

Optimizing Grid-Connected Photovoltaic (PV) Battery Energy Storage through Multi-Objective Ant-Lion Optimization (MOALO)

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Abstract:As the demand for renewable energy continues to rise, it becomes crucial to discover effective ways to enhance grid-connected photovoltaic (PV) battery energy storage systems. The Institute of Petroleum Studies (IPS) complex at the University of Port Harcourt in Rivers State, Nigeria, embarked on a quest to determine the optimal approach for optimizing their PV battery energy storage system. This research aimed to fulfill this need by employing a diverse research methodology, incorporating the innovative MOALO theory. To begin with, the research gathered primary and secondary data to construct models for the power grid, solarPV, and battery. Furthermore, it meticulously analyzed the load profile of the IPS complex, at the University of Port Harcourt. Leveraging the power of the MOALO theory, the researchers accurately sized the system and evaluated the potential outcomes of simultaneously interconnecting all loads. To gauge the system's performance, there was a calculation of various parameters such as economics, random walk, boundary conditioning, entrapping ants, and ant trap development. Remarkably, the outcome showed that the fitness responses between the two trial runs, facilitated by the integration of MOALO, were strikingly similar, revealing a typical concave-connected shape, which is characteristic of a multi-objective solver. The optimal multi-objective cost implication of the system was estimated to be around 4,300 USD, with a power mismatch performance of approximately -1.7819×10^9 . Based on these compelling findings, the study concluded that MOALO serves as an impressive optimization tool capable of minimizing power mismatches and optimizing costs. Moreover, it recommended the generation of excess power as a means to achieve sustainability.

Keywords: Optimizing Grid-Connected Photovoltaic (PV), Battery Energy Storage, Solar Energy Systems, Multi-Objective Ant-Lion Optimization.

Nomenclature

Abbreviations	Descriptions
PV	Photovoltaic
DER	Distributed Energy Resource
IPS	Institute of Petroleum Studies
MOALO	Multi-Objective Ant-Lion Optimization
BOS	Balance of System
GA	Genetic Algorithm
AC/DC	Alternating Current/Direct Current
RES	Renewable Energy Sources
DOD	Permissible Depth of Discharge
HMO-SAPSO	Hybrid Multi-Objective Simulated Annealing Particle Swarm Optimizer
PSO	Particle Swarm Optimization
USD	United States Dollars
AI	Artificial Intelligence
ALO	Artificial Lion Optimization
AVS	Automated Vehicle System
MPPT	Maximum Power Point Tracking

1. Background to the Study

The increasing concerns about the environment have led to the popularity of PV solar energy systems [10], which are now considered DER. Among the different types of PV systems available, grid-connected PV battery energy storage systems have gained significant attention [4] due to their ability to store surplus energy from PV panels, which can be supplied back to the grid when needed. This technology is particularly important for public institutions that have high energy demands, such as the IPS complex, University of Port Harcourt, Rivers State, Nigeria. Integrating solar energy into the grid poses a significant challenge due to its intermittent nature. Factors like seasonal changes and varying weather conditions can limit the performance of PV energy systems [18] [22], especially in regions with inconsistent and unreliable conditions. To address this issue, researchers have developed a metaheuristic algorithm called MOALO [8].

Inspired by the hunting behavior of ant lions, this population-based approach strikes the perfect balance between multiple objectives to ensure optimal performance. By iteratively improving solutions, MOALO finds the optimal trade-off between objectives such as energy efficiency, cost, and environmental impact for grid-connected PV battery energy storage systems. The advantages of these systems are eco-friendly, readily accessible, cost-effective, and noiseless. The optimization process involves determining the optimum capacity of PV panels, battery capacity, and control strategies that maximize energy efficiency, minimize costs, and reduce environmental impact.

1.1 Statement of the Problem

The scientific community worldwide has delved into the viability of solar energy systems, a prospect that has generated significant interest in the last few years. In Africa, stand-alone and grid-connected solar PV power systems have been the focus of research conducted on public higher educational institutions. Despite this, optimizing battery energy storage for grid-connected PV systems has proven a thorny issue, owing to myriad challenges such as erratic power supply from the national grid, financial implications, and environmental concerns from fossil fuel energy production. As a result, grid-connected solar PV has emerged as one of the most promising solutions to deal with these barriers. However, there have been unexpected failures, attributed to inconsistent natural phenomena, highlighting the need to strike a balance between electricity demand and supply while accepting solar energy's unpredictable nature. Determining the ideal size and configuration of battery storage systems remains crucial in enhancing their benefits and reducing operational costs in the IPS complex, University of Port Harcourt, Rivers State, Nigeria.

1.2 Aim and Objectives of the Study

This study was aimed at optimizing grid-connected PV battery energy storage through MOALO in the IPS complex, University of Port Harcourt, Rivers State, Nigeria. Specifically, the objectives were to:

1. Ascertain the size of the panels and the BOS components required to measure the load demand for the IPS complex, University of Port Harcourt, Rivers State, Nigeria.
2. Determine the optimum size for the most demanding loading (peak-loading) condition(s) in the IPS complex, University of Port Harcourt.
3. Identify the "What-if" scenario if all loads are interconnected at the same time at the IPS complex, University of Port Harcourt.

1.3 Research Questions

1. What size of panels and BOS components are needed to measure load demand for the IPS complex at the University of Port Harcourt?
2. What size is ideal for peak loading under the most demanding conditions for the IPS complex at the University of Port Harcourt?
3. What could be the potential consequences if all loads were interconnected simultaneously at the IPS complex, University of Port Harcourt?

2. Literature Review

Grid-connected PV systems, which are commonly known as grid-tied solar PV systems [19], harness the sun's energy to generate electricity that can be linked to the utility grid. These systems contain multiple components such as solar panels, inverters, and efficient gadgets that join forces to translate gathered solar radiance into usable electricity [19]. Public institutions such as hospitals, government buildings, and schools have embraced the implementation of these systems to reduce their carbon footprint and

achieve energy self-sufficiency [1]. In addition, battery energy storage makes use of excess electricity generated by the system, by storing it in a battery for later use. This offers a cost-effective and sustainable solution for managing energy surges and ensuring uninterrupted power supply.

Numerous studies have demonstrated that integrating battery storage with grid-connected solar-PV systems can result in significant cost savings [5], improved self-consumption rates[21],and reduced peak demand charges[6]. To maximize the efficiency and performance of this integrated system, optimization techniques like MOALO can be highly advantageous. For instance, a grid-connected PV system on a rooftop area was designed optimally using an analytical method in a study by [2]. The authors did not look at the grid-connected PV system life-cost analysis. Also, a grid-connected PV energy system optimal sizing for large-scale applications was carried out. In the work conducted by [13], the GA was used to determine the optimal sizing of grid-connected solar systems to reduce the net present value. However other goals were not taken into account during optimum sizing. [3] conducted a study that utilized MOALO to optimize the operation of a grid-connected PV system with battery energy storage in a public institution. The study yielded impressive results in terms of energy savings and self-consumption rate. In a similar vein, [14] explored the economic and environmental benefits of integrating battery energy storage with a grid-connected PV system in five climate zones. The researchers reported a significant reduction in dependence on fossil fuels and improved reliability and stability of the electrical grid infrastructure. Despite the growing attention towards the integration of battery storage with grid-connected solar-PV systems in recent years, more research is needed to address the gaps related to optimal sizing and the impact of various factors on system performance. Nonetheless, the integration of battery energy storage with grid-connected PV systems has tremendous potential to bolster the use of renewable energy sources across public institutions, reduce reliance on fossil fuels, and promote sustainability. In a nutshell, the MOALO approach and the integration of battery energy storage with grid-connected solar PV systems promise to revolutionize energy efficiency in public institutions and contribute to a more sustainable future.

2.1 Theoretical Framework

One theory for the theoretical framework for optimizing grid-connected PV battery energy storage through MOALO was proposed by[15].This theory averred that MOALO can be used to determine the optimal sizing of a grid-connected PV battery energy storage system by considering multiple objectives such as minimizing the cost, maximizing the reliability, and minimizing the environmental impact [15]. The theoretical application of this theory involves formulating a mathematical model that represents the PV battery energy storage system and its associated objectives. The MOALO algorithm is then applied to solve this multi-objective optimization problem, considering factors such as the size of the PV array, battery capacity, and inverter rating. By finding the Pareto-optimal solutions, which represent trade-offs between different objectives, this theory enables decision-makers to select the most suitable configuration for a grid-connected PV battery energy storage system.

2.2 Review Table

Table 1 portrays the objective, methodology, key findings, and contribution of the existing method. We considered eight papers that used a different methodology for the process. Each method has certain benefits and shortcomings that were explained in detail.

Table 1. Review Based on Existing Methods

Authors	Objective	Methodology	Key Findings	Contribution
Belboul et al., [3]	Optimize hybrid energy systems with renewables, batteries, and generators.	Multiobjective optimization approach	The optimal configuration for the hybrid system included a combination of photovoltaic panels, wind turbines, batteries, and a diesel generator.	Provides insights into the optimal design and operation of hybrid PV/wind/battery/diesel generator systems integrated into microgrids.
Nallolla et al., [17]	In-depth analysis of multi-objective optimization algorithms for hybrid AC/DC microgrids with RES.	Systematic literature review	Hybrid AC/DC microgrids optimized with successful multi-objective algorithms.	Enhancing AC/DC microgrid optimization with RES.
Shayeghi and Alilou [20]	Develop a smart microgrid DSM approach balancing economy and environment.	Multi-objective optimization framework	Optimized load scheduling and demand response balanced trade-offs.	Optimizing microgrids with economic and environmental goals for sustainability and efficiency.
Mohammad-Alikhani et al., [16]	Maximize AC mini-grid hybrid power efficiency through optimization.	Multiobjective genetic algorithm	The optimized approach found the best AC mini-grid hybrid power system.	AC mini-grid hybrid power system design with multiobjective optimization.
Ghiasi [7]	Efficiently analyze AC-DC smart microgrids with renewable energy resources.	A comprehensive methodology	Efficiently optimized AC-DC microgrid design with renewable energy.	Detailed study on multi-objective optimization for smart microgrids explained.
Hafez et al., [9]	Determine the optimal sizing of an offline microgrid using an HMO-SAPSO.	Mixed research design	The HMO-SAPSO algorithm successfully optimized the sizing of an offline microgrid.	Introduced a hybrid optimization algorithm for sizing offline microgrids.
Hemeida et al., [11]	Optimize a renewable energy sources-based microgrid system using a multi-objective multi-verse optimization algorithm.	Multi-verse optimization algorithm	The algorithm successfully optimized the design of a renewable energy sources-based microgrid system.	Established the concept of multiple universes for designing renewable energy-based microgrid systems.
Hossain et al., [12]	Maximize home renewable power system size using multi-objective hybrid optimization.	Hybrid optimization approach	The hybrid optimization approach nailed the perfect sizing for home renewable power systems.	Introduced a hybrid optimization approach that combines GA and PSO techniques for sizing hybrid renewable power systems.

2.3 Identified Research Gap

While there are existing studies on optimizing PV battery energy storage systems, the use of the MOALO algorithm for optimizing grid-connected PV battery energy storage systems has not been extensively explored in tertiary institutions in developing countries. By conducting research in this area, this study has contributed to the understanding of how the MOALO algorithm can be applied to optimize grid-connected PV battery energy storage systems in tertiary institutions in the developing world, potentially leading to improved performance, cost-effectiveness, and overall system efficiency.

3. Materials and Methodology

The successful evaluation of any renewable energy system requires that appropriate criteria of the chosen site be considered. Details are focused on power grid calculations, solar-PV calculations, battery model calculations, calculation of economics of the system and cost function presentation, random walk, boundary conditioning, sliding ants mimicking, entrapping the ants, ant trap development, ant capture and pit reconstruction, formulation and storage of elitist ants, finding the Pareto-optimal solution and archival storage (through improved distribution and decongesting of archives).

3.1 Power Grid Calculations

Generally, the power transferred to a given site may be expressed as [23]:

$$P_g(\tau) = \begin{cases} P_l(\tau)/\eta_r & \text{for } V_{r,\min} \leq V_g \leq V_{r,\max} \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

Where,

$V_{r,\min}$ = minimum voltage of an interconnected AVS, V

$V_{r,\max}$ = maximum voltage of an interconnected AVS, V

P_l = power demand load capacity response to sudden rise, kW

V_g = grid supply voltage, V

τ = hourly time within the year, 1, 2,..., 8760hr

η_r = efficiency of the AVS

The energy drawn from the power grid can be computed as:

$$E_g(\tau) = P_g(\tau)\Delta\tau \quad (2)$$

$\Delta\tau$ = constant hourly time step.

3.2 Solar-PV Calculations

Solar energy is a highly intermittent source of energy and as such, the minimum and maximum possible power supply boundaries need to be identified for a given site. This can be achieved by considering primarily the solar irradiance at a given tilt angle and time of energy capture. The solar power obtainable for a given location can be expressed as [24]:

$$P_{pv} = N_s \times N_p \times V_{oc} \times I_{sc} \times FF \quad (3)$$

Where,

$P_{pv(rated)}$ = rated PV power, kW

N_s = number of PV modules connected in series

N_p = number of PV modules connected in parallel

V_{oc} = open circuit voltage of single PV module at standard test conditions

I_{sc} = short-circuit current of single PV module at standard test conditions

FF = Fill factor of PV module

The parameters V_{oc} and I_{sc} may be computed as shown in Eqn8 and Eqn9 respectively:

$$V_{oc} = V_{oc(stc)} - K_v T_c \quad (4)$$

$$I_{sc} = (I_{sc(stc)} + K_i (T_c - 25))G \quad (5)$$

K_v = PV module open-circuit voltage temperature coefficient correction factor, V/oK

K_i = PV module short-circuit current temperature coefficient correction factor, A/oK

G = global solar irradiance, kW-hr/m²/day

T_c = PV cell temperature, oK

The cell temperature T_c , is influenced by ambient conditions and can be precisely estimated as:

$$T_c = T_{amb} + (0.0256 \times G) \quad (6)$$

T_{amb} = ambient temperature, oK.

3.3 Battery Model Calculations

The battery model computations for the design of a storage bank are taken from the approach proposed in [25][26][27]. This model typically takes into account the energy demands for a given period (days of

autonomy) without recourse to the use of a direct Solar-PV generation or the use of the Electric power grid:

$$C_{BAh} = \frac{E_{db} \times AD}{DOD \times \eta_{BAh} \times V_B} \quad (7)$$

Where,

E_{db} = energy requirement from battery bank considering load demand, *kWh*

AD = energy days of autonomy, *days*

η_{BAh} = battery ampere-hour efficiency

V_B = choice nominal voltage of battery block

DOD = permissible depth of discharge of the battery.

3.4 Calculation of Economics of the System and Cost Function Presentation

The economics of the system borders on the cost in Naira or the equivalent dollar value to assure affordability investigations. As described in [28], the costing (capital cost) can be described as an objective (cost) function including the Solar-PV size costs, the Battery-bank size costs, and design installation costs as described below:

$$C = C_{pv} \cdot N_{pv} + C_{bat} \cdot N_{bat} + C_0 \quad (8)$$

Where,

C_{pv} = unit cost of PV panel/module, USD

C_{bat} = unit cost of a single battery, USD

N_{pv} = number of series connected PV modules

N_{bat} = number of batteries to form the bank

C_0 = total cost constant (design and installation costs), USD

Considering the model, it is expected that the AI optimizer evolves the parameters, N_{pv} and N_{bat} such that the total costs are minimized. The evolution process will involve randomly choosing the values within a set of upper and lower boundary constraints.

3.5 Random Walk

This is modeled as a cumulative sum of conditioned random numbers in an iterative loop at a time step, t as:

$$X(t) = \begin{bmatrix} 0, \text{cumsum}(2r(t_1)-1), \text{cumsum}(2r(t_2)-1), \dots, \\ \text{cumsum}(2r(t_n)-1) \end{bmatrix}_{t=0:n} \quad (9)$$

Where,

cumsum = a cumulative sum function

n = maximum number of iterations of the ALO

t = random number step (iteration step)

r = a random number function

The stochastic function, r , can be obtained by the below stochastic function in rand, a random number function available in most programming languages:

$$r(t) = \begin{cases} 1, & \text{if } \text{rand} > 0.5 \\ 0, & \text{otherwise} \end{cases} \quad (10)$$

3.6 Boundary Conditioning

The ants may tend to overshoot their boundaries without control; however, they can avoid this situation by boundary control. To implement this feature, random walks are computed and normalized according to the formula below:

$$X_i^t = \frac{(X_i^t - a_i) \times (u_i^t - l_i^t)}{b_i - a_i} + l_i^t \quad (11)$$

Where,

a_i = minimum (lower-bound) of random walk inithant variable

b_i = maximum (upper-bound) of random walk inithant variable

l_i^t = minimum of it hant variable in t^{th} iteration

u_i^t = maximum of i^{th} ant variable in t^{th} iteration.

3.7 Sliding Ants Mimicking

Ants tend to slide into the ant-lions' pits and get trapped and hence eaten up by the ant-lions. To mimic this process, an adaptive decrease in the random walk boundaries should be performed. This is modeled as provided for the minimum and maximum ant variables respectively:

$$l' = \frac{l^t}{I} \quad (12)$$

$$u^t = \frac{u^t}{I} \quad (13)$$

Where,

I = a decrement ratio

The decrement ratio, I , is typically split into several sub-ratios to make the reduction process smoother. This process can be subsequently modeled using the equation below:

$$I = I + 10^w \frac{t}{T} \quad (14)$$

Where,

T = maximum number of iterations

w = an exploitation accuracy level adjustment factor

Typically, the parameter, w , is split into several uniform numeric values giving a set of uniform decrement ratios.

Entrapping the Ants

Ant-lions capture their prey (basically ants) by employing a mutation of random walks. This process can be modeled using the model equations for the minimum and maximum ant variables respectively:

$$l_i^t = Antlion_j^t + l_i^t \quad (15)$$

$$u_i^t = Antlion_j^t + u_i^t \quad (16)$$

Where,

$Antlion_j^t$ = position of the chosen j^{th} ant-lion at t^{th} iteration

3.8 Ant Trap Development

To ensure that the ants are captured effectively and with the highest possible accuracy, a fitness mechanism is necessary. In the ALO technique, this is achieved using a roulette wheel mechanism where the ant-lion(s) with the fittest values build bigger pits and hence attract more ants and are selected in the solution process

3.9 Ant Capture and Pit Reconstruction

To mimic the process of ant-lions catching and eating up their prey (mostly ants), it is normally assumed that when the ant(s) become fitter than the candidate ant-lion(s) i.e when they penetrate the sand in the antlion's pit, they can then be captured and eaten up by the corresponding ant-lion(s). The model describing this process is as shown in the equation below:

$$Antlion_j^t = Ant_i^t \quad \text{if} \left(f(Ant_i^t) > f(Antlion_j^t) \right) \quad (17)$$

Where,

Ant_i^t = position of the captured i^{th} ant at t^{th} iteration

Formulation and Storage of Elitist Ants

Elitism plays a key role in evolutionary algorithms from which the ALO technique draws inspiration from. It occurs when best-fitted individuals are saved and carried over to subsequent generations.

In the ALO, this is modeled as follows:

$$Ant_i^t = \frac{R_A^t + R_E^t}{2} \quad (18)$$

Where,

R_A^t = Ant random walk selected by roulette wheel at t^{th} iteration

R_E^t = Ant random walk around elite at t^{th} iteration

3.10 Finding the Pareto-Optimal Solution and Archival Storage through Improving Distribution

Here, the ant-lions are selected from the archives solutions with the least populated neighborhood using the probability model:

$$p_i = \frac{c}{N_i} \quad (9)$$

Where,

C = constant factor > 1

N_i = number of solutions in the vicinity of the i^{th} ant solution.

3.11 Finding the Pareto-Optimal Solution and Archival Storage through Decongesting Archives

Here, solutions are removed from the archive with the most populated neighborhood using the probability model:

$$p_i = \frac{N_i}{c} \quad (10)$$

In a constrained optimization problem, the decision (or solution) variable(s) are described as a finite position set with an upper bound (ub) and lower bound (lb) constrain i.e. their numerical values are strictly range-limited. These variables typically represent real-world or analytical parameters that form part of a model describing the process. In the multi-objective sense, it is necessary to have an Archive to keep track of best solution values as the iteration proceeds

3.12 Energy Data and Systems Specifications

The technical parameter specifications for the Solar-PV module and battery are as presented in Table 1 while that detailing the load appliances and their respective wattage, and the techno-economic evaluation of the Solar-PV grid-connected System, IPS complex, University of Port Harcourt are provided in subsequent Tables 2 in the results and discussions.

Table 2. Solar-PV and Battery Parameter ranges (Default Values)

Parameter	Min. Value	Max. Value	Unit
Number of Parallel Connected PV Modules (N_{pv})	1	196	NA
Global solar irradiance (G)	1	5	$kW \cdot hr / m^2 / day$
Ambient Temperature (T)	24	27.3	$^{\circ}C$
System Loading (T_L)	331.346	331.346	KWh
Autonomy Day (AD)	3	3	Days
Battery Ampere Hour Capacity, C_{bat}	279	1156	A-h
Number of Parallel Connected Battery Units (N_{bat})	1	438	NA

While other parameters in Table 1 are fixated, the parameters N_{pv} , N_{bat} , and C_{BAh} are searched for by the MOALO algorithm. The parameter N_{pv} is motivated by on-site hand (base) calculations of the Solar-PV system which amounted to a total of approximately 196 Solar-PV modules for a 24V, 350W, 14.58A unit Solar Panel/Module.

The parameter N_{bat} is similarly motivated by on-site hand (base) calculations of the battery units in consideration, which amounted to 438 Battery units for a 24V Battery with a total ampere-hour capacity of 87656A-h.

4. Results and Discussions

4.1 Answers to Research Questions

Research Question 1: What size of panels and BOS components are needed to measure load demand for the IPS complex, University of Port Harcourt?

The size of the panels and the BOS components such as solar charge controller, inverter, and battery that are deployed in the Solar-PV grid-connected system, IPS complex, University of Port-Harcourt are determined by the following mathematical computations:

➤ Solar Panel Sizing

Recall:

$$\text{Total power required for battery input} = \frac{\text{Total DC power required per day}}{\text{Battery efficiency}}$$

But, the total DC power required for IPS Center, University of Port Harcourt = 331346Wh

Battery efficiency = 85%

$$\begin{aligned}\therefore \text{The total power required for battery input} &= \frac{331346}{0.85} \\ &= 389818.8235 \\ &\cong 389819\text{Wh}\end{aligned}$$

$$\text{Required output power from panel per day} = \frac{\text{Total battery input power}}{\text{Controller efficiency}}$$

Mostly, the controller has a higher efficiency of 95%.

$$\begin{aligned}\therefore \text{Panel output power} &= \frac{389819}{0.95} = 410335.7895 \\ &\cong 410336\text{Wh}\end{aligned}$$

Thus, solar panels should supply 410336Wh/day.

$$\text{However, solar panel requirement} = \frac{\text{panel output power}}{\text{system voltage}}$$

Since the panel output = 410336Wh/day and system voltage = 24V

$$\begin{aligned}\text{Solar panel requirement} &= \frac{410336}{24} \\ &= 17097.33333 \\ &\cong 17097\text{Ah}\end{aligned}$$

But, sunlight available in the area = 6hrs

$$\text{Amps required in panel} = \frac{\text{Ah}}{\text{h}}$$

$$\begin{aligned}\therefore \text{Amps required in panel} &= \frac{17097}{6} \\ &= 2849.5 \\ &\cong 2850\text{A}\end{aligned}$$

In the market, we choose 24V, 350W, and 14.58A solar panels.

$$\begin{aligned}\therefore \text{No of panels required} &= \frac{\text{Total Amps Required}}{\text{Panel Amps}} = \frac{2850}{14.58} = 195.473251 \\ &\cong 196\end{aligned}$$

So, 196 Nos of 24V, 350Watts, 14.58A solar panels would be needed for the IPS complex, University of Port Harcourt. The panels will be connected in parallel.

196 x 350W = 68600W or 68.6kW solar panels will be needed for the IPS complex, University of Port Harcourt.

➤ Solar Charge Controller Sizing

Since 196nos of 24V, 350W, and 14.58A solar panels are required in the IPS complex, University of Port Harcourt.

$$\therefore \text{Total Watts} = 350 \times 196 = 68600\text{W}$$

But system voltage = 24V

$$\begin{aligned}\text{Since controller sizing} &= \frac{\text{Total watt}}{\text{System voltage}} \times 1.25 \\ &= \left(\frac{68600}{24}\right) \times 1.25 \\ &= 2858.33333 \times 1.25 \\ &= 3572.916666 \\ &\cong 3573\text{Amps}\end{aligned}$$

So, 60 units of 60A MPPT controllers will be wired in parallel (i.e. $\frac{3573}{60} = 59.55$) to be able to take care of 3573 Amps or 45 units of 80A MPPT controller will be wired in parallel (i.e. $\frac{3573}{80} = 44.6625$) to be able to take care of the 3573 Amps.

➤ Inverter Size

Since the total wattage consumption = 200327W

$$\begin{aligned}\text{The inverter value in VA} &= \frac{200327}{0.8} \text{ (P.f. = 0.8)} \\ &= 250408.75 \text{ KVA} \\ &\cong 250\text{KVA}\end{aligned}$$

Thus, the IPS complex, University of Port Harcourt needs an inverter unit of approximately 250KVA with a system voltage of 48V.

➤ Battery size.

Recall:

$$\text{Total DC power required} = \frac{\text{Total watt-hour per day}}{\text{Inverter efficiency}}$$

But, total watt-hour per day = 331346Wh

$$\begin{aligned}\text{Inverter efficiency} &= 90\% \\ &= 0.9\end{aligned}$$

$$\begin{aligned}\therefore \text{Total DC power needed} &= \frac{331346}{0.9} \\ &= 368162.2222\end{aligned}$$

$$\cong 368162\text{Wh}$$

$$\text{Recall: Battery sizing (Ah)} = \frac{\text{DC power}}{\text{Battery voltage}}$$

$$\begin{aligned}\text{Battery sizing (Ah)} &= \frac{368162}{24} \\ &= 15340.08333 \\ &\cong 15340\text{Ah}\end{aligned}$$

Since battery DOD is 70% (lead acid) and 80% (lithium)

$$\begin{aligned}\therefore \text{Battery size} &= \frac{15340}{0.7} = 21914.28571 \\ &\cong 21914\text{Ah}\end{aligned}$$

Assuming the number of days the battery can supply without significant sun power (i.e. days of autonomy) = 3days

Since battery size with autonomy = days of autonomy x battery Ah/day

$$\begin{aligned}\therefore \text{Battery size with autonomy} &= 3 \times 21914 \\ &= 65742\text{Ah}\end{aligned}$$

Thus, the total battery size = battery size per day + battery size with autonomy

$$\begin{aligned}\text{Required battery size} &= 21914 + 65742 \\ &= 87656\text{Ah}\end{aligned}$$

Since the battery size available in the market = 24V, 200Ah lead acid battery, and the required battery size for IPS complex, University of Port Harcourt = 24V, 87656Ah.

$$\begin{aligned}\therefore \text{The number of batteries required} &= \frac{87656}{200} \\ &= 438.28 \\ &\cong 438\end{aligned}$$

Thus, the IPS complex, University of Port Harcourt will require 438 Nos of 24V, 200Ah lead acid batteries, which are all connected in parallel.

➤ Battery Size (without considering days of autonomy)

Since the battery size available in the market = 24V, 200Ah lead acid battery.

Total DC power required/day = 368162Wh

$$\begin{aligned}\therefore \text{Battery size (Ah)} &= \frac{368162}{24} \\ &= 15340.08333 \\ &\cong 15340\end{aligned}$$

Since battery DOD = 70%

$$\begin{aligned}\therefore \text{The required battery Ah} &= \frac{15340}{0.7} \\ &= 21914.28571 \\ &\cong 21914\text{Ah}\end{aligned}$$

$$\begin{aligned}\text{Thus, the number of batteries required} &= \frac{21914}{200} \\ &= 109.57\end{aligned}$$

$$\cong 110$$

∴IPS complex, University of Port Harcourt will require 110Nos of 24V, 200Ah batteries. And the connections are all in parallel.

Research Question 2: What is the optimal size using MOALO for peak-loading under challenging conditions for the IPS complex, University of Port Harcourt?

It can be observed that the maximum single loading occurred by the exterior security lighting at the IPS complex, University of Port Harcourt at a value of 16.6kWh. Also, the peak loading was due to combined appliances at a value of 305.358kWh. An approach considering primarily the peak demanding appliance for a particular duration of the day was applied to obtain an approximate load profile representation for the said site (IPS complex, University of Port Harcourt) as shown in Fig. 1.

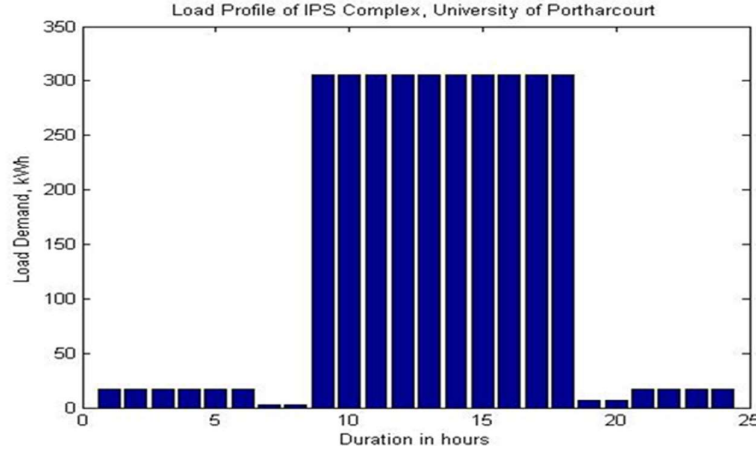


Fig. 1. Load profile of IPS complex, University of Port Harcourt

In this part, the MOALO is used to obtain the key appropriate sizing – number of parallels connected Solar-PV modules, N_{pv} , number of parallel connected Solar Battery units, N_{bat} , and the estimate of the battery ampere-hour capacity, CBAh for the peak combined loading (Pdemand) of 305.358kWh as earlier defined. The boundary constraints are as earlier defined in the methodology.

Presented are the fitness responses considering the dual objectives f_1 and f_2 , as shown in figures 2 and 3 for trial runs 1 and 2 respectively, at an irradiation level of 5000W/m² and 100 iterations (100iters); these figures describe the property of competing objectives in a multi-objective optimization process; in the figures, f_1 represents the mismatch in power demand-grid requirement for the Solar-PV and Battery power generation requirement while f_2 represents the cost objective including the Solar-PV modules and Batteries. Sample numerical results are provided in Tables 3 and 4, while numerical results considering optimization parameters are presented in Table 5. In addition, fitness responses of the MOALO for the case of an irradiation level of 1000W/m² are provided in Figures 5 and 6 for trial runs 2 and 3 respectively; the corresponding numerical values are presented in Tables 6 and 7, while the optimal parameter numerical results are as shown in Table 7.

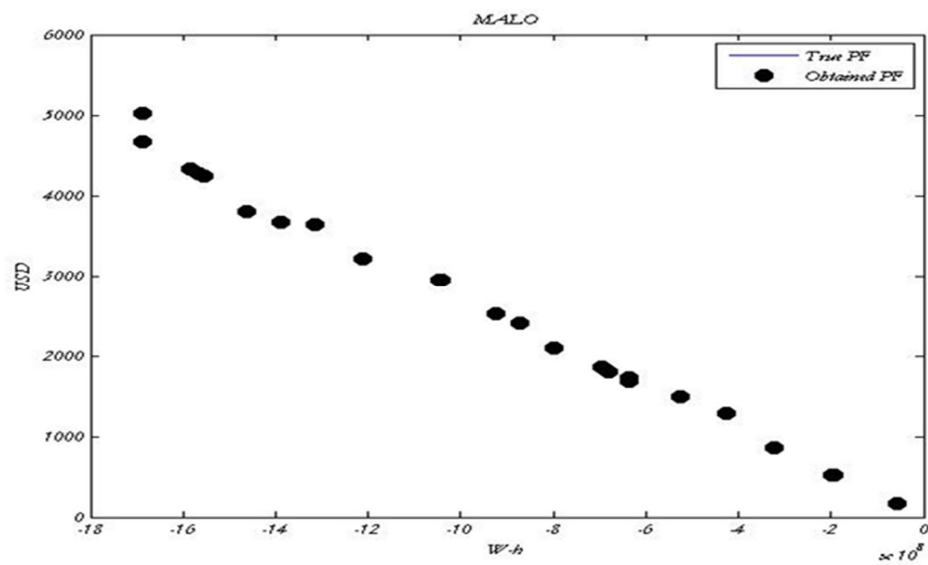


Fig. 2. Multi-objective solution of the first trial run, $I_{rr} = 5000W/m^2$,

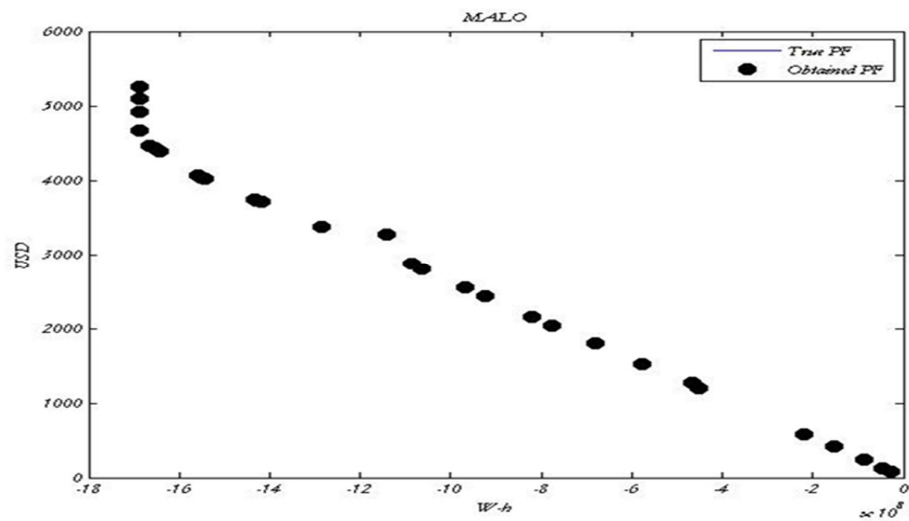


Fig. 3. Multi-objective solution of the second trial run, $I_{rr} = 5000W/m^2$

Table 3. Sample Numerical of the first trial run, $I_{rr} = 5000W/m^2$, 100iters

f1(W-h)	f2(USD)
-1E+09	2946.92
-2E+09	4324.06
-1E+09	2946.40
-2E+09	4275.21
-2E+09	4241.64
-6E+08	1729.25
-3E+08	865.72
-3E+08	865.78
-3E+08	865.76
-3E+08	865.78
-3E+08	865.76
-9E+08	2403.20
-9E+08	2403.19
-9E+08	2403.19
-9E+08	2403.20
-9E+08	2403.20

Table 4. Sample Numerical of the second trial run, $Irr = 5000W/m^2$, 100iters

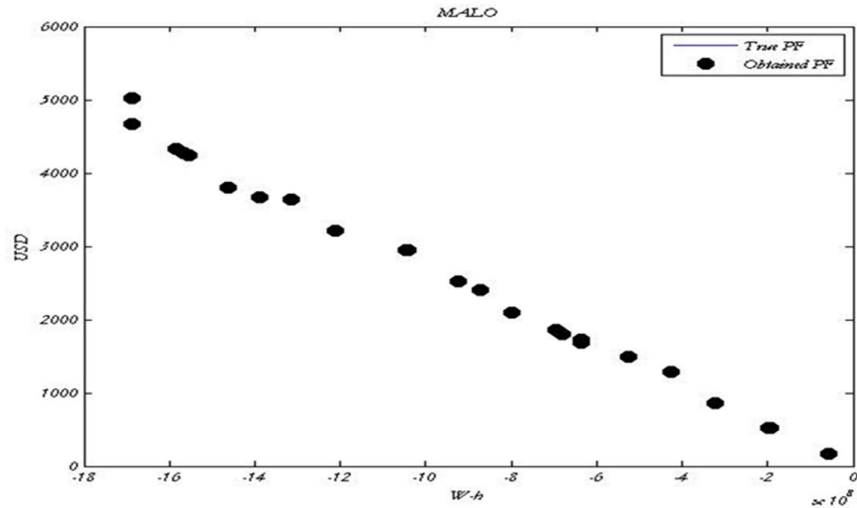
f1(W-h)	f2(USD)
-3E+07	75.7226
-4E+07	123.243
-9E+07	236.838
-9E+08	2440.73
-1E+09	2547.95
-8E+08	2043.13
-8E+08	2043.17
-8E+08	2043.18
-8E+08	2159.5
-8E+08	2159.5
-3E+08	865.76
-2E+08	413.166
-2E+08	413.165
-2E+08	413.17
-2E+08	413.169
-2E+08	413.167

The data in Tables 2 and 3 reveal numerical information obtained from the first and second trial runs of power. This data was collected under specific conditions: $Irr = 5000W/m^2$ (representing power per unit area) and 100iters (referring to the number of simulation steps). The Tables exhibit two columns, f1(W-h) and f2(USD). It seems that f1 denotes values in watt-hours (W-h), while f2 represents values in US dollars (USD). In the f1 column, watt-hours (W-h) measure the amount of electrical energy consumed or produced over time. Each row in the table represents a data point, with corresponding values in f1 and f2 columns. The f1 values range from $-1E+09$ to $-9E+08$, where the negative sign indicates negative energy values expressed in scientific notation (e.g., $-1E+09$ means -1×10^9). Conversely, the f2 values are positive and expressed in decimal notation.

Table 5. MOALO Optimization Results at, $Irr = 5000W/m^2$, $P_{demand} = 305.358kWh$

Parameter	Optimized Value (Run1)	Optimized Value (Run2)	Unit
N_{bat}	209	371	-
N_{pv}	1	1	-
$CBah$	655	937	Ah

Results in Table 4 include two optimization runs, labeled Run1 and Run2, with optimized values for N_{bat} , N_{pv} , and $CBah$. N_{bat} represents the battery count and remains at 209371 in both runs. Similarly, N_{pv} , representing the PV panel count, remains constant. $CBah$, a cost-related metric, indicates better optimization with lower values. In Run1, $CBah$ is 655937, with no change in Run2.

**Fig. 4.** Multi-objective solution of the first trial run, $Irr = 1000W/m^2$

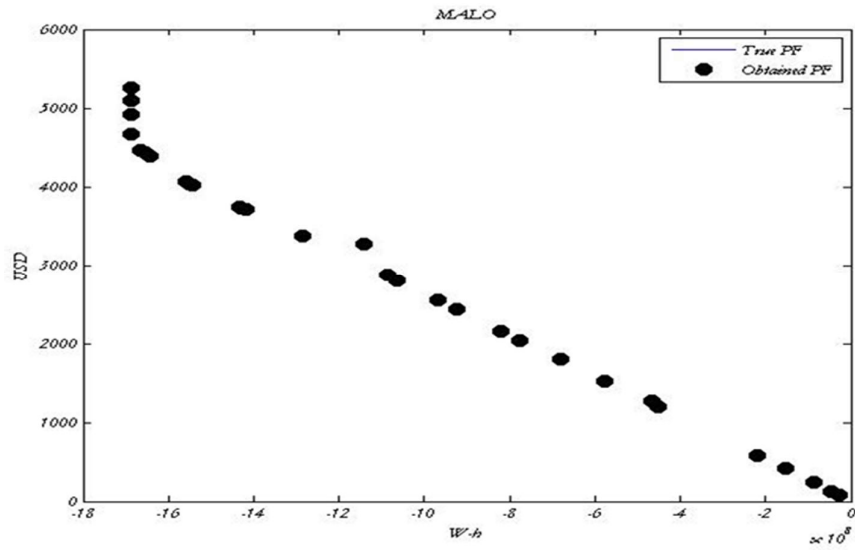


Fig. 5. Multi-objective solution of the second trial run, $I_{rr} = 1000W/m^2$

Table 5. Sample Numerical of the first trial run, $I_{rr} = 1000W/m^2$, 100iters

f1(W-h)	f2(USD)
-1E+09	2946.92
-2E+09	4324.06
-1E+09	2946.40
-2E+09	4275.21
-2E+09	4241.64
-6E+08	1729.25
-3E+08	865.72
-3E+08	865.78
-3E+08	865.76
-3E+08	865.78
-3E+08	865.76
-9E+08	2403.20
-9E+08	2403.19
-9E+08	2403.19
-9E+08	2403.20
-9E+08	2403.20

Table 7. Sample Numerical of the second trial run, $I_{rr} = 1000W/m^2$, 100iters

f1(W-h)	f2(USD)
-3E+07	75.7226
-4E+07	123.243
-9E+07	236.838
-9E+08	2440.73
-1E+09	2547.95
-8E+08	2043.13
-8E+08	2043.17
-8E+08	2043.18
-8E+08	2159.5
-8E+08	2159.5
-3E+08	865.76
-2E+08	413.166
-2E+08	413.165
-2E+08	413.17
-2E+08	413.169
-2E+08	413.167

Table 8. MOALO Optimization Results at, $I_{rr} = 1000W/m^2$, $P_{demand} = 305.358kWh$

Parameter	Optimized Value (Run1)	Optimized Value (Run2)	Unit
N_{bat}	209	371	-
N_{pv}	1	1	-
C_{Bah}	655	937	Ah

Table 8 presents the results of two optimization runs, referred to as Run1 and Run2. These runs focus on optimizing the values of Nbat, Npv, and CBah. Nbat represents the battery count, and it remains constant at 209371 in both runs. Similarly, Npv, which represents the PV panel count, also remains unchanged. The metric CBah, which is related to cost, indicates that lower values represent better optimization. In Run1, the CBah value is 655937, and there is no change in Run2.

Research Question 3: What are the possible outcomes of interconnecting all loads simultaneously using MOALO at IPS complex, University of Port Harcourt?

This part follows from the answer to research question 2, but with the loading increased to the total loading. The corresponding fitness responses considering an irradiation level of 5000W/m² for the first and second trial runs are shown in Figures 6 and 7. The corresponding numerical sample values are shown in Tables 9 and 10, while the numerical optimization results are shown in Table 11.

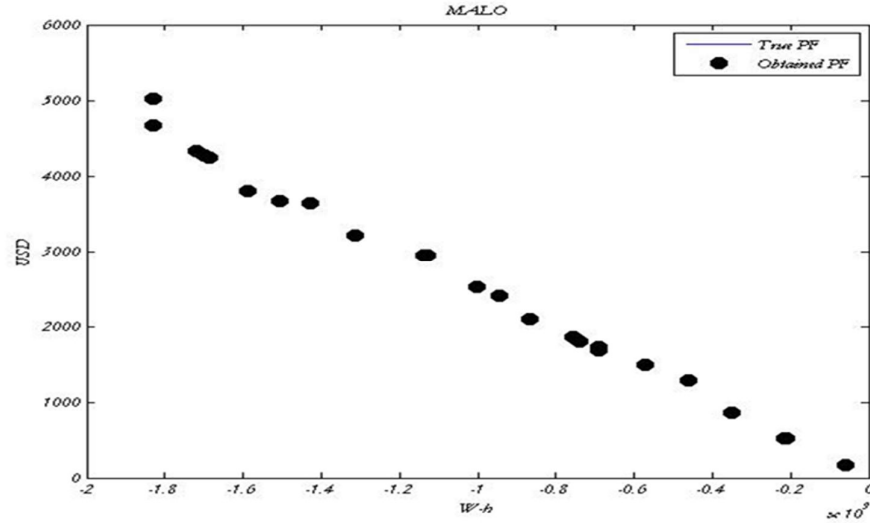


Fig. 6. Multi-objective solution of the first trial run, $Irr = 5000W/m^2$

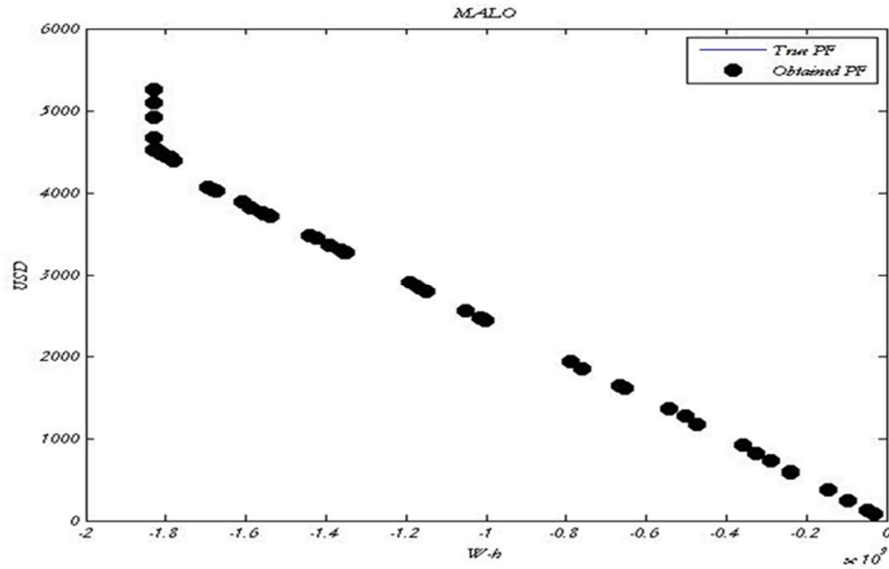


Fig. 7. Multi-objective solution of the second trial run, $Irr = 5000W/m^2$

Table 9. Sample Numerical of the first trial run, $Irr = 5000W/m^2$, 100iters

f1(W-h)	f2(USD)
-1E+09	2946.92
-2E+09	4324.06
-1E+09	2946.40
-2E+09	4275.21
-2E+09	4241.64
-6E+08	1729.25
-3E+08	865.72
-3E+08	865.78
-3E+08	865.76
-3E+08	865.78
-3E+08	865.76
-9E+08	2403.20
-9E+08	2403.19
-9E+08	2403.19
-9E+08	2403.20
-9E+08	2403.20

Table 10. Sample Numerical of the second trial run, $Irr = 5000W/m^2$, 100iters

f1(W-h)	f2(USD)
-3E+07	75.7226
-4E+07	123.243
-9E+07	236.838
-9E+08	2440.73
-1E+09	2547.95
-8E+08	2043.13
-8E+08	2043.17
-8E+08	2043.18
-8E+08	2159.5
-8E+08	2159.5
-3E+08	865.76
-2E+08	413.166
-2E+08	413.165
-2E+08	413.17
-2E+08	413.169
-2E+08	413.167

Table 11. MOALO Optimization Results at, $Irr = 5000W/m^2$, $P_{demand} = 331.346 kWh$

Parameter	Optimized Value (Run1)	Optimized Value (Run2)	Unit
N_{bat}	209	159	-
N_p	1	4	-
C_{Bah}	655	554	Ah

The results of the MOALO optimization process are shown in the Table for possible outcomes of interconnecting all loads simultaneously using MOALO at the IPS complex, University of Port Harcourt. In this scenario, the solar irradiance is $5000W/m^2$, which means that the power received from the sun per unit area is 5000 watts per square meter. The power demand is 331.346 kWh. In Run 1, the optimization process used 209 batteries (N_{bat}), 1 photovoltaic (PV) panel (N_p), and a battery bank capacity of 655 Ah (C_{Bah}). In Run 2, the optimized values for N_{bat} , N_p , and C_{Bah} were 159, 4, and 554 Ah, respectively. Hence, achieving the goal of the optimization process to find the most efficient combination of batteries, PV panels, and battery bank capacity to meet power demand based on the extent of solar irradiance.

4.2 Discussion

Regarding the numerical results in Research Question 2 (Figures 2 and 3), it may be observed that the fitness responses between the two trial runs owing to MOALO's integration are roughly identical. They also exhibit a roughly linear Pareto-front with a concave-connected shape at the top; a typical characteristic of multi-objective problem solvers. Also, in Figures 4 and 5, a roughly linear profile is exhibited. The numerical results also differ in their estimation where for instance, with the irradiation and power demand parameter settings: $Irr = 5000W/m^2$ and $P_{demand} = 305.358kWh$, the estimated battery size is higher in trial 2 than in trial 1. Also, observed is the increase in the required battery ampere-hour capacity, C_{Bah} for the second trial run when compared to the first. Similar patterns are

also exhibited for the other parameter settings and in the second scenario. These variations in optimized parameters can be attributed to the stochastic nature of evolutionary computing algorithms making them a robust optimization tool. In particular, from the fitness responses of the various scenarios (Figures 4 to 7), it can be seen that the optimal multi-objective cost implication is around 4,300USD while the power mismatch performance is around -1.5846×10^9 for Figure 4; -1.6422×10^9 for figure 5 and -1.7000×10^9 for Figure 6; -1.7819×10^9 for Figure 7 respectively. This implies the feasibility of providing excess power amounting to about 1.6GWh (Figures 4 and 5) and 1.7GWh (Figures 6 and 7) respectively to the power grid at reasonable cost per annum, which could be sold to the utility grid for profit.

4.3 Advantages and Disadvantages of Optimizing Grid-Connected PV Battery Energy Storage through MOALO

Optimizing Grid-Connected PV Battery Energy Storage through MOALO offers several advantages and disadvantages when compared to other multi-objective optimization techniques. Here are five of each:

- i. **Enhanced convergence speed:** MOALO utilizes the concept of ant-lion optimization, which is inspired by the hunting behavior of ant-lion insects. This technique enables faster convergence towards optimal solutions compared to other optimization algorithms. The algorithm's ability to quickly identify promising regions in the search space can significantly reduce the computational time required for optimization.
- ii. **Improved Economic Viability:** MOALO takes into account economic factors, such as the cost of PV panels, batteries, and energy storage systems. Optimizing these parameters can help reduce the overall cost of grid-connected PV battery energy storage, making it more economically viable.
- iii. **Optimal Battery Sizing:** MOALO considers multiple objectives, including battery capacity, to optimize the sizing of the battery in a grid-connected PV system. This ensures that the battery size is optimal for storing excess energy and minimizing energy wastage, leading to more efficient energy utilization.
- iv. **Robustness and Reliability:** MOALO incorporates robustness and reliability factors into the optimization process. It can find solutions that are not only optimal under normal operating conditions but also resilient to uncertainties, such as changes in weather conditions or load demands. This enhances the grid-connected PV battery energy storage system's reliability and stability.
- v. **Environmental Sustainability:** MOALO can consider environmental factors, such as reducing greenhouse gas emissions and minimizing the reliance on non-renewable energy sources. Optimizing the grid-connected PV battery energy storage system can contribute to a more sustainable and environmentally friendly energy solution.

4.4 Disadvantages of Optimizing Grid-Connected PV Battery Energy Storage through MOALO:

- i. **Computational Complexity:** MOALO involves complex algorithms and calculations to evaluate multiple objectives simultaneously. As a result, it may require significant computational power and time to find optimal solutions. This can be a drawback, especially when dealing with large-scale grid-connected PV battery energy storage systems.
- ii. **Sensitivity to Input Parameters:** The performance of MOALO can be sensitive to the selection of input parameters, such as the weightings assigned to different objectives. Suboptimal parameter settings may lead to suboptimal solutions. Thus, careful tuning and parameter selection are required to achieve the desired results.
- iii. **Limited Real-World Application:** MOALO is a relatively new optimization technique, and its real-world application in grid-connected PV battery energy storage systems may be limited. Further research and validation are needed to establish its effectiveness and practicality in different scenarios.
- iv. **Lack of Standardization:** Due to the novelty of MOALO, there may be a lack of standardized guidelines or benchmarks for evaluating its performance. This can make it challenging to compare the results obtained from MOALO with those obtained from other multi-objective optimization techniques.
- v. **Expertise and Knowledge Requirements:** Implementing MOALO in grid-connected PV battery energy storage systems requires expertise and knowledge in both optimization

techniques and renewable energy systems. The learning curve can be steep, and the availability of skilled personnel may be limited, posing a challenge for widespread adoption.

5. Conclusions and Recommendations

The investigation into optimizing grid-connected photovoltaic battery energy storage systems through MOALO has yielded a successful examination of several objectives. These include determining the required size for panels and BOS components, identifying the optimal size for peak-loading conditions, and testing various "What-if" scenarios. The numerical results indicate a linear response between trial runs, demonstrating the stochastic nature of evolutionary computing algorithms. Consequently, MOALO is a robust optimization tool capable of optimizing multi-objective cost implications and reducing power mismatch performance. The study also revealed that by generating an excess of 1.6-1.7 GWh of power per annum, organizations can offset their carbon footprint while earning a profit. Overall, this study serves as a foundation for large organizations aiming to create more sustainable operations while reducing reliance on non-renewable energy sources.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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