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An Optimal Sizing of Small Hydro/PV/Diesel Generator Hybrid System for Sustainable Power Generation

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Abstract

Concerns surrounding the environment along with inadequate energy supply and high cost of same are responsible for pollution, high energy demand, unpredictable and uneconomical power generation. These have contributed to the widespread agreement that sustainable renewable energy sources (RES) must be developed, particularly in isolated villages where expanding the grid may be challenging and financially unviable for power corporations. As a result, in order to effectively and cheaply utilize the plentiful renewable energy resources, an optimal sizing approach is required. This study is aimed at investigating the economic performance of the hybrid system of a stand-alone Small Hydropower/PV/Diesel generator with battery electricity production. The cost function was minimized using Dragonfly Algorithm (DA) in order to minimize the Cost of Energy (COE) generation. The decision variables are the number of small hydro turbines (N_{SHP}), number of solar panels (N_{PV}), number of batteries (N_{BATT}) and the capacity of Diesel generator (P_{DG}). The developed method is applied to a typical Kiri village in Shelleng Local Government area of Adamawa State. For uniformity, the hourly solar irradiance data were created by converting the monthly average solar irradiance data. A dragonfly optimization technique was utilized to reach an optimum solution for the hybrid system. The result obtained showed that the system components: small Hydropower, solar PV and Diesel generator were able to generate electrical power of 5,783,600 W, 56,259 W and 5.2941e-05 W respectively to meet the energy demand. Results obtained from the developed scheme were compared with those obtained when TORSCHE algorithm was used in optimizing the hybrid system. It was observed that a total energy cost of $5,224,500 was obtained for the developed technique while $5,839,600 was obtained as the total cost for the TORSCHE model. This showed that the developed scheme outperformed the system output from the TORSCHE algorithm in terms of cost of energy by 89.46%.

Keywords: Renewable energy sources, Cost of energy, Dragonfly Algorithm, TORSCHE algorithm

1. Introduction

The hybrid renewable energy systems have drawn a lot of interest recently since they offer a workable substitute for systems that only rely on fossil fuels. While high investment costs, poor capacity factors, and intermittent electricity generation are the key obstacles to the development of renewable energy systems [1], hybrid renewable energy systems are able to overcome these obstacles. The resources available and the load demand must be considered while designing an ideal hybrid energy system [1]. Utilizing RES is a successful strategy for dealing with the deteriorating ecological environment and meeting the rising energy demand [2]. Combining photovoltaic (PV) panels and hydrokinetic turbines with a traditional energy storage system via batteries and a diesel generator used solely in emergency situations enables the creation of a dependable energy source with minimal environmental effect and lower overall maintenance costs. Given the unpredictability of the weather and an ineffective storage technology, it is difficult to determine the ideal technical scaling of each component of a hybrid system to utilize the natural resources for a reliable energy supply [3], [4]. Because these renewable energy sources are intermittent, the supply of power fluctuates. Because of this, energy storage is crucial for balancing supply and demand and reducing variability. Due to the operational flexibility, low cost, and widespread availability of solar energy, hydro-PV systems are among the different HESs that are growing in popularity [5].

In many nations, small-hydro power is a particularly common kind of power generation for rural areas. However, the output of a hydroelectric plant varies greatly from season to season. Due to the low water levels in the river during the dry season, it would decrease or halt [6], [7]. Self-Excited Induction Generators (SEIG) are thought to be better suited for using renewable energy in outlying areas. SEIG is highly recommended for generation at remote places due to its amazing qualities, such as robustness, maintenance-free operation, brushlessness, and the fact that it doesn't need an external source for excitation [8]. Several scholars have employed various methods to size hybrid renewable energy systems optimally. The first hybrid power system (HPS) was developed in the middle of the 1980s, but it gained popularity in the early 1990s. Based on the amount of energy needed by the load, a genetic algorithm (GA) was utilized to reduce the overall system cost. A hydropower/PV hybrid system has been the subject of numerous research [9]. While some research have thought about combining solar and hydropower with other renewable energy options [10]. For the best design of hybrid systems, these studies have also used various tools and techniques [11]. Looked at the viability of producing electricity at a cheap cost utilizing a standalone solar/micro hydropower hybrid system. In comparison to diesel generation or grid extension, the hybrid system was proven to be the most cost-effective and environmentally friendly

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alternative for the particular site chosen. In order to simulate and size a micro hydropower/PV hybrid system for the rural electrification of a hamlet in Cameroon, [7] built a model. It was advised to adopt comparable systems in similar places based on the system's results. HOMER was used by [12] to model a hydropower and PV hybrid system with a biogas generator for outlying settlements in Cameroon. The findings of this study demonstrate that low power (10–50 kW) off-grid options based on renewable energy sources can be a feasible substitute for rural electrification in Cameroon. G. Bekele and G. Tadesse investigated the viability of a HOMER energy-based small-scale hybrid electric system for an area in Ethiopia [13]. A. M. Hemeida et al., developed a model based on hourly data for energy availability in India, to give an ideal hybrid system configuration [14]. The results of simulations revealed that alternative energy sources would be a feasible solution for distribution of electric power for stand-alone applications at remote and distant locations.

This work therefore applied Dragonfly Algorithm (DA) for the optimal sizing of SHP/PV/DG hybrid system based on the Net Present Cost (NPC), for minimizing Levelized Cost of Energy (LCOE), Loss of Power Supply Probability (LPSP) and DG usage for reliable and sustainable power generation of a local area.

2. Methodology

The procedures in achieving this methodology is given as follows:

2.1 Collection and sorting data of solar radiation, temperature, and hydro from NIMET.

For proper assessment of solar resource, there is need to have adequate knowledge of the solar irradiance on the collectors surface. The solar resource of a typical Kiri village in Adamawa state, Nigeria was used. The solar irradiance and air temperature data of the location chosen was collected for a year. The data collected were in hourly format. The solar insolation ranges from 0 W/m^2 to 550 W/m^2 depending on the time of the day. Minimum temperature obtained for the day chosen was also 15 degrees Celsius while a maximum whether temperature of 43 degrees Celsius was obtained. The solar radiation and whether temperature data obtained from NIMET is shown in figure 1. It is seen from Figure 1, that the solar radiation is not readily available all the time especially in time between 19:00 – 24:00 hrs and the early hours of the day.

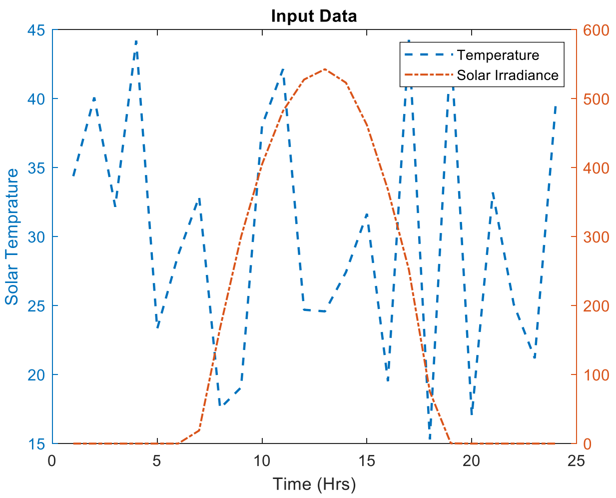


Fig. 1. Data for Solar Radiation and Temperature

For the year 2021, the actual registered hourly loads obtained from *NIMET* for the specified area is shown in table 3.1. These data collected (actual load and meteorological data) assist in the real feasibility study in implementing the hybrid energy system for the selected area.

2.2 Development of the mathematical equations for optimal sizing of PV/SHP/DG with battery hybrid power generation

The hybrid power generation system comprises of various electrical components (solar PV, small hydro power, diesel generator and battery and other accessory devices), that ensures necessary functions such as storage, energy generation and adaptation of electrical energy. For proper understanding of the hybrid system performance, the modeling of each component is done separately.

2.2.1 Modelling of the PV module

Solar panel is used in generating the required electrical energy based on the meteorological factors (temperature and solar radiation). Equation (1) was used in obtaining the PV module power output.

$$P_{out-pv} = P_{r-pv}\left[\frac{G}{G_{ref}}\right]\left[1 + kT\left(T_c - T_{ref}\right)\right] \quad (1)$$

Where, P_{out-pv} cell output power, P_{r-pv} is the rated power, G is the solar radiation (W/m2), G_{ref} is the reference solar radiation (1000W/m2), T_c is the cell temperature, T_{ref} is the reference cell temperature (25^{o}c), kT is temperature co-efficient of the maximum power (kT = -3.7x10-3/1^{o}C for Mono and Poly crystalline, Si) T_c is the $T_{amb} + 0.02256 \times G$ where T_c and T_{amb} are the cell and anti-temperature respectively. The rated power at reference condition as used in this work is 327 W, while the derating factor is 88%, the standard and incident solar irradiations are 1 kW/m^2 and 1 kW/m^2. The PV cell temperature (Tc) and standard PV cell temperature (Ts) are 0.35^{o}C and 25^{o}C respectively. The Tc was estimated by using equation (2)

$$T_c = T_a + G \times \left(\frac{T_{cnoct} - T_{anoct}}{G_{noct}}\right) \times \left(\frac{1 - PV_{efficiency}}{0.9}\right) \quad (2)$$

Where T_a is refer to as the atmospheric temperature, T_{cnoct} is nominal operating solar temperature with a value of 319.5^{o}C, T_{anoct} is the ambient temperature at normal operating temperature of 293^{o}C and the efficiency PV value was set as 0.214. The technical features related to the solar panel used on this work are as highlighted in table 3.1.

2.2.2 Modelling of the Small Hydro Power

The small hydro electrical power output is expressed as:

$$P_{SHP} = \eta_h \rho_{water} g H_{net} Q \quad (3)$$

Where, P_{SHP} is the turbine power output, η_h is the hydro efficiency, ρ_{water} is the density of water, g is the acceleration due to gravity, H_{net} is the effective head, Q is the flow rate. The hydro efficiency is set as 0.7, while the flow rate value used is 4280 kg/m^3. Parameters values used by [15] were also adopted in this work for the purpose of comparison.

2.2.3 Diesel Generator Model

The diesel generator helps convert energy from fuel to electrical energy with a conversion efficiency (η_D) that can be expressed as seen in equation (4).

$$E_{DG} = \eta_D \times \ total\ energy\ content \quad (4)$$

Furthermore, the model for the consumption rate of fuel in litres/hour of operation is expressed in equation (5). Where F_1 represents the intercept coefficient of the fuel curve, the slope of the fuel curve is illustrated with F_2, R_D represents the rated capacity of the diesel generator, while P_D depicts the generator's output at any given time.

$$F_c = \left((F_1 \times R_D) + (F_2 \times P_D)\right) \quad (5)$$

Furthermore, the diesel engine efficiency (η_D) was obtained using equation (6). The density of the fuel and LHV were assumed to be 820kg/m^3 and 43,200kJ/kg respectively. The values of the diesel generator parameters are as highlighted in table 3.1

$$\eta_D = \frac{3600 \times PD}{density \times F_c \times LHV} \quad (6)$$

The fuel cost can be expressed as:

$$C_{fuel} = C_{diesel} F(R_s) \quad (7)$$

Where C_{diesel} is the fuel price per litre*?*

2.2.4 Modelling of the Battery

In this research work, excess energy from the PV module is stored in the battery. The battery phenomenon is divided into two scenarios. Scenario 1, is when the total energy generated is greater than the total load demand. The excess power generated will be used to charge the battery. The battery bank capacity available at any time during this process can be expressed as:

$$C_{(t)} = C(t-1) - \eta_{batt} \left[\frac{P_B(t)}{V_{BUS}}\right] \Delta t \quad (8)$$

Where $C(t-1)$ depicts the battery capacity before increment, η_{batt} refers to the battery round trip efficiency, $P_B(t)$ is the power supplied, V_{BUS} is the bus voltage, Δt is the increment at time used. For scenario 2 where the required load from the consumer is greater than the energy generated from the renewable energy source, the battery will be used to supply the load energy. The discharging act of the battery can be described mathematically as seen in equation (9).

$$C_{(t)} = C(t-1) \times (1-\sigma) - \left(\frac{P_B(t)}{\eta_{inv}} - C_{(t)}(t)\right) \quad (9)$$

Where η_{inv} refers to the efficiency of the inverter and σ represents the battery self-discharge rate.

The power used by the battery is expressed as:

$$P_B(t) = E_g(t) - E_i(t) \quad (10)$$

$E_g(t)$ is the energy generated in that hour, $E_i(t)$ is the load that needs to be supplied.

2.2.5 Modelling of the Inverter

The inverter function in this work, is to link the AC and DC buses. Equation (11) helps determine the power output of the inverter.

$$P_{out} = P_{in} \eta_{inv} \quad (11)$$

Where P_{in} represents the power output of the inverter and the inverter efficiency was set at 95% while the required capacity of the inverter was calculated based on energy flow form DC to AC.

3. Analysis of the System

3.1 Loss of power supply probability

BESS is employed for viable performance of the hybrid system. The LPSP is implemented for a range of time 0 to T as expressed in equation (12) while the excess energy is calculated by equation (13). LPSP was calculated using the following equation.

$$LPSP = \frac{\sum_0^T P_{Load} - P_{pv} - P_{SHP} - P_{SOC_M}}{\sum_0^T P_{Load}} \quad (12)$$

$$Surplus\ Energy\ (SE) = \sum_0^T \frac{P_{Load} - P_{pv} - P_{SHP}}{P_{pv} + P_{SHP}} \quad (13)$$

3.2 System Costs Analysis

LCOE, replacement cost, initial cost and maintenance cost are used for the analysis.

3.2.1 Initial Cost

Several ways have been applied to calculate the system cost, for a system with configuration vector X, the total initial cost is given by equation (14).

$$C_{init} = X_1 * C_{init,pv} + X_2 * C_{init,DG} + \\ + X_3 * C_{init,battery} + X_4 * C_{init,SHP} \quad (14)$$

Where:
C_{init} = Total initial systems cost \$
$C_{init,pv}$ = Photovoltaic module unit cost in \$
$C_{init,DG}$ = Diesel generator unit cost in \$
$C_{init,battery}$ = Battery unit cost in \$
$C_{init,SHP}$ = Small Hydro unit cost in \$

3.2.2 Replacement cost

The replacement cost is also an important factor in the analysis since each component of the system has its own lifetime and calculated as follows:

$$C_{rep} = C_{unit} C_{nom} \sum_{i-1}^{N_{rep}} \left[\frac{1-f_o}{1+K_d}\right]^{\frac{N_t}{N_{rep}+1}} \quad (15)$$

Where:
C_{rep} = Present value of unit's replacement cost
C_{unit} = Unit component cost (\$/W)
C_{nom} = Nominal capacity (W) of the replacement
f_o = Inflation rate
K_d = Components interest rate
N_{rep} = Number of times the component is replaced

3.2.3 Maintenance cost

The operation and maintenance cost of the system component is analyzed as part of the system life cycle cost (LCC). These comprises of the operation and maintenance of PV, small hydro, DG and batteries. The value of the cost of maintenance and operation is calculated using equation (16).

$$C_{o\&m} = \begin{cases} C_{(o\,\&\,m)}\left(\frac{1+f_1}{Kd-f_1}\right)\left[1-\left(\frac{1+f_1}{1+k_d}\right)\right] for\ Kd \neq f \\ C_{(o\&m)0\times n}\ for\ Kd \neq f \end{cases} \quad (16)$$

3.2.4 Levelized cost of energy (LCOE)

The LCOE is used as measure for optimizing the system economically. The LCOE is expressed as:

$$LCE = \frac{CA_{total}}{Etotal} \quad (17)$$

Where $Etotal$ gives the total energy of the three sources.

3.3 Objective function and constraints

Minimization of the NPC was formulated as the objective function in this research. Equation (18) describes how the objective function was formulated. Where, $C_{A\text{-}P}$ represents the systems annualized capital cost, $C_{A\text{-}R}$ depicts the system's replacement cost and $C_{A\text{-}O\&M}$ is the system's operational and maintenance cost. CRF is the capital recovery cost whose value can be obtained using equation (18) where i (which is properly described in equation (19)) is the actual annual interest rate, f is the inflation rate, n is the number of years and $i^{'}$ represents the nominal interest rate.

$$MinNPC = \frac{C_{A-P} + C_{A-R} + C_{A-O\&M}}{CRF(\mathrm{i,n})} \quad (18)$$

$$CRF(\mathrm{i,n}) = \frac{i(\mathrm{I+i})^n}{(\mathrm{I+i})^n - 1} \quad (19)$$

$$i = \frac{i^{'} - f}{i + f} \quad (20)$$

Another critical criterion used for optimization of hybrid system configuration is the cost of energy (COE). The COE can be obtained using equation (21).

$$COE = \frac{C_{A-P} + C_{A-R} + C_{A-O\&M}}{annual\ energy\ saved} \quad (21)$$

Details of the different systems (both technical and financial) used in this research-work are highlighted in Table 1. While the project lifetime was set to be for twenty-five (25) years based on the highest component lifetime of the PV module which is twenty five years.

Number of batteries, PV, small hydro generator, diesel generator and inverter make up the decision variables subject to the following constraints:

$$N_{\min\_PV} \leq N_{PV} \leq N_{\max\_PV} \quad (22)$$

$$N_{\mathrm{min\_SHP}} \leq N_{SHP} \leq N_{\mathrm{max\_SHP}} \quad (23)$$

$$N_{\mathrm{min\_batt}} \leq N_{batt} \leq N_{\mathrm{max\_batt}} \quad (24)$$

$$N_{\mathrm{min,DG}} \leq N_{DG} \leq N_{\mathrm{max,DG}} \quad (25)$$

$$N_{\mathrm{min,Inv}} \leq N_{Inv} \leq N_{\mathrm{max,Inv}} \quad (26)$$

LPSP was considered in this research as the system reliability constraints. This can be expressed mathematically as:

$$LPSP \leq LPSP_{Desired} \quad (27)$$

The lower and upper limits of the desired variables as used in this work are highlighted in table 1.

Table 1. Data used for the components that make up the system

	Diesel Generator	SHP	PV Module	Inverter	Battery	Nominal Interest Rate	Inflation rate
Description	50/100 kW	22.00 kW	327 W	1 kW	6.91 kWh		
Capital Cost. ($)	370.00/kW	1k /kW	1300/kW	0.8k/unit	1.1k /unit	10%	2%
Replacement Cost. ($)	296.00 /kW	1k /kW	0	0.75k /unit	1k /unit		
O&M Cost. ($/yr)	0.05 /h	0.1k	20	20	10		
Lifetime. (yrs)	15,000 h	25.00	25	15	15		
Ni,min.	1	1	1	1	1		
Ni,max.	10	5.00	1000	200	200		

3.4 Dragonfly Algorithm

The dragonfly algorithm was used for sizing the hybrid system in order to minimize the NPC under a certain reliability (when LPSP is equal to zero). The objective function and constraints as illustrated in equation (18) to (27) ensure energy balance between the components that makes up the system. The dragonfly parameters are also set in MATLAB. The LPSP is calculated for each population.

4. Results

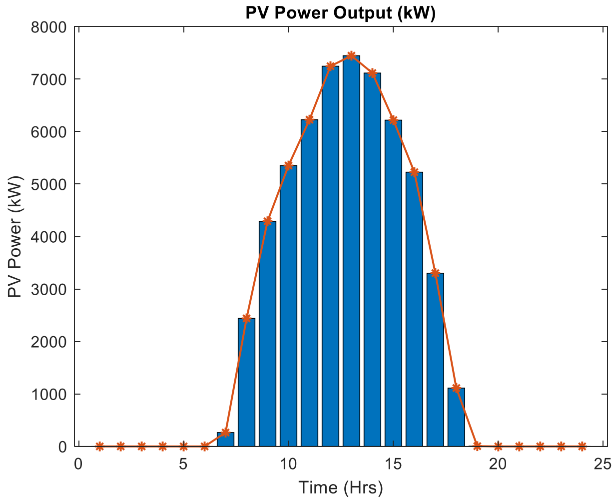
4.1 Results of the Developed Technique

The optimization of the hybrid system for proper sizing was done using drangonfly algorithm, which takes into account different configurations of the system (PV and battery only, only small hydro power, diesel energy generator and the hybrid system). Drangonfly algorithm helps size each configuration optimally while focusing on the cost in order to select the best scenario among the configurations. The optimization results from the proposed systems ae as seen in table 2.

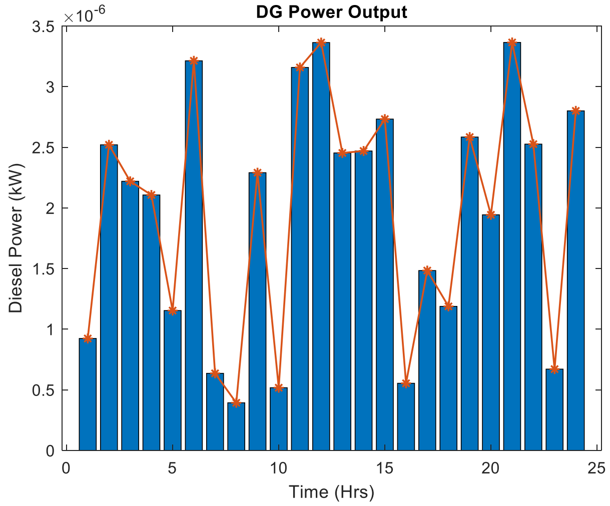
Table 2. Cost Analysis of the System's Components

Parameters	DA
Ppv	5.6259e+04
Pdg	5.2941e-05
Psh	5783600
Total Cost	5224500

Figure 2(a) and (b) show the plot of the PV power output (kW) against time obtained from the implementation of the developed scheme and the total power generated from the diesel generator



(a)



(b)

Fig. 2. Total Generated Power from (a) Solar PV and (b) diesel generator

It is observed from the figure that sufficient energy were generated at the early hours of the day by the diesel generator to compensate for the low energy generated by the solar PV at those periods. It was also observed that maximum energy was generated at time 12:00 hrs even though the solar PV generated at this time was also high. The reason for the high generation was because, of the maximum demand by the consumers at this period.

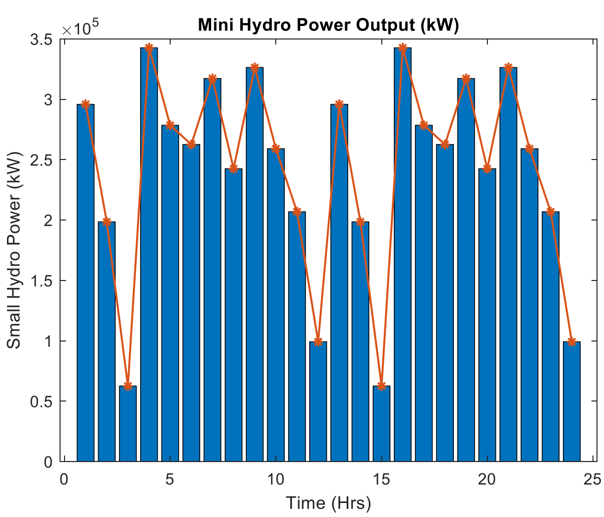


Fig. 3. Total Power Generated from Small Power Generator.

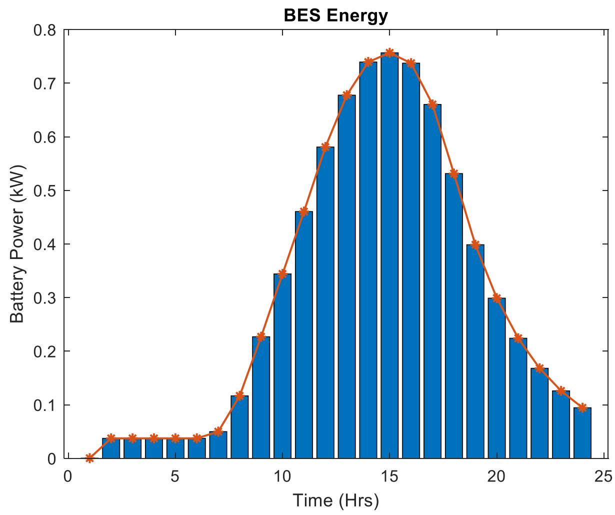


Fig. 4. BESS Power

The total power generated from the small hydro generator and the level of power supplied to the load from the battery energy storage system are as shown in Figure 3. Figure 4 shows the level of power supplied to the load from the battery energy storage system.

As expected, the amount of power supplied by this system is low (maximum energy being 0.75 kW) when compared to other sources. This is largely due to the fact that BESS is used as an alternative source of energy, and it gets its energy from the stored energy when the energy from other sources is above the maximum energy needed to power the load.

Figure 5 shows the total power generated by the different energy sources to meet the load demand. It is observed from the figure that each energy source (solar PV, DEG, small hydro and BESS) contributes effectively to generate the necessary power at any point in time to meet the load demand.

The economic importance of the developed scheme was evaluated using cost of energy. The cost considered include: initial capital cost, installation cost of equipment which was estimated as 10% of the other cost which vary from the different components as shown in table 1 and the insurance cost for the entire system cost. The total cost of energy was calculated from these input values and obtained as $5,224,500.

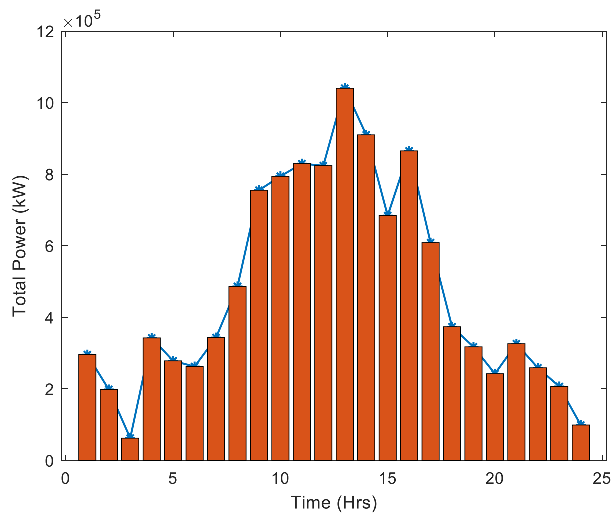


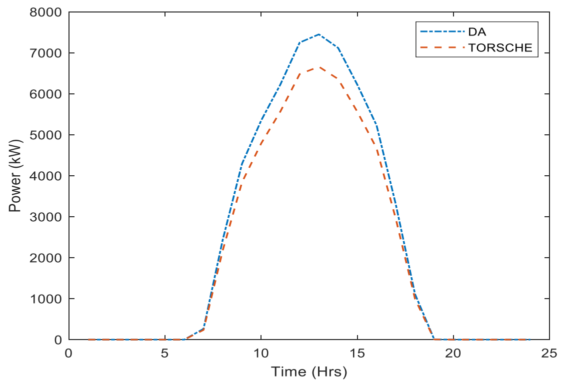
Fig. 5. Total Power Generated by the Energy Sources

4.2 Results Comparison

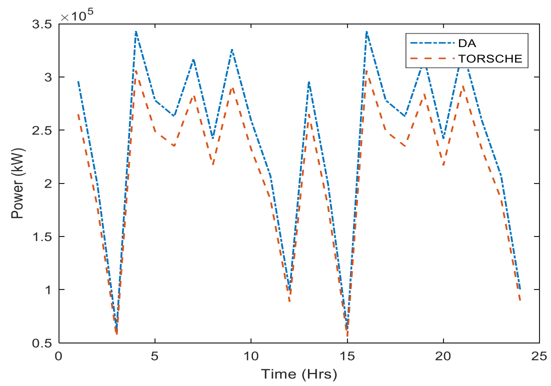
The results of the system using dragonfly algorithm for the optimization of the *hybrid system* were compared with those obtained when TORSCHE was used for the optimization based on the output power from the different energy sources and the LCOE.

The performance of the hybrid system using the dragonfly model and the TORSCHE model were evaluated using the figures 6 - 8. Table 3 also showed a comparison of the performance indices obtained from the system output of DA algorithm and TORSCHE.

The output of the power generated from solar PV and Power Generated from Small Power Generator when dragonfly algorithm and TORSCHE were used for the optimization is shown in Figure 6 (a) & (b).



(a)



(b)

Fig. 6. Power Generated form (a) Solar PV and (b) Power Generator

The total power output obtained from the solar PV when dragon fly was used is 5.6259*10^4 W, while that obtained from the TORSCHE algorithm was 50,295 W. this showed that the developed scheme was able to effectively optimize the system to extract maximum energy from the source.

Figure 6(b) shows the power generated from the small power generator when the two algorithm was used on the system separately. It was observed that the total power generated from the small power generator when dragonfly was used is 5,783,600 while that obtained from the TORSVHE algorithm is 5,175,600. This showed that the power output from the dragonfly optimized hybrid system generates more power than that of the TORSCHE.

Figure 7 illustrates the total power generated from the DG. It is observed from the figure that sufficient energy were generated at the early hours of the day to compensate for the low energy generated by the solar PV at those periods. This showed that both the techniques satisfactorily generated the power needed

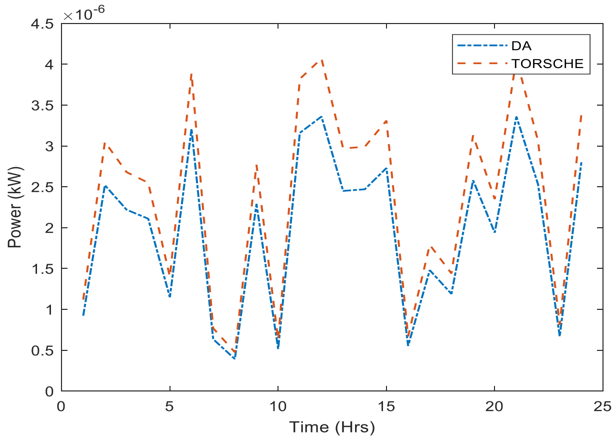


Fig. 7. Generated Power from Diesel Generator

To ascertain the effectiveness of the developed scheme, total cost of energy was used as performance metrics. The total cost obtained when the dragonfly algorithm model was used for optimizing the hybrid system was compared with the cost obtained when TORSCHE was used for the optimization. As seen in table 3, the total cost obtained from the developed scheme is $5,224,500 while that obtained from the TORSCHE model is $5,839,600. This showed that the developed scheme was able to minimize the cost of energy by 89.46% when compared with the cost obtained from the TORSCHE algorithm.

Table 3. Cost Analysis of the System's Components

Parameters	DA	TORSCHE
Npv (No of PV modules)	57	44
Nbt	62	53
Ndg	2	2
Nsh	2	2
Ppv	5.6259e+04	50295
Pdg	5.2941e-05	5.2083e-05
Psh	5783600	5175600
Total Cost	5224500	5839600

Figure 8 shows the convergence curve for the dragonfly algorithm and the TORSCHE algorithm. It was observed from the figure that both algorithms converges early. However, it was observed that the convergence of the dragonfly algorithm was more effective as it is done with less cost when compared with the TORSHE algorithm.

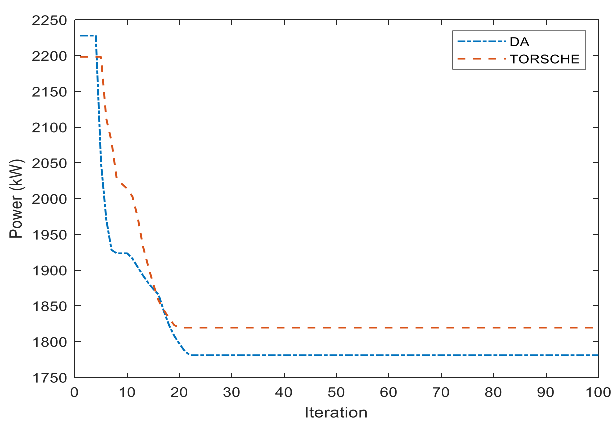


Fig. 8. Convergence Curves for DA and TORSHE Algorithm

5. Conclusion

This work presents DA metaheuristic approach to bring an optimal techno-economic sizing of stand-alone small hydro/PV/Diesel Generator hybrid system for sustainable power generation system. The developed scheme was implemented on a specific location (Kiri village in Shelleng Local Government area of Adamawa State) by collecting meteorological data from NIMET. The modelling of the system components was presented, while the optimal sizing of the hybrid system was done by employing drangonfly optimization technique. The optimal hybrid system was implemented in MATLAB 2018a and results obtained were compared with those obtained when TORSCHE technique was used for the optimization using total cost as the performance metrics.

From the analysis it was observed that for the developed scheme, the total cost of energy supplying the load was $5,224,500 while that obtained from the TORSCHE algorithm was $5,839,600. This showed that the developed scheme outperformed the system output from the TORSCHE algorithm in terms of cost of energy by 89.46%.

Acknowledgements
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