Sizing Hybrid Renewable Energy System Based on Nature-Inspired Search Method and Loss Power Supply Probability Model

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تحديد حجم نظام الطاقة المتجددة الهجين بناءً على طريقة بحث مستوحاة من الطبيعة ونموذج احتمالية فقدان إمداد الطاقة

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Abstract:
The increasing demand for sustainable and reliable energy systems has led to the development of hybrid renewable energy systems (HRES). These systems combine multiple renewable energy sources, such as solar, wind, and energy storage, to ensure a consistent and reliable power supply. This manuscript presents a detailed methodology for sizing an HRES using a nature-inspired search method and a Loss of Power Supply Probability (LPSP) model. The proposed approach aims to optimize the system configuration to minimize costs while ensuring a reliable power supply.

Keywords: Energy systems, HRES, multiple renewable energy sources, nature-inspired algorithms, LPSP.

الملخص:
أدى الطلب المتزايد على أنظمة الطاقة المستدامة والموثوقة إلى تطوير أنظمة الطاقة المتجددة الهجينة. تجمع هذه الأنظمة بين مصادر متعددة للطاقة المتجددة، مثل الطاقة الشمسية وطاقة الرياح وتخزين الطاقة، لضمان إمداد طاقة مستمر وموثوق. تقدم هذه المخطوطة منهجية مفصلة لتحديد حجم نظام الطاقة المتجددة الهجين باستخدام طريقة بحث مستوحاة من الطبيعة ونموذج احتمالية فقدان إمداد الطاقة. يهدف النهج المقترح إلى تحسين تكوين النظام لتقليل التكاليف مع ضمان إمداد طاقة موثوقًا.

لكلمات المفتاحية: أنظمة الطاقة، أنظمة الطاقة المتجددة الهجينة، مصادر متعددة للطاقة المتجددة، خوارزميات مستوحى من الطبيعة، احتمالية فقدان إمداد الطاقة.

1. Introduction

1.1 Background

The transition towards renewable energy sources is essential to mitigate the adverse effects of climate change and reduce dependency on fossil fuels [1]. Hybrid renewable energy systems (HRES) offer a promising solution by integrating multiple renewable energy sources, such as solar photovoltaic (PV) panels, wind turbines, and energy storage systems (ESS) [2], [3], [4]. However, the intermittent nature of renewable energy sources poses challenges in ensuring a reliable power supply. Therefore, optimal sizing of HRES components is crucial to balance cost, reliability, and efficiency.
Sizing a Hybrid Renewable Energy System (HRES) refers to the process of determining the optimal capacity and configuration of its components, such as solar panels, wind turbines, and energy storage systems, to meet energy demand reliably and cost-effectively [5]. This process is critical because renewable energy sources like solar and wind are intermittent, meaning their energy output varies depending on weather conditions, time of day, and season [6]. Proper sizing ensures that the system can balance supply and demand while minimizing costs and maximizing reliability [6].

1.2 Problem Statement

The primary challenge in HRES design is determining the optimal size of system components (e.g., solar panels, wind turbines, and energy storage) to minimize costs while ensuring a reliable power supply. Traditional methods often fail to account for the stochastic nature of renewable energy sources and the complex trade-offs between cost and reliability.

The intermittent nature of renewable energy sources, such as solar and wind, poses a significant challenge to their integration into power systems. Unlike traditional fossil fuel-based energy sources, which can provide a consistent and controllable supply of electricity, renewable energy generation depends heavily on environmental conditions.

For example, solar power generation varies with sunlight availability, which is affected by weather patterns, time of day, and seasonal changes. Similarly, wind energy production fluctuates with wind speed, which can be unpredictable and inconsistent.

This variability can lead to mismatches between energy supply and demand, potentially causing instability in the power grid. To address this issue, energy storage systems, hybrid configurations, and advanced grid management techniques are often employed to ensure a reliable and stable energy supply. By mitigating the intermittency of renewable energy sources, these solutions enable a smoother transition to a sustainable energy future.

1.3 Objective

This manuscript aims of the study are to:

1. Develop a robust methodology for sizing HRES components using a nature-inspired search method (Particle Swarm Optimization).
2. Incorporate a Loss of Power Supply Probability (LPSP) model to evaluate system reliability.
3. Optimize the system configuration to minimize total costs while meeting reliability constraints.

The main contribution of the article is to size a hybrid system using a nature-inspired algorithm consisting of (PV, WT, ESS, and Converter) to meet the demand with the proposed objectives to avoid power losses by implementing the LPSP technique. The remaining section of the article is divided into the following sections: Section 2, studying the following methodology to meet the proposed objectives along with the designed system diagram and the mathematical equation of the objective of LPSP. The implanted case study along with the

2. Methodology

2.1 System Description

The HRES under consideration consists of the following components and is presented in Figure 1. Additionally, the description of each of the utilized components is listed below.

1. Solar PV Panels: Convert solar energy into electrical energy.
2. Wind Turbines: Convert wind energy into electrical energy.
3. Energy Storage System (ESS): Stores excess energy generated by the PV panels and wind turbines for use during periods of low generation.
4. Power Converter: Converts DC power from the PV panels and ESS to AC power for use by the load.

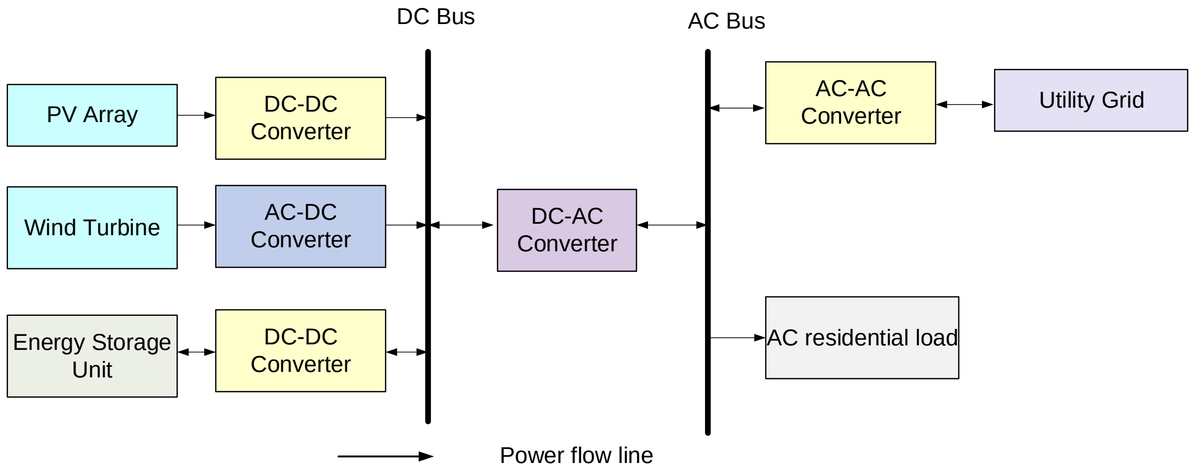

Figure 1: System Diagram.

2.2 . Loss of Power Supply Probability (LPSP) Model

The LPSP is a reliability index that quantifies the probability of the system failing to meet the load demand. It is defined as the ratio of the total unmet load to the total load demand over a specified period [7]. The LPSP can be expressed as in Eq. 1.

$$LPSP = \frac{\sum_{t=1}^{T} \max\big(0, L(t) - P_{total}(t)\big)}{\sum_{t=1}^{T} L(t)} \quad (1)$$

Where the $L(t)$ is the load demand at time t, $P_{total}(t)$ is the total power generated by the HRES at time t, and the T is the total number of time intervals.

2.3 Nature-Inspired Search Method

Nature-inspired search methods, such as Particle Swarm Optimization (PSO) [8], Genetic Algorithms (GA) [9], and Ant Colony Optimization (ACO) [10], are widely used for solving complex optimization problems. In this study, we employ the Particle Swarm Optimization (PSO) algorithm due to its simplicity and effectiveness in exploring large solution spaces.

2.3.1 Particle Swarm Optimization (PSO)

PSO is a population-based optimization technique inspired by the social behavior of birds flocking or fish schooling as presented in Figure 2 [11]. Each particle in the swarm represents a potential solution to the optimization problem is demonstrated in Figure 3. The particles move through the solution space, adjusting their positions based on their own experience and the experience of neighboring particles.

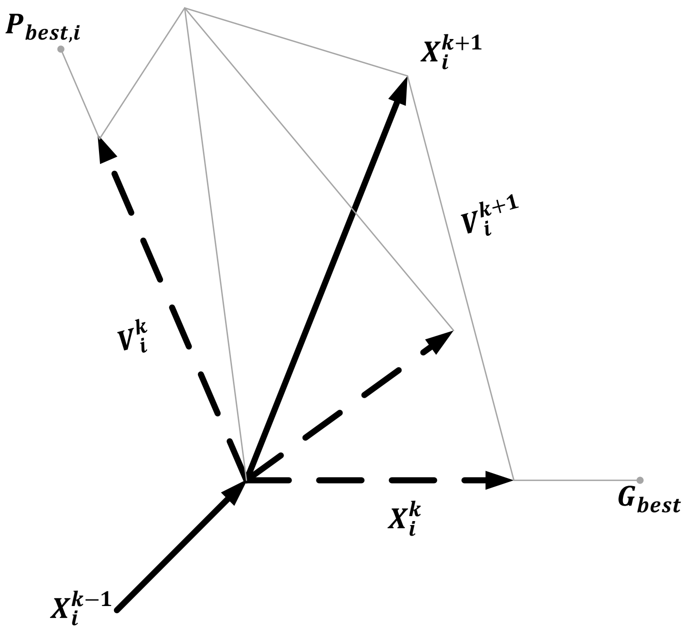

Figure 2: Movement steps of the PSO [12].

The position and velocity of each particle are updated using the following equations in Eq. 2 and in Eq. 3, respectively.

$$v_i^{k+1} = w.v_i^k + c_1.r_1.\left(P_{best,i} - x_i^k\right) + c_2.r_2.(g_{best} - x_i^k) \quad (2)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (3)$$

Where the v_i^{k+1} is the velocity of particle i at iteration k, x_i^k is the position of particle i at iteration k, w is the inertia weight, the c_1, c_2 are the cognitive and social acceleration coefficients, $r_1, r_2$are random numbers between 0 and 1, $P_{best,i}$ is the best position of particle i so far, and g_{best} is the best position found by the entire swarm. respectively.

2.4 Optimization Problem Formulation

The optimization problem aims to minimize the total cost of the HRES while maintaining the LPSP within acceptable limits. The objective function can be expressed as in Eq. 4 to meet the subject as in Eq. 5.

$$Minimize\ C_{total} = C_{PV}.N_{PV} + C_{WT}.N_{WT} + C_{ESS}.E_{ESS} + C_{conv}.P_{conv}. \quad (4)$$

$$LPSP \le LPSP_{max} \quad (5)$$

Where the $C_{total}$is the total cost of the HRES, $C_{PV}, C_{WT}, C_{ESS}, C_{conv}$ are the costs of PV panels, wind turbines, ESS, and power converters, $N_{PV}, N_{WT}, E_{ESS}, P_{conv}$ are the number of PV panels, wind turbines, ESS capacity, and converter power rating, and $LPSP_{max}$ is the maximum allowable LPSP, respectively [14].

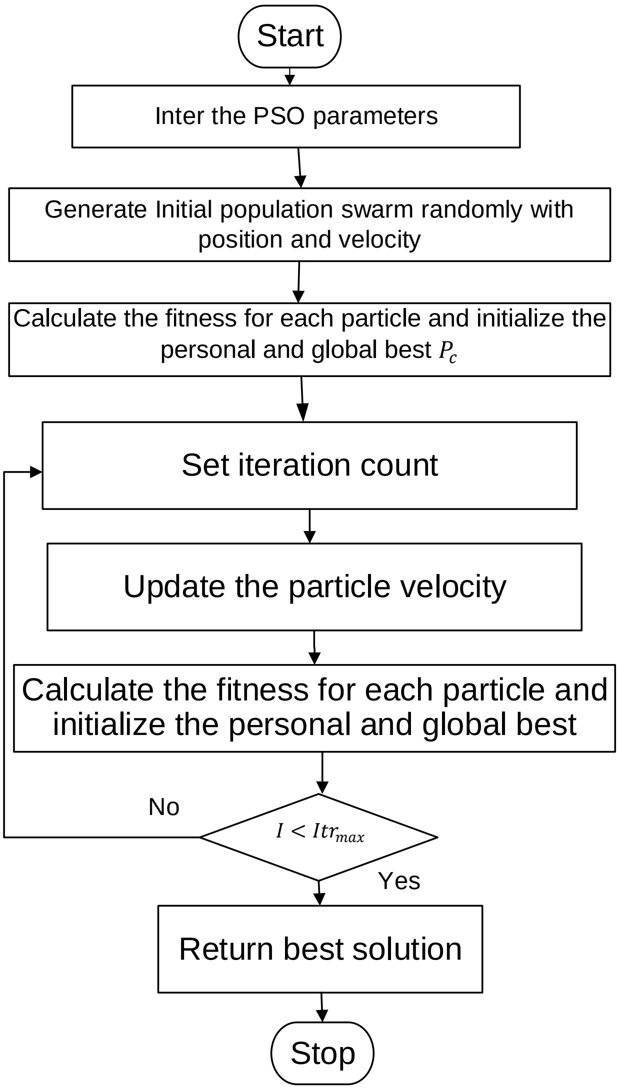

Figure 3: Flowchart of PSO [13].

2.5 Implementation Steps

The main implemented steps are tabulated in Table 1 with an explanation of each step.

Table 1: Implementation Steps [15].

Steps	Action	Explanation
1	Data Collection	Collect data on solar irradiance, wind speed, load demand, and component costs
2	Initialization	Initialize the PSO algorithm with a population of particles representing potential HRES configurations.
3	Fitness Evaluation	Evaluate the fitness of each particle by calculating the total cost and LPSP
4	Update Positions and Velocities	Update the positions and velocities of the particles based on the PSO equations.
5	Termination Check	Check if the termination criteria (e.g., maximum number of iterations or convergence) are met. If not, repeat steps 3-5.
6	Output Optimal Configuration	Output the optimal HRES configuration that minimizes the total cost while satisfying the LPSP constraint.

3. Case Study

Libya, a country in North Africa, has enormous potential for the development of renewable energy because of its substantial wind energy potential and wealth of solar resources [4]. However, the nation's energy demands are currently largely met by fossil fuels [16]. By switching to a Hybrid Renewable Energy System (HRES), Libya may lower greenhouse gas emissions, diversify its energy sources, and provide a more dependable and sustainable energy supply [17]. In light of Libya's distinct geographic and climatic characteristics, this case study investigates the sizing of an HRES for a fictitious location there [18].

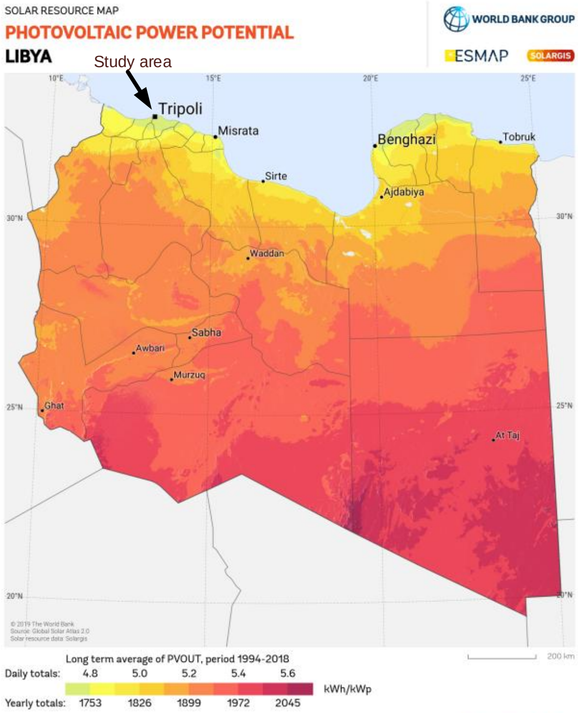

Figure 4: Libyan Map (case study) [19].

3.1 System Parameters

To demonstrate the proposed methodology, a case study is conducted with the following parameters as tabulated in Table 2. Along with the components costs as in Table 3.

Table 2: System Parameters [20].

Parameters	Values
Load Demand	100 kWh/day with a peak load of 10 kW
Solar Irradiance	Average daily solar irradiance of 5 kWh/m²/day
Wind Speed	Average wind speed of 6 m/s
LPSP Constraint	Maximum allowable LPSP of 5%.

Table 3: Component Costs [21].

Components	Costs
PV panel	\$200 per panel (300 W per panel
Wind turbine	\$1,500 per turbine (1 kW per turbine).
ESS	\$500 per kWh
Power converter	\$300 per kW.

3.2 Challenges in HRES Sizing

Sizing a Hybrid Renewable Energy System is a complex but essential process that involves balancing cost, reliability, and sustainability [15]. By leveraging advanced optimization techniques and reliability models, engineers can design HRES that effectively harness renewable energy sources to meet energy demand in a cost-effective and environmentally friendly manner [22]. Proper sizing is key to unlocking the full potential of hybrid renewable energy systems in the global transition to clean energy faces some challenges as presented in Table 4.

Table 4: Challenges in HRES Sizing.

Challenges	Remarks
Intermittency of Renewable Sources	Solar and wind energy are not constant, making it challenging to match supply with demand.
Cost Optimization	Balancing the cost of system components (e.g., solar panels, batteries) with the need for reliability.
Reliability Requirements	Ensuring the system meets energy demand with minimal interruptions, often quantified using metrics like Loss of Power Supply Probability (LPSP)
Geographic and Environmental Factors	Local climate, solar irradiance, wind patterns, and load profiles significantly influence system design.

4. Results and Discission

The results of the case study demonstrate the effectiveness of the proposed methodology in sizing an HRES. The PSO algorithm efficiently explores the solution space and identifies an optimal configuration that minimizes the total cost while maintaining the LPSP within acceptable limits. The integration of the LPSP model ensures that the system is designed to meet the load demand with a high degree of reliability.

The PSO algorithm is implemented with a population size of 50 particles and a maximum of 100 iterations. The optimal HRES configuration obtained is as follows: The total cost of the system is \$23,000, and the LPSP is calculated to be 4.8%, which is within the acceptable limit

Table 5: Breakdown compared results.

Number of PV Panels	Number of Wind Turbines	ESS Capacity	Converter Power Rating	LPSP
20	5	50 kWh	10 kW	4.8%

the performance of a Hybrid Renewable Energy System (HRES) over a 24-hour period for the PV and WT is presented in Figure 5.

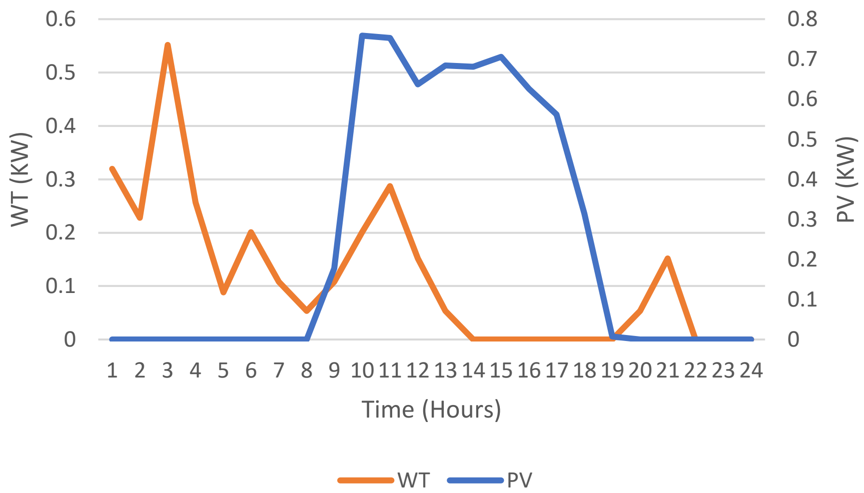

Figure 5: Output power from PV and WT.

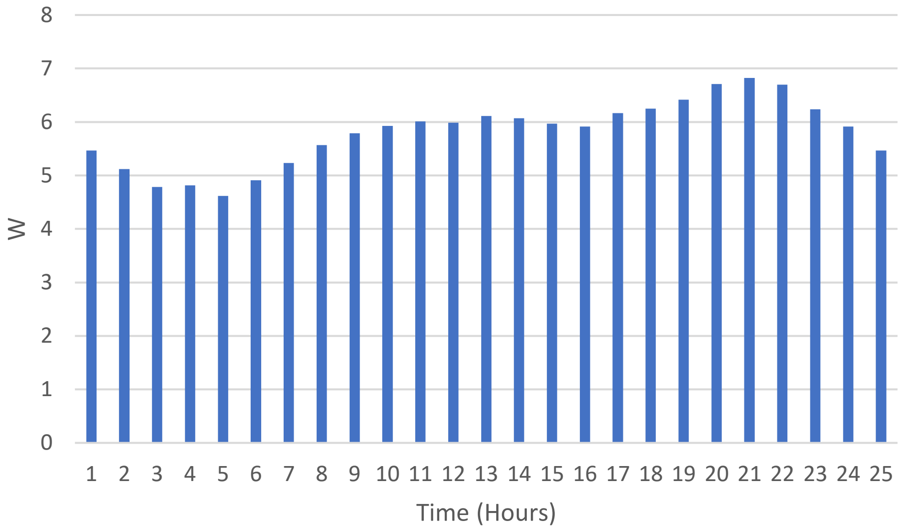

Figure 6: Utility Grid output.

Conclusion

This manuscript presents a detailed methodology for sizing a hybrid renewable energy system using a nature-inspired search method and an LPSP model. The proposed approach effectively optimizes the system configuration to minimize costs while ensuring a reliable power supply. The case study demonstrates the practical applicability of the methodology, and the sensitivity analysis provides insights into the impact of key parameters on the optimal configuration. Future work could explore the integration of additional renewable energy sources and the consideration of environmental factors in the optimization process.

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