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Optimal sizing and performance evaluation of hybrid photovoltaic-wind-battery system for reliable electricity supply

Youssef El Baqqal[1], Mohammed Ferfra[1], Reda Rabeh[2]
[1]Department of Electrical Engineering, Mohammadia School of Engineers, Mohammed V University, Rabat, Morocco
[2]LERMA Laboratory, School of Energy Engineering, International University of Rabat, Sala Al Jadida, Morocco

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ABSTRACT

Given the advantages of hybrid renewable energy systems over single-source systems, this study proposes the optimal sizing and performance evaluation of a hybrid photovoltaic-wind battery system to meet the electricity demand of an isolated community in Dakhla, Morocco. The objective is to achieve an economical approach to electricity generation. Particle swarm optimization (PSO) and grey wolf optimizer (GWO) techniques were used to determine the optimal configuration of system components, including photovoltaic (PV) panels, wind turbines, and battery storage. The annual system cost (ACS) is minimized as the optimization objective, and the levelized cost of electricity (LCOE) is used for economic comparison. MATLAB serves as the platform for implementation and evaluation. Results demonstrate the convergence and effectiveness of PSO and GWO in delivering high-quality solutions. PSO, however, achieves superior system reliability with a lower loss of power supply probability (LPSP) during peak demand. The optimal configuration achieves a minimal LCOE of 0.1065 USD/kWh, representing a 33.44% reduction compared to the applicable rate. These findings highlight the potential of advanced optimization techniques to improve the economic and operational performance of hybrid renewable energy systems, making them a viable solution for rural electrification in regions with limited grid access.

Corresponding Author:

Youssef El Baqqal
Department of Electrical Engineering, Mohammadia School of Engineers, Mohammed V University
Ibn Sina B.P 765, Agdal Rabat, Rabat 10000, Morocco
Email: youssef.elbaqqal@um5r.ac.ma

1. INTRODUCTION

The increasing energy demand, as well as the focus on the use of renewable energies for electricity production, especially for rural electrification, has resulted in the advancement of innovative methods to improve the efficiency of renewable energy systems. To address the issues associated with the limitations of these systems, the idea of a hybrid renewable energy system (HRES) has been suggested, which integrates renewable energy resources like solar photovoltaic (PV) and wind energy, along with energy storage solutions. Such systems may be more efficient and reliable than those relying on a singular energy source [1]. Moreover, they optimize the use of existing resources and lower the expenses associated with energy production. In recent years, there has been a notable rise in research interest in HRESs, highlighting a growing recognition of their potential. The primary focus of these studies has centered around optimizing HRESs to minimize system costs, while considerations for reducing carbon emissions have also gained attention. This optimization involves formulating an objective function that considers various parameters and limitations, integrating technical, financial, and environmental factors. This is a complex and multifaceted challenge that requires a comprehensive understanding of various objectives, factors, and limitations. These systems involve a range of objectives, variables, and constraints, which can be single-objective or multi-objective, integer or discrete, and linear or nonlinear, making them a highly complex problem [2]. Different methods have emerged to handle the challenges of optimizing the performance of HRESs, including metaheuristics algorithms such as particle swarm optimization (PSO) and grey wolf optimization (GWO). Metaheuristic methods are typically inspired by natural processes [3]. Having an excessive capacity in HRESs might make the initial cost higher. However, if the system does not have enough capacity, it cannot guarantee a reliable power supply. So, it is important to find the right balance and optimize the system's capacity to ensure both cost-effectiveness and long-term reliability [4]. Optimizing hybrid renewable energy systems aims to develop a solution that effectively integrates multiple energy sources, achieving a balance between minimizing costs and ensuring a reliable power supply [5]. key parameters used in the optimization process, particularly in terms of economic and reliability criteria. Additionally, among the economic criteria, the annual system cost (ASC) and the levelized cost of electricity (LCOE) are highlighted as the most commonly utilized [1].

The studies conducted in Morocco on HRESs, particularly PV/wind HRESs, have made significant contributions to the optimization and feasibility of these systems in various contexts. A recent study conducted by Bouafia *et al*. [6] specifically aimed to optimize the sizing of a PV/wind turbine HRES in 12 locations in Morocco. The PSO algorithm was used to minimize the LCOE while achieving the desired annual output. Another study by El Boujdiani *et al*. [7] optimized a stand-alone PV/wind/battery/diesel hybrid energy system using the PSO algorithm, ensuring a reliable and cost-effective power supply for remote areas in two cities in Morocco. Furthermore, Beyoud and Bouhaouss [8] investigated the feasibility and optimization of a hybrid generator-photovoltaic-wind farm system for a tourist lodge in Guergarat, southwest Morocco. Their study considered load profile constraints and provided valuable insights for designing cost-effective and sustainable energy systems in remote areas. Additionally, Kharrich *et al*. [9] present a novel application of the equilibrium optimizer for the optimal design of a hybrid PV/wind/diesel/battery microgrid in Dakhla, Morocco. They aimed to minimize costs, improve system stability, and enhance renewable energy integration. In another study, El-Houari *et al*. [10] assessed the viability of a hybrid renewable power generation system to provide sustainable electricity in the remote village of Tazouta in the Fes Meknes region of Morocco, using HOMER software. Anoune *et al*. [11] focused on the sizing optimization of a PV/wind/battery hybrid renewable energy system with electrochemical storage. They aimed to meet the load demand of an industrial prototype and developed a heuristic approach based on a genetic algorithm. MATLAB was used to solve the sizing optimization problem. Furthermore, Mouachi *et al*. [12] discussed the increasing need for renewable energy systems to meet electricity demand while reducing costs and environmental impact. They proposed a nature-inspired optimization algorithm called MDPSO to optimize the sizing of an advanced hybrid microgrid (A-HMG) in a fishing village in Morocco. The authors first proposed a smart energy management scheme (SEMS) to coordinate the power flow among the different components of the A-HMG. They then integrated the MDPSO algorithm with the SEMS to perform the optimal sizing for an A-HMG in a fishing village located in Essaouira, Morocco. The components considered in the A-HMG are photovoltaic panels (PV), wind turbines (WTs), battery storage systems, and diesel generators (DGs). Lastly, El Haini and Saka [13] presented a techno-economic assessment of a PV/wind turbine/battery hybrid energy system for powering a stand-alone load in Morocco. Using HOMER software, the study concluded that the PV/Battery system is the most economically feasible configuration in the selected geographical locations.

The adoption of HRESs is still gaining significant attention in Morocco for applications such as seawater desalination and rural electrification, with the latter presenting a veritable issue where providing reliable and sustainable electricity to isolated communities in regions such as Dakhla, Morocco. To address this issue, this study focuses on the simulation and optimization of an HRES that combines photovoltaic (PV), wind power, and battery storage technologies to meet the energy needs of remote communities. A key contribution of this study is the emphasis on designing HRESs that not only minimize costs but also ensure a consistent and reliable energy supply. While a system may appear economically attractive due to a low LCOE, its practical effectiveness lies in its ability to meet demand at all times. Therefore, incorporating reliability metrics such as the loss of power supply probability (LPSP) into the optimization framework is essential. This measure evaluates the system's capability to meet energy demands under different conditions. Prioritizing cost savings without considering reliability could result in power shortages, which would compromise the goals of rural electrification and sustainable energy availability.

The primary purpose of this work is to create a mathematical model of an autonomous hybrid PV/wind/battery energy system for generating electricity in an isolated area. The objective is to determine the appropriate sizes of the components used in the proposed system to achieve the lowest LCOE. While ensuring a specific level of reliability. The proposed system's objective function is the annual system cost

(ASC). The GWO and PSO algorithms are utilized to find the best configuration for the proposed HRES. These algorithms were selected due to their ability to deliver precise and dependable outcomes using fewer control parameters in comparison to other evolutionary algorithms. The choice of these algorithms is driven by their potential to provide accurate and reliable results with a relatively smaller number of control parameters compared to other evolutionary algorithms. To assess the efficacy of the proposed approach, the results obtained from the application of the GWO algorithm are compared against the performance of the PSO algorithm. A brief comparison is made based on the LCOE. The configuration with the lowest LCOE is considered ideal.

2. METHOD

2.1. System components modelling

The figure provided, Figure 1 shows the schematic diagram of the hybrid PV/wind/battery system studied in this research. This system consists of several components: PV panels, wind turbines, the Battery storage system, and a load. The system is designed for an isolated community. To establish the connection to the direct current (DC) bus system, the wind turbines, PV panels, and battery storage are appropriately linked through inverters or converters. On the other hand, the load is connected to the alternating current (AC) bus system.

When renewable energy sources, wind turbines, and PV arrays generate sufficient power to meet the demand, all the electricity is directly supplied to the load. Excess power is then stored in the battery bank. In instances where the generated power falls short of meeting the demand, the stored power in the batteries is utilized to compensate for the deficit.

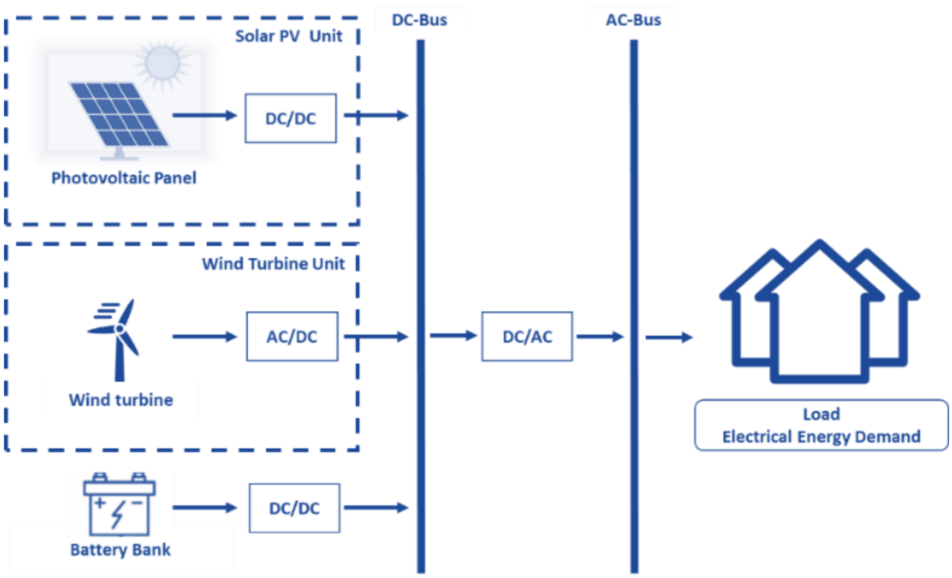

Figure 1. Overview of the proposed hybrid PV/WT/battery system

2.1.1. Simple efficiency PV module model

The power produced is calculated according to [14]:

$$P_{Pv}(t) = N_{Pv}\eta_{Pv}(t)\mu_{inv}f_d G(t) \tag{1}$$

where N_{Pv} is the number of PV unit (Kw), μ_{inv} is the efficiency of the inverter, f_d is a represents the derating factor, including several losses such as soiling and shading. While, $\eta_{Pv}(t)$, implies the actual overall efficiency of the solar module and $G(t)$ symbolizes the total radiation received by the modules at time t.

The precise estimation of solar radiation received by the solar field holds significant importance as it serves as a fundamental factor in determining the electricity energy production potential of PV plants. However, the available data may not always be exactly what we use for calculation. For example, Global solar radiation measurements are typically taken on horizontal planes, whereas solar PV modules are not installed horizontally but at a certain angle or with a tracking system to optimize the received solar radiation.

To improve the accuracy of the data, it is, therefore, necessary to convert the available data into useful data. To do so, the calculation of solar position and solar radiation, as well as the conception conditions such as the tilt angle and orientation, should be considered. This part is not included in this paper, but it is taken into account in the calculation process. The actual efficiency of the PV module at time t is calculated as (2):

$$\eta_{Pv}(t) = \eta_{Pv\_ref}\left(1 + \gamma_t\left(T_C(t) - T_{C\_ref}\right)\right) \quad (2)$$

where η_{Pv_ref} represents the nominal efficiency of the PV module, γ_t is the temperature factor (experimentally measured by the constructor). Additionally, T_{ref} is the temperature of the PV module under STC. The actual operating temperature at which, T_c is calculated based on their rated operating temperature [14].

2.1.2. Wind model

In the literature, various models are employed to estimate the output power production of wind turbines. These models typically consider different wind speed ranges and employ distinct characteristic techniques to evaluate the performance of the wind turbine. The wind turbine power generation P_{WT} can be presented as (3) [15]:

$$\left\{\begin{array}{c} P_{WT}(t) = 0 \\ P_{WT}(t) = A.V_{wind}(t)^3 - B.P_{rated} \\ P_{WT}(t) = P_{rated} \end{array}\right| \left.\begin{array}{c} V_{wind}(t) < V_{in} \ or \ V_{wind}(t) > V_{out} \\ V_{in} \leq V_{wind}(t) < V_r \\ V_{wind}(t) \geq V_r \end{array}\right\} \quad (3)$$

where,

$$\left\{\begin{array}{l} A = {P_{rated}}/{\left(V_r^{\,3} - V_{in}^{\,3}\right)} \\ B = {V_{in}^{\,3}}/{\left(V_r^{\,3} - V_{in}^{\,3}\right)} \\ P_{rated} = 0{,}5.A_{WT}.C_P.\rho_{air}.\eta_{WT}.V_r^{\,3} \end{array}\right. \quad (4)$$

in this *context*, P_{rated} refers to the rated power of the wind turbine, which represents the maximum power it can generate under optimal conditions. The parameter A_{WT} signifies the rotor area, the term V_{in} stands for the cut-in wind speed. On the other hand, V_r denotes the rated wind speed. Lastly, V_{out} represents the cut-off wind speed. According to the specifications provided in reference [16], we have adopted an air density (ρ_{air}) value of 1.225 kg/m³ for our calculations. Additionally, we have utilized a power coefficient (C_p) of 0.44.

2.2. Management strategies of HRESs

When sizing a hybrid PV/wind/battery system, carefully evaluating each component's contribution and determining the required storage capacity are critical steps. These considerations need to be adapted to the site weather data, the technical characteristics, and the conception conditions of each system, and the profile of the load being supplied. To select the best design for a hybrid PV/wind/battery system, an optimization algorithm is employed. This algorithm aims to optimize the proposed system by considering specific criteria, such as reliability and cost-effectiveness.

In this context, the HRES with the specific balance between PV and wind is designed to reply to the desired load, the total production could be written as (5):

$$E_{generated}(t) = N_{PV}.P_{Pv}(t) + N_{WT}.P_{WT}(t) \quad (5)$$

where $P_{Pv}(t)$, $P_{WT}(t)$ are power production by PV and wind turbine at time *t*, which could be calculated using (1) and (4), respectively. While, N_{PV} is the number of PV system unit (KW) and N_{WT} is the number of wind system unit (KW).

For each configuration (N_{PV}, N_{WT}), a total generated power could be calculated; this latter, in a certain time *t*, could be equal, greater, or less than the required load at this time. For this reason, the integration of a battery storage system is necessary. The required total battery capacity can be determined through a detailed sizing process.

2.3. Battery sizing

For each combination of PV and wind configurations, a specific battery capacity needs to be installed to meet the desired load. The determination of this capacity can be done through a sizing process. It is crucial to consider the state of charge (SOC) of the battery bank in this context. Two key modes should be considered in this context.

2.3.1. Charging mode

In the charging mode, there are also two sub-modes:

a. When wind power production exceeds the required load, the surplus energy is stored after supplying the load directly. In this scenario, the charging power is calculated with the formula (6):

$$P_{ch}\,(t) = \left(P_{WT}(t) - P_{load}(t)\right).u_{conv} + P_{PV}(t) \tag{6}$$

The energy charged at time *t*, $E_{ch}(t)$, is calculated as:

$$E_{ch}(t) = P_{ch}(t).1hr \tag{7}$$

In cases where the wind power production is not enough to satisfy the demand. The available produced wind energy is injected and the solar energy is used to bridge the gap. The charger power is calculated according to (8):

$$P_{ch}\,(t) = P_{PV}(t) - (P_{load}(t) - P_{WT}(t))/\,u_{conv}) \tag{8}$$

In the case of charging mode, the state of the battery is calculated using (9) as function of the state of charge in previous time $(t-1)$:

$$E_b(t) = E_b(t-1) + E_{ch} \tag{9}$$

However, this state of charge at time t noted $E_b(t)$ is condionned by the next conditions:

$$E_{ch}(t) \leq (E_{b_{max}} + E_b(t-1)) \tag{10}$$

where $E_{b_{max}}$ is the maximal SOC and $\mathrm{E_b(t-1)}$ represent the SOC in previous time $(t-1)$, this condition implies that $E_b(t)$ in all time must be less than the SOC maximal. If there is an excess of energy when the battery reaches its maximum SOC, a situation of wasted energy may occur as a result of excessive generation, the excess is dumped using a dumped load [7].

2.3.2. Discharging mode

In this scenario, (11) is employed to calculate the discharge power.

$$P_{distch}(t) = (P_{Load}(t)/\eta_{Inv}) - P_{PV}(t) - P_{WT}(t) \tag{11}$$

The energy discharged at time t, $\mathrm{E_{sitch}(t)}$, is calculated as:

$$E_{sitch}(t) = P_{distch}(t).1hr \tag{12}$$

In the case of discharging mode, the state of the battery is calculated using (13) as a function of the state of charge in previous time $(t-1)$:

$$E_b(t) = E_b(t-1) - E_{distch}(t) \tag{13}$$

However, this state of charge at time t noted $E_b(t)$ is condionned by the next conditions:

$$E_{ch}(t) = P_{ch}(t).1hr \tag{14}$$

where, $E_{b,min}$ is the minimum state of the battery. Figure 2 illustrates a basic flow chart outlining the operational strategy of the proposed HRES, which also covers battery management.

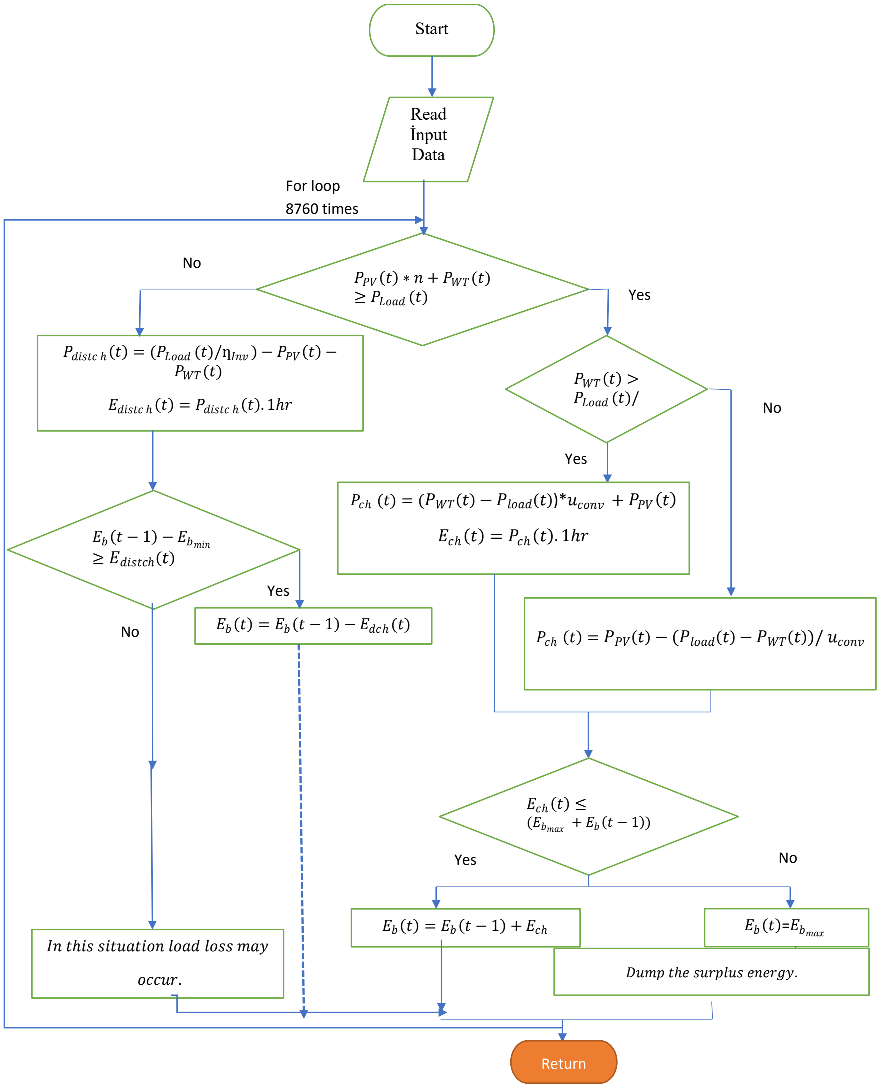

Figure 2. Overview of the operating strategy for the proposed HRES

2.4. Optimization problem formulation

The objective function ($f_{OBJETIVE}$) of the proposed hybrid PV/WT/battery system is designed to reduce the annualized system cost (ASC) while satisfying the constraint that the power system's reliability remains within a predefined limit (LPSP < LPSP*). Specifically, the objective is to determine the optimal values for N_{Pv}, N_{WT}, and N_{batt} representing the number of PV, wind turbines, and battery units, respectively, that satisfy this objective function. The configuration with the least ASC is deemed the most optimal solution to lower the levelized cost of energy (LCOE).

In this case, the optimization problem is framed to minimize the ASC, subject to specific constraints that will be discussed later. This is expressed as a function of a vector X, which includes the parameters to be optimized. The objective function for X, where X denotes a vector containing parameter indicesers ($N_{PV}, N_{WT}, N_{batt}, P_{inv}$) that must be optimally determined, can be expressed as [17]:

$$f_{OBJETIVE_X} = Minimize\ \text{ASC} = \text{F}[\text{N}_{PV} C_{PV} + N_{WT} C_{WT} + N_{batt} C_{batt} + P_{inv} C_{inv}] \quad (15)$$

where C_{PV}, C_{WT}, C_{batt} and C_{inv} are the cost of PV, wind turbine, battery and inverter units respectively. While, P_{inv} represents the rating power of the inverter.

The ASC incorporates various expenses related to the system. These costs include the capital cost, total operation and maintenance cost, and the cost of replacement. Each of these costs is calculated for every component of the system. The C_{PV}, C_{WT}, C_{batt} and C_{inv} could be calculated using (16) to (19) respectively.

$$C_{PV} = C_{PV}{}^{anual_{cap}} + C_{PV}{}^{annual_{rep}} + C_{PV}{}^{O\ and\ M} \quad (16)$$

$$C_{WT} = C_{WT}{}^{anual_{cap}} + C_{WT}{}^{annual_{rep}} + C_{WT}{}^{O\ and\ M} \quad (17)$$

$$C_{batt} = C_{batt}{}^{anual_{cap}} + C_{batt}{}^{annual_{rep}} + C_{batt}{}^{O\ and\ M} \quad (18)$$

$$C_{inv} = C_{inv}{}^{anual_{cap}} + C_{inv}{}^{annual_{rep}} + C_{inv}{}^{O\ and\ M} \quad (19)$$

Equation (20) is used to calculate LCOE based on ASC, as detailed in [17]:

$$\mathrm{L}COE = \frac{\mathrm{A}SC}{\sum_{\mathrm{t=1}}^{\mathrm{t=8760}} \mathrm{E}_{generated}(t)} . \mathrm{CRF}(\mathrm{d}, Y_i) \quad (20$$

the process for calculating the capital recovery factor (CRF) is outlined in [18].

$$CRF(d, Y_i) = \frac{d.(1+d)^{Y_i}}{(1+d)^{Y_i}-1} \quad (21)$$

In this context, d refers to the rate of interest, which includes the impact of inflation, while Y_i represents the complete lifespan of the hybrid system.

The analysis of power reliability is crucial in the design phase of such systems, serving as a vital parameter for evaluating system performance based on the load distribution. The calculation of power reliability is expressed through the loss of power supply probability (LPSP), which ranges between 0 and 1. An LPSP value of 0 indicates high reliability, where the load demand will always be satisfied. Conversely, an LPSP value of 1 signifies that the load demand can never be met. The LPSP expression for a year (T = 8760 hours) can be represented as (22):

$$LPSP = \frac{\sum_1^{8760} E_{deficit}(t)}{\sum_1^{8760} E_{load}(t)} = \frac{\sum_1^{8760}(E_{Load}(t) - E_{generated}(t))}{\sum_1^{8760} E_{load}(t)} \quad (22)$$

where, $E_{deficit}(t)$, $E_{Load}(t)$, $E_{generated}(t)$ present the energy deficit, the total consumer load and the total energy generated, respectively.

2.5. Optimization technique

The study uses PSO and GWO for their effectiveness in finding global optima. PSO is a population-based method inspired by natural swarm behavior, where particles adjust their positions and velocities based on both their own and the global best fitness values [19], [20]. GWO is a metaheuristic inspired by the social structure and hunting strategies of grey wolf packs [21]. Additional details on the PSO and GWO algorithms can be found in [20] and [22]. Table 1 summarizes the parameter settings and the main steps of the PSO and GWO algorithms used in this study.

Table 1. Parameter settings and the main steps of the PSO and GWO algorithms used in this study

Aspect	PSO	GWO
Parameters:		
Dimension	D = 3	D = 3
Agents	Particles = 44, Agents = 60	Agents = 60
Iterations	maxIter = 100	maxIter = 100
Inertia weights	wMax = 0.9, wMin = 0.2	—
Constants	c1 = 2, c2 = 2	—
Main steps:		
Initialize	Random positions and velocities, set P_best & G_best	Random positions, set α, β, δ
Evaluate	Compute fitness, update P_best & G_best	Compute fitness, update α, β, δ
Update	$V_i = wV_i + c_1r_1(P\_best - X_i) + c_2r_2(G\_best - X_i)$ $X_i = X_i + V_i$	$X(t+1) = (X_1 + X_2 + X_3)/3$ Using α, β, δ positions
Terminate	Until maxIter or convergence	Until maxIter

The objective of this work is to optimize the objective function while considering certain conditions. The number of each unit is limited by a maximum value, as well as the condition on the reliability using a value of LPSP. As a result, the PSO and GWO algorithms are employed to achieve the optimal design of the proposed configurations. These algorithms take into account the following constraints:

$$0 \leq N_{PV} \leq N_{PVMAX} \quad (23)$$

$$0 \leq N_{WT} \leq N_{WTMAX} \quad (24)$$

$$0 \leq N_{batt} \leq N_{bAttMAX} \quad (25)$$

$$0 \leq LPSP \leq LPSP^{*} \quad (26)$$

2.6. Case study description

Rural electrification is frequently constrained by a limited supply of electricity, which at certain times is only available for a few hours each day, even when supplied by renewable resources such as solar or wind. These are due to the intermittent nature of renewable resources. As a result, a major challenge is to design an optimal hybrid system that can meet the area's load demand continuously, with a minimal value of LPSP in Voisin of zero, while minimizing annualized system cost (ACS). The primary goal of this study is to conduct a feasibility analysis of a hybrid PV/Wind/Battery system to meet the electricity demand of a community in an isolated area within the province of Dakhla (east longitude: 23,41 and north latitude -15,58), situated in southern Morocco, as depicted in Figure 3. The weather data were obtained from the National Solar Radiation Database using the System Advisor Model software. The average wind speed and global horizontal irradiance are presented in Figure 4. It can be observed that the highest average wind speed is 6,05 m/s and the maximum global horizontal irradiance is about 308.93 W/m². The load demand for two typical days, one in winter and one in summer, is illustrated in Figure 5. The maximum electricity load demand is 150 kWh.

Figure 3. The proposed HRES location in Dakhla province

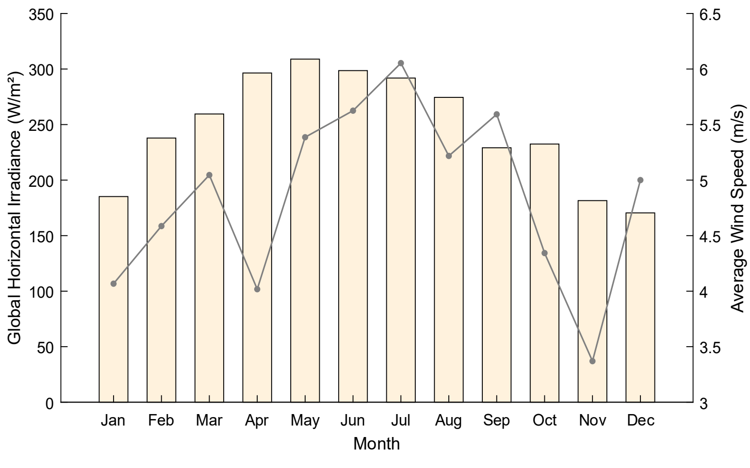

Figure 4. Average wind speed and global horizontal irradiance in Dakhla

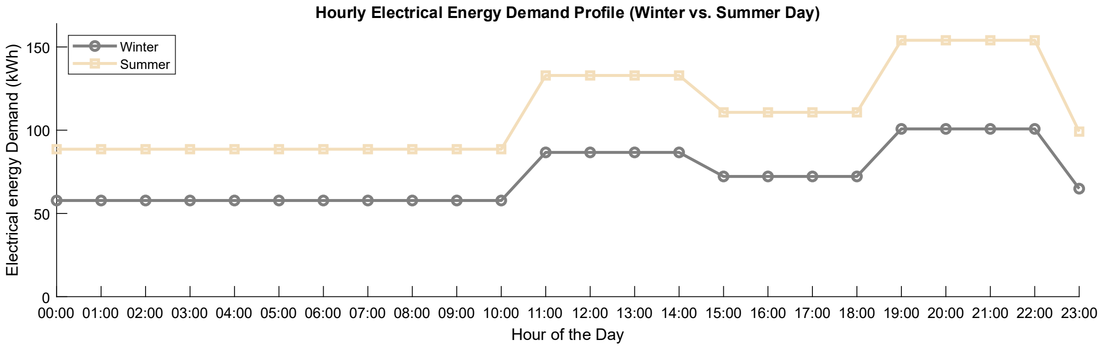

Figure 5. The hourly electrical energy load demand

3. SIMULATION RESULTS AND DISCUSSION

In this paper, a standalone HRES consisting of three components (PV, WT, and battery) is optimally assessed to meet the electrical demand of a remote community in Dakhla, Morocco. The hybrid PV/WT/battery system proposed in this research was thoroughly analyzed to assess the effectiveness of the suggested algorithms, specifically the GWO and PSO algorithms. The issue of identifying the optimal sizing for an isolated HRES and integrating PV, wind, and battery components was considered as an optimization problem. The suggested duration for the projected system was established at 25 years, assuming a 6% interest rate. MATLAB was utilized to apply the selected algorithms to optimize the problem. The optimization process consisted of 100 iterations, each executed independently, with the best solution determined based on the lowest fitness value. Both GWO and PSO algorithms were configured with a maximum of 100 iterations and 60 search agents.

3.1. Performance of optimization algorithms

The results obtained from the 100 runs of the GWO and PSO algorithms for ASC are identified, and the convergence behavior of GWO and PSO is illustrated in Figure 6. It is remarkable that the objective function values obtained by both techniques vary and fluctuate slightly but maintain a relatively stable level. Within 8 iterations, the GWO algorithm has achieved quick convergence, with a stable fitness value of 83111.33723 USD. This rapid stabilization demonstrates its ability to identify a near-optimal solution in a short time. In comparison, the PSO algorithm exhibited a slower convergence rate, gradually reducing its fitness value for 100 iterations. By the final iteration, PSO reached a slightly higher cost of 85934.2347 USD.

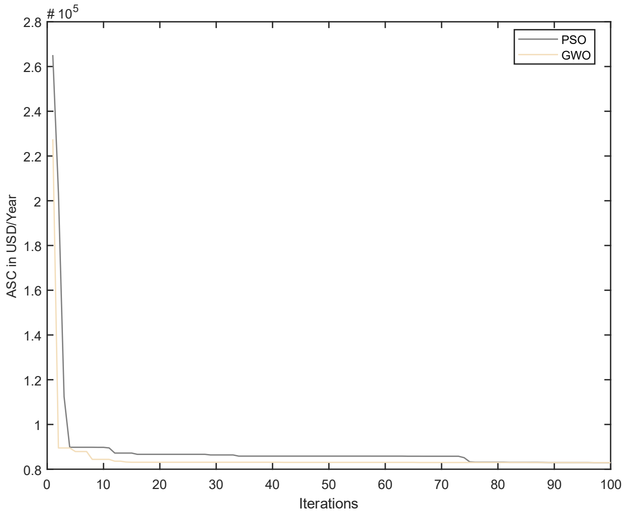

Figure 6. Conversion curves of objective functions using PSO and GWO algorithms

The statistical parameters of the obtained ASC values, including the mean, maximum, minimum, and standard deviation, were calculated alongside the final LCOE and LPSP. Table 2 summarizes the comparative performance metrics of the PSO and GWO algorithms. The GWO algorithm demonstrates a lower minimum ASC (82943.6955 USD/yr) and mean ASC (84890.9559 USD/yr) compared to PSO, which has higher values of 85934.2347 USD/yr and 118233.6849 USD/yr, respectively. Additionally, GWO exhibits greater consistency, with a significantly smaller standard deviation (14470.107) than PSO (142183.3376). In terms of LCOE, GWO achieves a lower value (0.0954 USD/kWh) than PSO (0.1021 USD/kWh), making it more cost-effective. However, PSO shows a slight advantage in reliability, with a lower LPSP of 0.0098 compared to GWO's 0.0099.

These results highlight the trade-offs between cost efficiency, consistency, convergence speed, and reliability when selecting optimization algorithms for HRESs. In terms of cost, GWO achieves a more economical result compared to PSO. However, when considering reliability, the LPSP of PSO (0.0098) is slightly better than that of GWO (0.0099). In terms of convergence speed, GWO demonstrates faster stabilization at an optimal solution, reaching better results in fewer iterations, while PSO requires more iterations to achieve its optimal performance. These differences highlight that GWO may be more advantageous for scenarios prioritizing quick solutions and cost efficiency, whereas PSO could be preferred in situations where ensuring system reliability is critical. Ultimately, the choice between the existing optimization algorithms depends on the specific priorities and constraints of the designed HRES.

Table 2. Comparative analysis of ASC, LCOE, and LPSP results from PSO and GWO algorithm

Metrics	GWO	PSO
ASC Value (USD/yr)		
Min	82943.6955	85934.2347
Mean	84890.9559	118233.6849
Max	227496.876	924662.8572
STD.	14470.107	142183.3376
Levelized cost of energy (LCOE) (USD/kWh)	0.1065	0.1104
Loss of power supply probability (LPSP)	0.0099	0.0098

3.2. System sizing and optimization results

Concerning the efficiency of the system and the determination of the best combination of the HRES presented in this study, PSO and GWO algorithms were employed to determine the best arrangement for the proposed PV/wind/battery system. These algorithms were used to assess and identify the best design parameters for the system. Table 3 offers a detailed overview of the findings achieved through these optimization algorithms.

According to the optimization result of the PSO algorithm presented in this table, the most efficient configuration of the proposed system achieves an LPSP of 0.0098 utilizing 177 units of PV modules, 86 units of the wind system, and 100 units of the battery storage system. This configuration results in the lowest ACS of 85934.2347 USD/yr and an LCOE of 0.01104 USD//kWh. While using GWO, the most efficient configuration achieves an LPSP of 0.0099 utilizing 168 units of PV modules, 77 units of wind system, and 278 units of the battery storage system.

The optimal solution for meeting the electrical energy demand of the selected community using the HRES consists of 168 PV modules combined with 77 wind turbines. In this configuration, energy is supplied by both PV modules and wind systems. This setup achieves the lowest ASC and LCOE, at 82,943.70 USD per year and 0.1065 USD per kWh, respectively, while also minimizing operating costs. Table 4 details the contribution of each system component to the total annual cost, highlighting that capital costs are the most significant factor, particularly for the PV system, where they are substantially higher compared to other elements.

The proposed hybrid PV/wind/battery system's management strategy was evaluated through a simulation covering the first week of January. Figure 7 depicts the system's energy exchange throughout this week, providing insights into the energy flow between its various components. As outlined in the management strategy, a battery system is used, storing excess energy produced when generation surpasses the load demand. This stored energy is then utilized during discharge mode when generation is insufficient to meet the load. Figure 7 reveals normal operation during the initial hours (0-100). Both wind and solar PV systems generate power to meet the desired load, with any surplus stored in the batteries. However, in the final hours (100-150) of the week, wind turbine production weakens due to lower wind speeds, resulting in insufficient power generation. To ensure a continuous and reliable electricity supply, the battery storage system automatically activates, delivering the necessary energy to bridge this gap. The analysis highlights the advantages of HRESs in contrast to single-source options. Through the integration of different energy sources, the HRES achieves a better balance of cost-effectiveness, reliability, and operational efficiency, demonstrating its capability to meet diverse energy requirements while minimizing costs.

The optimal configuration of each component in the hybrid system was determined through the use of the GWO algorithm. Then, an investigation into the system's operation over one year was conducted. The monthly energy output of each component is illustrated in Figure 8. Among the renewable energy sources in the proposed HRES, the solar PV system accounted for the largest contribution, representing 51.91% of the total energy output, while wind turbines and batteries contributed 24.94% and 23.15%, respectively.

Table 3. Optimal sizing results received from PSO and GWO algorithms

Algorithm	PV unit	Wind unit	battery unit	ASC(USD/yr)	LCOE (USD//kWh)	LPSP
PSO	177	86	100	85934.2347	0.1104	0.0098
GWO	168	77	278	82943.6955	0.1065	0.0099

Table 4. Technical characteristics of the simulated hybrid system components

Elements	Capital cost (USD/yr)	Replacement Cost (USD/yr)	Maintenance and operation Cost (USD/yr)	Total Cost (USD/yr)
PV	32 330,30	0	1 236,08	33 566,38
WT	28 745,51	-	168,43	28 913.94
Batteries	1 455,98	326,17	167,00	1 949,16
Inverter	4 428,97	-	400,00	6 209,95

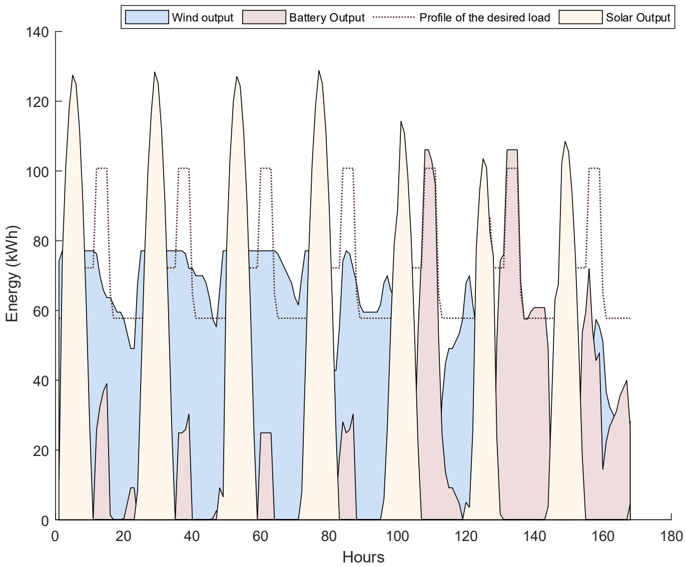

Figure 7. Energy exchange of the proposed system

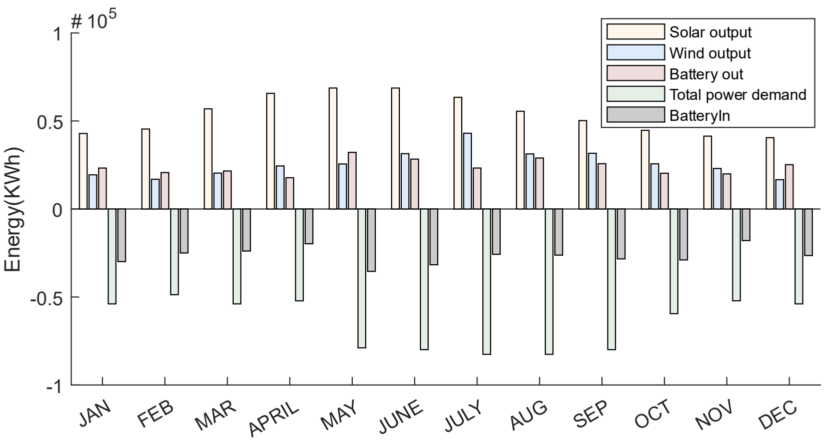

Figure 8. Monthly electricity production from the optimized system

3.3. Cost analysis and comparison

Office National de l'Électricité et de l'Eau Potable (ONEE) is considered the leading electricity provider in Morocco, supplying electricity to most of the country. The electricity pricing for different consumption levels is available on their website: *http://www.one.org.ma/* (accessed on 08 December 2024). For electrical demand exceeding 500 kWh per month, the applicable rate of 0.16 USD per kWh is applied to domestic use and private lighting. The most efficient configuration of the proposed HRES achieves a minimal LCOE of 0.1065 USD /kWh, representing a 23.93% reduction compared to the 0.14 USD/kWh LCOE of the Noor Ouarzazate I plant [23] and a 33.44% reduction compared to the applicable rate of 0.16 USD/kWh by ONEE. This shows that the proposed HRES is a cost-effective solution for rural electrification. With a much lower LCOE compared to current grid electricity rates, the HRES offers an affordable and sustainable energy source, especially for remote areas. By providing reliable, clean energy at a competitive price, the system supports both environmental and economic goals, making it an ideal option for rural areas that lack access to the main power grid.

Table 5 presents a comparative analysis of the proposed system's results alongside previous studies on similar systems. Given the differences in system designs and climate conditions across studies, the LCOE was chosen as the key metric for evaluation [24]. The LCOE of the proposed system is significantly lower than that reported in optimization studies, with the exception of those [6], [9]. In [6], although the hybrid PV/wind system in Dakhla, optimized by PSO, achieved an LCOE of 0.0800 USD/kWh, this study does not address the reliability aspect, and no reliability constraints are mentioned in the analysis. Comparatively, other configurations, such as the PV/wind/diesel/battery microgrid optimized by the Equilibrium Optimizer [9], reported an LCOE of 0.0917 USD/kWh, with the best LPSP achieved via EO being 0.0489. Despite the economic advantages of a reduced LCOE, this study presents a lower reliability compared to the results obtained in the current study. Our study demonstrates that advanced optimization algorithms like GWO and PSO can effectively improve the economic feasibility of HRES by balancing cost and reliability.

Based on the analysis of the data provided in Table 5, we can conclude that minimizing costs alone is insufficient and ensuring a reliable energy supply is equally critical. Although a system may appear economically attractive due to a low LCOE, its effectiveness ultimately depends on its ability to consistently meet demand. To address this, reliability metrics such as the LPSP need to be integrated into the optimization framework. This integration allows for an assessment of the system's capacity to maintain energy availability under variable conditions. Ignoring the importance of reliability could cause energy shortages, which would compromise the essential aims of rural electrification and sustainable access.

Table 5. Comparison with other studies

References	Location	Configuration	Methodology	LCOE (USD/kWh)	LPSP
[6]	Dakhla, Morocco	PV/WT	PSO	0.0800	Not indicated in the paper
[9]	Dakhla, Morocco	PV/WT/DG/BT	EO	0.0917	0.0489
[25]	Souss Massa, Morocco	PV-DG-Battery	HOMER	0.1294	Not indicated in the paper
[11]	Tangier, Morocco	PV/WT/Battery	GA	0.1915	LPSP value adopted in the paper is 0.0700
[12]	Essaouira, Morocco	PV/WT/DG/BT	MDPSO	0.1700	0.0012
[8]	Guerguarat, Morocco	PV/WT/DG/BT	HOMER	0.4100	Not indicated in the paper
This work	Dakhla, Morocco	PV/WT/BT	PSO	0.1104	0.0098
			GWO	0.1065	0.0099

4. CONCLUSION

This study addresses the critical challenge of providing reliable and affordable electricity to remote regions by investigating the optimal design and performance of a HRES combining PV, wind, and battery storage technologies in the Dakhla region of Morocco. Given the region's rich solar and wind resources but lack of grid access, the study aims to develop a sustainable energy solution that balances cost-effectiveness with operational reliability under variable load profiles. Using advanced optimization algorithms, GWO and PSO, the research systematically sized and evaluated hybrid system configurations to minimize the LCOE while maintaining high reliability, quantified by the LPSP. The study incorporated realistic load variability and operating reserve constraints to reflect the dynamic nature of energy demand in rural settings. Key findings reveal that GWO achieves a slightly lower LCOE of 0.1065 USD/kWh, making it more cost-effective and faster in optimization, while PSO excels in reliability, attaining a marginally better LPSP during peak demand. This demonstrates that the choice of optimization strategy can be tailored to emphasize either economic efficiency or system robustness, depending on project priorities. The hybrid system configuration optimized in this study significantly reduces energy costs compared to conventional alternatives, thereby enhancing the feasibility of rural electrification projects. Importantly, this work highlights the necessity of integrating both economic and reliability metrics into the design process of HRES to ensure a sustainable and uninterrupted power supply, a factor often overlooked in previous studies. By providing clean, reliable, and competitively priced energy, the proposed system supports environmental sustainability and socioeconomic development in off-grid communities.

Looking forward, future research will explore multiple HRES configurations using different optimization methodologies and constraints to determine the most cost-effective solution tailored to specific energy requirements. Specifically, a key focus will be on integrating hydrogen storage systems as an additional energy storage and conversion option. Hydrogen offers the potential to enhance system flexibility, increase energy autonomy, and provide longer-term storage capacity compared to conventional batteries.

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BIOGRAPHIES OF AUTHORS

Youssef El Baqqal received his master's degree in renewable energy systems and techniques of storage at the Faculty of Sciences of Rabat Mohammed V University in 2019. He is currently a Ph.D. student in electrical engineering at the Mohammadia School of Engineering. His research interests include renewable energy systems, optimization, and management of hybrid systems. He can be contacted at: youssef.elbaqqal@um5s.ac.ma.

Mohammed Ferfra received his B.S. degree in electrical engineering from Mohammadia School of Engineering in 1988 and his Ph.D. degree in electrical engineering at Laval University in 1993. His research interests include power systems, electrical machines, and photovoltaic systems. He can be contacted at email: ferfra@emi.ac.ma.

Reda Rabeh received his B.S. degree in electrical engineering from the Mohammadia School of Engineering in 2016 and his Ph.D. degree in electrical engineering from the Mohammadia School of Engineering in 2023. His research interests include power systems, control, and power quality in microgrids. He can be contacted by email: reda.rabeh93@gmail.com.