OPTIMIZATION OF SUSTAINABLE HYBRID MICROGRID FOR RURAL ELECTRIFICATION: TECHNO-ECONOMIC AND ENVIRONMENTAL PERSPECTIVES

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Abstract

The energy crisis problem in rural communities of developing countries is fast becoming a contemporary challenge to advancing global socioeconomic systems. Finding sustainable solutions for improving the energy supply to rural communities is significant. Thus, this paper presents the optimization of a hybrid microgrid with integrated energy components of Photovoltaic (PV) systems, Diesel Generators (DG) and Battery Energy Storage Systems (BESS). These energy components were configured and techno-economically investigated in three different scenarios of PV/BESS, PV/DG/BESS and DG only for load power supply to an isolated unelectrified Nigerian community. To the relevant decision factors, the chosen objective functions of the Deficit Power Supply Probability (DPSP), the Cost of Energy (COE), and the Net Present Cost (NPC) were minimized. In addition, new intelligent multi-objective computational methods such as Ant Colony Optimisation (ACO), Flower Pollination Algorithm (FPA), Genetic Algorithm (GA), and Particle Swarm Optimisation (PSO) were applied to handle the optimization problems. Based on the input techno-economic and meteorological data applied for the simulations, the best solution for the optimal sizing configuration was obtained by the PV/BESS through the FPA with the NPC value of $95,432.02, COE of 0.165 $/kWh and zero GHG emissions. A value of 1.72% DPSP was also obtained for the PV/BESS hybrid configuration. This indicates that unlike PV/DG/BESS and DG alone, PV/BESS is techno-economically viable for the electrification of the case study community.

Keywords: Renewable energy, Multi-objective optimization, Sizing configuration, Hybrid microgrid, Techno-economic analysis.

1. INTRODUCTION

The current pace in the growth of the human population and the ensuing soaring demand for electricity has promoted increasing demand for renewable energy (RE) (Amini et al., 2021; Kartite & Cherkaoui, 2019). In the present global socioeconomic development, sustainable access to electricity is one of the main pivots for a high standard of living. Over the years, the global electricity supply has immensely relied on fossil fuel consumption with damaging environmental consequences. This situation has redirected the focus of modern energy researchers to the development of reliable, richly available, and environmentally friendly Renewable Energy Technologies (RETs) (Madhura & Boddapati, 2022). Production of electricity through RETs results in zero emission of greenhouse gases (GHGs) and is consequently considered to be environmentally friendly (Sanajaoba, 2019). RETs create opportunities for reliable and clean energy for users, especially if energy systems are designed and integrated with sustainable energy technologies. A small-scale electric power system based on distributed generation (DG) is is a microgrid system (Mohammed et al., 2022). Conventional MG can use Renewable Energy (RE) generators or a mixture of renewable and non-renewable energy generators combined with storage systems for small power generation. There are different ranges of RETs such as solar energy, wind energy, hydropower, geothermal and biomass. Solar and wind energy have good naturally endowed replenishing potential, but unfortunately, they are environmentally weather sensitive. Therefore, it is important to integrate them with other generators or energy storage systems to eliminate the intermittency associated with their power output. There are many important benefits of an integrated Hybrid Energy System (HES) such as the reduction of emissions, promotion of energetic independence for rural communities, and provision of an economical energy system to off-grid communities. From a techno-economic perspective, the design and implementation of hybrid RE must be achieved in such a manner that the NPC, COE and power supply probability (PSP) are satisfactorily good, especially for rural energy customers.

The ideal techno-economic design of an independent HES for rural electrification has been the subject of numerous research studies. For example, a study was done on the best hybrid renewable energy microgrid architecture utilizing several algorithms (Muleta & Badar, 2023). To determine the best solution for the suggested hybrid system, the study used a variety of optimization techniques, including Differential Evolution (DE), Manta Ray Foraging Optimisation (MRFO), Particle Swarm Optimisation (PSO), Reptile Search Algorithm (RSA), and others. To tackle the techno-economic optimization difficulties of an integrated hybrid PV-diesel-battery storage system for the electrification of a rural village located in the southern part of Algeria, Yahiaoui et al. (2017) used a Grey Wolf Optimiser (GWO). Movahediyan & Askarzadeh (2018) used a Crow Search (CS) algorithm to build a PV/diesel hybrid power system that minimizes the system's net present value (NPC), reduces emissions, and minimizes the probability of power supply outage. The optimal sizing problem in a hybrid power system was solved using a Supply-Demand-based Optimisation (SDO) method (Alturki et al., 2021). the superiority of the SDO over the big-bang-big-crunch (BBBC), PSO, GA, and GWO algorithms for the ideal sizing configuration. Based on the minimization of the loss of power supply probability (LPSP) and annualized system cost (ASC), the efficacy of the optimal sizing SDO method was demonstrated. Additionally, a case study of Saudi Arabia was investigated in reference (Mas'ud & Al-Garni, 2021) to determine the best configuration for the sizing of a hybrid RE system, taking into account advanced battery storage units, depending on characteristics spanning many years. Over the hybrid power system's planned 25-year lifespan, it was discovered that the elements of multi-year input and battery deterioration parameters had a noticeable impact on the output of energy production. Fodhil et al. (2019) used a PSO optimization algorithm to conduct a techno-economic feasibility analysis of hybrid PV/diesel/battery storage for the electricity of a rural hamlet in Algeria. Hybrid Optimisation of Multiple Energy Resources was used to perform a comparative examination of the outcomes produced by the PSO algorithm (HOMER). The techno-economic optimization outcomes produced by the PSO algorithm were the best. In light of the presentations made thus far, the following are the primary contributions of this paper:

- Optimal design configuration of hybrid PV/diesel/battery microgrid for the load satisfaction of a rural community in Nigeria.
- Application of various multi-objective algorithms based on the minimisation of NPC and COE for the techno-economic optimisation of the suggested hybrid MG.
- Optimal design of hybrid energy systems considering the total greenhouse gas emissions and reliability by the evaluation of deficit power supply probability (DPSP).
- Comparative analysis of the different multi-objective algorithms based on multiple-choice optimization solutions of the different hybrid configurations of the microgrids.

The successive sections of this paper are made up of problem formulations presented in section 2. In section 3, the paper presents the mathematical modeling of the energy components, while section 4 gives a summary of the benefits of the multi-objective optimization algorithms used in the study. The description of the study location and the load profile are presented in section 5. Simulation results and discussions based on the findings as well as the sensitivity analysis are presented in section 6. The paper concluded with the presentation of key findings in section 7.

2. Problem Formulation

The problem formulation based on the collection of research objective functions is presented in this section. The integration of PV, DG, and BESS is taken into account in the proposed hybrid power system.

2.1 Objective Function

The following is the expression for the optimization problem's objective function:

$$\mathrm{Min}\,[\mathrm{NPC}, \mathrm{COE}, \mathrm{DPSP}, \mathrm{TE_{GHG}}]$$

where $\mathrm{TE_{GHG}}$ is the total emission of greenhouse gases. To minimise the objective function given in the previous Eq. (1), a few crucial boundaries must be established.

2.1.1 Generation Unit Constraints

The constraints imposed based on the generated power (P_G) capacity of the participating generators in the hybrid power system can be expressed as follows:

$$P_G = \begin{cases} P_{PV\_minimum}(t) \le P_{PV}(t) \le P_{PV\_maximum}(t) \\ P_{DG\_minimum}(t) \le P_{DG}(t) \le P_{DG\_maximum}(t) \end{cases} \tag{2}$$

where $P_{PV\_minimum}$ = minimum amount of PV power generated at time t, P_{PV} = the required solar PV power generated, $P_{PV\_maximum}$ = maximum amount of PV power generated, $P_{DG\_minimum}$ = minimum power generated by the DG, P_{DG} = generated DG power at time t and $P_{DG\_maximum}$ = maximum power produced by the DG.

2.1.2 Variable Component Capacity Constraints

In a hybrid power system, a number of components are required to be combined to produce the amount of electricity needed for the satisfaction of the load demand by the customers. The constraints in the number of components (N_{PC}) for the optimal sizing of the proposed hybrid microgrid can be expressed in Eq. (3):

$$N_{PC} = \begin{cases} 0 \le N_{PV} \le N_{PV\_maximum} \\ 0 \le N_{INV} \le N_{INV\_maximum} \\ 0 \le N_{BESS} \le N_{BESS\_maximum} \\ 0 \le N_{DG} \le N_{DG\ maximum} \end{cases} \quad (3)$$

where N_{PC} = the number of components for sizing the hybrid systems. N_{PV}, N_{INV}, N_{BESS} and N_{DG} represent the number of the required PV, inverter, BESS and DG.

2.1.3 Demand-Supply Constraint

At any given time, it is expected that the total power supply $P_S(t)$ equates to the power demand $P_D(t)$, and thus yields a power demand and supply balance as expressed in Eq. (4).

$$P_S(t) = P_D(t) \quad (4)$$

In a situation where this is not achievable, a power deficit or surplus may exist.

Power surplus (P_{Surp}) condition:

$$P_S(t) > P_D(t) = P_{Surp} \quad (5)$$

Power deficit (P_{Def}) condition:

$$P_S(t) < P_D(t) = P_{Def} \quad (6)$$

2.1.4 Battery Constraints

Constraints in the usage of BESS depend on the state of charge $\mathrm{SOC(t)}$ at a given time and the depth of discharge (DOD). Therefore, the $\mathrm{SOC(t)}$ is mathematically related to the minimum state of charge ($\mathrm{SOC_{min}}$), maximum state of charge ($\mathrm{SOC_{max}}$) and the DOD as follows:

$$\mathrm{SOC_{min}} \le \mathrm{SOC(t)} \le \mathrm{SOC_{max}} \quad (7)$$

$$\mathrm{SOC_{min}} = (1 - \mathrm{DOD}) \times \mathrm{SOC_{max}} \quad (8)$$

3. Techno-Economic Modelling of the Proposed Hybrid System

The structural configuration of the proposed hybrid microgrid is shown in Figure 1 with the PV and DG as the main energy generators. The system is integrated with BESS for energy backup in case of P_{Def}. Primarily, the system power supply is expected to be met using the electricity generated by the PV while the DG is to act as the secondary standby power supply system. A combination of AC and DC bus with power electronic inverters is required for the utilization of power generated by the hybrid system. Therefore, the mathematical modelling of the power components is presented in the subsections below.

3.1 Modelling of Solar PV System

Solar energy from sunlight can be exploited for the production of electricity through various modern solar energy techniques. However, the focal technology in this present study is based on the application of solar photovoltaic panels for electricity generation. The mathematical expression of PV power performance is shown in Eq. (9) (Jumare et al., 2020) and the module working temperature $T_c(t)$ (Mohammed et al., 2022) is presented as follows:

$$P_{PV} = Y_{PV} D_{PV} \frac{G_r}{G_R} [1 + \tau (T_c(t) - T_o)] \quad (9)$$

$$T_c(t) = T_A(t) + [0.0256 + G_r] \quad (10)$$

where Y_{PV} = rated capacity of the solar PV under the standard test condition (25^oC) in kW

D_{PV} = is the derating factor, G_r is the solar hourly irradiance (kWh/m^2)

G_R = solar radiation at the reference point given as 1 kW/m^2

$T_c(t)$ = module working temperature (^{o}C)

T_o = reference temperature (25^{o}C)

$T_A(t)$ = ambient temperature at any given time t

τ = constant known as temperature coefficient of power

Therefore, the total electric power (P_{PV_Total}) generated by a given number of PV (N_{PV}) can be calculated using Eq. (11):

$$P_{PV\_Total} = N_{PV} \times P_{PV} \quad (11)$$

3.2 Modelling of the Diesel Generator

The PV panels, which are the main energy source in the suggested hybrid system, are primarily dependent on the local weather where they are installed. Environmental constraints imposed by cloudy weather conditions affect the output power produced by the PV. This could lead to a deficit power supply that needs to be catered for to satisfy the electric power supply to the customers. Therefore, the integration of the DG system with the PV for a stable and reliable power supply becomes an ideal option. Unlike the PV generator, DG provides a continuous power supply with the potential to operate at full load capacity. The operation of a DG depends on its rated power (Onyegbadue et al., 2022) as presented in Eq. (12). The lifespan of the DG used in this study is taken to be 10 years and the presented estimated cost of diesel fuel in Nigeria is \$1.7/L. The generator loading ratio was assumed to be 20% (Mohammed et al., 2022).

$$CF_{C-DG} = C_\xi \sum_{t=1}^{8760} [\alpha P_{DG}(t) - \beta P_{rated}] \quad (12)$$

where CF_{C-DG} = cost of DG fuel consumption, C_ξ = cost of fuel per liter, $P_{DG}(t)$ = output generated power at time t, P_{rated} = DG rated power, Where α (l/kWh) and β (l/kWh) are the coefficients of fuel consumption curve typically given by the generator manufacturer. The values for α = 0.246 l/kWh and β = 0.08145 l/kWh (Mohammed et al., 2022).

3.3.1 Modelling of Battery Energy Storage System

BESS especially the secondary batteries, has favourably been used in hybrid RE systems providing electricity to rural communities and energy-demanding facilities in off-grid locations. Their ability to be recharged easily has constituted their economic viability for small-scale off-grid electricity production with reliable energy efficiency. BESS exhibits some kind of dynamic situations that rely on their SOC(t). The dynamic modelling of BESS fluctuates between the charging and discharging conditions of the storage system as given in Eqs. (13) – (16) (Hatata et al., 2018).

(i) Charging condition:

$$P_{PV}^{T}(t) > P_L(t) \tag{13}$$

$$P_{BESS}(t) = P_{BESS}(t-1) \times (1-\sigma) + \left[\left(P_{PV}^{T}(t) - \frac{P_L(t)}{\eta_{INV}} \right] \eta_{BESS} \tag{14}$$

(ii) Discharging condition:

$$P_{PV}^{T}(t) < P_L(t) \tag{15}$$

$$P_{BESS}(t) = P_{BESS}(t-1) \times (1-\sigma) + \left[\frac{P_L(t)}{\eta_{INV}} - \left(P_{PV}^{T}(t) \right] \eta_{BESS} \tag{16}$$

where $P_{BESS}(t) =$ BESS power at time t, $P_{BESS}(t-1) =$ BESS power at $t-1$, $\sigma =$ battery self-discharge rate (%), $\eta_{BESS} =$ BESS charging efficiency (%) and $P_{PV}^{T}(t) =$ total generated power by the PV at t.

3.4 Modelling of the Converter

Inverters are important equipment for the conversion and usage of PV power. They usually represent the smallest part of the total investment cost in a hybrid microgrid, but they are very essential for the operation of a power system containing a blend of AC and DC load. The inverter model used in this study shown in Eq. (17) was presented by Hemeida et al. (2020):

$$P_L = P_{INV} \times \eta_{INV} \tag{17}$$

The required number of inverter (N_{INV}) can be calculated as follows:

$$N_{INV} = \frac{P_L}{P_{INV}} \tag{18}$$

where $P_L =$ peak load power and $P_{INV} =$ power rating of the inverter.

3.5 Modelling of Emission of Greenhouse Gases (GHGs)

Emissions of GHGs from fossil fuel power plants bring environmental challenges in the context of sustainable development. The basic purpose of utilizing RE is to create access to environmentally sustainable energy. It is however an acknowledged fact that a hybrid power system integrating RE power system and DG produces environmental emissions based on the frequency of usage and the power capacity of the power plant. The main component gases of the GHGs from the operation of a DG power plant are carbon dioxide (CO_2), oxides of nitrogen (NO_X) and Sulphur dioxide (SO_2). Emissions of these GHG gasses can be modeled as shown in Eq. (19) (Maleki et al., 2017):

$$TE_{GHG} = min\left(\sum_{t=1}^{8760} (\pi CO_2 + \pi SO_2 + \pi NO_X) * P_{DG} \right) \tag{19}$$

3.6 Cost Modelling of the Hybrid Power System

The cost modeling of a hybrid power system has two basic components of NPC and COE. The NPC is the lifecycle cost of the hybrid power system over its specified lifetime, while the COE depends on the average value of the NPC. These costs can be modeled through the investment cost (C^{IT}) of the energy components, replacement cost (C^{RP}) and operation and maintenance cost (C^{OM}). The mathematical modeling of the NPC of the proposed hybrid system is given by Eqs. (20) – (24) (Fathy et al., 2020). The lifetime of the project $n = 25$ years and the annual interest $i = 6\%$ are used in this study in accordance to the work presented by Mas'ud & Al-Garni (2021).

$$\text{NPC} = [C^{IC} + C^{OM} + C^{RP}]$$

$$\text{NPC}_{PV} = N_{PV}\left[C_{PV}^{IT} + C_{PV}^{IC} + C_{PV}^{OM}\left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) \right] \tag{21}$$

$$\text{NPC}_{DG} = N_{DG}\left[C_{DG}^{IT} + C_{BP}^{IC} + C_{DG}^{OM}\left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) + C_{DG}^{RC} \times \sum_{k=1}^{\left(\frac{n}{n_{DG}}-1\right)} \left(1 + \frac{1}{(1+i)^{kn_{DG}}} \right) \right] \tag{22}$$

$$\text{NPC}_{BESS} = N_{BESS}\left[C_{BESS}^{IT} + C_{BESS}^{IC} + C_{BESS}^{OM}\left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) + C_{BESS}^{RC} \times \sum_{k=1}^{\left(\frac{n}{n_{BESS}}-1\right)} \left(1 + \frac{1}{(1+i)^{kn_{BESS}}} \right) \right] \tag{23}$$

$$\text{NPC}_{INV} = N_{INV}\left[C_{INV}^{IT} + C_{INV}^{IC} + C_{INV}^{OM}\left(\frac{(1+i)^n - 1}{i(1+i)^n} \right) + C_{INV}^{RC} \times \sum_{k=1}^{\left(\frac{n}{n_{INV}}-1\right)} \left(1 + \frac{1}{(1+i)^{kn_{INV}}} \right) \right] \tag{24}$$

$$\text{NPC}_T = \text{NPC}_{PV} + \text{NPC}_{DG} + \text{NPC}_{BESS} + \text{NPC}_{INV} \tag{25}$$

Where $\text{NPC}_T =$ total net present cost, $\text{NPC}_{PV} =$ net present cost of PV, $\text{NPC}_{DG} =$ net present cost of DG plant, $\text{NPC}_{BESS} =$ net present cost of BESS and $\text{NPC}_{INV} =$ net present cost of the inverter unit.

The expression for the COE which depends on the capital recovery factor (CRF) as given by (Mohammed et al., 2022) and shown in Eqs. (26) and (27) respectively.

$$\text{COE} = \frac{\text{NPC}_T}{\sum_{t=1}^{8760} P_L} \times \text{CRF} \tag{26}$$

$$\text{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{27}$$

3.7 Deficit Power Supply Probability

In a hybrid power system utilizing a RE, there is a likelihood that the total energy demand may not be supplied at all times due to the impact of stochastic weather conditions. Subsequently, the concept of DPSP, which is the probability index representing the power supply situation, becomes a very important factor. The typical extreme values of DPSP are 0 (electricity demand is completely supplied) and 1 (electricity demand is completely not supplied to the customers). A value of the probability between 0 and

1 indicates that only a portion of the electricity demand is supplied. The evaluation of the DPSP of the hybrid power system is presented in Eq. (28):

$$\text{DPSP}(t) = \sum_{t=1}^{8760} \frac{[P_L(t) - P_{PV}(t) + P_{DG}(t)]}{P_L(t)} \quad (28)$$

4. Optimization Algorithms

Traditionally, optimization algorithms were applied for solving challenging problems using the set of desirable inputs to a given objective function for minimization or maximization of functional evaluations. There are various commonly used optimization algorithms in the collection of scientific problem-solving optimization procedural codes. In most cases, selecting the appropriate algorithm from the hundreds of existing algorithms could be troublesome.

In this study, four different emerging optimization algorithms of Ant Colony Optimization (ACO) (Ahmed et al., 2020; Dorigo & Stützle 2019; Moghaddam et al., 2019; Rossoni et al., 2022), Flower Pollination Algorithm (FPA) (Fares et al., 2022; Ram et al., 2020), Genetic Algorithm (GA) (Fan et al., 2022; Wang et al., 2022), and Particle Swarm Optimization (PSO) (Akhter et al., 2022; Muhammad et al., 2022; Wang et al., 2018) are used for comparing the various optimal solutions to obtain the most reliable techno-economic solutions. The flowcharts of the selected optimization algorithms are shown in Figure 2 – 5.

5. Study Location and the Load Profile

An off-grid rural community, Ogule, was selected for this study. The choice was made for the study based on the absence of electricity supply to the rural community, which is located in the Loko district of Nasarawa State, Nigeria. Loko has geographical information of 7º 59' 56'' N and 7º 50' 26'' E.

The major occupational activities of the inhabitants of the rural community are based on subsistence farming and the rearing of animals. The details of the electrical load profile of the community are presented as shown in Figure 6. There are about 52 households located in the community with various electricity needs for domestic load appliances and operation of community facilities such as the primary healthcare center, water pump and electricity for the school. Additionally, load demand for small commercial shopping activities was considered. The estimated daily load profile from the lowest value of 5 kW to a peak value of 22 kW is shown in Figure 6. The average monthly solar radiation of the study area is presented in Figure 7.

6. Simulation Results and Discussion

Computer-based simulations performed through different optimal hybrid microgrid configurations of PV/BESS, PV/DG/BESS and DG only produced different techno-economic results. Since the case study area has no access to the national grid due to geographical and economic constraints, therefore, electrification of the community with off-grid hybrid energy solutions is a key option. The simulations were conducted with the application of different hybrid optimization algorithms in MATLAB simulation environment with via input techno-economic and meteorological data. The simulation parameter values and the techno-economic input data of the energy components applied are presented in Table 1-5. The simulations were conducted for 50 iterations, and the time of executions was keenly noted. The three systems evaluated based on the minimization of costs have different NPC and COE.

The evaluated costs are subject to different functional costs such as the initial cost of the energy generator, cost of auxiliary energy components, installation cost, component replacement cost and maintenance and ruining cost.

Table 1: Useful parameters and values of the selected algorithms

Algorithms	Parameters	Values
ACO	Population size	100
	Pheromone persistence coefficient	0.8
PSO	Swarm	100
	Inertia weight	1
	Cognitive constant	0.25
	Social constant	1.75
FPA	Number of flowers	100
	Probability switch	0.5
GA	Population	100
	Selection	Roulette wheel
	Mutation	0.2
	crossover rate	0.8

Table 2: Techno-economic specifications of the PV system

Parameters	Values
P_{PV}	500 W
Lifetime	20 years
Capital cost	$3800/kW
Replacement cost	-
Derating factor	90%
O&M cost	$20/year

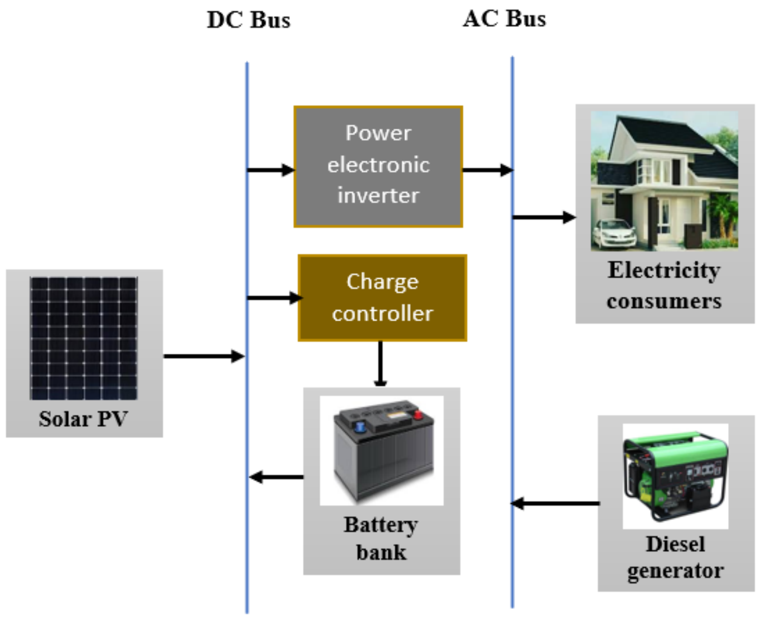

Figure 1: Integrated hybrid microgrid solar PV/DG/BESS

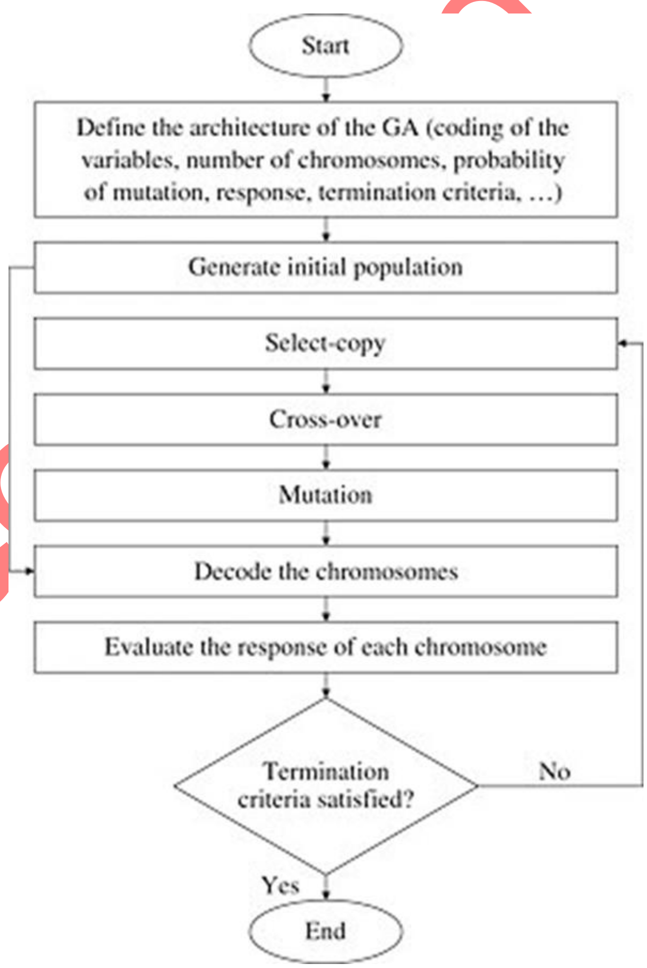

Figure 2: Flowchart of the optimization of the hybrid power system through Genetic Algorithm (Niazi & Leardi, 2012)

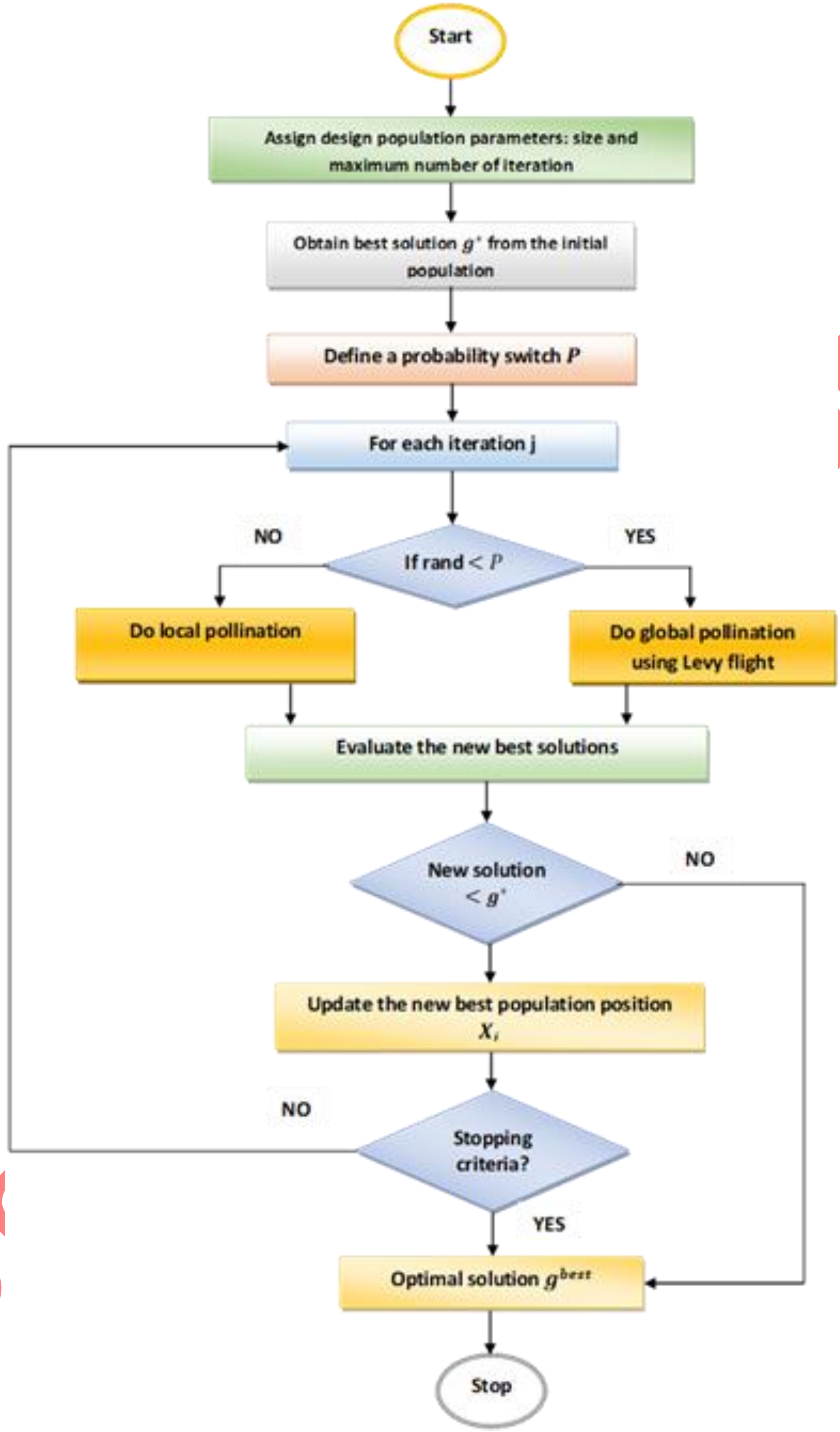

Figure 3: Flowchart of the Flower Pollination optimization of the hybrid power system (Mohammed et al., 2022)

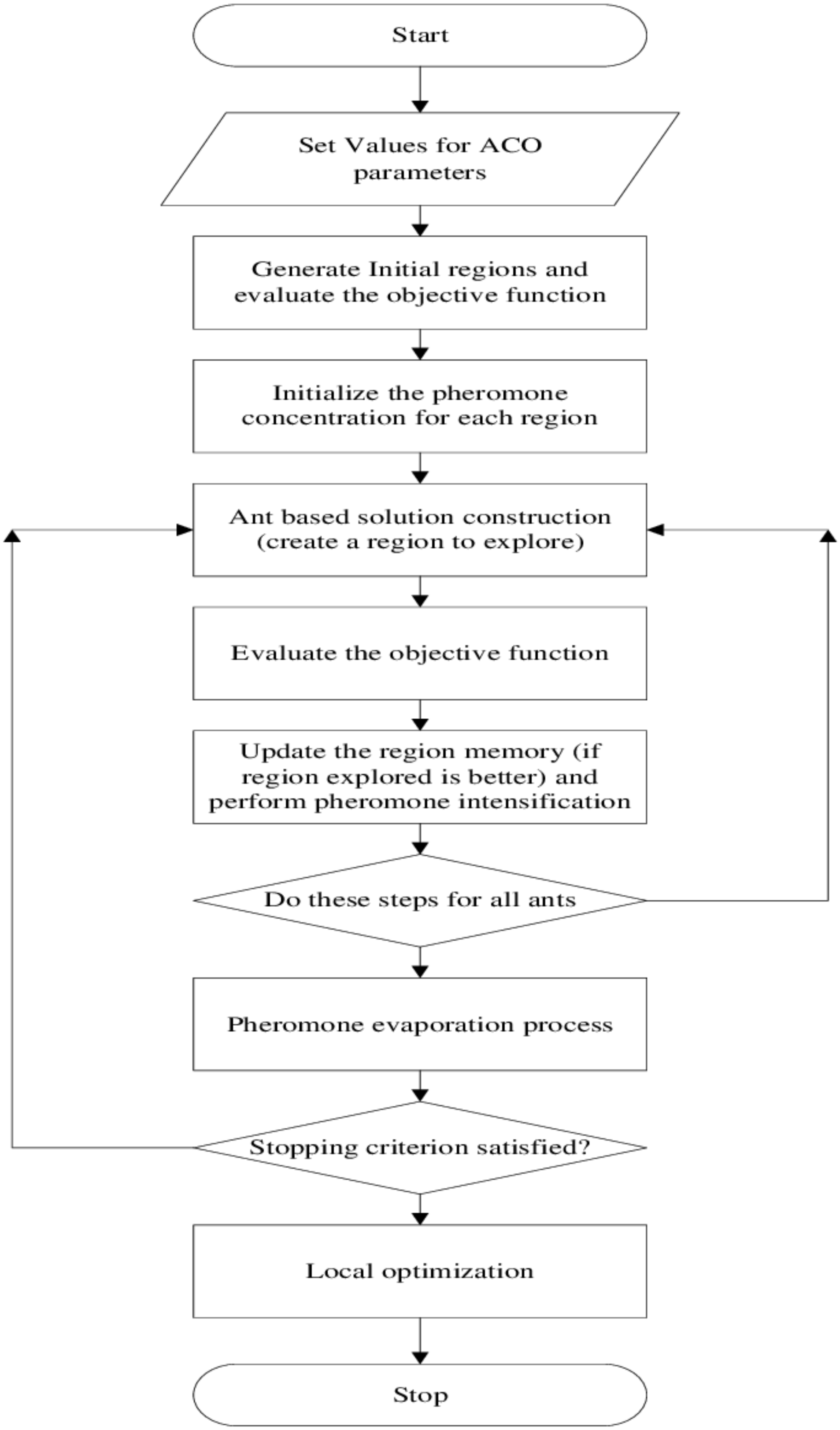

Figure 4: Ant Colony Optimization (ACO) procedural flowchart of the proposed hybrid power system (Khanna et al., 2015)

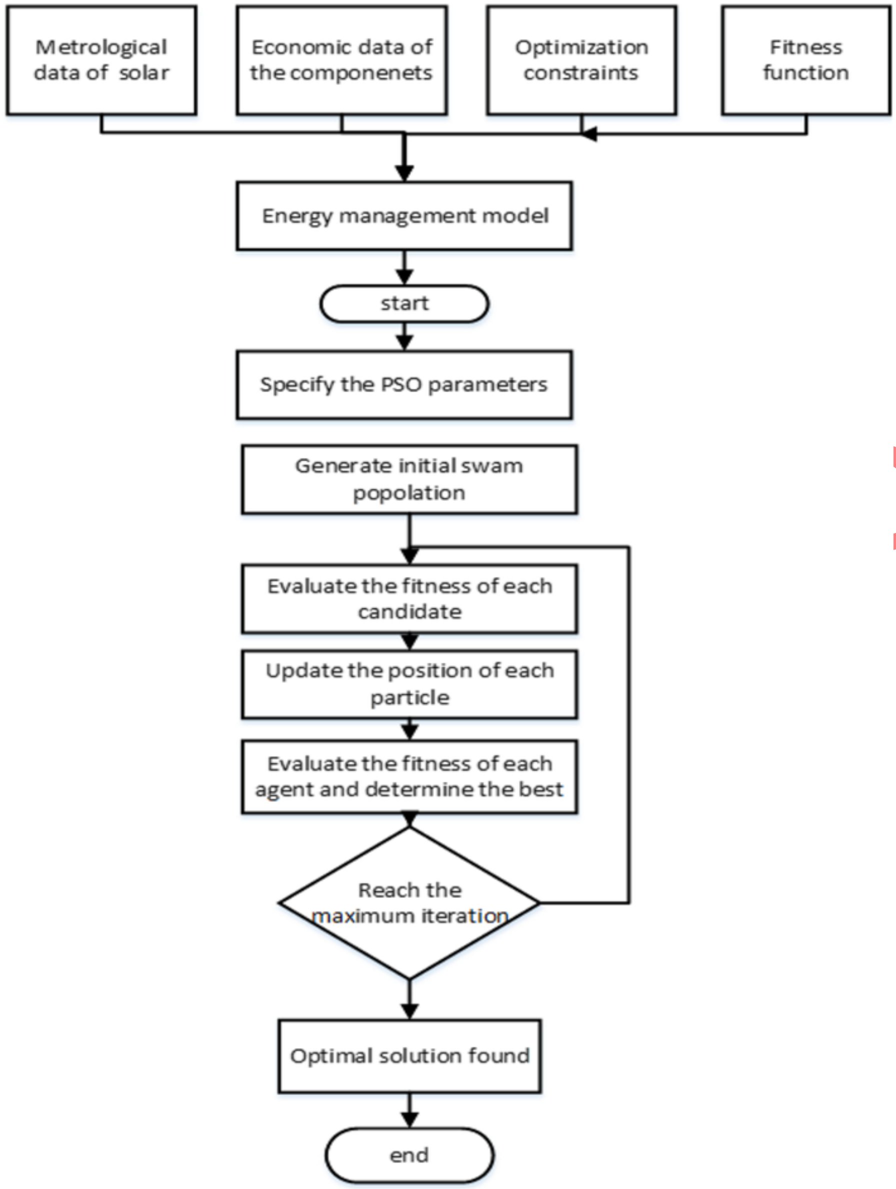

Figure 5: Structural flowchart of the Particle Swarm optimization algorithm of the hybrid microgrid optimization (Kamal et al., 2022)

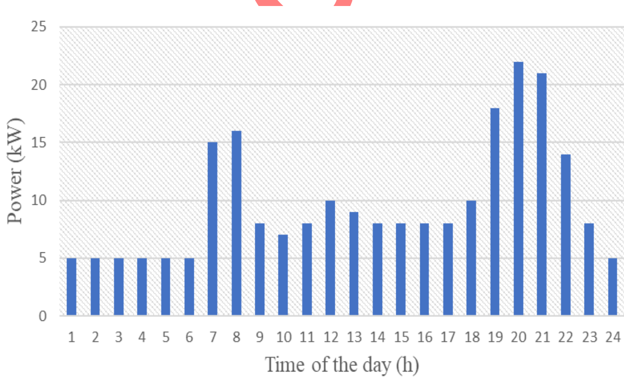

Figure 6: Daily load profile of the study area (Mohammed et al., 2022)

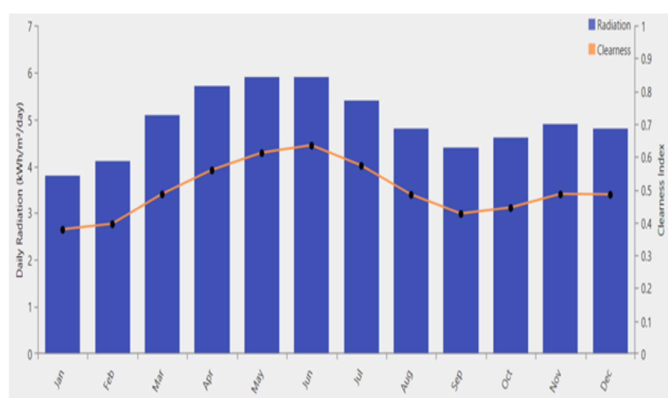

Figure 7: Average monthly solar radiation (NiMET, 2021)

Table 3: Techno-economic specifications of the BESS

Parameters	Values
Battery type	Lead acid
Battery capacity	200 Ah
Nominal voltage	24V
Charge efficiency	90%
Minimum state of charge	40%
DOD	0.2
Lifetime	10 years
Capital cost	$200/unit
Replacement cost	$200/unit
O&M cost	$10/year

Table 4: Techno-economic specifications of the inverter system

Parameters	Values
Rated power	10 kW
Phases	3
Efficiency	0.95
Operational lifetime	10 years
Capital cost	$500
Replacement cost	$500
O&M cost	$10/year

Table 5: Techno-economic specifications of the DG system

Parameters	Values
Rated power	5 kW
Efficiency	0.95
Initial capital cost	1000 $/kW
Replacement cost	1000 $/kW
Annual O&M cost	0.014 $/kWh
Fuel cost	$1.7/kW

6.1 Techno-economic Results of the Hybrid Configurations

Hybrid Configuration I: The configuration scheme of the proposed hybrid microgrid consists of PV/BESS. Computation of the optimal solutions through the imposition of the algorithms of ACO, FPA, GA and PSO is shown in Table 6. The simulations for each of the algorithms were executed and repeated for 50 runs. It is noted from the results presented in Table 6 that the lowest NPC and COE of $95,432.02 and 0.165 $/kWh, respectively, were both generated by the FPA optimization technique. In addition, the simulations conducted by the algorithm of the FPA were also the fastest to accomplish the optimal sizing solutions. The stated performance of the FPA optimization technique was followed by the PSO, ACO and GA. The component configuration in this scenario gives 35 solar PV, 22 batteries, and 5 units of the inverter. The DPSP for each of the algorithms is 2.00%, 1.72%, 2.42% and 1.89% respectively, for ACO, FPA, GA and PSO. The DPSP of value 1.72% obtained by FPA is the lowest generated among the four optimization algorithms and it is techno-economically reasonable for a rural community.

Hybrid Configuration II: In Table 7, the hybrid configuration consists of PV, DG and BESS. This proposed hybrid microgrid configuration was also simulated with the four algorithms explored in this study. By all indications, the NPC and COE of this system is higher than that of PV/BESS. However, the NPC and COE obtained in this hybrid configuration through the four optimization algorithms are generally higher due to additional required components compared to the PV/BESS system. In this case, grid power quality can be assured by this hybrid design configuration, especially during the night time when the sun is not available. This consequently results in zero DPSP in all the results generated by the optimization algorithms. In this second hybrid system configuration of PV/DG/BESS, the best techno-economic result is still offered by the FPA algorithms. In this case, the NPC and COE generated by the FPA are $97,134.00 and 0.171$/kWh respectively. The next techno-economically viable option was generated by the PSO optimization technique, which correspondingly has NPC and COE of $98,428.00 and 0.189 $/kWh. Interestingly, in all the results produced by the four optimization techniques, the values of the DPSP = 0.00% indicate that the overall energy demand by the electricity customers can be satisfied by the configuration of PV/DG/BESS without any expected deficit.

Hybrid Configuration III: Table 8 displays the techno-economic outcomes of the configuration for the DG-only system. In this scenario, emissions are higher compared to the other two hybrid configurations. This can be attributed to the excessive consumption of diesel fuels, but by the load demand satisfaction, the system can meet up the expectations since DPSP = 0.00% as shown in Table 8. However, this system is uneconomical compared to other configurations due to the high NPC and COE. For example, the optimization results through FPA give NPC value of $147,834.20 and COE of 0.275$/kWh. This cost of electricity of 0.275$/kWh presented by the use of DG alone for electricity supply to the rural community represents approximately 38% and 40% increase in the COE obtained by PV/BESS and PV/DG/BESS configurations, correspondingly. In addition, it was found that the total cost of the power equipment of DG alone represents just 3.6% while the remaining 96.4% represents the price of fuel for the 25 years lifetime of the proposed project. This system of DG alone therefore, presents the worst economically performing system in the optimization for electrification of the case-study rural community.

6.2 Environmental GHG Emissions

As an integral part of this study, the estimation of GHG emissions was accomplished in line with the global quest for savings in ecological contamination orchestrated by poisonous gases. Conducting a study on the hybrid integration of renewable and non-renewable energy systems requires the estimation of the emission capability of such a power system since that can be related to the global warming potential.

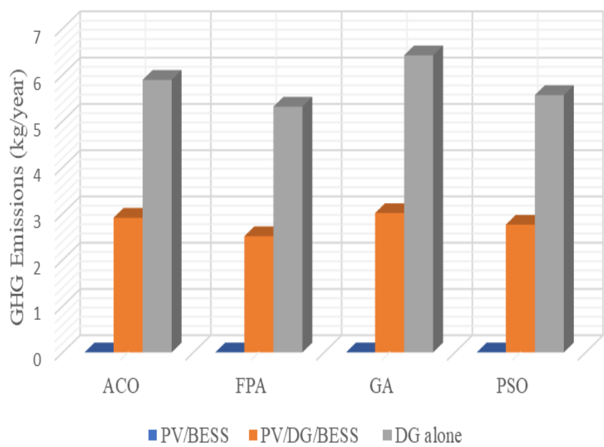

Figure 8: Comparative emission analysis of the hybrid system configurations

Two of the three scenarios investigated which are PV/DG/BESS and DG alone configuration emit a certain amount of GHG gasses as presented by the optimization results. The combustion of fossil fuel by the DG produces emissions that contain a variety of different environmentally poisonous gasses such as the oxides of carbon, nitrogen and sulphur, and usually a small quantity of unburned hydrocarbon and particulate matter. The case of PV/BESS emits zero GHG due to the absence of fossil fuel consumption as shown in Figure 8. However, the DG alone configuration emits the highest total emissions with the GA optimization technique leading with 6.42 kg/year while FPA shows the lowest of 5.31 kg/year. In the PV/DG/BESS hybrid configuration, the emission results generated by the four optimization algorithms are 2.91 kg, 2.51 kg, 3.01 kg and 2.76 kg, respectively, for ACO, FPA, GA and PSO per annum. This demonstrates that by reducing fuel usage, adding PV to a DG system might potentially lower GHG emissions when compared to the emissions emitted by the other two systems (PV/DG/BESS and DG only).

6.3 Convergence Features of the Optimization Algorithms

The convergence appearances of the four algorithms applied in this study are shown in Figure 9. The algorithms exhibit different speeds of convergence in their computation for the attainment of their optimal results. Based on the performances presented in terms of the speed of execution of the optimization to attain the optimal solution and effectiveness of the algorithms for cost reduction function, the FPA has demonstrated its effective and robust optimization capability over other algorithms used in this study. That of the PSO and ACO trailed the FPA's performance. The minimum convergent speed was demonstrated by the GA optimization technique. Therefore, the multi-objective optimization superiority and computational efficacy of the FPA over the other selected algorithms used in this study have been demonstrated.

6.4 Sensitivity Analysis on the Impact of DOD on the Energy Component and Cost Indices

This section presents the results of the sensitivity analysis that was done to look into how changes in Depth of Discharge (DOD) impact the sizing optimization of hybrid power systems. Tables 9 and 10 show the outcomes of adjusting the DOD with respect to the energy components of the hybrid PV/BESS and PV/DG/BESS, respectively. It was observed that the number of some components changed while some remained unchanged. The change in the number of some components altered the NPC and COE of the hybrid systems. Furthermore, the NPC and COE, as well as the reliability constraints of the hybrid systems, increase with the increase in the percentage of DOD.

6.5 Sensitivity Analysis Based on Changing cost of Diesel Fuel

The sensitivity analysis conducted in this subsection deals with investigating the impact of the rise in the cost of diesel fuel on the NPC. This analysis was conducted on the optimum system configuration of PV/DG/BESS. The initial diesel fuel price of $/1.7L was used for the simulations, but subsequently, for the sensitivity analysis, $2.0/L, $2.3/L, $2.6/L, $2.9/L and $3.2/L were used. The results obtained showed that increasing the diesel fuel price correspondingly increases the NPC of the optimal hybrid system as illustrated in Figure 10. It was noted that the rise in the cost of diesel fuel is proportionally linear. For instance, a linear increment of 0.6% of the NPC is produced when the price of fuel is raised from $2.0/L to $2.3/L.

6.6 Sensitivity Analysis Based on Varying Solar Irradiation

The upward varying impact of solar irradiation on the NPC of the optimal hybrid configuration of PV/BESS and PV/DG/BESS is presented in Figure 11. By increasing the average solar irradiation from 4.95 kWh/m2/day to 6.15 kWh/m2/day through 5.15 kWh/m2/day, 5.35 kWh/m2/day, 5.55 kWh/m2/day, 5.75 kWh/m2/day and 5.95 kWh/m2/day, the sensitivity analysis revealed a general decrease in

NPC as shown in Figure 7. The results obtained can be justified by the fact that increasing solar radiation charges the battery faster and therefore reduces the number of solar PV required in both cases. Furthermore, there will be a decrease in the quantity of diesel fuel used in the PV/DG/BESS hybrid arrangement.

Table 6: Results of optimal hybrid PV/BESS configuration

Hybrid integration	Optimization Algorithm	N_{PV}	N_{BESS}	N_{Inv} (kW)	NPC ($)	COE ($/kWh)	DPSP (%)	Emission (kg/yr)
PV/BESS	ACO	38.0	27.0	6.0	97,342.30	0.182	2.00	0.00
	FPA	35.0	22.0	5.0	95,432.02	0.165	1.72	0.00
	GA	42.0	29.0	6.0	99,160.20	0.198	2.42	0.00
	PSO	38.0	26.0	6.0	95,901.33	0.170	1.89	0.00

Table 7: Results of optimal hybrid PV/DG/BESS configuration

Hybrid integration	Optimization Algorithm	N_{PV}	N_{DG}	N_{BESS}	N_{Inv} (kW)	NPC ($)	COE ($/kWh)	DPSP (%)	Emission (kg/yr)
PV/DG/ BESS	ACO	26.0	3.0	23.0	4.0	99,262.50	0.192	0.00	2.91
	FPA	25.0	3.0	20.0	3.0	97,134.00	0.171	0.00	2.51
	GA	28.0	3.0	24.0	4.0	102,125.05	0.202	0.00	3.01
	PSO	26.0	3.0	20.0	3.0	98,428.00	0.189	0.00	2.76

Table 8: Results of optimal DG alone configuration

Hybrid integration	Optimization Algorithm	N_{DG}	NPC ($)	COE ($/kWh)	DPSP (%)	Emission (kg/yr)
DG only	ACO	5.0	150,125.55	0.288	0.00	5.89
	FPA	5.0	147,834.20	0.275	0.00	5.31
	GA	5.0	152,500.40	0.299	0.00	6.42
	PSO	5.0	149,008.20	0.281	0.00	5.56

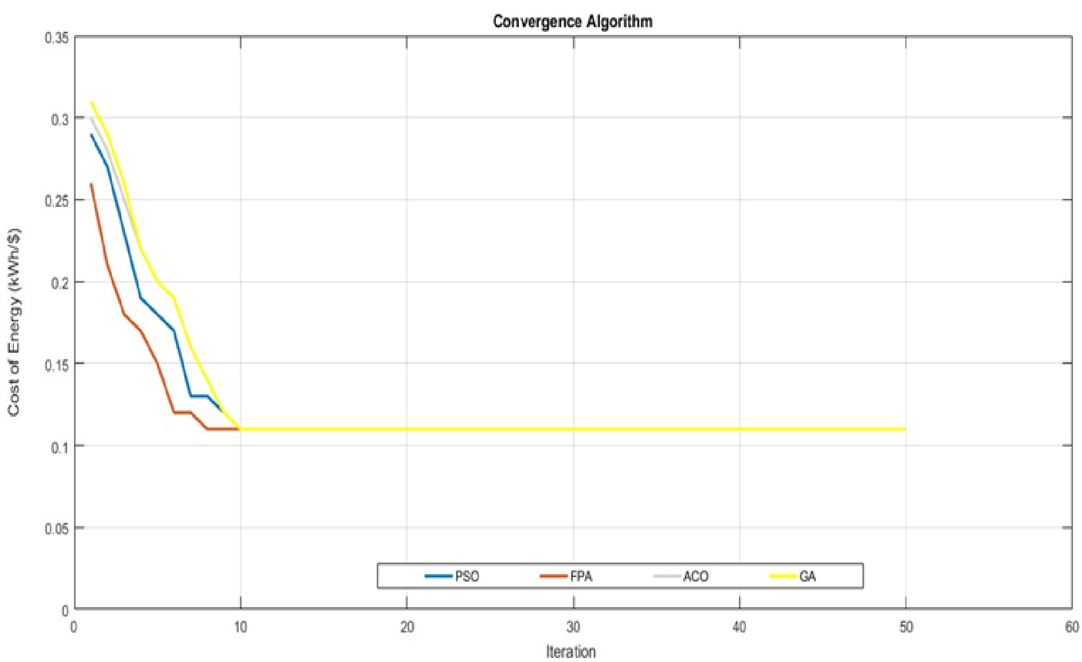

Figure 9: Convergence performance of the optimal sizing algorithms

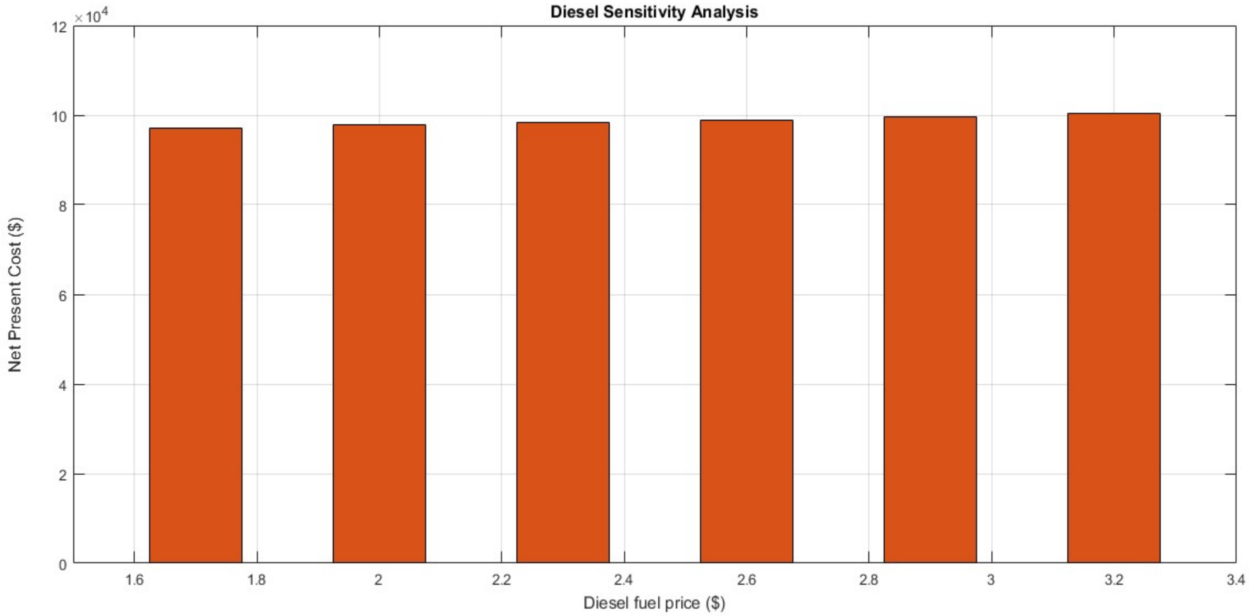

Figure 10: Impact of varying the diesel fuel price on the optimal NPC of the hybrid PV/DG/BESS

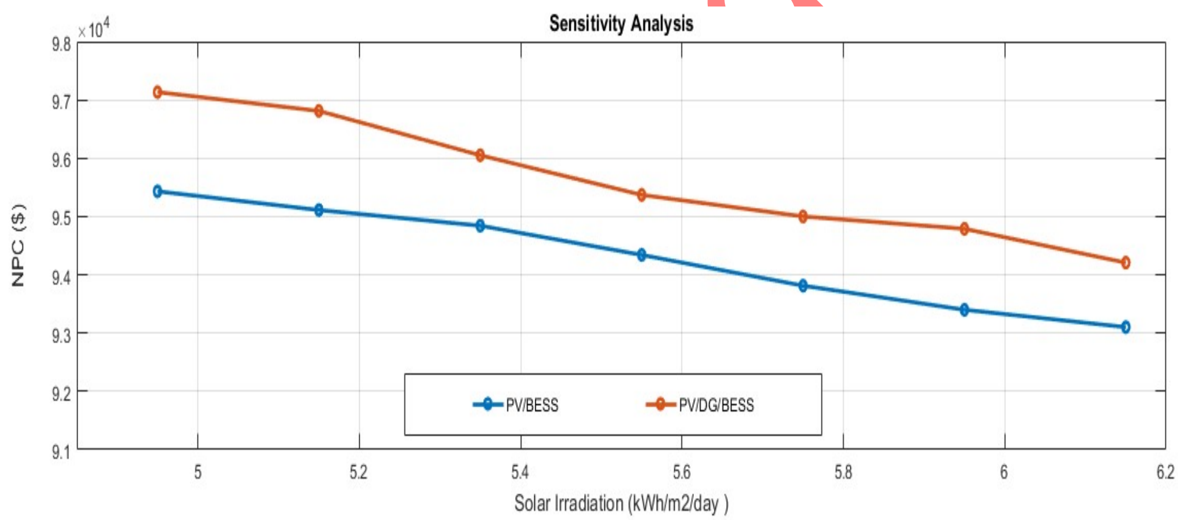

Figure 11: Impact of varying solar radiation on the NPC

Table 9: Results of the sensitivity analysis of the optimal sizing of hybrid PV/BESS configuration based on the FPA optimization technique

Energy component	**DOD = 0.3**	**DOD = 0.4**	**DOD = 0.5**	**DOD = 0.6**
N_{PV}	37.00	40.00	43.00	46.00
N_{BESS}	25.00	27.00	30.00	32.00
N_{INV}	5.00	5.00	5.00	5.00
NPC ($)	96,224	97,261	98,561	99,661
COE ($/kWh)	0.169	0.174	0.181	0.189
DPSP (%)	1.81	1.88	2.20	2.62

Table 10: Results of the sensitivity analysis of the optimal sizing of hybrid PV/DG/BESS configuration based on FPA optimization technique

Energy component	**DOD = 0.3**	**DOD = 0.4**	**DOD = 0.5**	**DOD = 0.6**
N_{PV}	27.00	30.00	34.00	36.00
N_{BESS}	22.00	24.00	27.00	30.00
N_{INV}	3.00	5.00	5.00	5.00
N_{DG}	3.00	3.00	3.00	3.00
NPC ($)	98,637	99,540	101,210	102,688
COE ($/kWh)	0.183	0.195	0.201	0.214
DPSP (%)	0.00	0.00	0.00	0.00

7. Conclusion

For the evaluated systems analyzed in this study, a variety of computational intellectual algorithms have been utilized for the design and sizing optimization of small-scale hybrid power systems. Three different configurations of PV/BESS, PV/DG/BESS, and DG only have been investigated. The meteorological solar data of a case study (Ogule community in Nigeria) was considered for the feasibility study based on the prospect of meeting the time-varying load demand of the community. In the different scenarios investigated for the optimal techno-economic sizing, the best optimal solutions were presented.

- The NPC value of $95,432.02 and COE of 0.165 $/kWh with no GHG emissions were obtained by the FPA in a hybrid configuration of PV/BESS. It is also important to point out that the energy demand in the case study rural community cannot be satisfied completely by this hybrid configuration. This is based on the fact that the optimization solution generated a DPSP value of 1.72% contrary to the zero DPSP of the PV/DG/BESS configuration. This value of DPSP presented by the PV/BESS configuration is quite reliable for a rural community considering that rural people are usually not economically buoyant to purchase electricity at a high cost.
- The fact that producing energy from BES is more cost-effective than DG, which requires fuel use, accounts for the low cost of the PV/BESS hybrid system design. The hybrid system configuration of PV/DG/BESS with complete load satisfaction tendency consequently generated increased NPC and COE values of $97,134.00 and 0.171 $/kWh. It is interesting to point out that the comparative analysis of the economic results shows that the differences in the values of NPC and COE between PV/DG/BESS and PV/BESS are 1.8% and 3.5% respectively.
- Therefore, the results obtained by FPA for the design of PV/BESS configuration have faster convergence speed, lower NPC and COE with no GHG emissions. Additionally, using the FPA optimisation technique, sensitivity analysis was carried out based on the effects of solar radiation, battery DOD, and diesel fuel costs on the hybrid systems.
- The results obtained indicated that increasing the DOD of the BESS increases the NPC and COE of the proposed hybrid microgrid. It was also observed that an increase in the cost of diesel fuel drastically increased the NPC and the COE while increasing solar irradiations decreased both NPC and COE.

Declaration of Interest

The authors state that no known competing financial interest or personal relationship may have had any influence on any of the work disclosed in this study.

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