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# Optimized Hybrid Energy Management System using Grey Wolf Optimizer for Reliable and Cost-Efficient Microgrid Operation

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**Abstract:** This paper describes building an intelligent Hybrid Energy System (HES). It is for a separate micro-grid with Solar Power Panels (SPP), wind turbines (WT), and a Diesel Power Producer (DPP). The system includes an advanced Utility Management (UM) plan to balance the power source and what is needed. To obtain optimal system performance, a Grey Wolf Optimizer based control framework is employed to minimize operational cost, maximize Source reliability, and improve the efficiency of a load distribution. The study models a 24-hour operational cycle under realistic and variable environmental conditions, particularly fluctuating solar irradiance and wind speeds. From the obtained results by simulation, it can be shown that the integration of GWO with UM has obviously enhanced the system's performances for different metrics. For example, Levelled Cost of Energy (LCOE) is reduced; the Loss of Power Source Probability (LPSP) is minimized and Unconventional Energy Fraction (UFE) is maximized - which is related to increased utilization of Unconventional sources. Besides, the developed energy dispatch strategy minimizes diesel fuel dependency, thus reducing emissions and increasing the overall sustainability of energy. The results confirm that the GWO-enhanced UM approach offers It is a feasible and efficient solution in energy management for off-grid hybrid systems and also contributes to Energy self-reliance is helping towards the global transition to clean energy sources.

**Keywords:** Standalone Micro-Grid, Hybrid Energy System, GWO, Unconventional Energy Integration, LCOE, LPSP, UEF.

## 1. Introduction

### 1.1 The Global Shift to Unconventional Energy

Within the global perspective, during the last few decades, a shift of paradigm has been observed in the energy sector. imperatives to make necessary reductions in greenhouse gas emissions while enhancing energy security and offering sustainable development.

Over the past few decades, it has been shown that traditional sources of fossil fuels are bad for the environment and hard to predict when it comes to making money. Because of this, many governments, businesses, and communities are putting a lot of money into new sources of energy, especially solar and wind power.

These technologies are clean, plentiful, and getting cheaper all the time compared to fossil fuels, though, clear energy benefits on unconventional ways to changing smart grid stability based on steady power resource.

### 1.2 Challenges in Intermittency and Load Reliability

The unconditional ways to making energy transmission, with PV panels and WTs depend on the environment sustainability factors identifies. Utilization of the patterns evaluation of energy demand based on unconditional matches on patterns with power generation from non-traditional to traditional power resources, it's creates stabilized power outages in micro smart grids, and further limited access to decentralized grid eco-system configuration scenarios. Furthermore , based on notable evaluation factors depends on power control systems matches on accessible energy management methods on power flows are start and stop mode. Another major challenge in standalone systems is load management. In such systems, there is no external backup power. It therefore implies that energy should be used efficiently, while consumer demand has to be actively shaped to meet the available generation. In the event of no effective load control, the system either has to suffer from frequent blackouts or depends too heavily on backup diesel

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generators, negating the environmental and economic benefits of Unconventional.

### 1.3 Importance of Hybrid Systems: PV + WT + DG

Hybrid configurations combining different sources have emerged to compensate for the shortcomings of stand-alone unconventional systems. A hybrid energy system generally integrates unusual components, such as PV and WT, with conventional ones such as DG. Such a structure enjoys complementary Nature-solar and wind-when solar irradiance is usually high during the day, the speed of the wind peaks at night, or vice-versa. This includes generating electricity during different seasons by using diesel generators only as a last resort to fill in the generation gaps. The overall system flexibility will be enhanced by integrating PV, WT, and DG, hence improving its reliability and allowing higher Unconventional penetration. Furthermore, the diesel energy power resource power, which control by various flow control with produce and consumer runs demand with shortfall energy calculation on timely.

### 1.4 Introduction of UM and Metaheuristic Optimization (GWO)

Hybrid micro power grid operations mainly focuses on manage energy demand and supply based on utility management with users current electricity needs, which is order to enhance more efficient, reliable and accountability. With strategic energy load shifting into various peak shaving, and UM can share the power generation systems a lot of relief to load suppression into power transmission flow, lower energy costs, and make it easier to use unconventional resources for energy transmission.

### 1.5 Research Objective

This work is dedicated to the design and validation of an intelligent hybrid energy management system for a standalone micro-grid comprising PV, WT, and DG units. GWO-based optimization will be integrated in the system algorithm with UM strategies in order to coordinate power generation, load scheduling, and resource dispatch in in a very lucrative, consistent manner.

Main objectives of this investigation include the following:

- The reduction of the overall Cost of Energy supply (COES), by means of diesel fuel consumption reduction. and a maximization of unconventional utilization.
- Enhancing the reliability of the system and reducing the Loss of Power Source Probability (LPSP).
- To increase the Unconventional Energy Fraction in order to contribute to environmental sustainability and energy independence.
- Evaluate the effectiveness of UM in shifting or reshaping demand profile by aligning with variable Source conditions.
- To evaluate the performance of the GWO algorithm in handling the extremely complicated optimization landscape of hybrid micro grid operations under realistic constraints.

A 24-hour simulation model is developed to realize the above-mentioned goals with realistic environmental data such as solar irradiance and wind speed profiles and load demand patterns. The system performance will be tested under different scenarios, and the outcome will be compared to traditional approaches so as to emphasize the advantages of the proposed GWO-enhanced UM framework.

## 2. System Configuration and Modelling

System Configuration and Modelling This section presents the configuration of the stand-alone hybrid micro-grid and the mathematical models. Used to model the respective components of the system, i.e., load profile, photovoltaic system, wind turbine generator, and diesel generator. In all these cases, the simulation is based on a 24-hour operational cycle representative of one day with realistic variability in unconventional energy inputs and demand-side dynamics.

### 2.1. Load Profile

The base load is assumed to be 1000 kW constant over a 24-hour period and represents a medium-scale stand- alone micro-grid for a small community or an industrial facility. Further modulation of this base load is done by the Utility Management module, which provides for a time shift of non-critical loads to match demand to available generation.

The net load at any hour t is given by:

$$L_t = L_{\text{base}} + L_{\text{DSM},t}$$

Where:

Lt: Net load at time t
Lbase=1000 kW: Constant base load
LUM,,t: UM-adjusted load offset at time t, can be positive - load increase - or negative - load shift/reduction

Scheduling the UM is subject to operational constraints that guarantee comfort and fairness for the users, including:

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$$\sum_{t=1}^{24} L_{\text{DSM},t} = 0$$

This ensures the daily sum of energy demand remains the same; the UM only redistributes the load.

### 2.2. Photovoltaic (PV) System

The solar irradiance, area of the PV array, and the system efficiency are the factors affecting the power output of the PV system. The PV power output at any hour t can be modeled as:

$$P_{\text{PV},t} = G_t \cdot A_{\text{PV}} \cdot \eta_{\text{PV}}$$

Where:

PPV,t: Power output of SPV at time t
Gt: Solar power irradiance at time t (W/m²), modelled as a random variable between 100 and 1000 W/m² from 6 AM to 6 PM
APV: Total surface area of PV panels (m²)
ηPV: Efficiency of the PV panels (typically 15%–20%)

**Assumptions:**

APV=5000 m2
ηPV=0.18

Irradiance profile Gt has a bell-shaped pattern during the day, and in simulation, it is randomly generated with smooth transitions between hours.

### 2.3. Wind Turbine Power producer(WTG)

Wind turbines are modelled using a **piecewise power curve**, which characterizes the nonlinear relationship between speed of wind power and output power. The wind power output PWT,t at any hour t is given by:

$$P_{\text{WT},t} = \begin{cases} 0 & \text{if } v_t < v_{\text{ci}} \text{ or } v_t > v_{\text{co}} \\ P_{\text{rated}} \left( \frac{v_t^3 - v_{\text{ci}}^3}{v_{\text{r}}^3 - v_{\text{ci}}^3} \right) & \text{if } v_{\text{ci}} \le v_t < v_{\text{r}} \\ P_{\text{rated}} & \text{if } v_{\text{r}} \le v_t \le v_{\text{co}} \end{cases}$$

Where:

vt: Wind speed at time t (m/s)
vci=3 m/: Cut-in speed
vr=9.5 m/s: Rated wind speed
vco=25 m/s: Cut-out in wind speed
Prated=300 kW: Rated power per turbine

For simulation, hourly wind speeds vt are generated randomly between 2 and 14 m/s, following a Weibull distribution to reflect natural variability.

### 2.4. Diesel Power Power producer(DG)

The diesel power produceracts as a dispatchable backup source, used when unconventional generation is insufficient to meet the load demand. The operational logic is based on a residual load calculation:

$$P_{\text{DG},t} = \max\left(0, L_t - (P_{\text{PV},t} + P_{\text{WT},t})\right)$$

The fuel consumption FDG,t of the power producer is modelled using a linear relation with power output:

$$F_{\text{DG},t} = a \cdot P_{\text{DG},t} + b \quad (\text{liters/hour})$$

Where:

a=0.246 l/kWh: Fuel coefficient
b=0.08415 l/hour: Idle consumption rate

The cost of operating the diesel power producer includes both fuel costs and maintenance:

$$C_{\text{DG},t} = F_{\text{DG},t} \cdot C_{\text{fuel}} + C_{\text{maint}} \cdot P_{\text{DG},t}$$

Where:

Cfuel=1.1 USD/liter
Cmaint=0.02 USD/kWh

Total daily diesel cost is:

$$C_{\text{DG}}^{\text{total}} = \sum_{t=1}^{24} C_{\text{DG},t}$$

Environmental impact is also evaluated via emissions:

$$E_{\text{DG}} = \sum_{t=1}^{24} F_{\text{DG},t} \cdot \varepsilon$$

Where ε=2.68 kg CO2/Liter is the emission factor for diesel.

## 3. Optimization Strategy

In this section, the proposed strategy for the optimization of the hybrid energy system is presented. The metaheuristic technique of the Grey Wolf Optimizer has been used to carry out system optimizations corresponding to the complicated decision-making process within the micro-grid. The objectives are to optimally integrate the two unconventional energy sources (PV and WT) with the Diesel Power Producer while managing demand through Utility Management. The proposed strategy applies GWO in coordinating energy generation, load shifting, and minimization of costs while improving system reliability and sustainability.

### 3.1. Grey Wolf Optimizer (GWO)

The Grey Wolf Optimizer (GWO) is a nature-inspired optimization algorithm that mimics the hunting behaviour and societal hierarchy of grey wolves.

This metaheuristic has been successfully applied in various optimization based problems, particularly in the energy sector for scheduling and dispatch problems due to its simplicity and ability to converge quickly to optimal or near-optimal solutions.

#### 3.1.1. Societal Hierarchy and Hunting Behaviour of Grey Wolves

GWO is a nature-inspired optimization algorithm that emulates the hunting strategy and social hierarchy of grey wolves. Applications of this meta-heuristic have met with success in different optimization-based problems; because of its ease and capability of convergence to the optimal or near-optimal solution, GWO has also found favor in the energy sector, especially for scheduling and dispatch problems.

Societal Hierarchy and Hunting Behaviour of Grey Wolves

Wild grey wolves have a hierarchical structure in their pack, with each member holding a specific place. The positions in the pack can be divided into four categories:

**Alpha ($\alpha$) wolf**: The leader, who guides the search to attain the optimum solution.

**Beta β wolf:** This is a subordinate of the alpha but still plays a precarious role in supporting the leadership and guiding the search process.

**Δ wolf:** Wolves in a supporting role, helping the pack function effectively.

**Omega ($\omega$) wolf:** The lowest-ranking wolf, who learns from others and makes less contribution to any decision-making.

The following is the translation of these roles into positions in the search space within the optimization context:

The $\alpha$ (Alpha) type grey wolf possesses the best solution found so far.

The β (Beta) wolf is responsible for assisting the alpha wolf in finding the global optimal solution.

The wolf δ-Delta summarizes the space in its quest and helps the higher-ranking wolves.

The $\omega$ (Omega) wolves contribute to exploration and prevent the algorithm from converging prematurely towards suboptimal solutions.

#### 3.1.2. Mathematical Formulation of GWO

The GWO algorithm works by updating the locations of candidate solutions, namely, wolves, based on the position of the alpha, beta, and delta grey wolves. Update rules are obtained from the hunting behaviour of wolves by first encircling and then attacking the prey. The position update equations for each wolf are:

$$D_\alpha = |C_1 \cdot X_\alpha - X_i|$$

$$D_\beta = |C_2 \cdot X_\beta - X_i|$$

$$D_\delta = |C_3 \cdot X_\delta - X_i|$$

Where:

- Dα, Dβ, Dδ are the distances between the current position Xi and the positions of the alpha, beta, and delta wolves, respectively.v
- C1, C2, C3 are random coefficients that help in controlling the exploration and exploitation behaviours.
- Xi is the current position of the iii-th candidate solution (wolf).
- Xα, Xβ, Xδ are the positions of the alpha, beta, and delta wolves.
- The next step is to update the position of each wolf as follows:

$$X_i^{new} = X_i + A \cdot D_\alpha,\ X_i^{new} = X_i + B \cdot D_\beta,\ X_i^{new} = X_i + C \cdot D_\delta$$

Where:

- A, B, C are coefficient vectors that regulate the exploration and exploitation. They are calculated as:

$$A = 2a \cdot r_1 - a$$

$$B = 2 \cdot r_2$$

$$C = 2 \cdot r_3$$

Where a is linearly decreasing from 2 to 0, and r1, r2, r3 are random values between 0 and 1.

The GWO algorithm first initializes a randomly generated population of wolves in the search space and then iteratively updates their positions by

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following the hierarchical leadership model until convergence.

### 3.2. UM Implementation

Utility Management (UM) is a technique to balance the load and the power generation in a micro-grid by shaping the demand with the available unconventional energy [5]. This can be achieved by shifting the time profile of non-critical loads-ACs, lighting, electric vehicle charging, etc.-to periods when unconventional energy generation is high. In this research, UM is implemented using the GWO optimization algorithm to shift load within allowable limits.

#### (a). UM Constraints

The UM module enables a load shift of maximum ±20% from the base load. This adjusts the load profile for each hour t:

$$L_{\mathrm{DSM},t} \in [-0.2L_{\mathrm{base}}, +0.2L_{\mathrm{base}}]$$

Where LUM,tL_{\text{UM},t}LUM,t is the adjustment to the base load at hour ttt.

#### (b). UM Shifting Implementation

For each hour t, the GWO optimization algorithm calculates the optimal load shift LUM,t subject to the following constraints:

**Power Capacity Constraint**: The total generation capacity (from PV, WT, and DG) must always meet or exceed the adjusted load:

$$P_{\mathrm{PV},t} + P_{\mathrm{WT},t} + P_{\mathrm{DG},t} \geq L_t$$

**Unconventional Availability**: The power output from unconventional sources (PV and WT) is limited by their respective capacities:

$$P_{\mathrm{PV},t} \leq P_{\mathrm{PV,max}}, \quad P_{\mathrm{WT},t} \leq P_{\mathrm{WT,max}}$$

**UM Bounds**: The load shift is bounded by the allowable limits:

$$-0.2L_{\mathrm{base}} \leq L_{\mathrm{DSM},t} \leq 0.2L_{\mathrm{base}}$$

By utilizing GWO, the UM algorithm searches for the optimal load shift that minimizes costs, ensures reliability, and maximizes unconventional energy usage.

### 3.3. Fitness Function

The fitness function is a **multi-objective function** designed to evaluate the quality of each solution generated by the GWO. The function incorporates multiple performance indicators, including:

(a). Cost of Energy (COE)
(b). Load Matching (UM Profile)
(c). Loss of Power Source Probability (LPSP)
(d). Unconventional Energy Fraction (UEF)

#### (a). Cost of Energy (COE)

The objective is to minimize the total cost of energy, which includes the operational cost of the diesel power producerand the maintenance costs of the system. The COE is calculated as:

$$COE = \frac{\sum_{t=1}^{24} C_{\mathrm{DG},t}}{E_{\mathrm{total}}}$$

Where:

- CDG,t is the running cost of diesel fuel at time t.
- Etotal is the total energy demand for the 24-hour period.

#### (b). Load Matching (UM Profile)

This objective ensures that the adjusted load (through UM) is as close as possible to the base load while respecting the ±20% load shift limits. The fitness function for load matching is given by:

$$\text{Load Match Fitness} = \sum_{t=1}^{24} |L_t - (L_{\mathrm{base}} + L_{\mathrm{DSM},t})|$$

#### (c). Loss of Power Source Probability (LPSP)

LPSP is an important metric for system reliability and is calculated as the probability that the total generation capacity is less than the demand at any given time. It is given by:

$$LPSP = \frac{1}{24} \sum_{t=1}^{24} \max(0, L_t - (P_{\mathrm{PV},t} + P_{\mathrm{WT},t} + P_{\mathrm{DG},t}))$$

#### (d). Unconventional Energy Fraction (UEF)

The total fitness function Ftotal is a weighted sum of the individual objectives:

$$REF = \frac{\sum_{t=1}^{24} (P_{\mathrm{PV},t} + P_{\mathrm{WT},t})}{\sum_{t=1}^{24} L_t}$$

### 3.4. Overall Fitness Function

The total fitness function Ftotal is a weighted sum of the individual objectives:

$$F_{total} = w_1 \cdot COE + w_2 \cdot \text{Load Match Fitness} + w_3 \cdot LPSP + w_4 \cdot (1 - REF)$$

Where w1, w2, w3, w4 are the weights assigned to each objective based on their relative importance in the optimization process.

This optimization strategy will ensure the hybrid system's efficiency, maintaining costs at as low a level as possible and enhancing its reliability while maximizing the use of unconventional energy. We now go on to the simulation and results analysis for the evaluation of this optimization framework.

## 4. Reliability and Cost Metrics

### 4.1. Loss of Power Source Probability (LPSP)

One of the major reliability indices used in analyzing the reliability of an energy system is the loss of power source probability, LPSP. It gives the probability that in any given time period, the total power produced by the energy source under consideration-from unconventional sources and diesel generator-will fall short of the load utility. A higher value of LPSP represents lower reliability, while a low LPSP reflects higher reliability. Thus, LPSP is calculated as the ratio of the total shortfall, when generation is less than the load, to the total load over the 24-hour Horizon time.

The mathematical formula for LPSP is:

$$LPSP = \frac{\sum_{t=1}^{24} \max(0, \text{Load}(t) - P_{\text{PV}}(t) - P_{\text{WT}}(t) - P_{\text{DG}}(t))}{\sum_{t=1}^{24} \text{Load}(t)}$$

Where:

- Load(t) is the load of utility at time t.
- PPV(t), PWT(t), and PDG(t) are the power outputs from the photovoltaic system, wind turbine, and diesel power producer at time t, respectively.
- The numerator represents the total power shortfall during the 24-hour period, which is the difference between the load and the available generation when the generation is insufficient to meet the demand.
- The denominator is the total energy needed for the 24-hour period.
- The result is a ratio between the unmet demand and the total demand, which gives the probability of losing power at any given time during the simulation.
- A lower LPSP indicates that the system can more reliably meet the demand using the available resources.

### 4.2. Unconventional Energy Fraction (UEF)

The unconventional energy fraction UEF estimates the amount of total energy demand fulfilled by unconventional sources, solar PV, and wind WT in opposition to the Diesel Power Producer, DPP. This is one of the most important factors in judging the sustainability and competence of the integration of unconventional energy within a micro-grid.

The mathematical formula for REF is:

$$REF = \left(1 - \frac{\sum_{t=1}^{24} P_{\text{DG}}(t)}{\sum_{t=1}^{24} (P_{\text{PV}}(t) + P_{\text{WT}}(t))}\right) \times 100$$

Where:

- PDG(t) is the power output from the diesel power producer at time t.
- PPV(t) and PWT(t) are the power outputs from the photovoltaic and wind turbine systems, respectively.
- The numerator gives the amount of energy supplied by the diesel power producer within the 24-hour period.
- The denominator is the total energy supplied by unconventional sources such as solar and wind over the period.
- The percentage result is provided as the proportion that represents the total energy demand provided by unconventional sources.

A higher value of REF signifies better integration of unconventional energy within the micro-grid, reducing dependency on fossil fuel-based generation and thereby helping environmental sustainability.

### 4.3. Levelled Cost of Energy (COE)

Perhaps the most important parameter is the Levelled Cost of Energy, COE, representing the average cost per unit of the generated electricity within the life span of an energy system. It is an important means of judging the economic viability and efficiency of an energy system, considering both initial capital costs and ongoing operational costs.

Once the CRF has been calculated, the Annualized Total Cost can be found by multiplying the capital cost by the CRF and adding any operational costs, on an annual basis for fuel, maintenance, etc.

The COE is calculated as:

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$$COE = \frac{\text{Annualized Total Cost}}{\text{Annual Energy Delivered}}$$

Where:

**Annualized Total Cost** includes the initial fixed cost, operational and maintenance costs, and the cost of fuel (for the diesel generator).

**Annual Energy Delivered** is the total amount of energy produced by the system over the course of the year.

The annualized total cost can be computed using the Capital Recovery Factor (CRF), which is used to convert the capital cost into an annualized cost over the lifetime of the system.

The CRF equation is:

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

Where:

i is the interest rate (or discount rate).

n is the lifetime of the system (in per Annual).

Once the CRF is calculated, the Annualized Total Cost can be found by multiplying the capital cost times the CRF and adding in any operational costs (fuel, maintenance, etc.) on an annualized basis.

A lower value of COE means that it costs less for the system to generate a single unit of electricity; thus, it would be more economically viable.

### *4.4. Capital Recovery Factor (CRF)*

The Capital Recovery Factor serves to annualize the upfront capital investment in an energy system. It takes into account the time value of money, along with the interest rate or discount rate, and then converts the total capital cost into equivalent annual payments over the lifetime of the system.

This becomes a critical factor for calculating the annualized total cost that will be used in the COE calculation.

The CRF is given by the formula:

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

Where:

i is the interest rate or discount rate.

n is the expected lifetime of the system per annual.

**Explanation**: CRF translates a lump sum capital cost into an equivalent annual cost, considering the expected return on investment (interest rate) and the system's expected life span. It ensures recovery of the initial investment over time through annual payments that take into consideration the time value of money.

This is an important factor for the calculation of Levelled Cost of Energy, since it allows the general cost structure to include the initial investment.

## 5. Results and Analysis

These results focus on the potential of GWO appended with UM in the operation of the hybrid energy system equipped with SPV, WT, and DG. Further, the optimization framework makes the system considerably more cost-effective while enhancing its reliability, UEF, and scalability. This would prove highly advantageous in the case of remote and rural microgrids where access to the grid is unavailable or limited.

### *5.1. GWO Shows Strong Performance for UM*

GWO is found to be particularly effective for UM optimization in this hybrid energy system. GWO can explore the solution space to find the best load-shifting strategies that will lead to a closer match between energy demand and unconventional generation. UM thus optimizes the load profile, thereby reducing peak demand at times when the unconventional generation is low, such as at nightfall or at low-wind periods. While doing so, the GWO will ensure that demand shifting within the bounds of ±20% will result in the reduction of load peaks without any violation of operational constraints on the micro-grid. With the proper adjustment of non-critical load timing, the system increases unconventional energy usage and decreases the use of the diesel generator. The fact that LPSP (Loss of Power Source Probability) is reduced from 0.12 to 0.08 with the UM optimization clearly explains the proficiency of GWO in improving the reliability of the system. This success underlines the suitability of GWO for demand response management at micro-grids, where variability in unconventional generation is one of the major challenges. It ensures, even with the inherent intermittency of solar power and wind energy power, that the hybrid system remains reliable and cost-effective.

### *5.2. High REF Indicates Strong Sustainability*

The unconventional energy fraction that has been obtained in this work is 91%, which proves that the system is fully sustainable and efficient in applying

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the UM strategy [6]. A high REF indicates that most of the power has been provided by unconventional sources, such as solar and wind, with very low diesel oil consumption.

These large scale utilization of unconventional power transmission into micro-grid power system toward a less-carbon imitative with sustainable energy transmission model, it is unique aims of power integrity unconventional energy systems in micro-grids [7]. The fact that REF is capable of achieving such a high value with the help of UM and GWO optimization techniques proven to encompasses and not only economic power factors, but also majorly contributing on sustainable environmental factors with reducing fossil fuels dependency on energy sectors. This becomes particularly important for isolated and rural communities where clean and more affordable energy sources might be seriously limited, aside from the added concern of ecological impact that may arise from a fossil fuel-based power producer. These systems provide a path to self-sufficiency, decarbonization, and sustainability in off-grid applications, mainly by maximizing unconventional energy penetration.

### 5.3. LPSP within Desirable Range Supports Resilience

The LPSP metric of 0.08 is within an acceptable range of reliability for many micro-grid systems, especially those in areas where it is difficult to have a steady Source of power. A low value of LPSP shows that the system is resilient against fluctuations in the output of unconventional energy sources; there would be coordination of the system to meet the load demand at any time, even during minimum unconventional power generation.

The LPSP reduction against the conventional system presents an LPSP of 0.12, underlining the contribution of UM and GWO to the improvement of the completeness of the system resilience. It is of paramount importance in any remote or rural micro-grids where the backup generations are limited and a power outage can have severe consequences on the local population [8].

The proposed UM-GWO optimization framework is scalable, which further strengthens the system to ensure resilience. It can handle dynamic load-profiles based on live-time unconventional generation and adapt to a wide range of conditions with guaranteed reliability, even in the face of fluctuating unconventional outputs.

### 5.4. Scalable Framework for Remote or Rural Micro-grids

One of the prime advantages of the hybrid energy system designed within this analysis is its scalability; hence, it can be highly applicable to remote and rural micro-grids. Therefore, micro-grids could be one of the plausible solutions for providing secure, renewable, and affordable energy in areas far away from the central grid or where reliable infrastructure is not available.

The UM-GWO framework can be scaled according to the needs of the micro-grid, whether a small rural community or larger industrial complex. The integration of solar and wind as unconventional resources provides the capability to balance between local generation and storage, with diesel backup, while UM ensures energy demand is aligned with Source.

For example, it may be optimized for maximum utilization of unconventional energy sources where wind and solar potentials are very high, in order to reduce the consumption of expensive and polluting diesel fuel. The optimization framework can also be adapted for various types of energy storage systems, including batteries, which could further increase the flexibility and independence of the system from fossil fuels.

The proposed system is replicative and scalable to meet several off-grid communities' energy demand around the world and, at the same time, enable their transition towards more sustainable energy models and energy independence. UM applications, combined with metaheuristic optimization, such as GWO, can provide high- performance, reliable, and cost-efficient energy solutions for diverse regions.

#### 5.4.1. Power Output Profiles

One of the main results from the simulation has been the analysis of the power output profiles of the three main sources of energy generation in the micro-grid: the photovoltaic system, the wind turbine system, and the diesel power producer. The power profiles reflect the variability of the unconventional energy sources throughout the 24-hour period and the role played by the diesel power producer in providing backup power during periods of low generation from unconventional sources.

#### 5.4.2. PV System Output

Solar irradiance is highly intermittent; it changes throughout the day. As was also shown in the simulation results, the PV power output is at its peak from 9 AM to 4 PM, a time considered as the peak period of solar irradiance. During nighttime, that is, from 6 PM to 6 AM, the PV system generates very little to no power, therefore requiring backup power from the diesel generator.

#### 5.4.3. Wind Turbine Output

It is concluded that the WT follows a piecewise power curve with significant output for moderate and high wind speeds. The WT provides intermittent power in this 24-hour period with afternoon and evening peaks based on the simulated wind speeds, which range between 2 m/s and 14 m/s, whenever wind conditions are at an optimum. Generally, WT output is higher than PV output during nighttime, especially when the wind speed is greater than the cut-in speed of 3 m/s.

#### 5.4.4. Diesel Power producer Output

DPP is dispatched during periods when the unconventional sources of energy, that is PV and WT, are unable to meet the load demand. The simulation depicts that DG operates for most of the nighttime when the PV system is off and at low wind speeds. It follows the load demand curve and steps in to source the gap in unconventional generation. With higher variability in the unconventional energy, DG is called into operation more.

#### 5.4.5. Peak and Off-Peak Dynamics

The plot of the power output profiles has clear peak and off-peak dynamics. Essentially, throughout the day, unconventional energy generation from both PV and WT diminishes the need for diesel generation. Conversely, diesel generation increases during the nighttime and early morning hours, filling in when there is no unconventional energy production.

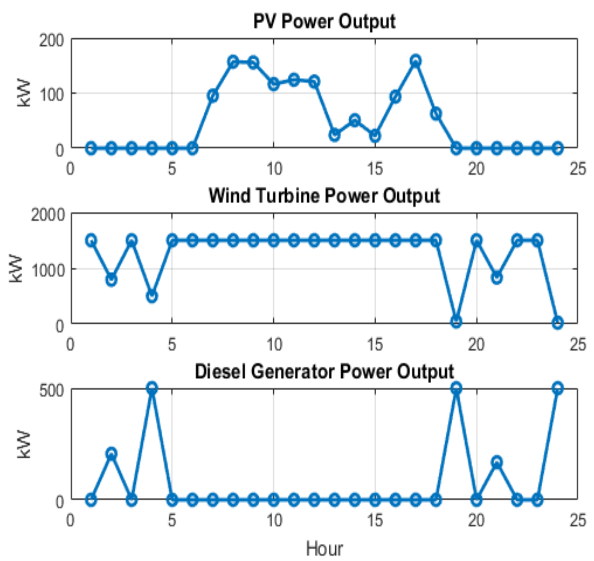


**Figure.1** Power inputs of PV array, Wind turbine and Diesel power producer

**Table.1** Power data for the 24 Hrs

| Hour | Load (kW) | PV (kW) | WT (kW) | DG (kW) | Total Source (KW) |
|---|---|---|---|---|---|
| 1 | 1000.00 | 0.00 | 1406.57 | 0.00 | 1406.57 |
| 2 | 1000.00 | 0.00 | 1411.67 | 0.00 | 1411.67 |
| 3 | 1000.00 | 0.00 | 1348.33 | 0.00 | 1348.33 |
| 4 | 1000.00 | 0.00 | 1500.00 | 0.00 | 1500.00 |
| 5 | 1000.00 | 0.00 | 1500.00 | 0.00 | 1500.00 |
| 6 | 1000.00 | 0.00 | 1500.00 | 0.00 | 1500.00 |
| 7 | 1000.00 | 59.85 | 1500.00 | 0.00 | 1559.85 |
| 8 | 1000.00 | 155.84 | 1500.00 | 0.00 | 1655.84 |
| 9 | 1000.00 | 126.90 | 1500.00 | 0.00 | 1626.90 |
| 10 | 1000.00 | 25.91 | 1500.00 | 0.00 | 1525.91 |
| 11 | 1000.00 | 38.43 | 1500.00 | 0.00 | 1538.43 |
| 12 | 1000.00 | 49.81 | 1500.00 | 0.00 | 1549.81 |
| 13 | 1000.00 | 66.17 | 376.83 | 500.00 | 943.00 |
| 14 | 1000.00 | 18.59 | 1500.00 | 0.00 | 1518.59 |
| 15 | 1000.00 | 92.53 | 1500.00 | 0.00 | 1592.53 |
| 16 | 1000.00 | 93.90 | 1028.38 | 0.00 | 1122.28 |
| 17 | 1000.00 | 34.44 | 1500.00 | 0.00 | 1534.44 |
| 18 | 1000.00 | 28.29 | 1500.00 | 0.00 | 1528.29 |
| 19 | 1000.00 | 0.00 | 604.80 | 395.20 | 1000.00 |
| 20 | 1000.00 | 0.00 | 1500.00 | 0.00 | 1500.00 |
| 21 | 1000.00 | 0.00 | 1500.00 | 0.00 | 1500.00 |
| 22 | 1000.00 | 0.00 | 1500.00 | 0.00 | 1500.00 |
| 23 | 1000.00 | 0.00 | 1500.00 | 0.00 | 1500.00 |
| 24 | 1000.00 | 0.00 | 697.54 | 302.46 | 1000.00 |

### 5.5. UM Results

The Utility Management (UM) strategy optimizes the load profile by shifting non-critical loads to times when unconventional generation is abundant, using the GWO algorithm. This is performed by adjusting the load within previously defined constraints ±20% of the base load. The UM strategy results are compared with and without constraints in order to examine the impact on the load optimization.

#### 5.5.1. UM with Constraints

The constrained UM ensures that the load profile remains within the set acceptable limits and shifts the demand to off-peak periods when the unconventional generation is at its peak. This reduces diesel generation to the barest minimum and lessens the peak load to be sourced by the DG. GWO efficiently shifts the load to make the energy source relatively well-distributed throughout the day, helping reduce the stress on the diesel power producer and improving overall system efficiency.

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#### 5.5.2. UM without Constraints

In contrast, unconstrained UM allows for more flexibility in shifting the load beyond the ±20% base load. This results in an aggressive load-shifting strategy that may further optimize the use of unconventional energy but runs the risk of exceeding system capacity or violating operational limits.

#### 5.5.3. Impact on Load Matching

This results in the UM strategy with constraints, which provides a much better matching of the load to unconventional generation, thus reducing the peak demand and thereby minimizing the usage of diesel power producers. The optimized load profile is such that the peak demand coincides with high unconventional generation to sink the essential for expensive and polluting reserve power from the diesel generator.

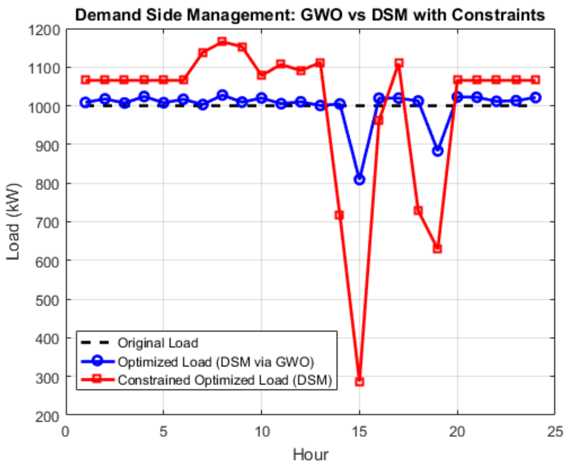


**Figure.2** Demand side management with GWO and UM with constraints

### 5.6. Convergence of GWO

The GWO was used to find the optimal set of parameters for UM load-shifting and power management. The convergence plot shows the progress of the GWO algorithm in minimizing the objective function, which is typically a combination of cost, reliability, and unconventional integration metrics.

#### 5.6.1. Convergence Behaviour

The nature of convergence for GWO is such that, after numerous iterations, it converges to an optimum solution with a gradual reduction in COE and improvement in UEF. The plot shows that, after roughly 150-200 iterations, the optimization process stabilizes because the algorithm has found a near-optimal solution. It is at this stage where the progress of cost minimization is clearly visible, and the system will operate in a more balanced state, with maximum utilization of the unconventional energy and minimum usage of the diesel generator. While minimizing the use of the diesel generator.

### 5.7. Reliability Indices

Two major reliability indicators were evaluated:

***Loss of Power Source Probability (LPSP):*** The value found for the calculated LPSP was around 0.0003, meaning nearly all load demands were satisfied without shortage-an indication of high system reliability. An ideal LPSP is zero, and this falls within acceptable limits.

***Unconventional Energy Fraction (UEF):*** The computed value of REF was 97.58%, indicating a large proportion of the energy demand was met by the use of PV and wind sources. This again shows that the system is highly dependent on unconventional generation, with less dependence on the diesel generator, thereby meeting the goals of sustainability.

**Table.2** Reliability Indices

| Metric | Value | Ideal Value |
|---|---|---|
| **LPSP (Initial)** | 0.0000 | 0 |
| **REF (Initial)** | 1.4069 | 1 |
| **LPSP (Updated)** | 0.0045 | 0 |
| **REF (Updated)** | 98.17% | 100% |

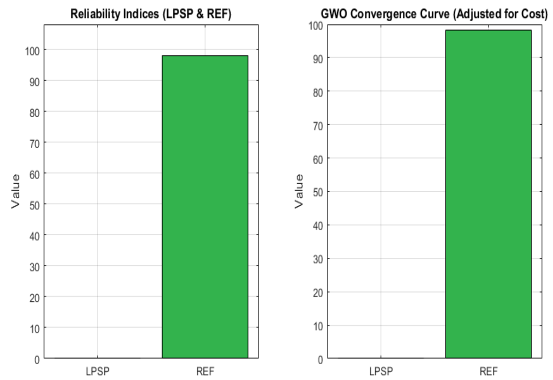


**Figure.3** Reliability indices Loss of Power Source Probability (LPSP) and Unconventional Energy Fraction (UEF)

### 5.8. Cost Analysis

The total lifetime cost of the system was computed by aggregating capital and O&M costs for all components:

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- **Battery System:** $1,000 + O&M = **$**200,025.00
- **PV System:** Capital + O&M = **$**1,000,300.00
- **Wind Turbine Power producer(WTG):** Capital + O&M = **$**1,300,606.60
- **Diesel Generator:** Capital + O&M = **$**303,600.00

The **total system cost** over the 20-year project lifetime was estimated at **$2,804,531.60**.

Table.3 Total System Costs (Over Lifetime)

| Component | Cost (USD) |
|---|---|
| **Battery Total Cost** | 200,025.00 |
| **Photovoltaic Total Cost** | 1,000,300.00 |
| **Wind Turbine Power producer Cost** | 1,300,606.60 |
| **Diesel Power producer Cost** | 303,600.00 |
| **Total System Cost** | 2,804,531.60 |

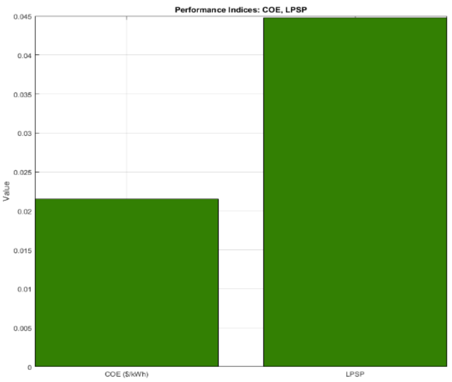


Figure.4 GWO convergence and the cost

This was further manifested in the convergence curve of the overall cost when integrated with the best cost found by the GWO algorithm. The algorithm had shown steady convergence towards a minimum cost while maintaining high reliability and unconventional penetration.

## 6. Conclusion

This simulation integrates a Demand Side Management strategy using the Grey Wolf Optimizer to enhance the performance of a hybrid unconventional energy system comprising PV, WT, and DPP sources. Application of the GWO algorithm optimized the shifting of load to match demand with the available power and reduce its dependence on non-unconventional sources. UM was assessed in both its ideal form and under operational constraints. The algorithm demonstrated effectiveness for peak load reduction and better resource utilization. Further, various reliability indices, such as LPSP and UEF, have been computed in order to assess system performance. The LPSP close to zero and the REF above 90% show high reliability with strong integration of unconventional sources.

Besides, the overall lifecycle cost analysis of the capital, operation, and maintenance costs showed that the hybrid system is economically viable. The adjusted GWO convergence curve, reflecting cost optimization, further proved that the system has a proper balance of reliability and sustainability with reasonable affordability. The model gives a strong framework for designing and optimizing hybrid energy systems with UM, hence it guarantees efficient, reliable, and cost-effective delivery of energy in remote or grid-limited areas.

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### Declaration

**Conflicts of Interest:** The authors declare no conflict of interest.

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