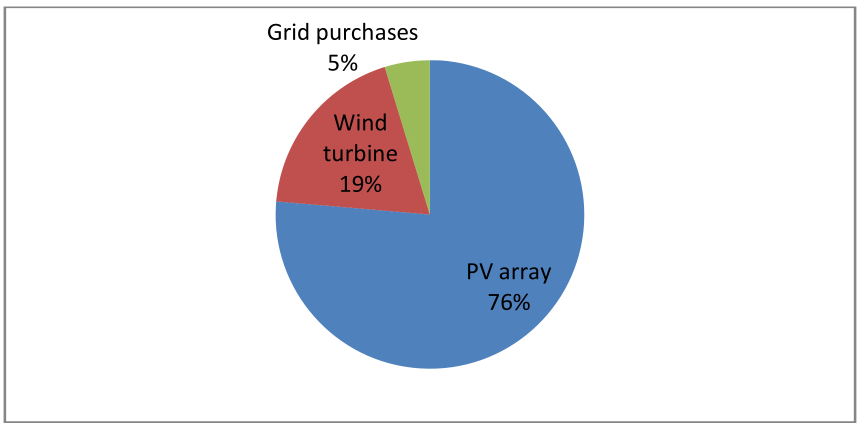


**Fig. 13. Summary of electrical energy production by source for Bulindo**

The composition of the energy generation system is as shown in Table 2 below; 1,000 kW of energy is sold to the grid, the PV array contributes 50,000 kW, the wind turbine contributes 10,000 kW, the battery 25,779 kWh, the converter 5,000 kW and the dispatch strategy is cycle charging.

**Table 2. Summary of the energy system configuration**

| No | Component | Capacity (kW) |
|---|---|---|
| 1 | Grid | 1,000 kW |
| 2 | PV array | 50,000 kW |
| 3 | Wind turbine | 10,000 kW |
| 4 | Battery | 25,779 kWh |
| 5 | Converter | 5,000 kW |
| 6 | Dispatch strategy | Cycle charging |

The energy requirement for cooking will be met by the excess electricity which is generated from the PV array and the wind turbine as well as biogas derived from the organic component of municipal solid waste as feedstock. Households will be supplied with containers to dispose of their waste. Homesteads will be encouraged to sort their waste and rewards will be given to those who comply and those who fail to comply will be penalized. This means that there are no emissions associated with household cooking.

The transportation system is subdivided into two i.e. transport within the system boundaries and transport across the system boundaries. Emissions from a person moving in and out of the village have been assumed to be shared by the system and its environment making the analysis to be based on a single route i.e. to or from the village. Transport to or from the village has been incorporated in the analysis of transport within the village. For transport across the system boundary, there is no air, rail and water travel, the only available means of travel is by road. Motorized transport in the village will be used mainly by commuters and visitors as well as suppliers of goods and services. The village is expected to have 2,500 commuters and about 4,000 visitors annually. In order to abate $CO_2$ emissions in the transport sector, there will be need for intervention measures in form of more fuel efficient engines, strong incentives not to use a car, use of green cars and emission penalties. There will be buses moving around the village to transport commuters and visitors expected to be 3000 per year by 2025. The average distance travelled is expected to be 1.6 km by every visitor to or from the village. The $CO_2$ emissions are expected to be 100g/km, giving a total of 480 kg/year.

Road transport is considered to be the best means of transport in the village. The sector will be public with the road network designed to accommodate pedestrians, cyclists and public transport (buses). A private company can be established to manage the public transportation system. Travel in the system is assumed to be 15 km per person per year by 2025. Assuming 40% of the commuters have personal cars and then travel $CO_2$ emissions are assumed to be 0.10 kg $CO_2$/km. This gives $CO_2$ emissions of 1800kg/year. Assuming vehicle fuel consumption of 0.08 l/km, travel of 584 km per person per year and a population of 10,000 residents by 2025, the required diesel is 467,200 kg/year. If the calorific value of diesel is 43.2 MJ/kg, the total energy is 16.5 TJ/year and is equivalent to 16.5 GJ per capita per year. Therefore total emissions associated with the transport sector are 1.98 ton $CO_2$ per annum. Since all the energy requirements are being met by renewable sources, there are no emissions associated with energy production. The only emissions are as result of transport in and out of the system boundaries which is 1.98 ton per year.

Fresh water will be supplied to the eco village by NWSC since the village is connected to the water pipeline. The energy to pump and distribute the water to the various residential, commercial and industrial zones will be generated within the system as the water supply system has been modeled as a deferrable load in the sustainable energy system for the eco village. To reduce on the energy requirement for water pumping as well as the energy bills, households will be encouraged to install roof top rain water harvesting systems on their houses to take advantage of rain water especially during the wet season. This will be used for various activities such as car washing, laundry and house cleaning making the water supply system more sustainable. In order to provide hot water for use in kitchen and lavatories, households will be encouraged to install solar water heaters on their roofs to meet this demand and save on their energy bills.

There will be waste collection centers in the eco village where homesteads can dump their waste. These will be located close to residential and commercial centers for convenience. Households will be sensitized about the benefits of proper waste management and they will also be required to sort their waste before dumping. To ensure that this is adhered to, a carrot and stick approach will be used i.e. rewards to those who abide (sort their waste) and penalties to those who fail to comply. Both the rewards and penalties will be determined and enforced by the system managers. The waste after sorting will be classified as organic, plastics, metals and glass. Organic waste will be used for energy generation (biomass feedstock); plastics and metals will be taken for recycling and incineration while the glass will be dumped at the landfill in Kitezi.

Every individual in the eco village will be responsible for upholding the norms of the eco village. The authorities will be instrumental in funding the different activities as well as implementing policies that will be used to manage the eco village. Engineers, surveyors, architects and economists will be responsible for designing and constructing sustainable buildings, a modern road network as well as cheap but highly efficient energy system. Policy makers will be responsible for formulating policies of the eco village while social scientists will be responsible for sensitization of the general public about the eco village. Crucial aspects to consider include building control regulations, energy efficiency and conservation, emissions penalties, blending of fuels and the taxes to be imposed on imported cars. MBL Utility Company which is 60% government and 40% privately owned will be the one responsible for management of the system. Prepaid meters will be available to both the public and industry with discounts given to users during the off-peak period of the day.

### 3.4 Economic Analysis for the Designed Energy System

The levelised cost of energy from the system is \$0.028/kWh; this is relatively low compared to most power systems. The relatively low cost of energy can be attributed to the low cost per unit of PV and wind generation, in addition to the low cost per unit of generation equipment. Table 3 and Table 4 show a summary of component costs while Figs. 15 and 16 show the cash flows during the project life. The interest rate is 6.56% per annum and the project life is 50 years.

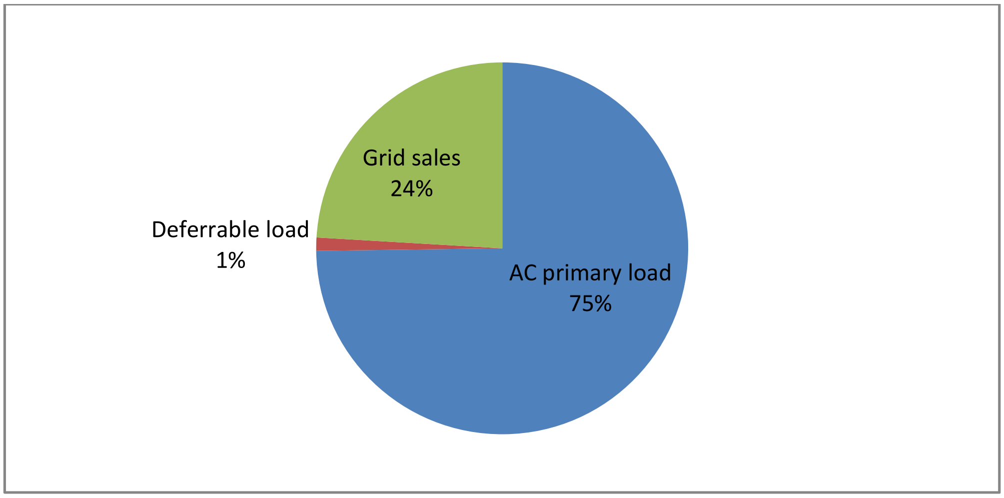


**Fig. 14. Summary of monthly electric consumption system for Bulindo**

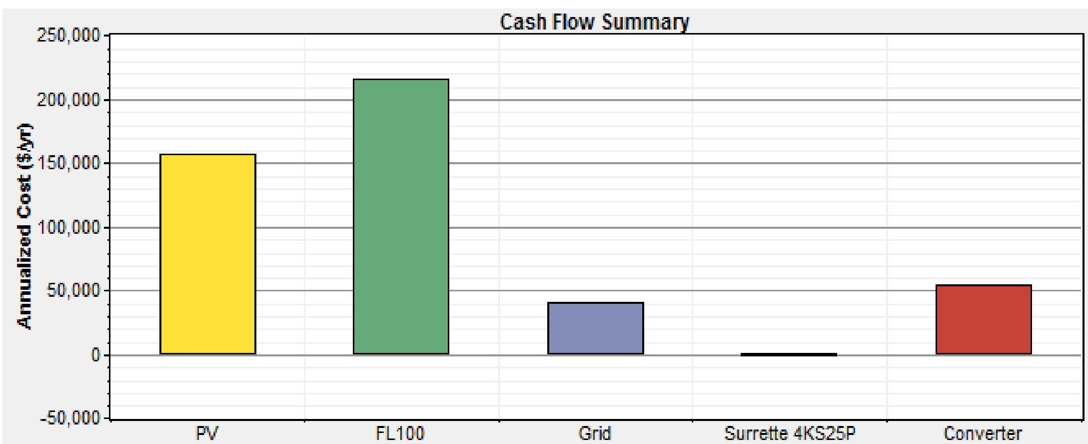


**Fig. 15. Annualized cash flow summary for each system component**

**Table 3. Summary of cost of energy services**

| Cost | Value($) |
|---|---|
| Total net present cost (NPC) | 6,813,167 |
| Levelised cost of energy (COE) | 0.028/kWh |
| Operating costs (OC) | 192,876/year |

## 4. SUMMARY

The aim of this study was to plan and design Bulindo eco village to accommodate 10,000 residents with the main emphasis on the sustainable energy system that meets the energy demand under given constraints i.e. technical and economic viability. This was accomplished by ascertaining the current state of Bulindo village as well as determining the energy requirements of this village and the available resource potential in the area. Using the above data as input to computer simulation model using HOMER software and GIS, the land use allocation for Bulindo was developed and an energy system configuration that meets the energy demand for this village was also obtained. The cost of the generated energy has been given and the system managers have also been suggested. The results were discussed and various recommendations made on how to better improve the system and proper management. It has been found that the available energy resource potential for Bulindo village can meet 95% of its energy demand with the remaining 5% being met by the national grid. The cost of this energy is also relative low compared to the current tariff being levied by UMEME, i.e. $0.028/ kWh compared to $0.18/ kWh. However, the challenge will be getting the human resource to maintain and manage this system.

**Table 4. Summary of cash flow for each component**

| Component | Capital ($) | Replacement ($) | O&M ($) | Fuel ($) | Salvage ($) | Total ($) |
|---|---|---|---|---|---|---|
| PV | 1,500,000 | 449,206 | 365,200 | 0 | -26,072 | 2,288,334 |
| Fuhrländer 100 | 2,000,000 | 1,064,740 | 146,080 | 0 | -50,068 | 3,160,763 |
| Grid | 0 | 0 | 589,617 | 0 | 0 | 589,617 |
| Surrette 4KS25P | 4,367 | 4,095 | 1,595 | 0 | -800 | 9,257 |
| Converter | 500,000 | 221,821 | 73,040 | 0 | -10,429 | 784,432 |
| System | **4,004,367** | **1,739,862** | **1,175,532** | **0** | **-87,359** | **6,832,403** |

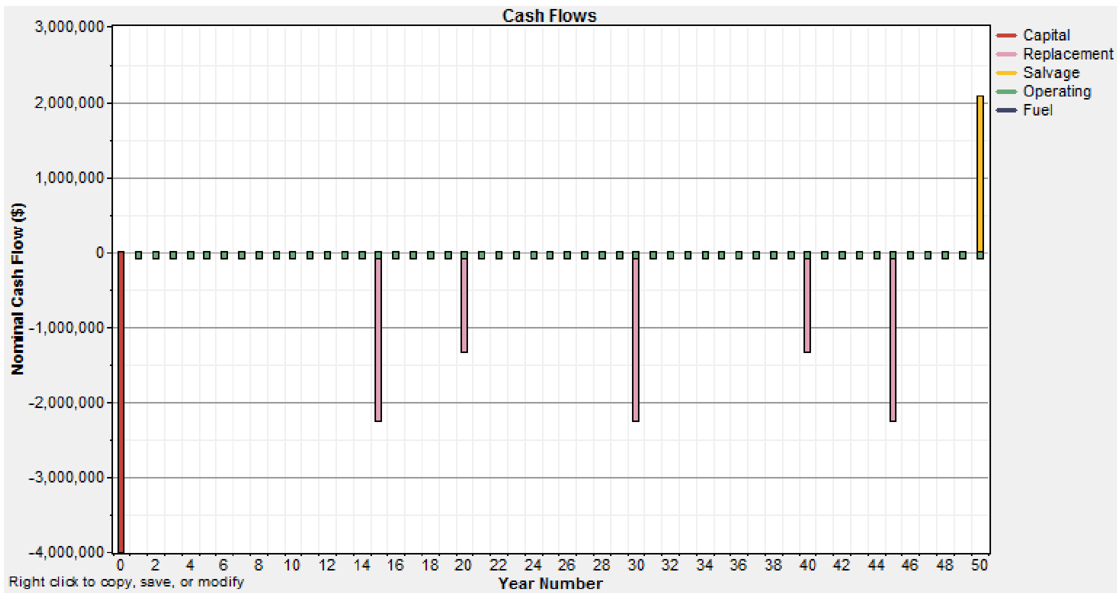


**Fig. 16. Cash flow diagram for the energy system**

## 5. CONCLUSION AND REMARKS

The designed system is believed to offer a better performance due to its sustainability as well as its ability to meet all the energy requirements of the village i.e. energy and fresh water demand. Simulation results demonstrate that using green energy sources such as solar PV and wind generators will reduce the operating costs, greenhouse gas emissions and particulate matter through the use of clean green energy with no environmental impact. In addition, the system also supplies fresh water for residential, commercial and industrial use making it more sustainable.

A questionnaire was used to ascertain the energy requirement for Bulindo. However, most households visited lacked a clear knowledge about the energy consumption. This forced the author to rely on the data obtained from a literature survey of similar systems such as Masdar. This could have significantly affected the results for this section of the research. During the modeling and simulation stage, consideration was not given to the importation and taxation fees levied on the system components due to failure to obtain a clear figure especially for the wind turbine as wind energy has never been used for energy generation in Uganda. Also, the interest rate was taken as 6.56%, although most renewable energy projects worldwide do not exceed a 10% interest rate, 6.56% is far below the rate charged by commercial banks in Uganda which could have significantly affected the unit cost of energy. The amount of energy produced by the system is 63,658,616 kWh/year at a unit cost of $0.028/ kWh. 76% of the generated energy is consumed by the system i.e. AC primary load and the deferrable load while the surplus (24%) is sold to the national grid which earns crucial revenue to the village for better management of the system hence guaranteeing sustainability.

Also, from simulation results, it can be seen that the most feasible solution consists of a PV array, the wind turbine and the national grid. However, since these renewable primary energy sources are intermittent in nature, a biomass generator has been incorporated in the designed energy system as a backup. This has been justified by the high biomass resource potential available in the system and its surroundings. The design of a sustainable energy system for Bulindo village to be moved in by 2025 has been presented here. However in future there should be need for;

A possibility of considering energy storage by hydrogen due to its cleanliness and environmental benefits as opposed to lead acid batteries despite their high conversion efficiency.

Future work in this field should consider other modeling and optimization tools such as particle swarm optimization, bees' algorithm, genetic algorithm, TRNSYS, etc.

The existing infrastructure most especially the road network should not be destroyed. Instead, it should be upgraded to city standards so that it can be able to accommodate vehicles, cyclists and pedestrians.

## ACKNOWLEDGEMENTS

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## COMPETING INTERESTS

Authors have declared that no competing interests exist.

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