Techno-Economic Analysis of Grid-Connected PV Systems Using BAT Algorithms and Comparison with other Algorithms

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Abstract— **This paper proposed a new approach for optimizing and sizing a grid-connected PV system based on an improved algorithm. The novel and improved bat algorithm (IBAT) for optimization was used, which is principled on teaching processes, with a specific aim of minimizing the total net current cost of these systems. There are several techniques, including the very well-known particle swarm optimization (PSO), in addition to the whale optimization algorithm (WOA), and cuckoo search (CS), that are commonly used to handle this optimization. However, to maximize productivity, novel approaches are required. Optimized grid-connected PV systems, also in countries where fossil fuel is abundant, can reduce production expenses. The grid-connected PV system's net current cost (NPC) and energy cost (COE) are more competitive at $19595 and $0.134/kWh, respectively. The COE and NPC were calculated and then compared with the most used algorithms for optimization, such as PSO, WOA, and CS, with the aim of validating the method proposed herein, and determining the accuracy and speed of the IBAT algorithm. A policy for energy efficiency was then illustrated. The loss of power supply probability (LPSP) was then calculated to determine the degree of operating stability. As the IBAT is both easy to construct and does not require a high number of control parameters, it was determined to be more feasible. The modelled system was tested on a grid-connected PV system installed at the Libyan Center for Solar Energy Research and Studies in Tripoli, Libya. Annual data of irradiance, load profile, and temperature of the PV system were obtained and used for comparing the performances of the IBAT with the other algorithms. Obtained results prove that the proposed IBAT algorithm provides better optimal configuration than commonly used algorithms. The LPSP value of the IBAT algorithm is 0.0965 compared with 0.415, 0.625, and 0.845 for WOA, PSO, and CS, respectively.**

Keywords— **techno-economic analysis; PV power system; IBAT algorithm; particle swarm optimization; whale optimization; Cuckoo Search.**

I. INTRODUCTION

The growing requirement and necessity of electrical energy added to the cost of oil, and the depletion of fossil fuel sources, combined with environmental pollution as the result of the conventional thermal electric units used to generate energy, have caused great concern worldwide regarding research into alternative methods for electric energy production. To achieve this, grid-connected photovoltaic (GCPV) systems are commonly utilized for injection of the energy that is produced using PV modules in to electrical grids [1] [2].

Currently, the instalment of GCPV systems has become normal practice in a great number of developed countries, including the USA, Spain, and Japan [3]. Aside from the benefits that they provide environmentally, PV systems also offer numerous other benefits, both technically and economically. They are not only beneficial for decreasing losses, but they also offer a significant improvement in the voltage profile of the feeder that they are connected. Moreover, PV system owners are often given incentives by utilities, in the form of a higher sale price for the energy that these systems generate. As an example, Canada's Ontario Power Authority proposed payment of 42 cents/kWh for power that was generated through the use of PV systems as an aspect of their Standard Offer Program, which was established in 2006 [4] [5].

As alternative approaches to traditional methods, techniques of artificial intelligence are becoming more popular. They can learn from examples, overcome nonlinear issues, and very quickly carry out predictions. The most efficient optimization algorithms used in various studies include particle swarm optimization (PSO) [6], genetic algorithms (GAs[7], harmony search algorithms [8] [9], ant colony algorithms[10], simulated annealing[11], cuckoo search (CS) [12], artificial bee colony algorithms[13], hybrid algorithms[14][15], and multi-objective optimization[16]. Different systems and systems of optimization are used in various works, as shown in Table 1. The initial cost of components is very high because of the use of complex structures in these studies. In certain countries, however, the use of grid power is considerably less inexpensive than such complicated systems.

Since solar energy, and in particular PV panels, is among the most utilized renewable systems that can be used in any location, a PV system has been chosen as a power source herein. The suitability of solar radiation in Libya is another reason to use this system. The meteorological data herein comprised real data that was collected from the Libyan Center for Solar Energy Research and Studies in Tripoli, Libya, and hourly loads for the Libyan Center for Solar Energy Research and Studies were also collected as the actual loads that had been registered during the same time. Since real data were the basis of this study, it is possible to use them in an actual a feasibility study implementing the proposed system. In summary, this paper offers contributions to the literature in analysing the performance of a GCPV system based on the concepts of loss of power supply probability (LPSP), net present cost (NPC), and cost of energy (COE), which are indeed significant considerations in such a system.

The optimum system size was determined and performance analysis of a GCPV system was implemented using the improved bat algorithm (IBAT). In solving optimization problems, a comparison of this algorithm with the whale optimization algorithm (WOA), CS, and PSO demonstrates its superiority.

In this study, firstly the mathematical modelling of the grid-connected generation system was explained and the meteorological data for the specific area of study in addition to the load profile were provided. Later, the optimization problem proposed herein was outlined. Finally, the results of the simulation of the newly proposed MATLAB program were discussed.

TABLE I. A SUMMARY OF THE VARIOUS OPTIMIZATION TECHNIQUES THAT WERE USED FOR RENEWABLE ENERGY SYSTEMS IN VARIOUS AREAS.

Reference	Year	Hybrid renewable energy sources	Optimization method	Location
[17]	2018	PV/WT/BAT	GA-PSO and MOPSO	Iran
[18]	2016	PV/WT	HOMER	Saudi Arabia
[19]	2018	PV/WT/FC/BAT	NA	Tunisia
[20]	2011	PV/WT/DG	Direct algorithm	Senegal
[21]	2018	PV/FC	Dispatched control strategy	United Arab Emirates
[22]	2016	PV/WT/FC	Mine blast algorithm	Egypt
[23]	2019	PV/WT/ BT/ DG	Grasshopper optimization alg. (GOA)	Nigeria
[12]	2017	PV/WT	Cuckoo search (CS) algorithm	Algeria
[24]	2016	PV/Combined heat and PowerChip/Battery	Mixed-integer linear	Germany
[25]	2019	PV/WT/Battery	Bat algorithm	Tunisia
[26]	2019	PV/Electrolyzer/ Hydrogen tank/Fuel	Genetic algorithm	Australia
[27]	2017	PV/DG/Battery	Grey wolf optimizer	Algeria
[28]	2019	PV/WT	Crow algorithm	Libya
[29]	2018	PV/WT	RNSYS	Morocco

II. MATHEMATICAL MODEL OF PROPOSED GRID-CONNECTED SYSTEM

The GCPV system that was proposed herein entailed the combination of various components, including a power inverter, solar PV panels (SPVPs), and a utility grid, which are presented in Figure 1.

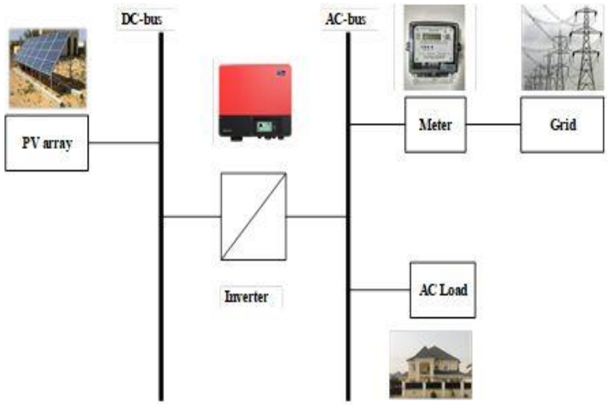

Fig. 1. Diagram illustrating the proposed grid-connected PV system.

III. METEOROLOGICAL DATA OF THE STUDY AREA AND THE LOAD PROFILE

A. Location

The location of this study is the Libyan Center for Solar Energy Research and Studies in Tripoli, located on the Libyan coast of the Mediterranean Sea (32°48.9′N, 13°26.3′E; approximately 6 m above sea level). An application was made for the method proposed herein to be designed and build a GCPV system to contribute power for the Libyan Center for Solar Energy Research and Studies as seen on Figure 2.

B. Solar potential

The air temperature and real solar radiation data of the test location were obtained directly from the climatic database of the Libyan Center for Solar Energy Research and Studies for all of 2019[30].Solar insolation ranged between 1.9 kWh/m^2 and 8.2 kWh/m^2. The minimum temperature recorded was 3 °C and maximum was 45 °C. All data were collected at 5-minute intervals. The 2019 solar radiation profile is presented in Figure 3.

Fig. 2. The designed GCPV system.

Fig. 3. The solar radiation profile for one year.

C. Load profile

For the Libyan Center for Solar Energy Research and Studies in Tripoli, Libya, the actual reported hourly loads over the course of 2019 were collected. As this analysis is focused on real meteorological and load data, it may be beneficial for actual feasibility studies on the introduction of a hybrid green energy system in the region concerned. In Figure 4, the hourly load pattern is provided. With a load averaging 17 kW, the actual load is around 37 kW.

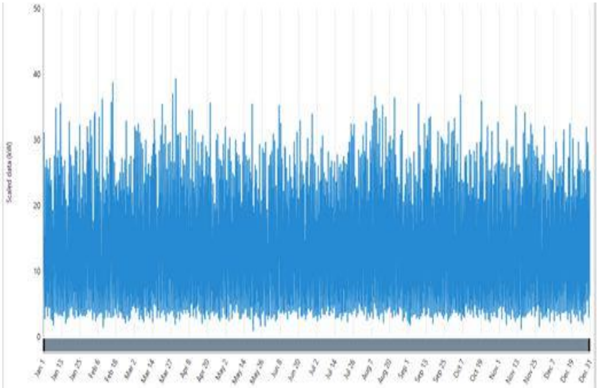

Fig. 4. The load power profile for 2019.

IV. OPTIMIZATION PROBLEM AND PROPOSED STEPS

The proposed system for energy conservation, and steps to be adopted for designing the system in an optimum condition. The proposed GCPV optimization algorithm is summarized in Figure 5. Among the most relevant architectural specifications for GCPV power plants are the seven decision variables shown in green in Figure 5.

A. Total cost of the proposed system

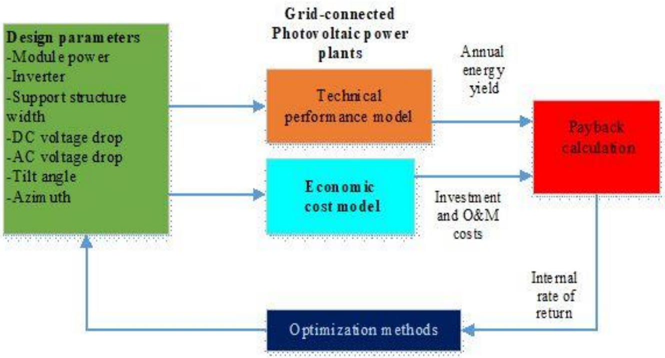

Fig. 5. The design of the optimization process involved in GCPV power plants.

The overall cost for this system is the sum of numerous other costs as calculated investment cost by Equation (1)., where C_{pv} represents the price of a PV panel and N_{pv} project the amount of PV panels used. CRF represents the capital recovery factor, which can be used for converting all these costs to the present value. These can be expressed by Equation (2)., where r represents the interest rate and L_p represents the project lifetime. The start-up investment cost comprises the installation cost for the whole system [31].

The operating cost and maintenance cost of the system are the biggest expenses, and can be calculated by the Equation (3)., where $C_{pvo\&m}$ represents the costs to operate and maintain the presented PV system/unit time and t_{pv} represents the operating time of the PV system. For the yearly cost of operation and maintenance (O&M) of α_{MPV} ($/m^2/year), the sum NPV of the total cost of O&M can be calculated by Equation(4)., where $\mathcal{E}_{PV}$ represents the yearly cost growth rate, A_{PV} represents the PV array total surface area in m^2, and R represents the internal rate of depreciation [32].

$$C_{in} = (C_{Pv}\ N_{PV}) * CRF \quad (1)$$

$$CRF = \frac{r(1+r)^{L_P}}{(1+r)^{L_P}-1} \quad (2)$$

$$C_{o\&m} = C_{pvo\&m} * t_{pv} \quad (3)$$

$$OM_{NPV_{PV}} = \alpha_{OMPV} * A_{PV} * \sum_{K=1}^{N} \left(\frac{1+\mathcal{E}_{PV}}{1+r}\right)^{j} \quad (4)$$

Due to bidirectional flowing of the energy in the system, the cost can be calculated in two different parts. The cost for the power that is procured from the grid C_{gp} and the supplied power to the grid C_{gs} can be calculated by the Equation (5) and Equation(6)., where C_p and C_g represent the cost/unit for the purchased power and the supplied power to the grid, and N_{gp} and N_{gs} represent the cumulative procured and supplied power amounts to the grid, respectively [33].

$$C_{gp} = N_{gp} * C_p \quad (5)$$

$$C_{gs} = N_{gs} * C_s \quad (6)$$

The total costs of system consist of replacement cost C_r, which comprises all replaced parts of system along the running period because of defect or aging, in addition to all the expenses explained above. The replacement cost C_r is important if the lifespan of any of the components is not correlated with project lifetime. So, the total cost of the system can be calculated by the Equation(7) [34].

$$C_{total} = C_{A\ in} + C_{o\&m} + C_{gp} - C_{gs} + C_r \quad (7)$$

B. Constraints and optimized parameters

Net present value (NPV) represents a reliable budgeting method because it makes allowances for the time value of money using discounted cash flows. It entails estimating net cash flows that may be encountered at any time in the future, using a discount rate to discount these flows, and, using the project risk level, then deducting the net start-up investment from the present-day value of these net cash flows, as can be seen in Equation(8), where *IRR* represents the internal rate of return, projected to be 10%; and *n* represents the predicted running period in years, and C_{ashin} represents the cash inflow, which can be measured as seen on Equation(9) [34].

The payback period comprises the duration of time when the cash outflow of the original start-up investment is considered to have been finally regained the investment. It is an extremely uncomplicated appraisal technique that can be calculated as seen on Equation (10). And Cost of energy (COE) can be calculated by using the Equation(11) [35].

$$NPV = \left(Cash_{in} * \frac{1-(1+IRR)^{-n}}{IRR}\right) - \left(C_{in} + C_{gp}\right) \quad (8)$$

$$Cash_{in} = kWh_{price} * Load \quad (9)$$

$$Payback\ Period = \frac{C_{in}(initial\ investment)}{Cash_{in}} \quad (10)$$

$$COE = \frac{(Total\ cost\ of\ generated\ energy\ for\ one\ year)}{(Total\ energy\ supplied\ in\ one\ year,\ kWh)} \quad (11)$$

In this model, the reliability that this system possesses is tested using the LPSP, which can be explained as a load which the system is incapable of fulfilling in the study period divided by the total load and can be calculated by Equation (12). The value of the LPSP is in the range of [0, 1], which confirms the system's efficiency until the total provided power from the integrated grid-connected solar PV system covers the load. While LPSP values of 0 mean that the load is always fully met, a value of 1 indicates that the required load is totally unmet. Permissible LPSP values are usually believed to be 0.05 or 5%. To minimize the COE with a stable method, the variable to be considered is NPV. The suggested restrictions are seen on Equation(13), where N_{PV} min and N_{PVmax} represent the minimum and maximum amount of PV panels, respectively [24] [35].

$$LPSP = \frac{\sum(P_{load} - P_{PV} - P_{GO})}{P_{load}} \quad (12)$$

$$N_{PVmin} \leq N_{PV} \leq N_{PVmax.} \quad (13)$$

V. RESULTS AND DISCUSSIONS

The algorithm that was newly proposed herein was applied for investigation of an autonomous electrical grid-connected PV system, used by the Libyan Center for Solar Energy Research and Studies in Tripoli, Libya. The experimental data that were used herein for the solar insolation in 2019 were collected from the Libyan Center for Solar Energy Research and Studies meteorological station. The data were recorded at 5-min intervals and the mean/hour was used for this study. Costs associated with the components of the GCPV system are tabulated in Table 2. The environment provided within MATLAB was used for the implementation and coding of the algorithm that was newly proposed herein, which was conducted on an Intel Core i7-7500U CPU @ 2.9 GHz. A comparison of the performance of this newly proposed method was performed with other metaheuristic approaches, namely the PSO, WOA, and CS algorithms.

The MATLAB Software was used for the implementation and coding of the algorithms to compare the performance of proposed algorithm and the PSO, WOA, and CS, and the results were tabulated. The algorithm parameters are modified to maximize the objective function used in this study as seen below:

- **PSO:** Number of iterations = 100, size of the swarm = 60, C1 = 2, C2 = 2, inertia weight (ω) = 0.7.
- **CS:** Number of iterations = 100, number of nests = 7, alien egg discovery rate = 0.25, Beta (β) = 1.5, Levy multiplying coefficient = 0.1.
- **WOA:** Number of iterations = 100, population (N) = 50, r (random number) in [0,1], a (distance control parameter) decreased from 2 to 0.
- **IBAT:** Population (N) = 50, Number of iterations = 100, Loudness (A) = 0.95, pulse rate (r) = 0.45, Minimum frequency (f_{min}) = 0, parameters to improve the algorithm's performance and regularized the result (w_{Min}, w_{Max}) ∈ [0.5, 1], velocity (V_{max})=10.

We compared the results using most used, well-known, and strong algorithms with the IBAT algorithm to determine validity of the results. The results of IBAT are compared with the outcomes of the WOA, PSO, and CS algorithms.

A particle population travels within the optimization problem's search space in the PSO, WOA, and CS. The particle location constitutes a possible way to solve the optimization problem. Each one of the particles performs a scan of the search space searching for a better location. Herein, one of the terminal criteria is a certain and specific number of iterations. The size of each of the systems is equal to one final total price, and there are two objective functions that minimize the COE and NPC. For all the algorithms, the search space was the same and the variables were the sizes of the components. Table 3 provides a comparison of the algorithm parameters as well as the statistical results of the two specific criteria, as an indicator of the robustness of the algorithms. Determined in this table were the minimum (min), maximum (max), and mean NPC and COE values, respectively. As can be seen, for the three objective functions, the results for the IBAT algorithm were the best with regards to the min, max, and mean values.

The best LPSP is obtained by the proposed IBAT at 0.0965, while the worst is obtained via CS at 0.845. In determining the optimum size of the GCPV system, these observations affirm the superiority of the proposed IBAT algorithm. Figure 6 shows bar charts of the COE and LPSP values that were obtained using the specified approaches. The problem with the PSO, CS, and WOA lies in assigning many PV panels, which leads to secure operation but a solution that is uneconomical. The proposed IBAT algorithm gives a preferable structure for the GCPV system as there is not significant surplus power as seen with the other approaches. This confirms the ability of the proposed GCPV system to achieve secure and economic operation.

TABLE II. COST RELATED TO GCPV SYSTEM COMPONENTS.

	Initial capital costs	**Replacement costs**	**Maintenance costs (/year)**	**Lifetime (years)**
PV array	2800 $/kW	Null	15 $/kW	25
Inverter	327 $/kW	359 $/kW	28 $/kW	10
Structures	$1930	Null	$20	25
Total cost	$17565	$1795	$235	

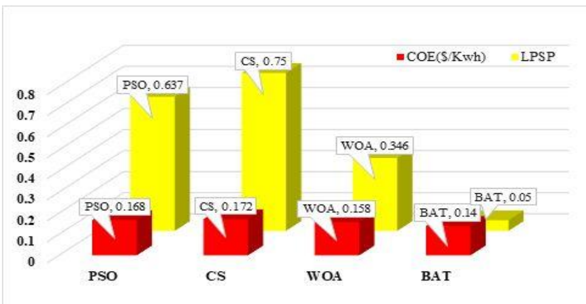

Fig. 6. COE and LPSP values were obtained using the optimization techniques.

TABLE III. TECHNICAL PARAMETERS OF THE CS, PSO, WOA, AND IBAT, AND STATISTICAL RESULTS

Algorithm	NPC ($)			COE ($/kWh)			LPSP
	max	mean	min	min	mean	max	
IBAT	19760	19604.8	19595	0.134	0.136	0.14	0.0965
WOA	19761	19611	19600	0.151	0.153	0.158	0.415
PSO	19768	19617	19607	0.159	0.161	0.168	0.625
CS	19778	19620	19612	0.165	0.167	0.172	0.845

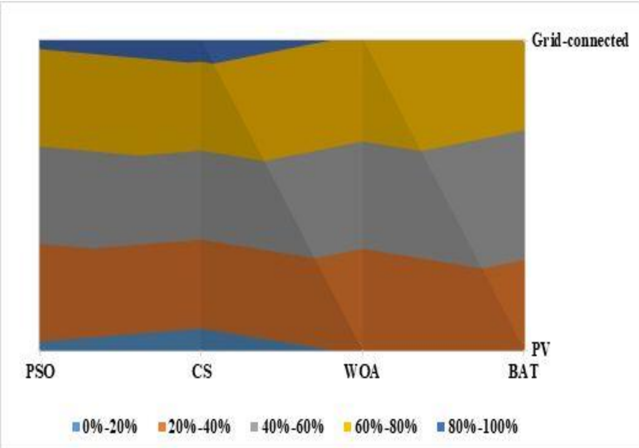

Fig. 7. Annual contributions from PV and grid-connected components using various methods.

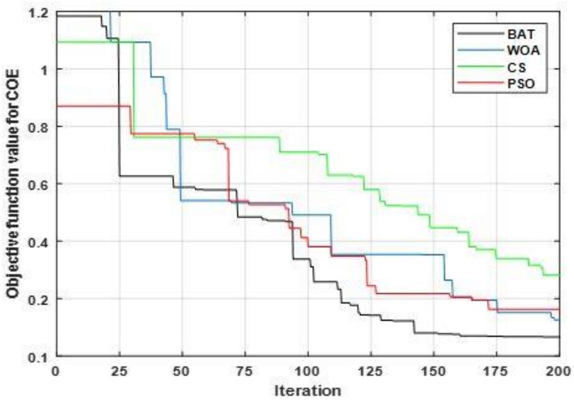

Fig. 8. Comparison between algorithms' convergences for minimum COE ($/kWh).

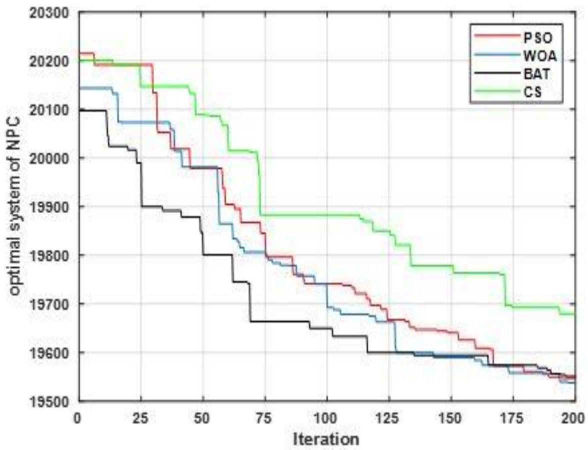

Fig. 9. Comparison between algorithms' convergences for minimum NPC ($).

The percentages of participation for each of the energy sources in attaining the annual load that were obtained using the IBAT proposed herein, and the other algorithms are shown in Figure 7. With this newly proposed methodology that was presented herein, the constricted PV system was able to cover 26% of the load, while 74% of the energy required was grid-connected. Regarding the other optimization methods, the PV system contributes 18%, 15%, and 21%, respectively, via PSO, CS, and WOA, while 82%, 85%, and 79% of the load is grid-connected.

The trends of the NPC and COE in attaining the optimal solution are presented in Figures 8 and 9, where it is seen that the IBAT algorithm achieved the optimal solution more quickly than WOA, PSO, and CS, further demonstrating the convergence speed advantage that the IBAT possesses. With the progression of the algorithm, it was able to find new answers and the NPC and COE values decreased. IBAT's trends are depicted in the figures, depicted via a black line. This algorithm was able to exhibit the most rapid movement to the minimum solution. As was seen using the NPC, the IBAT also exhibited the fastest convergence speed for the COE criterion. In addition to ease of implementation, these benefits result in the IBAT being among the most powerful of the algorithms.

CONCLUSIONS

In this paper, a GCPV system has been presented as a system for power generation to contribute electricity for public places during business hours. Since PV systems that have batteries are more expensive in comparison with PV systems that do not have batteries, the most reasonable use of PV system equipment is in GCPV system installations to contribute to the electricity demand for the daytime period only. In the optimum techno-economic analysis of the proposed method, the IBAT algorithm was used, and the last objective function entailed the minimization of both the NPC and COE.

We compared the IBAT algorithm, and the WOA, PSO, and CS showed the superiority of IBAT for optimization problem solving. In the optimally sized system for the Libyan Center for Solar Energy Research and Studies, the PV panels met an average of 26% of the consumption and the electrical grid was able to supply the remaining electrical load. In contrast, with the other three algorithms, the NPC and COE had 12.7% and 13.4% increases, respectively. The GCPV system designed here is installed at the Libyan Center for Solar Energy Research and Studies in Tripoli, Libya, and this study used annual real electrical and climatic data recorded by the Libyan Center for Solar Energy Research and Studies. The results obtained with IBAT were compared to WOA, PSO, and CS, and the proposed algorithm exhibited the most superior optimal architecture for the GCPV system, achieving a LPSP of 0.0965 and a COE of 0.1359 $/kWh. The elapsed time of the IBAT approach was 497.326 s, comprising the best time when compared to the other the approaches presented.

Contrubition Of The Authors

The contributions of the authors to the article are equal.

Conflict Of Interest

There is no conflict of interest between the authors.

Statement Of Research And Publication Ethics

Research and publication ethics were observed in this study

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