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Optimal and Economic Evaluation of a Stand-alone Microgrid for Electricity and Water Supply for Namibia's Rural Village

Tom Wanjekeche[*], **Theophilus Ananias**

Department of Electrical and Computer Engineering, University of Namibia, Ongwediva, Namibia

Email address:
wanjekeche@yahoo.com (T. Wanjekeche), mycrystal0@gmail.com (T. Ananias)
[*]Corresponding author

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Abstract: Stand-alone microgrid hold a primary solution for electricity and water supply in remote areas access to National grid is not possible. This paper presents a detailed optimal sizing and economic evaluations of a stand-alone microgrid for a remote village (Amarika) in Namibia. Several renewable energy sources such as wind turbines and photovoltaic arrays were considered with a battery backup storage system and a reverse osmosis desalination plant for water supply. Modelling of the microgrid was done based on the meteorological data, the daily water and energy demand of the village. Particle swarm optimization was employed for the system techno- economic optimization: to determine a suitable microgrid configuration that can be established at minimum cost. Sensitivity analysis of the system was performed to examine the effect of variation of LPSP on LCOE. The results demonstrate that the optimized microgrid configuration and the optimization algorithm are effective and can be adopted in supplying power and water to the village. The levelized cost of electricity proves the economic feasibility of the microgrid. The levelized cost of electricity falls within a 90% standard deviation ($\sigma = 0.065$) of the mean. This proved to be economically feasible with a 96.5% reliability of power supply.

Keywords: Stand-Alone Microgrid, Water Desalination, Optimization, Economic Evaluation

1. Introduction

By 2016, approximately 18% of the global population living in developing countries especially in rural and underdeveloped areas lacked access to electricity [1]. Nowadays, considering people's necessities, electricity has positive impacts on poverty eradication, education and public health around the globe. Access to electricity and water is one of the objectives of the fight against poverty in all developing countries [2]. The society depends on a reliable supply of water and electricity to make a living [3]. In remote areas, electricity and water infrastructures are located far from people or they are costly to access. Therefore, stand-alone microgrid system with renewable energy sources for electricity and water supply capabilities is an ideal option.

A microgrid system provides an opportunity and a desirable infrastructure for improving the efficiency of energy consumption when operating in an off-grid state. This system is an integration of renewable energy generators, energy storage system, control and protection systems designed to supply power to the loads [4]. For greater balance and higher system efficiency, a suitable configuration is selected with micro-source sizes optimized according to their performance and operational costs to meet the load demands.

The optimization problems from microgrid sizing are usually multi-objective and nonlinear dynamic problems when a variable load is taken into consideration [5]. Incorporating a desalination plant that already existing in selected village, makes the optimization problem more complex. Therefore, in order to access different configuration options and micro-source sizes; a technical and economic analysis needs to be performed and an appropriate algorithm capable of handling multiple objective functions and performing time step simulation adopted to explore several designs and operational alternatives.

Several researches on hybrid systems optimization have been done over the years. A model for determining the optimal size of an energy storage system in microgrid was proposed using an expansion planning strategy [6]. This model was grid connected and aims to minimize operational costs for the microgrid energy storage system. A constrained objective function was considered in reducing emissions (Carbon Dioxide, Sulphur Dioxide and Nitrogen oxides) and minimize costs on a microgrid with a smart thermal storage system. This was done using particle swarm optimization technique [7]. A more in-depth model was proposed to determine the optimal size and operation strategy of a smart microgrid with renewable and non-renewable sources supplying domestic loads [8].

In other sources, other optimization techniques were proposed over the years for sizing of hybrid system components and predicting renewable generator output under various operating conditions. The linear programming method was used for economic optimization of off-grid energy systems [9]. And a focus algorithm for optimum sizing of a renewable energy system considering component performance degradation issue was applied [10].

Amongst these optimization techniques, particle swarm optimization technique was extensively used in problems regarding hybrid power systems and it is known for fast convergence to the global solution while avoiding premature convergences [11]. Comparison between particle swarm optimization, linear optimizations techniques such as HOMER software and Cascade, with an artificial intelligence technique such as Genetic Algorithm was investigated in [12]. Particle swarm optimization (PSO) yielded results with high accuracy and converged much quicker than all other techniques. On the other hand, genetic algorithm could be an alternative, but it is quite computationally intensive and too complex leading to higher convergence time. According Y. Wang, H. Jiang and P. Xing, PSO is also capable of handling multi-objective, multi-constraint and nonlinear dynamic optimization problems [5].

Most of these literatures focused on the operation and optimization of grid-connected hybrid systems which may not apply to regions far from the grid. And literatures that discussed off-grid hybrid system optimization and economic evaluation did not deal with a water supply system such as desalination plant.

The village selected has a desalination plant that does not meet the water demand by the village. This paper proposed an optimal configuration of the micro-sources that will adequately supply power both for electricity and water demand. In Amarika village, water production is prioritized so in cases of power deficit and when the generated power is sufficient to supply the desalination plant but not enough to supply the net load; the desalination plant is powered. This was achieved by scheduling the desalination plant to operate during time periods where there is high power surplus.

2. System Design and Modeling

As shows in Figure 1, stand-alone microgrid system discussed in this paper is a cluster of microsources such as photovoltaic arrays, wind turbines and storage batteries, the residential loads and the reverse osmosis desalination plant for water supply. It consists of AC and DC busbars interfaced with a bidirectional converter. The DC sources, photovoltaic arrays and storage batteries, and auxiliary dc loads are connected to the DC busbar while the AC sources, wind turbine, desalination plant and residential loads are connected to the AC busbar. The bidirectional converter allows the transfer of power from the AC busbar to the DC busbar for storage or power transfer from DC busbar to the AC loads.

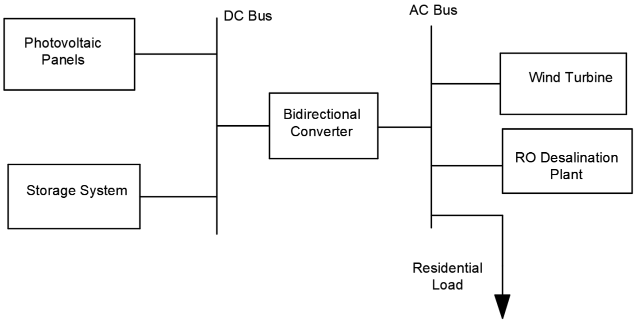


Figure 1. *Typical stand-alone microgrid architecture.*

2.1. Modeling of Photovoltaics

The total power generated by the photovoltaic arrays depend upon the solar intensity (insolation), the hours of direct sunlight, the ambient temperature and the efficiency. The angle of incidence and the module tilt angle also have an effect on the power generated. In this research, the angle of incidence and the module tilt angle has been disregarded on assumption that the photovoltaic panel will be installed in an ideal position to generate maximum power.

The photovoltaic module is modelled by equation (1) [13];

$$P_{pv} = \frac{\%df \times P_{nom} \times G\left[1 + K_T\left(T_c - T_{ref}\right)\right]}{G_{ref}}$$

$$T_c = T_{amb} + 0.0256G \tag{1}$$

Where, G_{ref}, K_T and $\%df$ is the reference solar radiation (1000W/m^2), temperature coefficient (-3.7×10^{-3}/°C) and the module derating factor respectively. T_c, T_{amb} and T_{ref} are the cell temperature, ambient temperature and reference cell temperature (25°C) respectively.

2.2. Modeling of Wind Turbine

Similar to the photovoltaic module, the power generated by the wind turbine depends on the weather conditions under consideration. The nature of wind that the wind turbine receives depend on the vegetation, height of the hub above the ground, sweep area, wind speed, temperature and the atmospheric pressure.

The power output of the wind turbine is primarily depended on the wind speed which defines the operational boundary conditions of the turbine. If the wind speed is less than the rated wind speed and greater than the cut-in wind speed, the generated power is expressed by equation (2) [14];

$$P_w = \frac{\rho A v^3 C_p(\lambda)}{2} \tag{2}$$

If the wind speed is less than the furling wind speed and greater than the rated wind speed, the generated power is expressed by equation (3) [14];

$$P_w = \frac{\rho A v_{max}^3 C_p(\lambda)}{2} \tag{3}$$

And if the wind speed is less than the cut-in wind speed or greater than the furling wind speed, the generated power is expressed by equation (4) [14];

$$P_w = 0 \tag{4}$$

Therefore;

$$P_w = \begin{cases} \frac{\rho A v^3 C_p(\lambda)}{2}, (v_c \le v \le v_r) \\ \frac{\rho A v_{max}^3 C_p(\lambda)}{2}_r, (v_r \le v \le v_f) \\ 0, (v < v_c \; or \; v > v_f) \end{cases} \tag{5}$$

If the wind speed data were not recorded at the wind turbine hub height, the expression (6) can be used to perform the conversion [14].

$$v = v_0 \left(\frac{H}{H_0}\right)^{\alpha} \tag{6}$$

Where, α is the friction coefficient equal to 0.25 for Amarika and H_0, H, v_0 and v are the measured wind speed altitude, wind turbine hub height, measure wind speed at H_0 and the wind speed at the hub height.

It is important to consider the temperature and altitude correction for air density since the corrected wind speed might not give a realistic reflection of the actual wind speed at the turbine's hub height. The air density correction is performed according to expression (7) [14].

$$\rho = \rho_T \rho_A$$

$$\rho = \frac{P_{ST}^2 \times M.W. \times e^{-1.185 \times 10^{-4} H}}{RT} \times 10^{-3} \tag{7}$$

2.3. Modeling of Storage Battery

The storage batteries are scheduled when the primary sources of energy cannot meet the total load demand. In case of power surplus, the excess power is stored in the battery if the state of charge is low. The state of charge of the batteries is strictly monitored based on equation (8) to maintain the battery lifetime [5].

$$SOC^t = SOC^{t-1} + \begin{Bmatrix} \frac{\eta_c P_e \Delta t}{C_b} & | \, P_e > 0 \\ -\frac{P_e \Delta t}{\eta_d C_b} & | \, P_e < 0 \end{Bmatrix} \tag{8}$$

And the battery state of charge is constraint to equation (9),

$$50\% \le SOC \le 85\% \tag{9}$$

Where the total load demand and generated power difference is denoted by equation (10),

$$P_e = P_L - \sum_n P_n \tag{10}$$

2.4. Modeling of Loads

2.4.1. Residential Loads

Currently, there is no electricity in Amarika village thus, the load demand of 1700 kWh/day was estimated through load forecasting by the author of [15]. It follows the rural load profile for medium households illustrated in [16]. Figure 2 shows the estimated load demand profile for the village.

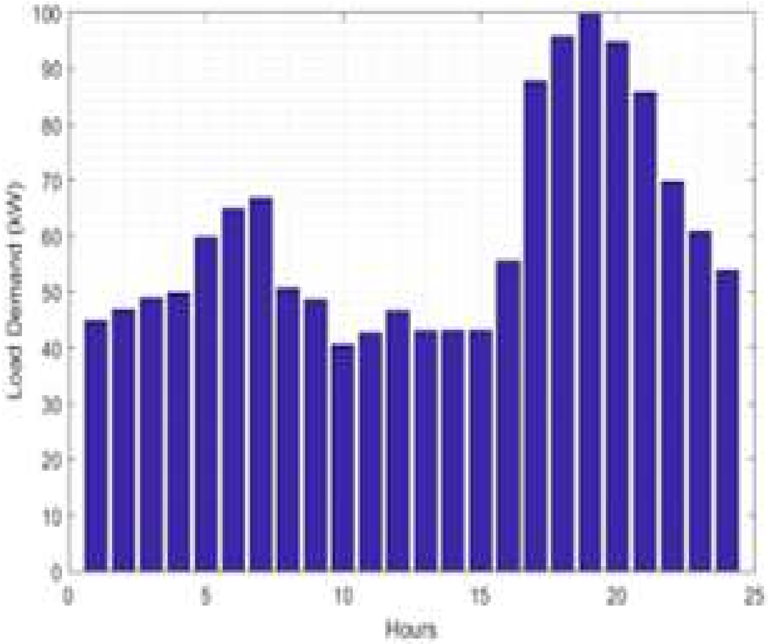


Figure 2. *Residential load profile for Amarika village.*

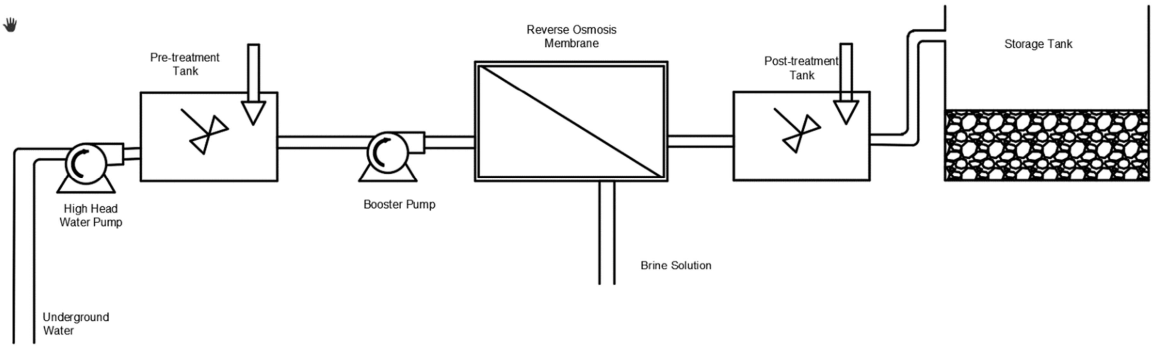
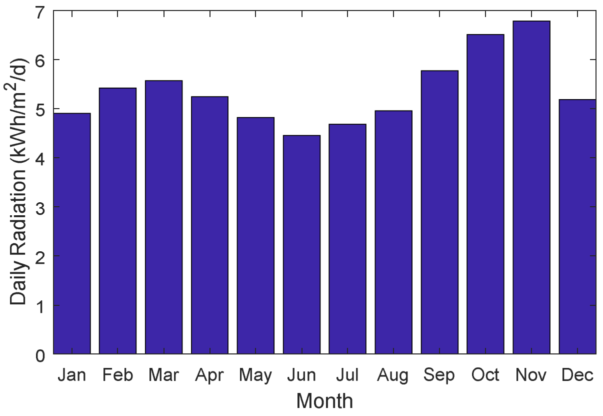


Figure 3. *Reverse osmosis desalination plant.*



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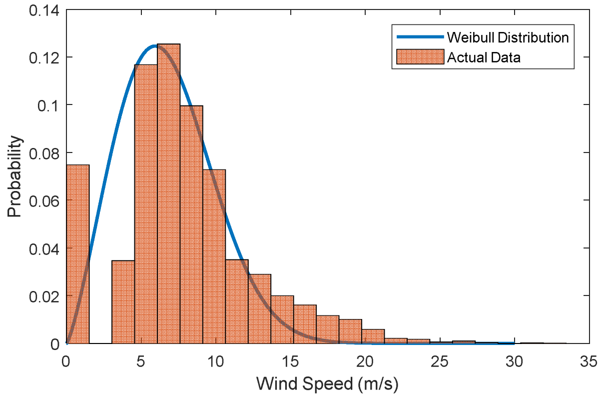

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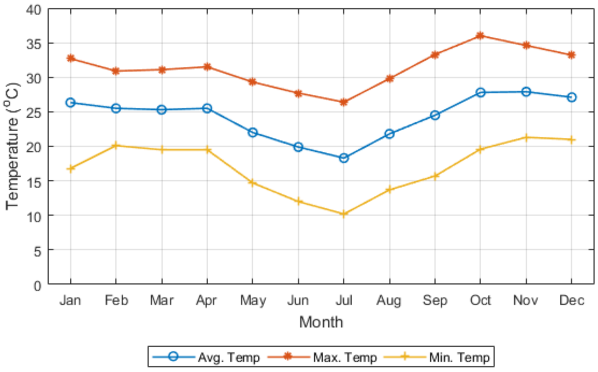

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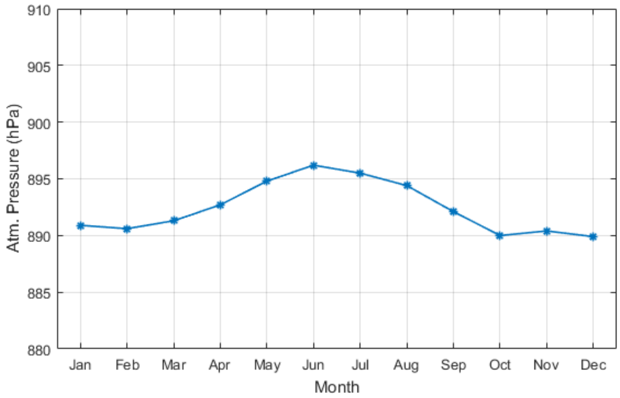


(d)

Figure 4. *Weather profile 2016 for Amarika village. (a) monthly solar irradiance (b) wind speed distribution (c) monthly temperature (d) monthly average atmospheric pressure.*

2.4.2. Reverse Osmosis Desalination Plant

Reverse osmosis (RO) is a pressure-driven membrane process that separate solutes (ions, molecules and large particles) from a solvent [16]. In the reverse osmosis desalination plant, the concentrated saline solution is forced, at high pressures, through a spiral-wound RO membrane that filter out brine solution while allowing fresh water to continue with the system [17]. The fresh water is treated in the post-treatment tank before channeled to the storage tank.

2.4.3. Weather Resources

Figure 3, shows a typical model of a desalination plant;

The performance of the renewable energy generation units depends upon the weather profile of the area under consideration. The meteorological dataset used for Amarika village were obtained from the Namibia Meteorological Service for a closed by weather station (Okahao weather station). This dataset consists of wind speed recorded at a 1000m altitude, solar radiation, temperature and atmospheric pressure as shown in Figure 4. The solar irradiance and temperature were used to predict the total power that can be generated by photovoltaic arrays and wind speeds, atmospheric pressure and temperature were used to predict the total power that can be generated by wind turbines.

3. System Optimization

The objective of modelling this optimization problem is to minimize the total net present cost (NPC) of the microgrid system taking into account the investment cost, the operation and maintenance cost and the replacement cost of the power generators and the storage system [19]. It also aims to maximize the amount of energy and water produced, thereby maximizing the lifespan of the storage system and the overall performance of the microgrid. The search of the optimal configuration is based on the weather profiles and load demand characteristics. The desalination plant scheduling algorithm is also introduced.

3.1. System Costs

The model of the stand-alone microgrid is implemented based on three objective functions; the net present cost, levelized cost of electricity and loss of power supply probability. The NPC was calculated according to equation (11) [20].

$$min\ NPC = \sum_n \left(C_{I,n} + \frac{C_{O\&M,n}}{CRF(i,N)} + K_n C_{REP,n} \right) P_n \qquad (11)$$

The capital recovery factor (CRF) is defined by equation, (12) [19].

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \qquad (12)$$

The Levelized Cost of Electricity (LCOE) evaluates the economic feasibility of the microgrid and it is considered feasible when the LCOE is minimum. This is expressed as in equation (13), [21];

$$min\ LCOE = \frac{Total\ Annual\ Cost}{Annual\ load\ served} \qquad (13)$$

3.2. System Reliability

The reliability of power supply is considered important in the selection of a suitable microgrid configuration. It is expressed in terms of the loss of power supply probability (LPSP) which is the probability an insufficient power supply results when photovoltaic arrays, wind turbines and storage batteries are unable to meet the load demand [22]. The LPSP is 0 and 1 when the load is sufficiently supplied and insufficiently supplied respectively. The loss of power supply probability (15) is a quotient of the loss of power supply (LPS), expressed by equation (14) and the total energy demand [23].

$$LPS(t) = \begin{cases} 0, & P_L < P_G \\ \left(P_L(t) - P_{pv}(t) - P_w(t)\right) \cdot \Delta t + C_b(t-1) - C_{bmin}, & P_L > P_G \end{cases} \qquad (14)$$

$$min\ LPSP = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} P_L(t) \cdot \Delta t} \qquad (15)$$

The microgrid should be able to meet the total load demand to guarantee reliability; most importantly, the desalination plant must be prioritized. Hence, the objective functions must meet the following constraints (16);

$$\min P_{error} = \min \left(P_L - \sum_n P_n \right)$$

$$P_L = P_{L,desalination} + P_{L,residential} \qquad (16)$$

The microsources capacity is constraint to the inequality equation (17);

$$P_{n,\min} \leq P_n \leq P_{n,\max} \qquad (17)$$

3.3. System Optimization Methodology

Once particle swarm optimization has been initialized, the meteorological data are imported from the excel files. The meteorological data, wind speed, atmospheric pressure, temperature and solar irradiance are used to predict the power that the wind turbines and photovoltaic arrays can generate at each time step. The total generated power from wind turbines and PV arrays, and the residential load demand are used to find the longest time span, common in most days, where the generated power is in excess.

The selected time span is reserved as the period of operation of the desalination plant. The desalination plant scheduling is performed based on the following pseudocode;

```
1. Read the forecasted load and power generated,
2. Determine the hours in the $d^{th}$ day where $P_{gen}$ is greater than $P_{residential}$,
3. Group the adjacent hours that meet the criteria described in step 2,
4. Calculate the length of the groups and the probability that the group will appear at the same time in all the other days,
5. Select the group with the highest length (period) and the probability of appearing on other days.
```

The selected group describes the hours of the day in which the desalination plant is scheduled. With the daily water demand of Amarika, 10.8 kL per day; the daily energy consumption of the desalination plant can be predicted. The process goes through a time series battery charging and discharging operation, afterward the net present cost, levelized cost of electricity and the loss of power supply probability of the microgrid is calculated with equation (16), (18) and (20) respectively based on the current microgrid configuration.

The program checks whether the optimization criteria are met then return the micro-sources sizes, NPC, LCOE and LPSP as the optimum solution, otherwise a new microgrid configuration is generated then it iterates over again.

The step by step optimization process is described by the flowchart in the Figure 6.

4. Results and Discussion

In this paper, a particle swarm optimization algorithm was adopted to optimize the microgrid based on the system performance and costs. The optimization model was simulated in the MATLAB scripting environment. This model was implemented based on the daily water demand, load demand and the meteorological dataset for Amarika village. The initial parameters of the simulation, the optimization results and the sensitivity analysis of the microgrid is presented in this section.

A brief description of the microgrid system components with their techno-economic details are summarized in Table 1. These are the initial input data to the optimization model obtained from Wuxi Wonderful Online Technology Co. a gold supplier of wind technologies in China and Sustainable in South Africa. Table 1:

Table 1. *The technical and economic summary of the system components.*

Component Parameters	Values
Photovoltaic Array	
Investment Cost	N$ 12799.46 /kW
O&M Cost	2% of IC per yr
Replacement Cost	N$ 12799.46 /kW
Lifetime	25 years
De-rating factor	0.9
Model	WON-WT-HEC30000
Rated Power	30 kW
Investment Cost	N$ 226702.30
O&M Cost	5% - 10% per yr
Replacement Cost	N$ 226702.30
Lifetime	25 years
Storage Battery	
Type	Lead Acid
Investment Cost	N$ 1776.20 /kWh
O&M Cost	N$ 2.30/kWh
Replacement Cost	N$ 1776.20 /kWh
Lifetime	12
Bidirectional Converter	
Efficiency	0.97

The capital recovery factor represented by equation (17) requires the interest rate and the project lifetime to be evaluated. Table 2 presents the prime interest rate for Namibia 2017 and the project lifetime [24].

Table 2. *The interest rate and projection lifetime.*

System Parameters	Value
Interest rate	10.5% (prime)
Project lifetime	25 years

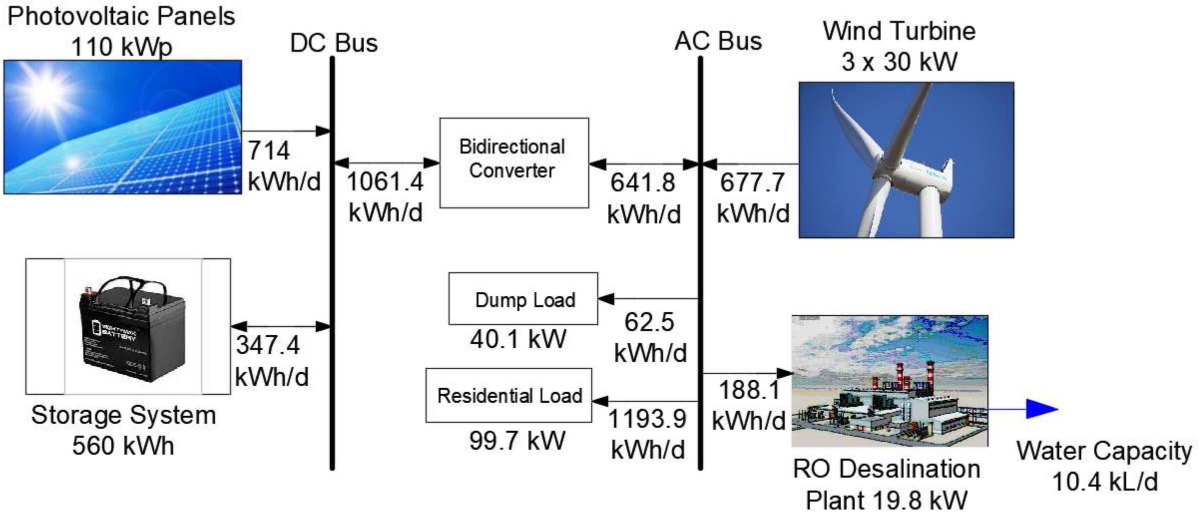


Figure 5. *The daily average electrical energy and water flow in the optimal case.*

4.1. Optimal Results

The optimum sizes of the photovoltaic system, wind turbine and storage battery, the desalination plant based on the daily water demand, and the economic parameters are shown in Table 3. The techno-economic parameters of the optimized microgrid system are presented in Error! Reference source not found.,, where the levelized cost of electricity and loss of power supply probability are N$ 2.23 per kWh and 3.5% respectively. These parameters are important in the assessment of the model.

Table 3. *The optimal parameters of the microgrid system.*

Microsource	Size
Photovoltaic Array	110 kW
Wind Turbines	3 x 30 kW
Storage Battery	615 kWh
Reverse Osmosis Desalination Plant	
Water demand	10.8 kL/d
Desalination Plant Energy demand	153.7 kWh/d
Economical Parameters	
Net present cost	N$ 35 592 000
Levelized COE	N$ 2.23/kWh
Annual Energy	667 342 kWh/yr
LPSP	0.035

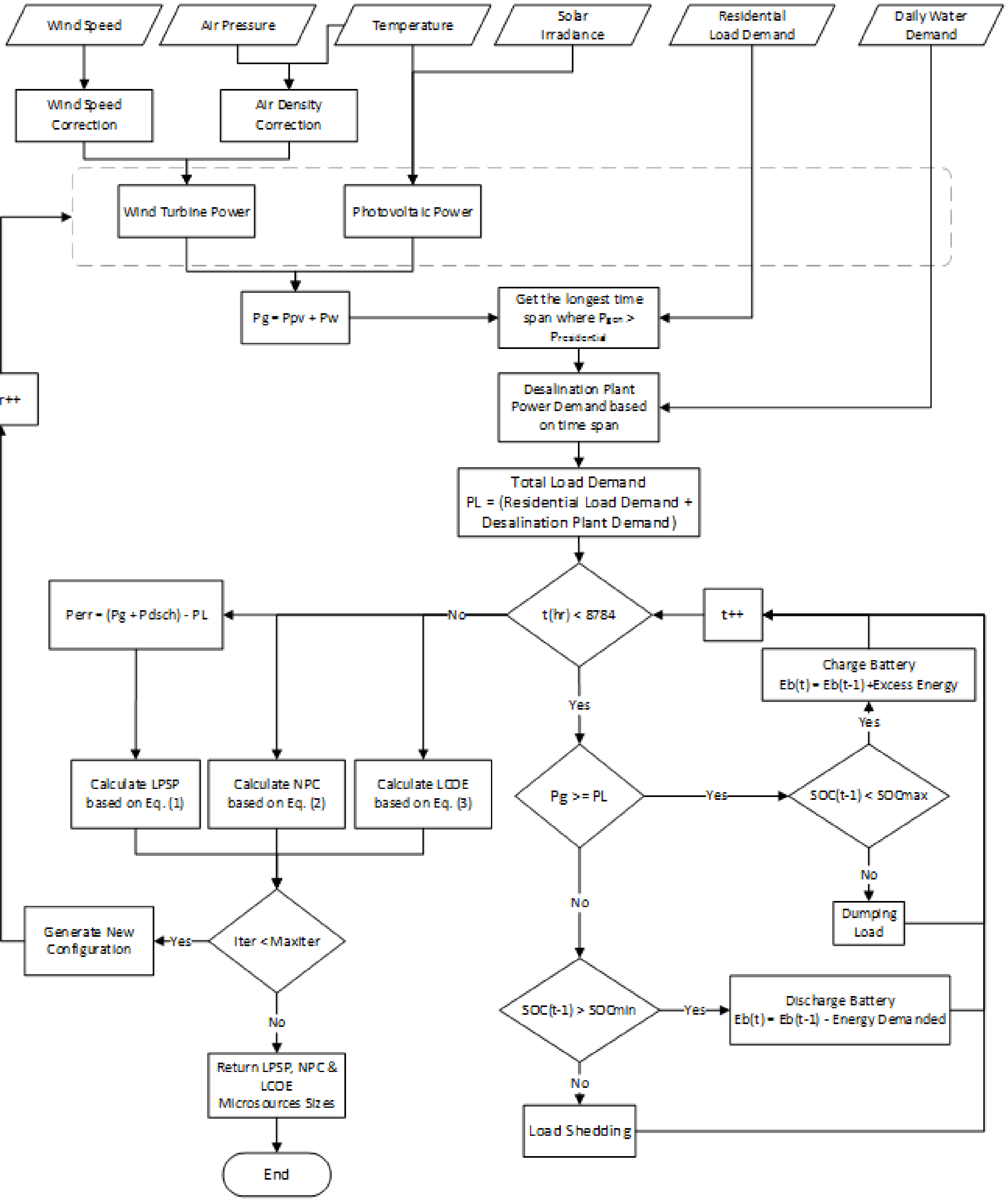


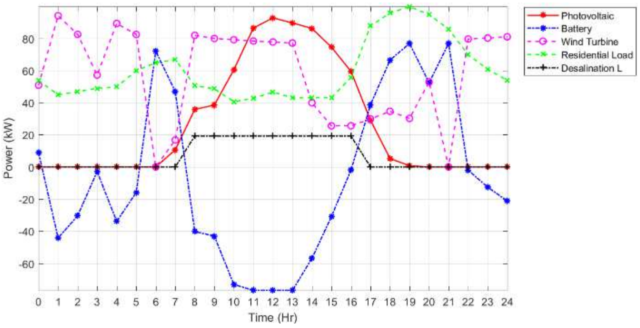
Figure 6. *Flowchart of the fitness function.*

Two cases were considered to analyze the relationship between the micro-sources and load demand on an hourly basis.

Case 1: When the solar irradiance and wind speeds are high

Figure 7 (a), illustrates the one-day hourly power contributions from photovoltaic arrays, wind turbines and storage batteries, and residential load and desalination plant demand variations on 01 November 2016. During the morning and afternoon hourly, 00hrs until 16hrs, the total generated power by the wind turbines and photovoltaic arrays was more than sufficient to supply the loads, hence the surplus power is transferred to the storage batteries. During the peak hours, the power from the wind turbines and photovoltaic was in deficit hence the batteries discharged to the loads to cover up for the deficits. The loss of power supply probability of this day was minimal.

Figure 7 (b), illustrates the hourly difference between the total generated power and the total load demand, and the hourly battery charging state from 01 to 03 November 2016. During these days, the weather conditions have been conducive to the renewable energy generators to produce energy. A maximum surplus power of 52 kW can be generated where a significant percentage of it is transferred to the batteries and the rest is dumped. A few spikes of power deficit can be observed and based on the state of charge of the storage batteries, it will discharge to the load ensuring that all loads are supplied.



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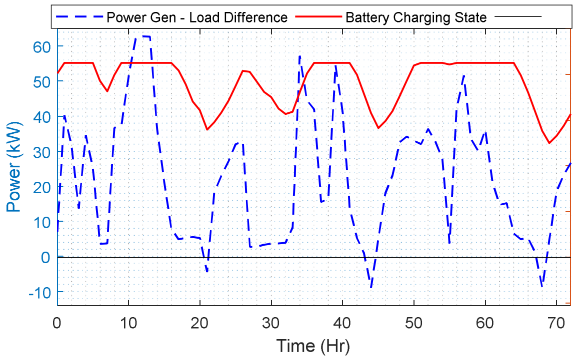


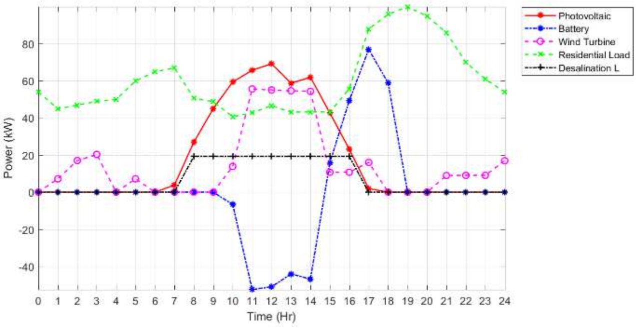
(b)

***Figure 7.** (a) One-Day Hourly Power Contributions and Load Demand when Solar Irradiance and Wind speeds are high (b) Hourly difference between the total generated power and total load demand, and battery charging state (01 - 03 November 2016).*

Case 2: When the solar irradiance and wind speeds fairly low

Figure 8 (a), illustrates the one-day hourly power contributions from photovoltaic arrays, wind turbines and storage batteries, and residential load and desalination plant demand variations on 01 July 2016. During the morning and evening hours, the total generated power is insufficient to supply the loads but from 8 am until the rest of the afternoon, a considerable amount of energy is produced sufficient to meet the load demand and charge the storage batteries to some extent. The excess energy stored in the batteries, that was generated during the day, is supplied to the loads in the evening hours. If the stored energy cannot meet the entire power deficit during the evening hours, demand-side management strategies should be incorporated to maintain the stability of the microgrid.

Figure 8 (b), illustrates the hourly difference between the total generated power and the total load demand, and the hourly battery charging state for 01 to 03 July 2016. During these periods, much power deficits can be observed as a result of poor wind speeds and solar irradiance. In this case, the storage batteries cannot cover up for the power deficits since it possesses insufficient energy to supply the load.



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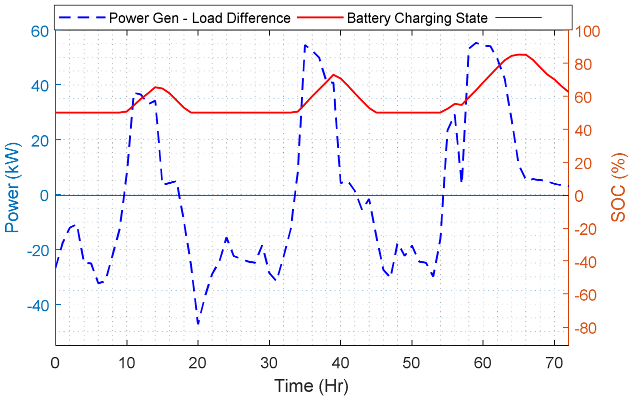

(b)

***Figure 8.** (a) One-Day Hourly Power Contributions and Load Demand when Solar Irradiance and Wind speeds are low (b) Hourly difference between the total generated power and total load demand, and battery charging state (01 - 03 July 2016).*

4.2. Sensitivity Analysis

Hybrid power systems are designed to meet 100% of the load demand at low costs. If the load has to be sufficiently supplied at all time, with the variation in daily demand and weather conditions, the system costs will be higher since larger generation units will be required to meet the net load. This is a scenario when the loss of power supply probability is 0. When the loss of power supply probability is 1, no load has been sufficiently supplied hence the reliability of power supply is low; the system cost is also low since small generation units are chosen to supply the load.

Figure 9, illustrates the relationship between the levelized cost of electricity and the percentage loss of power supply probability. During the simulation, the optimization algorithm search for a solution where the levelized cost of electricity and the percentage loss of power supply probability are minimal. At the optimal configuration, the loss of power supply probability is 0.035 and the levelized cost of electricity is N$ 2.23 per kWh. This shows that the proposed algorithm gives an optimized microgrid system design which meets most of the load demands at a lower cost of electricity.

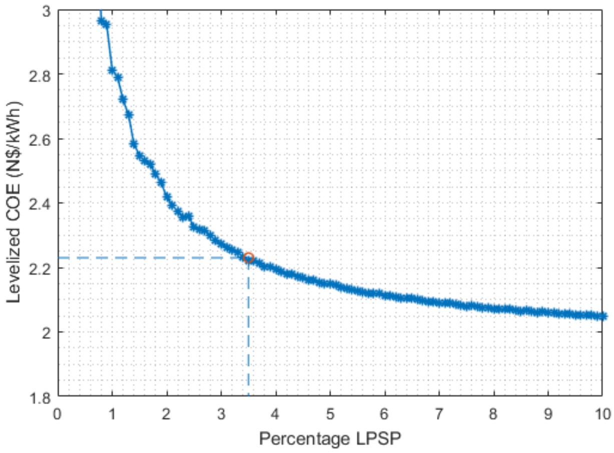

Figure 9. *The relationship between the* ^{Levelized} *COE and Loss of Power Supply Probability.*

5. Conclusions

The optimal sizing of a (wind, PV and storage batteries) stand-alone microgrid for electricity and water supply in Amarika was performed through a multi-objective particle swarm optimization simulation. The main objective is to minimize the net present cost, the levelized cost of electricity and the loss of power supply probability over a project lifetime of 25 years. The net present cost, levelized cost of electricity and loss of power supply probability described the overall system cost evaluates the economic feasibility of the microgrid and the reliability of power supply of the microgrid, respectively.

The developed methodology was executed using the hourly meteorological data, wind speed, solar irradiance, temperature and atmospheric pressure obtained from a weather station close to the Amarika village (Okahao weather station). In conjunction with the load demand and water demand of Amarika, an optimization model was developed to determine the optimum microsources sizes and the capacity of the desalination plant required to meet the daily water demand, and the residential load demand.

The levelized cost of electricity proves the economic feasibility of the microgrid. Even though the computed value is higher than the electricity tariffs, the levelized cost of electricity falls within a 90% standard deviation ($\sigma = 0.065$) of the mean. This proved to be economically feasible with a 96.5% reliability of power supply given that the renewable energy supply for rural areas will be cost-effective and competitive in the future with the government involvement.

Nomenclature

NPC	Net present cost
$LPSP$	Loss of power supply probability of microgrid
$LCOE$	Levelized cost of energy
LPS	Loss of power supply
CRF	Capital recovery factor
$\mathrm{C_t}$	Investment cost
$C_{O\&M}$	Operation and maintenance cost
C_{REP}	Replacement cost
P_L	System load demand
P_n	Output power of a micro-source
P_{pv}	Output power of a PV module
P_{nom}	Nominal power of a PV module
P_w	Output power of a wind turbine
C_b	Battery storage capacity
W	Desalination plant capacity per hour
Q	Feed flow
p	Pump pressure head

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