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Reliability Support of Undependable Grid Using Green Energy Systems: Economic Study

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ABSTRACT Developing countries' energy sector faces a multitude of challenges, ranging from inadequate generation to unstable grids. Power outages are among the most common issues, particularly in remote areas. Utilizing grid-tied green energy resources to address this issue and to cover for power outages from local grids. This article presents a cost-effective design of a grid-tied, hybrid green energy system (GES) consisting of wind, PV, and batteries considering the influence of the grid availability. A multi-objective, optimal techno-economic design, optimized by multi-objective particle swarm optimization technique is presented for the grid-tied GES linked to a small hamlet in the north of Egypt. The multi-objective function introduced in this work includes three objective functions which are, the Loss of Power Supply Probability (LPSP), the Cost of Energy (COE), and the System Surplus Energy Rates (SSER) considering the grid availability. The grid availability (GA) of 100% was considered as a base case and it was reduced to 70% with a step of 5%. The simulation consequences had cleared that the lowest and largest percentage values of SSER were obtained at GA of 85 %, and 70 %, respectively. When the value of SSER equal to 0.33%, the system design for solving the grid unavailability consists of 12 PVs, one WT, and 1420 batteries with COE of 0.145$/kWh and TNPC of 3,699,800 ($).

INDEX TERMS Grid availability, multi-objective optimization, loss of power supply probability, system surplus energy rates, sizing, and optimization.

ACRONYMS AND NOMENCLATURE

AASI	Average availability service index
C_{grid}	Cost of energy purchase
C_I	Initial capital cost of system devices ($)
$C_{O\&M}$	Operation and maintenance cost
CR	Replacement cost
Df	PV derating factor (0.85)
Eb	Amount of energy in the battery
$E_{Bat,cap}$	Battery capacity
$E_{bat,max}$	Maximum allowable capacity of the battery
$E_{bat,min}$	Minimum allowable capacity of the battery
$E_{grid\_buy,t}$	Energy purchased from the utility at assured period, t.
$E_{grid\_sell,t}$	Energy sold to the utility at assured period, t.
E_{served}	Primary load served (kWh/year)
G	Global utility fallen on the titled plane (kW/m2)
G_{ref}	Solar radiation at base conditions (1 kW/m2)
I	Interest rate
I_f	Inflation rate
I_r	Real interest rate
K_T	Peak power temperature coefficient
N_{bat}	Number of batteries
N_p	Number of pareto front points
N_{PV}	Number of PV modules
N_{WT}	Number of the wind turbines
$P_{ch,b}$	Charging power of the battery
$P_{dis,b}$	Discharging power of the battery
P_{PV}	PV produced power (kW)
P_r	Rated wind turbine power (kW)
P_{rated}	Module output power (kW)
P_{re}	Power produced by the renewable system at hour t
P_w	Produced power of the wind turbine (kW)

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R_{grid}	Sales of electricity to the public utility
$rate_{feed-in}$	Feed-in tariff rate
S	Salvage value
T_{amb}	Ambient temperature (°C)
T_c	PV cell temperature (°C)
T_{comp}	Component lifespan (year)
T_{proj}	Project lifespan (year)
T_{ref}	Temperature at base conditions (°C)
V_{ci}	Cut-in wind speed (m/s)
V_{co}	Cut-out wind speed (m/s)
V_r	Rated wind speed (m/s)

ABBREVIATIONS

COE	Cost of electricity
CRF	Capital recovery factor
DOD	Depth of discharge
GA	Grid Availability
GES	Green Energy System
LPSP	Loss of Power Supply Probability
MOPSO	Multi-Objective Particle Swarm Optimization
NWCT	Normal working cell temperature
PPA	Power Purchase Agreements
SSER	System Surplus Energy Rates
$P_{ch,b}$	Charging power of the battery
$P_{dis,b}$	Discharging power of the battery
P_{PV}	PV produced power (kW)
P_r	Rated wind turbine power (kW)
P_{rated}	Module output power (kW)
P_{re}	Power produced by the renewable system at hour t
TNPC	Total net present cost
WT	Wind turbine

GREEK SYMBOL

η_b	Efficiency of each battery
η_{inv}	Inverter efficiency
η_w	Wind turbine efficiency

I. INTRODUCTION

Instability, power block-outs, significant distribution network outages, and frequently scheduled load shedding impact the centralized electricity grids, especially the developing countries. The reliability of the grid is determined based on the ratio of the total number of customer hours that service was available during a given period to the total customer hours requested, which is known as the average availability service index (AASI). The AASI is expected to be 0.9988 for a reliable grid whereas an unreliable grid is characterized by random power outages [1]. The best way to address these grid issues and consequently supporting the grid reliability is widely incorporate the production of clean green energy into the power distribution networks. Grid-connected green energy systems (GESs) could be an applicable option to provide sustainable electric outfits to developing countries.

Mondal and Islam analyzed the frugal viability of utility-connected PV systems and concluded that this system must be utilized to overcome power shortages [2]. Robert and Goplan had made twenty scenarios to investigate the integration of GES into the grid and concluded that the utility-linked GES is the most expense-efficient energy system compared to the island systems [3]. The optimal sizing of grid-connected three renewable energy sources (PV, wind, and fuel cell) was investigated to supply some domestic loads [4].

A grid-linked grouped heat and energy project for supplying household loads was investigated with several tariffs for buying and selling electricity from the utility [5]. A model was developed for estimating the energy production, selling electricity to the local grid using wind turbine (WT)/Hydrogen system, thermal recovery from fuel cells (FCs) [6]. The potential of both off-grid and on-grid PV, WT, FC, and biomass hybrid systems for the electrical energy generation with a focus on the optimal size of the GES has been inspected [7]–[14].

A detailed study about how to overcome the power outages in a rural area in Egypt by integrating a hybrid PV/WT/FC to the electrical utility was presented in [14]. This study focused on maximizing the profit from integrating these three GESs to the Egyptian electric utility considering the cost of these GES sources. The objective function in this study was a single objective function with one objective, which is to minimize the cost of electricity (COE). It is worth noting that this study had presented a proposal to use FCs as storage units instead of batteries.

Another investigation for the optimal size of an island hybrid GES supplies a new society in Egypt was presented in [15], [16]. In the preceding studies, the optimal size with minimum capital and running costs for this proposed feeding system was introduced. Wang *et al.* investigated the common consequences of combining renewable energy with the electrical network on provincial energy efficiency. The authors have concluded that the effect of renewable energy generators integrated into extra-high voltage and ultra-high voltage power grids are either not noteworthy or even negative [17]. Kamal, et al proposed a grid-connected GES including WT, solid oxide FC, Electrolyzer, and batteries to serve the electric demand of twenty-five homes in Islamabad, the metropolis of Pakistan [18]. A comprehensive literature exploration was conducted to assemble accessible information about unreliable grid modeling but went over a couple of such examinations [19]. Murphy et al completed an analytical survey for Uganda dealing with the uncertain utility by devising a method in which a producer is produced with one hundred efficacy percentage. The survey notified that uncertain utility consideration raised the estimate of energy contrasted to 24h availability of the utility [20]. Harish *et al.* [21] had made a comparison among utility expansion and distributed generation (DG) alternates to solve the problem of power outages in rural India. Various utility reliability tactics were simulated. The authors concluded that off-grid DG does not seem to be competitive with utility expansion at distances less than seventeen kilometers. This is because whenever the location of the new society or the village is far from the network, on-grid GES is the best choice from the frugal viewpoint. While an island GES is a better choice for closer locations from the network.

The GES integration to the electric utility is a rich area of research in recent times to solve both the energy supply and environmental problems. This research area has many challenges. These challenges are summarized around the optimal utilization of the available resources through sound economic studies especially for the new communities and through tracking the maximum power point for optimal exploitation of the available GES [22], [23].

As discussed before, the economic study of such GES integrated into the electrical utility is a difficult issue and almost to the stage of complexity. This difficulty of such issues is related and not limited to, a large number of variables, the non-linear characteristics of GES, and the dependence of these GES on some environmental factors which in turn affect the power generated from these GES. Evolutionary computing techniques are used for such mixed-complex optimization problems.

Genetic and particle swarm optimization (PSO) mechanisms were applied to economic studies of off-grid GES [24]. This study is presented also a comparison between these two optimization mechanisms and the results showed the superiority of PSO.

Harmony search (HS), enhanced flower pollination algorithm (FPA), an electromagnetic field optimization is utilized for enhancing the performance of grid-connected GES in the form of FC [25].

Rezvani *et al.* utilized lexicographic optimization and hybrid augmented weighted epsilon-constraint algorithms for the optimal tabulating of a micro-grid to mitigate both the overall working estimation and the emission that was resulted from the generating stations. The results showed that the proposed hybrid optimization technique leads to good outstanding solutions [6]. Improvement of off-grid hybrid system performance was improved by optimal PI controllers optimized by the cuckoo search mechanism [23]. This optimization technique is applied to achieve maximum power point tracking of three GESs (PV/WT/FC) and consequently achieving the maximum economic benefit and reducing the cost of generation. The extreme learning machine (ELM) mechanism was used to develop a model to forecast the amount of the produced power of utility-tied PV system installed at a roof-top of PEARL laboratory at the University of Malaya, Malaysia [19]. The consequences from the introduced model were contrasted with those obtained from the support vector regression and the artificial neural network (ANN). The comparison illustrated that the ELM model has higher exactness with less predestined time.

The risk theory into the allocation and placement of distributed generation (DG) units, [26] suggested a risk-based, multi-objective optimum allocation model to maximize the placement and configuration of DG units and provide a stable and cost-effective method. While Singh *et al.* [27] recommended the reformed electric system cascade analysis (RESCA) approach to design the hybrid renewable energy system (HRES), using wind conversion systems, photovoltaic systems, the battery storage system, the non-intermittent source, and the grid as components. Four distinct HRES structures are considered for study in off-grid and grid-connected mode. The four HRES configurations are configured with restrictions from RESCA, such as final surplus capacity, renewable energy rate, LPSP, and annual system cost (ASC).

The topic of integrating renewable energy sources in the unreliable grid is a major technical and economic challenge, especially for small or rural villages.

The issue of unreliable grids is addressed in this article since these grids commonly suffer from the problem of frequent power outages a grid-connected green energy system composed of solar PV, wind turbines, and battery banks have been suggested as a backup system used to compensate for blackouts.

In this work, the situation where the grid is completely available was first considered, and then the availability of the grid was decreased by 5 percent per time from 95 percent to 70 percent to show the influence of network availability on the design of the proposed hybrid system.

The optimal number of components of the grid-connected PV/WT/battery system has been identified by utilizing the Multi-Objective Particle Swarm Optimization (MOPSO) which was used for reducing three objective functions of Loss of Power Supply Probability (LPSP), Cost of Energy (COE), and System Surplus Energy Rates (SSER) under varying conditions in the weather; by using actual on-site hourly power demand data for the studied village. The Pareto front and decision-making processes are used to obtain the final optimal system.

This article is structured as follows: Section 1 addresses the background and literature review of the study. Section 2 lays out the methodology. Details of the Fitness Function and Energy Management Scenarios are explained in Section 3. Section 4 discusses the findings of the simulation and the optimization of the study case. Conclusions are outlined in section 5.

II. METHODOLOGY

The objective of this research is to manifest the techno-economic feasibility through a case study of a village in Northern Egypt. This hybrid GES comprises solar PV generators, wind turbines, and battery banks. The system is attached to an unreliable grid for remote rural electrification.

MOPSO has been used to design a hybrid power system to assess the optimum size of its components by performing a techno-economic analysis. Figure 1 shows the approach used for the effective configuration and the techno-economic study of the proposed scheme.

Information concerning energy demand and environmental data, such as solar radiation, ambient temperature, and wind speed were collected for one year between the

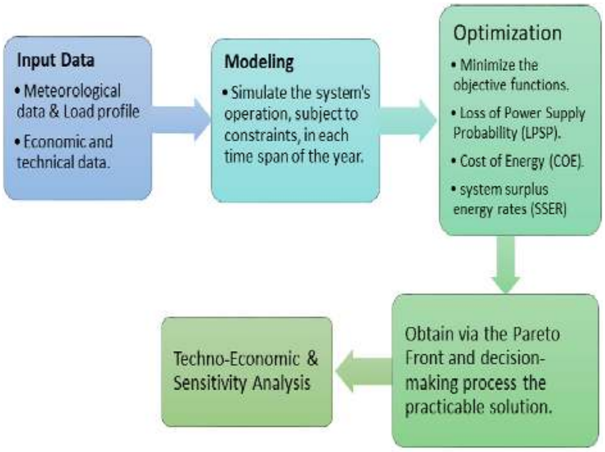

FIGURE 1. Framework for optimal design and techno-economic assessment of the proposed system.

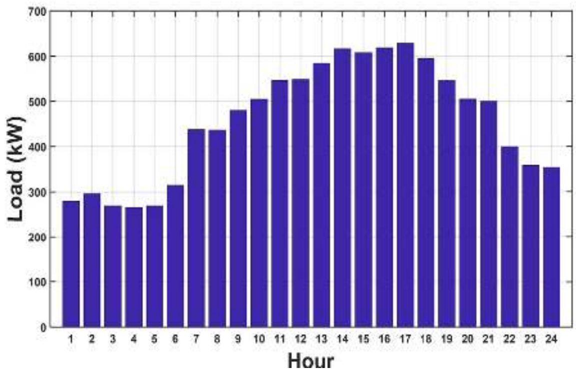

FIGURE 2. The daily load profile of the selected village.

1st January 2019 and the 31st December for Qesm Remanah, North Sinai, Egypt (latitude 31.03641 °N, longitude 32.62705 °E). Renewable energy supplies with an estimated annual solar radiation of 2027kWh/m2 and an average wind velocity of 4.22 m/s, are the main feature of this area. This analysis uses actual hourly data in-site for the village energy demand, with an average of 457 kWh hourly, an average demand of 897 kW, and a load factor of 0,509. The average daily load for the selected area is seen in Figure 2. The solar radiation and the wind speed of the field under study were shown in Figures 3 and 4.

A. DESCRIPTION OF THE GRID-TIED SYSTEM

The renewable energy system presented in this work includes two renewable sources which are PV and WT systems. These renewable energy sources are connected to an unreliable grid. The system components include an inverter, converter, charge controller, and battery banks. Figure 5 presents a straightforward graphic of the given system. Generally, the grid availability for a particularized period (e.g. a day, week, month, year) can be defined as [30]:

$$\textit{Grid availability GA}\ (\%) = \frac{\textit{Grid available in period}}{\textit{Hoursi theperiod}} \times 100 \quad (1)$$

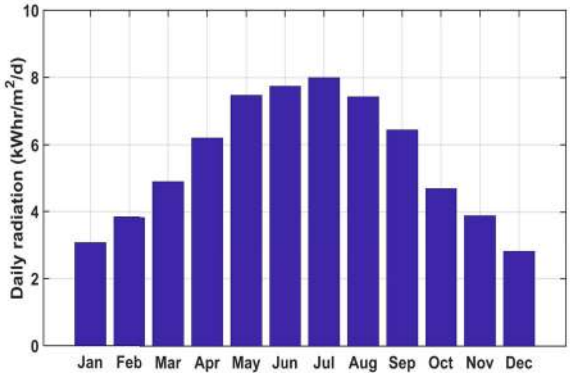

FIGURE 3. The selected village's annual solar radiation.

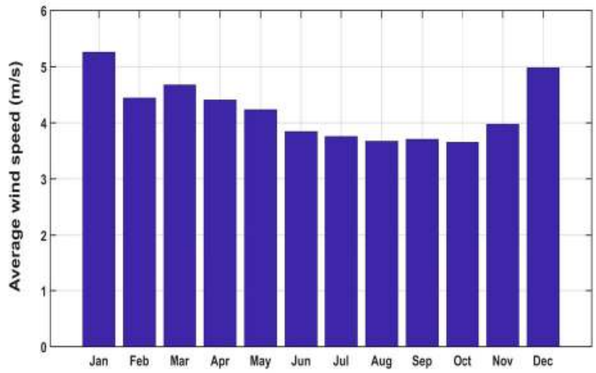

FIGURE 4. Average monthly wind velocity during the year.

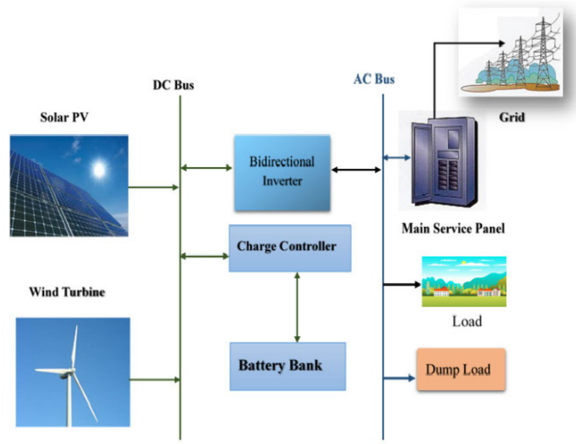

FIGURE 5. General schematic of the suggested system.

The grid blackout intervals are randomly modeled.

1) PV MODEL

The produced energy by the PV arrays was estimated as [28],

$$P_{PV} = \left(P_{rated} N_{pv} D_f\right)\left(\frac{G}{G_{ref}}\right) \times \left(1 + K_T\left(\left(T_{amb} + G\left(\frac{NWCT - 20}{0.8}\right)\right) - T_{ref}\right)\right) \quad (2)$$

The solar system consists of 80 solar panels, 375W each, and three inverters each of 10kW to connect the PV system to the AC grid side with a 25-years old lifetime assumed [29]. The PV system along with the three inverter's capital cost is 42,000 $ with annual maintenance of 40$ [30].

2) WIND TURBINE

The generated power by the wind turbine was approximately computed as [7], [31].

$$P_w = \begin{cases} N_{WT} \times \eta_w \times P_r \\ \quad \times \sum_{t=1}^{T} \left(\dfrac{V(t)^3 - V_{ci}^3}{V_r^3 - V_{ci}^3} \right), & V \leq V_r \\ N_{WT} \times \eta_w \times P_r, & V_r \leq V \leq V_{co} \\ 0, & V_{co} \leq V \ or \ V \leq V_{ci} \end{cases} \tag{3}$$

where: V(t) is the adjusted wind speed at the hub high in (m/s) that can be defined as:

$$V(t) = V_r \left(\frac{H_{WT}}{H_r} \right)^{\alpha} \tag{4}$$

where HWT is the wind turbine hub height, H_r is the base height, and α is the friction coefficient, and equal 0.1428 for low roughness, surface, and well-exposed site [32], [33].

In this analysis, a 50-kW wind turbine is used. A wind turbine's capital is \$50,000, with \$25,000 and \$ 75 a year as a replacement and O&M expenses [34]. The wind turbine is 20 years with a hub height of 20 m.

3) BATTERY BANK

In the hybrid system, the batteries are used as storage media. During the low power demand, the battery bank saves the surplus electricity and releases the stored energy at higher loads or when the clean energy sources are inadequate.

Because of its numerous benefits, lithium-ion batteries have been used in this research. These batteries have a depth of discharge of up to 100% (DOD), with a self-discharge of 1 % per month, and operating efficiency of 95% [35], [36].

A dynamic model is used to describe the operating of the battery, in which the energy stored in the battery is calculated at any given interval as:

$$E_b(t) = E_b(t-1)(1-\sigma) + \left(P_{b,ch}(t) \times \eta_b - P_{b,dis}(t) \right) \times dt \tag{5}$$

Noting that during the discharging process, the battery discharging efficiency is set equal to 1.

The energy storage of the batteries is subjected to the following constraints:

$$E_{Bat,min}(t) \leq E_b(t) \leq E_{Bat,max}(t) \tag{6}$$

$$E_{Bat,max} = E_{Bat,cap} \tag{7}$$

$$E_{Bat,min} = E_{Bat,max}(1 - DOD) \tag{8}$$

A Li-ion battery (LiFePO4 type) is used in this study, with capital and replacement costs of \$630 / kWh, \$2 per year as O&M costs, and 15 years of a lifetime [37], [38].

4) INVERTER

The output of both the WT and PV system is DC. This DC output of the two GREs is connected to a DC link. To attach this DC link to the electrical grid at the AC bus, an inverter is needed. As the proposed on-grid hybrid system is embedded with a battery (as a storage system), the inverter used is a bi-direction type to allow charging the batteries from the AC side, if the output power of the REGs is not sufficient as shown in Figure 5.

The size of the inverter depends primarily on the demand for peak load

$$P_{inv} = P_L^{max} / \eta_{inv} \tag{9}$$

5) GRID MODELLING

The grid is represented as an energy supply that can absorb/generate electric power. Because of the restrictions imposed on power transformers, transmission lines, and other heavy power equipment of the grid, there is a border on how much energy in a specific time frame can be absorbed or provided. The following equations are used to model a grid energy exchange [39]:

$$\mathrm{E_{grid,t}} \leq \mathrm{E_{grid\_max}} \tag{10}$$

$$\mathrm{E_{grid\_buy,t}} < 0 \tag{11}$$

$$\mathrm{E_{grid\_sell,t}} > 0 \tag{12}$$

The uncertain utility contains accidental or random power outages. The frequency, the time interval, and the diversity in blackouts have an opposite influence on the estimate of utility-tied GES.

III. FITNESS FUNCTION

A. ENERGY MANAGEMENT SCENARIOS

For the suggested system, three scenarios are proposed:

- Scenario 1, the generated electricity from the GES equals the required demand: in this case, neither the battery bank nor the grid will participate in the load demand.
- Scenario 2, the produced electricity from the GES's is greater than the demand and the excess energy will be stored in the batteries. The surplus energy could be used for charging the batteries, the energy will be sold to the grid if the grid is available else this energy will be directed to a dump load.
- Scenario 3, the energy generated from the GES's is not enough to meet the demand. In this case, the deficit will be drawn from the battery bank, but if the shortage hits the minimum level, the remaining demand will be purchased from the grid.

A flowchart of the energy administrative scenarios of the submitted system is cleared in figure 6.

B. PROBLEM FORMULARIZATION

The main objective of this work is to optimize the generating cost of electrical energy while satisfying the stability of the system and assessing the hybrid system's usability and performance.

The cost of electricity (COE) refers to the costs of producing electricity over the lifespan of the project.

It is a very valuable indicator because, while the rating power and investment costs are different, it permits a distinction between diverse energy technologies [39], [40].

The COE of the grid-connected PV/WT/battery hybrid system is defined as:

$$COE = \frac{(CRF \times TNPC) + C_{grid} - R_{\mathrm{grid}}}{E_{served} + E_{grid_{selling}}} \tag{13}$$

where: Capital recovery factor (CRF) is a ratio used over the life of a project to determine the total value of a set of equivalent cash flows. The estimation of this factor is given by:

$$CRF = \frac{\left(\frac{I_r - I_f}{1+I_f}\right)\left(1 + \frac{I_r - I_f}{1+I_f}\right)^N}{\left(1 + \frac{I_r - I_f}{1+I_f}\right)^N - 1} \tag{14}$$

TNPC is the total net present cost of the system which is composed of the NPC of the PV, WT, and battery banks.

$$TNPC = \sum_{\mathrm{n=0}}^{\mathrm{N_{proj}}} (\mathrm{C_I(n) + C_R(n) + C_{O\&M}(n) - S(n)}) \times \frac{1}{(1+\mathrm{I_r})^{\mathrm{n}}} \tag{15}$$

$$C_I = \sum N_{PV} C_{I_{PV}} + N_{WT} C_{I_{WT}} + N_{bat} C_{I_{bat}} \tag{16}$$

$$C_R = \sum N_{PV} C_{R_{PV}} + N_{WT} C_{R_{WT}} + N_{bat} C_{R_{bat}} \tag{17}$$

$$C_{O\&M} = \sum N_{PV} C_{O\&M_{PV}} + N_{WT} C_{O\&M_{WT}} + N_{bat} C_{O\&M_{bat}} \tag{18}$$

$$S = \sum N_{PV} S_{PV} + N_{WT} S_{WT} + N_{bat} S_{bat} \tag{19}$$

The salvage value (S) was estimated by:

$$\mathrm{S} = \mathrm{C_R}\left(\frac{\mathrm{N_{comp}} - \left(\mathrm{N_{proj}} - \mathrm{N_{comp}} \times \mathrm{INT}\left(\frac{\mathrm{N_{proj}}}{\mathrm{N_{comp}}}\right)\right)}{\mathrm{N_{comp}}}\right) \tag{20}$$

Sales of electricity to the public utility and cost of energy purchase can be estimated as:

$$R_{\mathrm{grid}} = \sum_{t=1}^{8760} rate_{feed-in}.E_{grid_{\mathrm{selling}}} \tag{21}$$

$$C_{grid} = C_p \times \sum_{t=1}^{8760} E_{grid_{\mathrm{purchased}}} \tag{22}$$

where: $rate_{feed-in}$ is the feed-in tariff rate (0.0617 \$/kWh) and Cp is equivalent to \$0.0425 / kWh baased on the Egyptian grid tariff [41].

The loss of power supply probability is described as the prospect that an inadequate power supply occurs when the GES is incapable of meeting the load needs. The loss of power supply probability of zero value means the load demand is contented, and if its value is one then the load demand will eternally be served [42], [43].

The LPSP can be described as:

$$LPSP = \frac{\sum_{t=1}^{T} P_{deficit}(t).\Delta t}{\sum_{t=1}^{T} P_{demand}(t).\Delta t}, \quad T = 8760 \tag{23}$$

The SSER is the percentage of the surplus energy in the hybrid system compared with the total renewable energy generated by GES [44]. The SSER is subject to the constraint $0 \leq SSER \leq 1$.

$$SSER = \frac{\sum surplus\ energy}{\sum E_{PV} + E_{WT}} \tag{24}$$

The fitness function for this multi-objective optimization can be expressed as follows.

$$minimize: \begin{cases} F_1 = COE \\ F_2 = LPSP \\ F_3 = SSER \end{cases} \tag{25}$$

$$subjct\ to: \begin{cases} N_{PV}^{min} \leq N_{PV} \leq N_{PV}^{max} \\ N_{WT}^{min} \leq N_{WT} \leq N_{WT}^{max} \\ N_{bat}^{min} \leq N_{bat} \leq N_{bat}^{max} \\ 0 \leq LPSP \leq LPSP_{max}, LPSP_{max} = 2\% \\ 0 \leq SSER \leq SSER_{max}, SSER_{max} = 15\% \end{cases} \tag{26}$$

C. MULTI-OBJECTIVE PARTICLE SWARM OPTIMIZATION ALGORITHM (MOPSO)

MOPSO technique had been used in this article to tackle the energy management dilemma.

Therefore, the MOPSO algorithm is utilized to achieve the Pareto front of the optimization problem. The MOPSO procedure (Figure 7) in this research work was adapted from [45], [46].

D. DATA PREPARATION FOR THE SIZING OPTIMIZATION PROCESS

The hourly load demand, the solar irradiance (kWh per m^2 per day), the ambient temperature (°C), and the wind speed (m/s) for the hamlet used in this study are recorded in 2019 (8760 points). A code for the MOPSO technique is progressed in MATLAB™ software package is introduced to minimize the multi-objective function proposed in this study based on the recorded data all over 2019 for this village.

IV. RESULTS AND DISCUSSIONS

This article suggests a complementary PV / WT / Battery system linked to an unreliable grid to support the grid performance through compensating the power outage and consequently increase the reliability of the system in addition to minimizing the generating cost for a village in Egypt.

The grid unavailability was expressed by the grid availability factor (GA), in which the whole situation of the grid availability (GA = 100%) was considered as a base case, and then GA is reduced to 70% with an increment of 5%.

The optimized objectives presented in this article are to minimize the COE, the LPSP, and the SSER where COE is

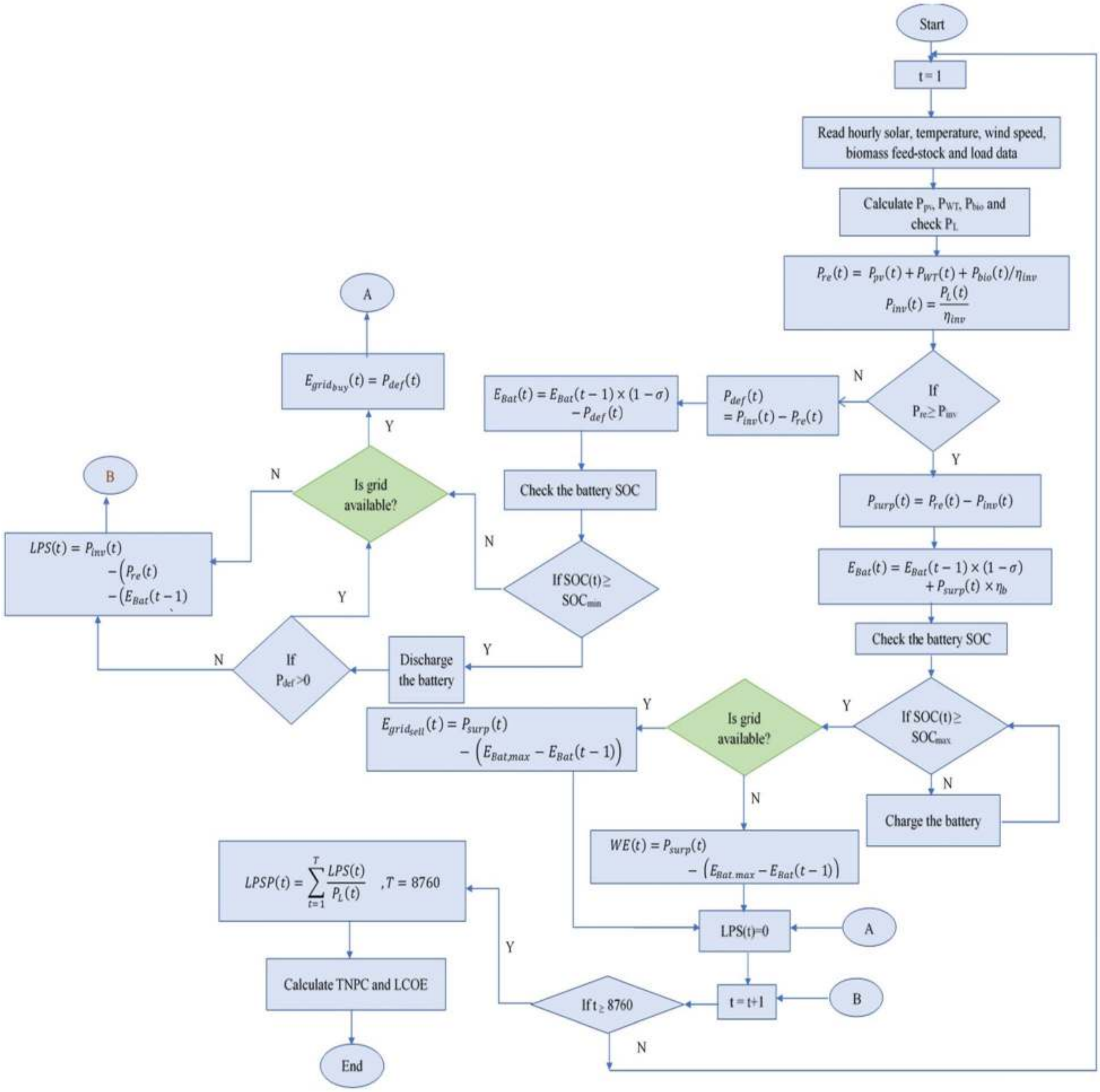

FIGURE 6. Flowchart of the energy administration scenarios of the submitted system.

used to assess hybrid system economies; LPSP is for reliability assessments, and SSER is to measure hybrid system usability and efficiency. The optimization variables include the total number of WT, PV, and battery banks.

The Pareto front estimation of the MOPSO algorithm for GA from 100% to 70% with a step of 5% is shown in Figure 8.

The Pareto front allows the decision-maker to choose an optimum solution based on expectations for lower COE, LPSP, or SSER from the optimal solutions collection. The compromise between the three objective functions is clearly shown in Figure 8. From this figure, the effect of GA on the three objective functions can be concluded as follows:

A. THE EFFECT OF GA ON COE

The effect of the GA percentage change on the proposed system's COE can be seen in Figure 8, where it can be observed that in the base GA case when GA = 100 percent, the MOPSO has achieved an optimal solution where the COE was \$0.098/kWh, but when this percentage decreased to 95 percent, the COE value increased to \$0.1263/kWh. It can be noticed that COE increases with decreasing GA percentage.

B. THE EFFECT OF GA ON LPSP

The maximum LPSP was set as 2% in the fitness function constraint, Figure 8 indicates that the MOPSO obtained an

1. Set MOPSO parameters:
(population size (N_{Pop}) = 100, Repository Size (N_{Rep}) = 100, inertia weight (w) = 0.5, inertia weight damping ratio (w_{damp}) =0.99, personal learning coefficient (c_1) =1.8, global learning coefficient (c_2) =2, Leader Selection Pressure (β)=2, Deletion Selection Pressure (λ)=2, Mutation Rate (μ)=0.1, total number of iterations = 100).
2. Set dimension of the search variables: the lower and upper bound respectively.
    - lower and upper bound of number of PV systems (0,50).
    - lower and upper bound of number of wind turbines (0,10).
    - lower and upper bound of number of battery banks (0,2500).

2. Set repository Rep =φ
3. For $i = 1{:}N_{pop}$
4. Randomly initialize population of particles having positions X_i and velocities V_i are set to zero.

$$X_i = [N_{PV}, N_{bat}, N_{WT}], \quad V_i = 0$$

5. Calculate fitness of particles and find the index of the best particle $P_{best,i} = X_i$
6. End
7. Determine domination: $Rep = Dominance(P_{best})$
8. k=0
9. While $k \leq MAX_{iter}$
10. For $i = 1{:}N_{pop}$
11. $leader = selectleader\ (Rep)$
12. Update velocity and position of particles

$$V_i^{k+1} = \omega V_i^k + c_1 r_1 (Pbest_i^k - X_i^k) + c_2 r_2 (leader_i^k - X_i^k)$$
$$X_i^{k+1} = X_i^k + V_i^{k+1}$$

6. Evaluate fitness
7. Apply Mutation: $X_i = Mutate(X_i)$
8. If X_i dominates $P_{best,i}$ set $P_{best,i} = X_i$
9. End
10. End
11. $Rep = Dominance(P_{best})$
12. $\omega = \omega \times \omega_{damp}$
13. If k< max iteration, then k=k+1 and go to step 10 else go to step 14.
14. End

FIGURE 7. The MOPSO established procedure.

optimal solution with a low LPSP of 0.01 percent in the base GA scenario, but when this percentage dropped to 95 percent, the LPSP value increased to 0.62 percent. It can be observed that LPSP rises with declining GA percentage, but not linearly because the amount of battery banks has risen, which affects the LPSP percentage.

C. THE EFFECT OF GA ON SSER

The maximum SSER was set at 15% in the objective function constraint, Figure 8 reveals that the MOPSO obtained an optimal solution with zero SSER in the base GA scenario, however, when this percentage drops to 95%, the SSER value increased to 2,88%. It can be noted that SSER increases with decreasing GA percentage, but not linearly as the number of battery banks has increased, impacting the SSER percentage. The minimum SEER for GA was 85 percent, while the mean SSER for GA was 70%. SEER hits its lowest value when GA was 85% whereas it achieves its highest value when GA was 70%.

In this article, a decision-making approach is implemented to thoroughly illustrate the availability of the optimization mechanism and enable the decision-maker to properly assess the capability of the hybrid system [47]. In this analysis, each point on the Pareto front is viewed as a three-dimensional variable [COE(i), LPSP(i), SSER(i)], and then measured the Euclidean distance for each three-point. As the final optimum solution, the point that shows the minimum distance from other points on the front of Pareto is selected and described as [39], (27), as shown at the bottom of the page, where, $[COE\,(i) - COE\,(k)]$, $[LPSP\,(i) - LPSP\,(k)]$, and $[SSER\,(i) - SSER\,(k)]$ denotes three random points on the Pareto front and N_p is the total number of points of the Pareto front. The final optimal solution for each GA is given in Table 1.

TABLE 1. MOPSO results of the sizing problem for different GA.

GA	TNPC ($)	COE ($/kWh)	LPSP	SSER	N_{pv}	N_{WT}	N_{bat}
100.0%	2,521,722	0.098	0.01%	0.00%	0	0	0
95.0%	3,222,000	0.126	0.62%	2.88%	40	3	670
90.0%	3,622,400	0.142	0.35%	3.42%	20	10	979
85.0%	3,699,800	0.145	0.62%	0.33%	12	1	1420
80.0%	3,966,000	0.155	0.33%	8.42%	29	7	1461
75.0%	4,305,500	0.168	0.39%	4.27%	20	1	2158
70.0%	4,493,900	0.175	0.26%	9.78%	28	5	2199

Table 1 explicitly illustrates the impact of increasing the GA ratio on optimum system configuration and shows the impact of the selected three objective functions. The greatest influence is on the number of batteries used in the proposed system is indicated. The less availability of the grid, the greater the need to store and use energy through batteries.

The table also illustrates that the rising number of batteries used in the system retained a low LPSP level, despite the absence of a completely available grid, which confirms that the proposed system was extremely reliable.

It is also observed that a reasonable SSER was maintained as the lowest percentage (0.33 %) in the case of GA was 85 %, while the largest percentage (9.78 %) in the case of GA was 70 %.

Through analyzing the impact of the grid availability rate on the cost of energy production of the proposed scheme, it was observed that the lower the grid availability rate, the higher the cost of energy. A drop of 30% in grid supply contributed to a rise of 178,657 % in kWh costs.

Figure 9 demonstrates the influence of decreasing GA on the three objective functions.

While Figure 10 indicates the impact of reducing GA on the rising share of renewable energy sources in the proposed scheme, where the percentage increases from 0% for full grid availability to 52.1 % for GA = 70 %.

$$Optimal\ Sol. = min \sum_{k=1}^{N_p} \sqrt{(COE(i) - COE(k))^2 + (LPSP(i) - LPSP(k))^2 + (SSER(i) - SSER(k))^2} \quad i \in [1, N_p] \tag{27}$$

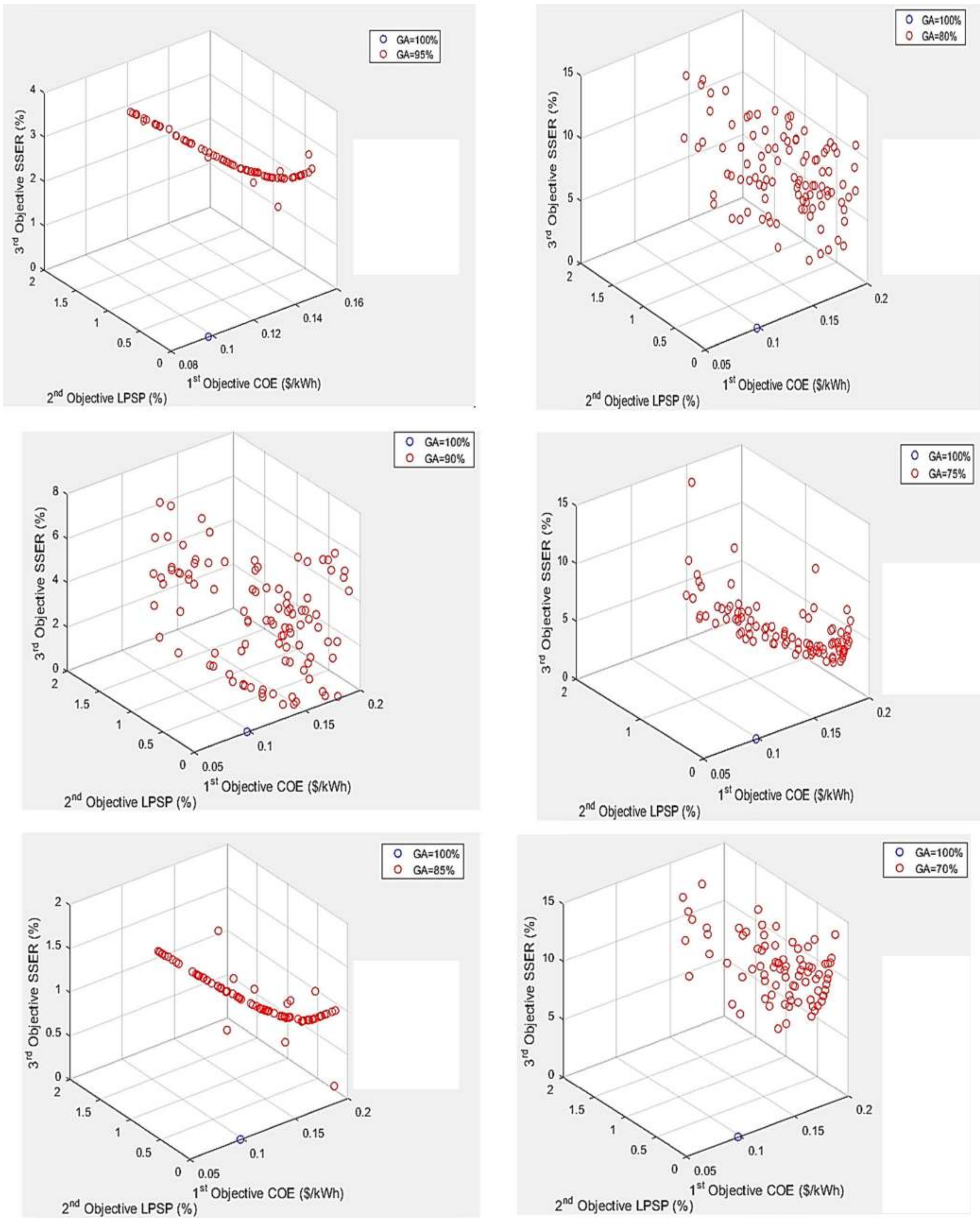

FIGURE 8. Comparing the base GA case, the Pareto front of the three objective functions for various GA states.

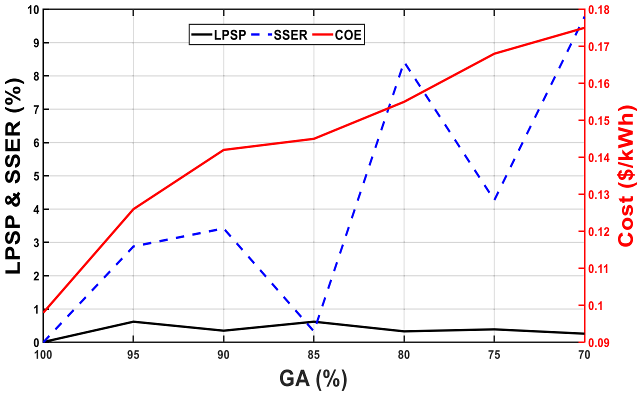

FIGURE 9. The impact of decreasing GA on the three objective functions.

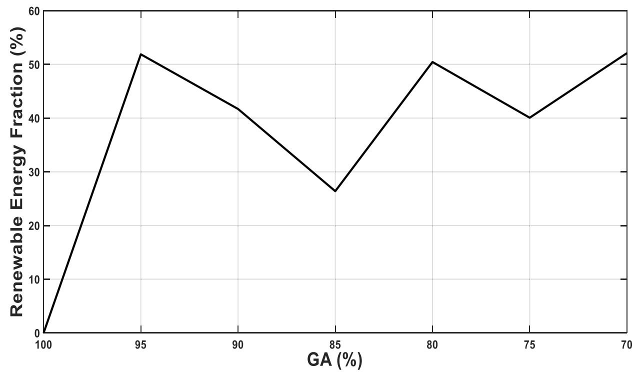

FIGURE 10. The effect of GA on the renewable energy fraction.

The energy costs estimated in this analysis are consistent with previous research. T Azerefegn *et al.* have explored the feasibility of incorporating a hybrid PV/WT system into existing unreliable grid/diesel generator networks [48]. The focus of the analysis is to provide vital industrial park loads in three distinct Ethiopian territories. For the three locations, the authors estimated the energy costs of the suggested approach from 0,044 to 0,049 $/kWh. The cost of energy of a self-sufficient wind / PV / diesel system that electrifies a broad resort facility in the Malaysian South China Sea was stated to be $0.279 / kWh [49]. The energy cost was stated to be $0.307 / kWh for a grid-connected system for PV-fuel cell feeding the Ayazaga campus loads from the Faculty of Electric & Electronics of Istanbul University of Technology [50]. Likewise, the PV / Wind hybrid was planned for a farm in Egypt's Toshka region at $0.597 per kWh for generating electricity [51].

V. CONCLUSION

This article proposed a MOPSO-based optimization model for the sizing of a green energy system connected to a randomly disrupted grid. The paper suggests a PV / WT / battery hybrid power system to mitigate for frequent outages that adversely influence the standard of service delivered to a small hamlet in northern Egypt. In this respect, three objective functions are proposed, namely: the energy cost (COE) for evaluating hybrid system economies; the loss of probability of power supply (LPSP) for reliability assessments, and the System Surplus Energy Rates (SSER) for evaluating hybrid system compatibility and efficiency.

Concerning the design variables, three variables, such as the number of solar photovoltaic systems, wind turbines, and battery banks were considered. In this work, the condition where the grid is entirely accessible was considered as a base case, and then the availability of the grid has been decreased by 5 % per time from 95 % to 70 % to illustrate the effect of grid availability on the configuration of the proposed GES.

The study findings revealed that the major influence of GA was on increasing the usage of the hybrid system battery. It also indicates that in the absence of a full grid the scheme proposed was extremely efficient, the rising number of batteries used retained a low LPSP level throughout the system. A fair SSER has also been preserved. Regarding the impact of GA on the COE, the lower the grid availability levels, the higher the energy cost. A 30% decrease in grid availability led to a 178,657% surge in kilowatt-hour price.

Sizing an unreliable grid-connected hybrid system is a multi-objective optimization challenge, including numerous, overlapping objectives with simple trade-offs. Such challenges are hard to address and time-consuming in modeling and engineering systems.

The suggested technique, therefore, resulted in a practical and systemic evaluation of such processes which permits the simultaneous treatment of several factors, including decision variables and objective functions. The Pareto front offers helpful mechanisms to evaluate the interconnections between the objectives and to provide decision-making processes to support design.

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