Sizing optimization of a standalone PV/wind hybrid energy system with battery storage using a genetic algorithm

Manal Kouihi, Mohamed Moutchou, Abdelhafid Ait Elmahjoub
Department Research Group of Smart Control, Diagnostic and Renewable Energy "SCDRE",
Laboratory of Complex Physical Systems (LCCPS), ENSAM, Hassan II University, Casablanca, Morocco

Article Info

Article history:

Received Aug 28, 2024
Revised Mar 7, 2025
Accepted Mar 29, 2025

Keywords:

Battery storage
Cost
Genetic algorithm
Hybrid energy system
Levelized cost of energy
Low power supply probability
PV/wind energy

ABSTRACT

Renewable energy sources, such as wind and solar, are clean and widely available, they have significant advantages over conventional power. However, the climate has an inherent influence on their production. Due to growing energy costs and decreasing solar and wind turbine prices, the use of PV/wind hybrid energy systems has grown in popularity. Determining the ideal number of PV panels and wind turbines required is essential to minimize costs and ensure the continuous production of energy to fulfill the intended demand before building a renewable energy generating facility. The goal of this research is to identify the optimal design for a hybrid PV/wind system that includes battery storage for standalone uses. The suggested analysis uses the low power supply probability (LPSP) as a guiding metric and a genetic algorithm (GA) to optimize costs while reliably satisfying load requirements. With this technology, the ideal quantity of PV modules and wind turbines may be precisely determined at the lowest possible cost. The outcomes show that the hybrid systems have undergone effective optimization.

Corresponding Author:

Manal Kouihi
Research Group of Smart Control, Diagnostic and Renewable Energy "SCDRE"
Laboratory of Complex Physical Systems (LCCPS), ENSAM, Hassan II University
Casablanca, Morocco
Email: manal.kouihi@gmail.com

1. INTRODUCTION

Since the 1970s, increasing greenhouse gas emissions have accelerated climate change, prompting the rise of renewable energy sources such as wind and solar power for their lower environmental impact. Hybrid PV/wind systems combine both energies, offering a reliable, small-scale power solution, especially for remote areas. However, further improvements in efficiency and cost-effectiveness are needed to maximize their role in combating climate change [1]-[3].

Designing an efficient hybrid PV/wind system involves key considerations including minimizing cost and ensuring a reliable power supply under varying atmospheric conditions. Proper sizing of a hybrid PV/wind system with batteries is essential for efficient and economical use of these resources. Several optimization techniques, such as genetic algorithms and simulated annealing, have been explored for this purpose [4]-[9]. Among these methods, researchers have found genetic algorithms to be particularly effective in optimizing costs.

My contribution enhances the optimization approach for hybrid PV/wind systems with battery storage integration. By focusing on an improved application of the genetic algorithm, aimed at refining the determination of optimal configurations that balance cost-effectiveness and reliability, measured through the loss of power supply probability (LPSP) [10]-[12]. The paper consists of two main sections: the first discusses the methodology, covering wind turbines, PV panels, battery storage, criteria for optimal sizing, and application of the genetic algorithm. The second section presents the study's findings, including an in-depth discussion of the results.

2. METHOD

2.1. Hybrid energy system configuration

Hybrid energy systems incorporate multiple energy conversion devices to meet energy needs, often using at least one renewable energy source. These systems can be used in isolated applications or dispersed generation in traditional electrical grids. They overcome limitations inherent in conventional energy systems and offer a diverse range of options [13], [14]. The hybrid PV/wind energy system with battery storage comprises a PV array, wind turbines, battery bank, inverters, controllers, and additional components [13]. Figure 1 shows the system architecture and energy flow for the suggested hybrid PV/wind energy system with battery storage.

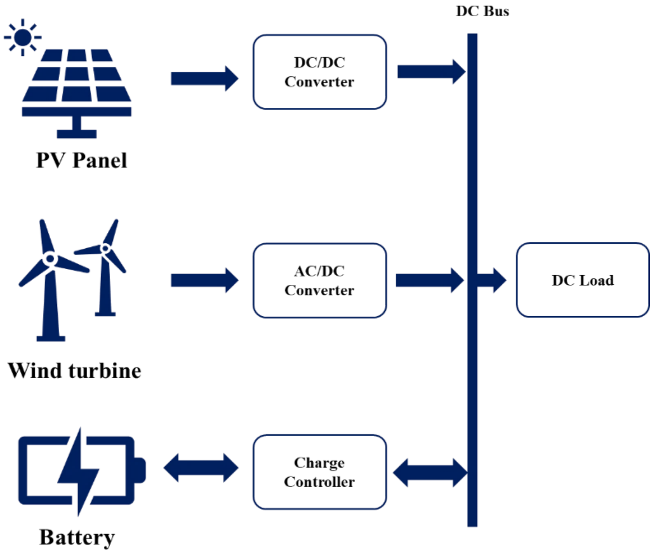


Figure 1. The energy flow diagram of the proposed system

2.2. System modeling

Modeling the hybrid PV/ wind system is an essential step towards accurately assessing system performance. This modeling process involves several key components and considerations [15] are as follows.

2.2.1. Load profile

The average daily base load for the location chosen was estimated at 110 kWh/day, which represents a reasonable energy consumption profile for the area over the course of a year, the hourly load profile during different months is illustrated in Figure 2 providing a detailed understanding of how energy demand varies throughout the year [13], [16].

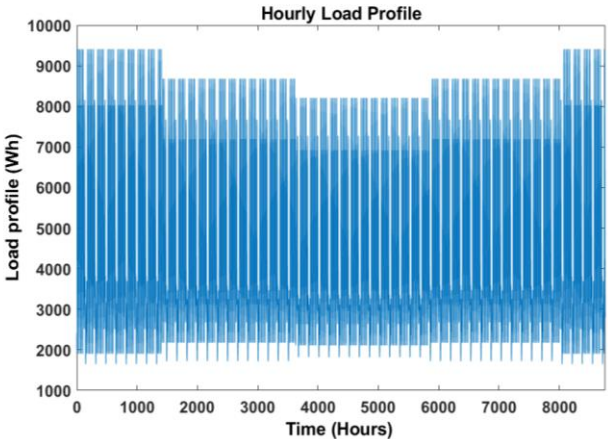


Figure 2. Hourly load profile during a year

2.2.2. Renewable energy resource

This paper evaluates renewable energy resources in Casablanca, Morocco, with an emphasis on solar and wind energy. The region has high solar potential, receiving an average of 5.80 kWh/m²/day. Figures 3 and 4 present the annual solar radiation and wind speed data.

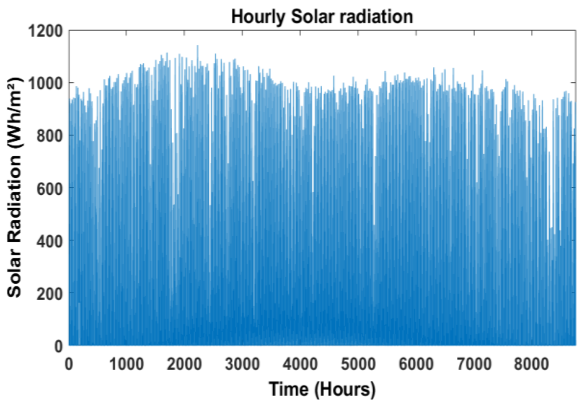


Figure 3. Hourly solar radiation

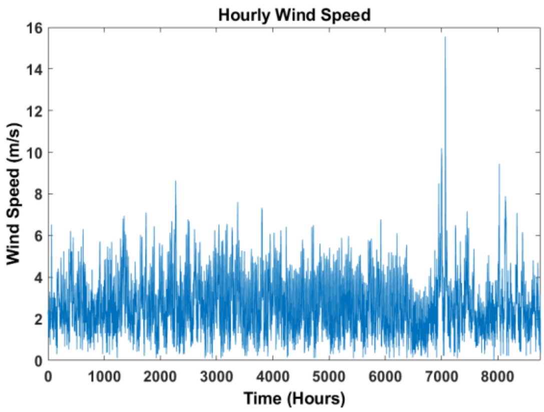


Figure 4. Yearly wind speed

2.2.3. Models of system components

The following section describes the modeling of each main component in the system:

- Solar panel

The output energy of the PV system is fully dependent on solar radiation, which directly influences its efficiency and power generation capabilities [7], [17], [15]. This relationship is given by (1) and (2).

$$E_{pv} = E_s * S * \eta \quad (1)$$

$$PV_{array} = N_s * N_p * P_{pv} \quad (2)$$

Where Es represents the solar irradiation energy (kW/m²), S is denotes the surface area of the PV module (m²), η indicates the power conversion efficiency of the PV module, Ns and Np refer to the number of PV modules in series and parallel, respectively, and Ppv is signifies the power of the PV module.

- Wind turbine

The cut-in wind speed Vin, and the cut-out wind speed Vout must be taken into account in the model we have looked at. As seen in Figure 5 and the (3), (4), and (5) the wind generator begins to produce power if the wind speed exceeds Vin, continues to produce power if the wind speed reaches the rated wind speed Vrs, and ceases to operate to protect the wind generator if the wind speed exceeds Vout [16], [18]. Consequently, the power output can be expressed mathematically as (3)-(5).

$$P_w = 0 \qquad V > V_{out}\,,\ V < V_{in} \quad (3)$$

$$P_w = \frac{Pr}{Vrs-Vin} * (V - V_{in}) \qquad V_{in} < V < V_{rs} \quad (4)$$

$$P_w = P_r \qquad V_{rs} < V < V_{out} \quad (5)$$

Where Pw denotes the output power of the wind generator at wind speed V, Pr represents the rated power, and Vrs signifies the rated wind speed.

- Battery modeling

Battery modeling is crucial for energy system analysis, providing insights into the performance, efficiency, and longevity of battery types. Accurate models optimize energy storage system design, especially in hybrid systems, balancing supply and demand [5], [8], [19]-[21]. A battery bank stores the energy produced by solar and wind power sources for usage at any time. The energy produced minus the energy required for the load is called EB. As determined by (6), this calculation helps figure out whether there is an energy surplus or deficit compared to demand [22].

$$EB = EP - EL \tag{6}$$

Where EB: difference between energy generated and load demand, EP: energy produced, and EL: load demand.

- Charging process

The excess energy is put to use charging the batteries when EB(t) > 0. The quantity of energy needed to charge the batteries is determined by their maximum capacity, charging efficiency, and amount of energy stored in them before charging. It also depends on the amount of excess energy that is available. In (7) is the expression for it [22].

$$E_{ch}(t) = min\ (EB(t),\ \frac{1}{\eta_{chb}} * (E_{batt}^{max} - E_{batt}(t-1))) \tag{7}$$

Then calculate the energy stored in the batteries using (8).

$$E_{batt} = E_{batt}(t-1) * (1 - \sigma) + \eta_{chb} * E_{ch}(t) \tag{8}$$

- Discharging process

The batteries go into discharge mode to make up the difference in energy when EB(t) < 0, which occurs when the demand is greater than the total energy produced by the wind and photovoltaic. The energy required by the loads and the amount of energy that was previously in the batteries determine how much energy the batteries can supply. The energy provided by the batteries is expressed in (9) [22].

$$E_{dis}\ (t) = min\ (|EB(t)|,\ \frac{1}{\eta_{disb}} * (E_{batt}(t-1) - E_{batt}^{min})) \tag{9}$$

Then use (10) to determine how much energy the batteries can store for running in discharge mode.

$$E_{batt} = E_{batt}(t-1) * (1 - \sigma) + \frac{1}{\eta_{disb}} * E_{dis}\ (t) \tag{10}$$

Where, Ech is the energy required to charge the batteries, Edis is the energy of discharging the batteries, η_{chb} is the charging efficiency of the batteries, η_{disb} is the discharging efficiency of the batteries, E_{batt} is the energy present in the batteries, and σ is the time step. In (11) determines the minimum energy level in the batteries based on the specified depth of discharge (DOD) [22].

$$E_{batt}^{min} = (1 - DOD) * E_{batt}^{max} \tag{11}$$

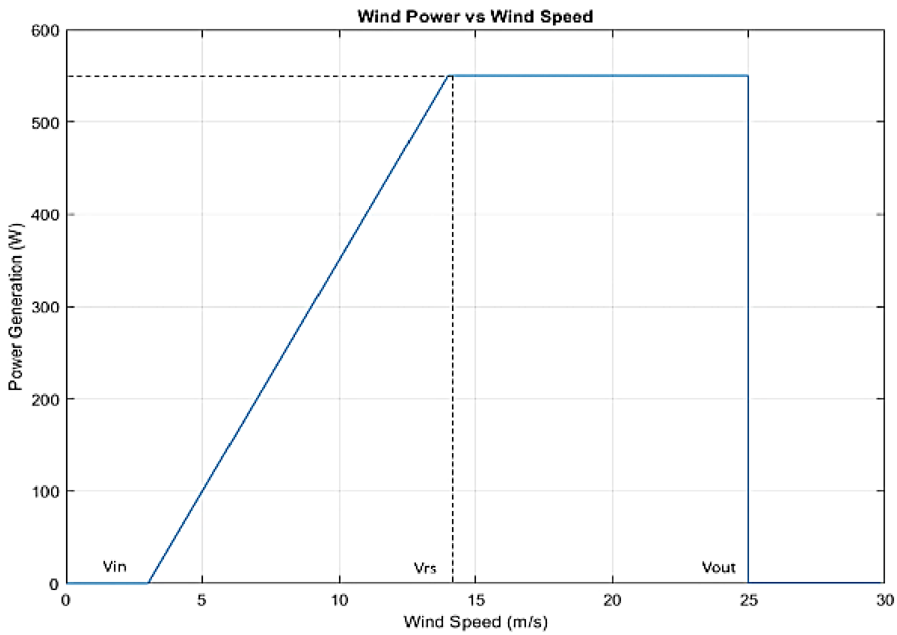


Figure 5. Wind speed vs generation

2.3. Criteria for optimal sizing
2.3.1. Reliability criteria
A reliable electrical power system consistently meets load demand, which is reflected by a low loss of power supply probability (LPSP). LPSP measures the likelihood that a hybrid system (solar panels, wind turbines, and battery storage) fails to meet demand. An LPSP of 0 indicates perfect reliability, while 1 signifies complete failure. Numerous studies have employed this reliability criterion [9], [10], [22]-[24]. In (12) is used to calculate it.

$$LPSP = \frac{\sum_{t=1}^{t=8760}\{E_{Load}(t)-(E_{pv}(t)+E_{W}(t)+E_{batt}(t))\}}{\sum_{t=1}^{t=8760}E_{Load}(t)} \tag{12}$$

Where ELoad is the energy of the load demand, Epv is the solar energy, Ew is the wind energy, and Ebatt is the battery energy.

2.3.2. Economic criteria
To evaluate the suggested new hybrid system's financial cost and viability, a number of economic parameters were modeled, which are the levelized cost of energy (LCOE) and the project's total cost (TC) [22].

- Total cost (TC)

The total cost comprises the initial capital expenses for the solar panels, wind turbines, and batteries, as detailed in (13), with the costs for each component derived from (14), (15), and (16) [25].

$$TC = TCpv + TCw + TCbatt \tag{13}$$

$$TCpv = Cpv * Npv \tag{14}$$

$$TCwt = Cw * Nw \tag{15}$$

$$TCbatt = Cbatt * Ebatt \tag{16}$$

Where Cpv represents the cost of the photovoltaic panel, Cw denotes the cost of the wind turbine, Cbatt indicates the cost of the battery, Nw signifies the optimized quantity of wind turbines, Npv refers to the optimized quantity of photovoltaic panels, and Ebatt represents the energy stored in the battery.

- Levelized cost of energy (LCOE)

The average cost of producing energy over the course of the project is estimated using the levelized cost of energy criterion. The formula given in (17) is used to compute the LCOE in MAD/kWh [10], [24].

$$LCOE = \frac{TLCC}{\sum_{i=1}^{n}\frac{Eg}{(1+r)^n}} \tag{17}$$

Where TLCC is the total life cycle cost, Eg is the total energy generated, r is the interest rate, and n is the life cycle of the project.

2.4. Genetic algorithm application
2.4.1. Problem description
Choosing components that can economically meet load demand and optimize system configuration and battery charging and discharging costs are the main concerns when developing a hybrid energy system that integrates renewable energy sources. The goal of this study's optimization is to lower the project's lifetime total cost. It's a single objective optimization problem. In (18) provides the corresponding mathematical expression. Therefore, the components of the system are discovered to be sensitive to i) minimizing down on system cost and ii) ensuring the reliable fulfillment of energy load demand.

2.4.2. Objective function
The objective function is to minimize the standalone hybrid PV and wind system's total cost (Costmin). In this study, the initial expenses are considered to be associated with the number of solar panels, wind turbines, and the battery bank. This specific form of the objective function, as written in (18), has been chosen to align with the technical and economic goals of our study.

$$Costmin = Cw * Nw + Cpv * Npv + Cbatt * Ebatt \tag{18}$$

2.4.3. Constraints

To address the problem, specific constraints are imposed: power generation must exceed load demand as outlined in (21), the number of PV panels and wind turbines must remain within allowable limits as described in (20) and (19), respectively, and battery storage must stay within defined energy levels as described in (22). These constraints are expressed as (19)-(22).

$$0 < Nw < Nwmax \tag{19}$$

$$0 < Npv < Npvmax \tag{20}$$

$$LPSP \leq LPSP_{limit} \tag{21}$$
$$Ebattmin \leq Ebatt \leq Ebattmax \tag{22}$$

Where Npv, Nw, $LPSP_{limit}$, and Ebattmax are the number of PV panels, wind turbines, the limit of LPSP, and the maximum battery capacity, respectively.

2.4.4. Optimization algorithm

The genetic algorithm uses random selection of individuals to produce children for future generations through selection, crossover, and mutation, continuously modifying the population to evolve towards an optimal solution. Figure 6 (see Appendix) shows the flowchart of the genetic algorithm used in the sizing procedure. The GA implementation involves initialization, evaluation, selection, crossover, mutation, and termination criteria. It creates a starting population of potential solutions, evaluates each individual's fitness, and selects those with higher fitness. The linear crossing of parents is used, generating three children. Following crossover, half of the population is made up of parents, and the other half is made up of children. A distance and a variable percentage of children are used to induce mutation. After that, the termination criteria are examined [26], [27].

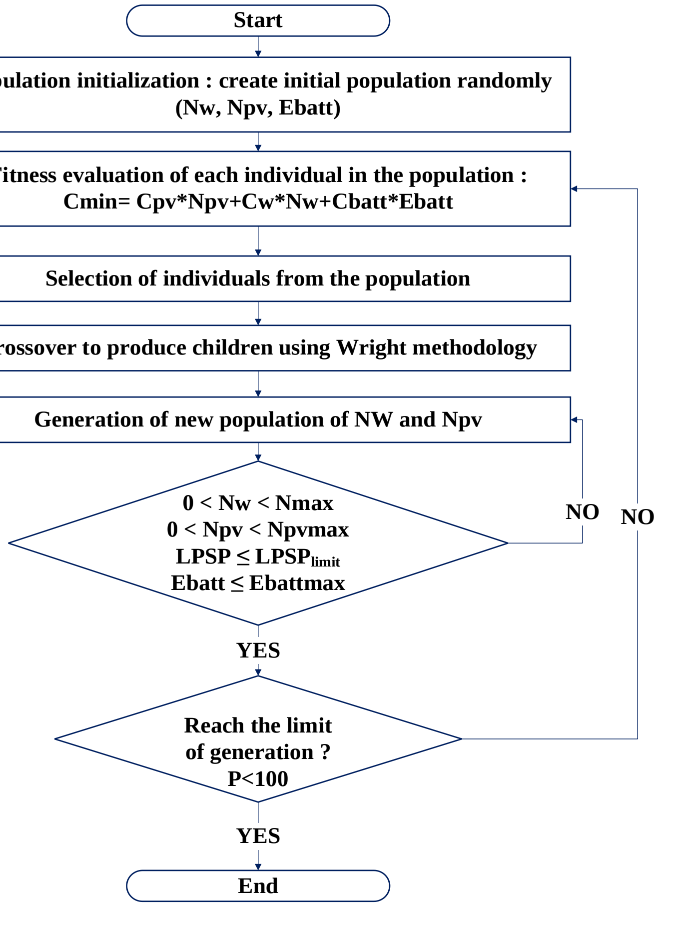


Figure 6. Flowchart of the algorithm used

3. RESULTS AND DISCUSSION

The results obtained in this study, based on the hybrid PV/wind energy system model and the applied methodology, were obtained using a simulation program developed in a MATLAB environment. The findings demonstrate satisfactory optimization, confirming the efficiency of the genetic algorithm in minimizing system costs. Additionally, the energy reliability of the system is notably high. The following graphs provide a detailed presentation of the results.

The output of solar and wind energy generated by the system is illustrated in Figure 7. Additionally, the annual energy production of the photovoltaic and wind-based hybrid system, along with the corresponding load demand, is depicted in Figure 8, while a detailed 48-hour zoom, highlighting the energy surplus, is shown in Figure 9. These figures provide a comprehensive overview of the system's performance and its ability to meet the energy requirements throughout the year.

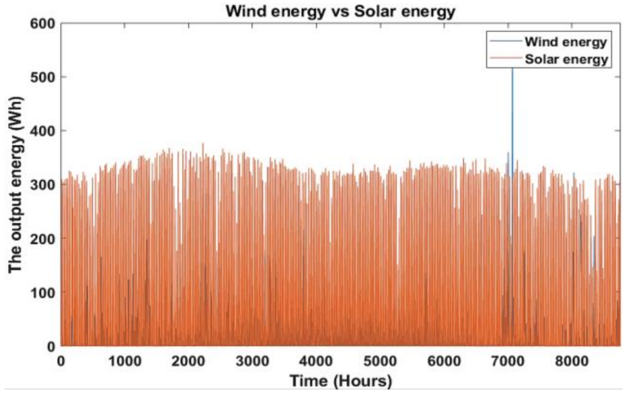
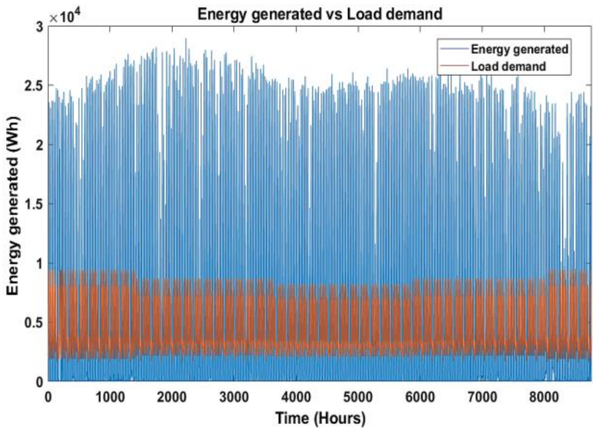


Figure 7. The output of solar and wind energy



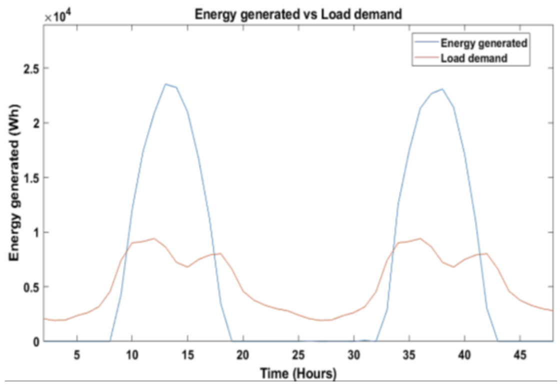


Figure 8. Energy generated vs load demand

Figure 9. Zoom in-energy generated vs load demand - over a 48-hour period

Figure 10 illustrates the battery energy, generated energy, and load demand, highlighting the surplus energy used to charge the battery bank. When power generation is insufficient, the battery bank supplies energy until it is fully discharged, ensuring a reliable energy supply. Figure 11 provides a 48-hour zoom for a closer examination of the graphs.

The energy production is illustrated in Figure 12, while the difference between the generated energy and the load demand is depicted in Figure 13. As shown, there are certain days when the system is unable to meet the load demand, highlighting periods of energy deficit. According to the simulation results, as shown in Figure 14, the optimum cost is approximately 10,921 million dirhams (MDH). This optimization is accomplished by carefully choosing the optimal quantity of solar panels, wind turbines, and battery capacity based on the results of our genetic algorithm. In Figure 15, the fitness function converges toward the optimal solution under the influence of the genetic algorithm during the system's iterations. This convergence illustrates the algorithm's effectiveness in optimizing the system parameters to achieve the best possible cost.

In addition to showing the evolutionary algorithm's efficacy, the graphical representations shed light on the convergence dynamics and minimized fitness attained in cost optimization for hybrid PV/wind power systems. The optimization process is conducted under varying loss of power supply probability (LPSP) values to ensure a thorough evaluation of system performance across different scenarios. The results obtained from this comprehensive analysis can be effectively summarized and are presented in Table 1. As shown in the graphs in Figures 16 and 17, the LPSP limits in function with total system cost and LCOE.

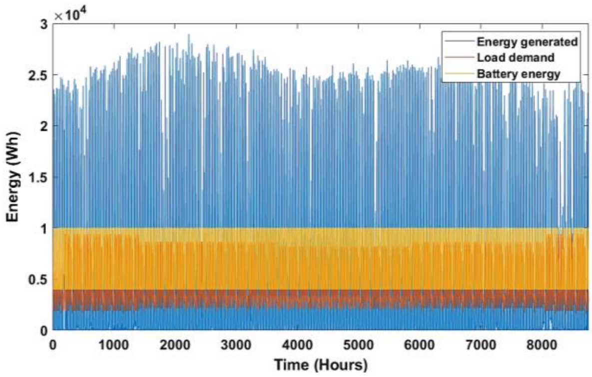


Figure 10. Energy available by the system

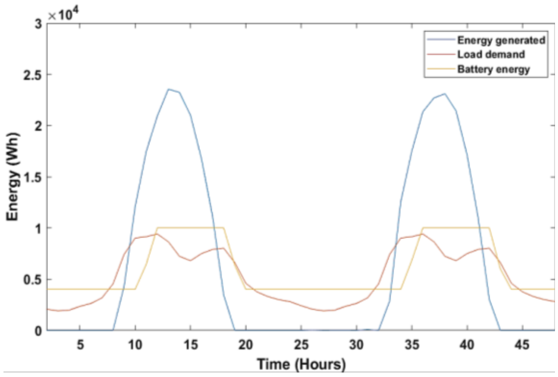


Figure 11. Zoom in-energy available-over a 48-hour period

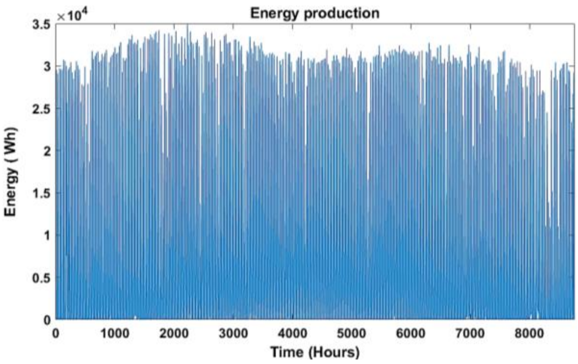


Figure 12. Energy production

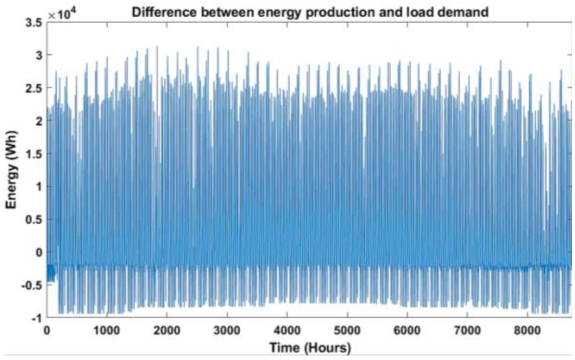


Figure 13. Difference between energy production and load demand

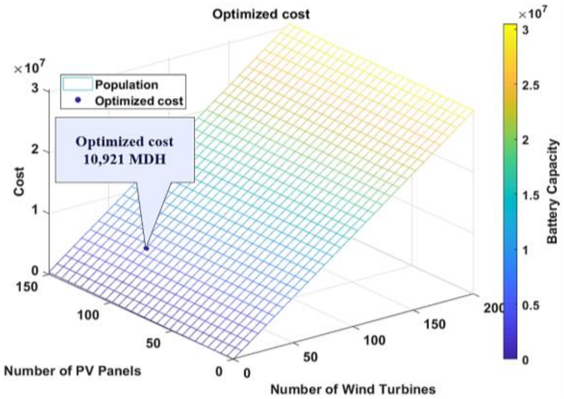


Figure 14. Optimized cost

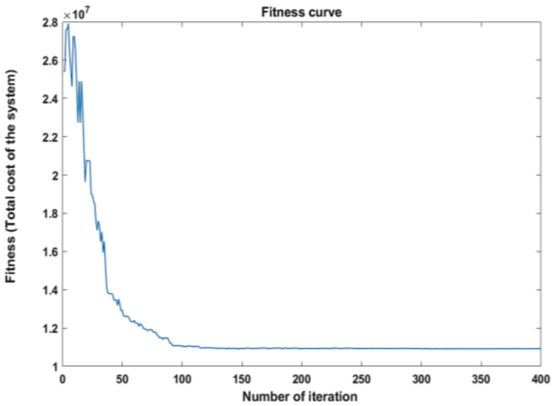


Figure 15. Fitness curve

Table 1. Summary of the optimization outcome using different LPSP

N°	Population	LPSP	Optimized cost (MDH)	Energy generated (kWh)	LCOE (MAD/kWh)	Execution time (s)
1	40	≤0.05	10.930	58,158	0.21190	2,267
2	80	≤0.04	10.941	57,405	0.21491	2,899
3	100	≤0.03	10.921	57,405	0.21452	3,451
4	140	≤0.02	10.928	57,405	0.21466	6,643
5	200	≤0.01	10.929	57,405	0.21468	6,157

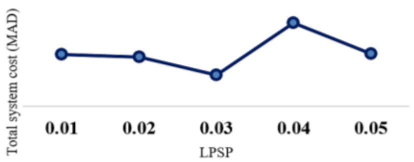


Figure 16. LPSP vs total system cost

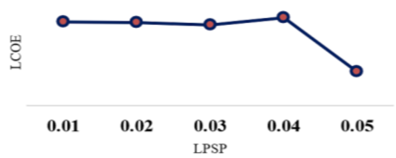


Figure 17. LPSP vs LCOE

4. CONCLUSION

This study aimed to optimize a hybrid energy system by employing a genetic algorithm to minimize total cost over its lifetime. The system's reliability was assessed using loss of power supply probability (LPSP). The optimal cost was found to be 10.921 million Moroccan dirhams, with the optimal LPSP limit being 0.03.

In terms of system optimization, the genetic algorithm effectively determined the optimal number of PV panels, wind turbines, and the appropriate battery capacity, ensuring that the system is both cost-effective and reliable over its lifespan. This research underscores the importance of precise optimization in the design of hybrid energy systems to balance cost, reliability, and energy production efficiency. Future research will expand by integrating grid integration into hybrid energy systems, using the genetic algorithm approach. This will analyze grid support's benefits in improving system reliability, reducing costs, and enhancing performance.

ACKNOWLEDGEMENT

Authors would like to express gratitude to the LCCPS Laboratory Director, thesis director, tutor, and department staff for their support, encouragement, and valuable suggestions in conducting their research in a supportive environment.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

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Manal Kouihi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
Mohamed Moutchou	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	
Abdelhafid Ait Elmahjoub				✓	✓		✓			✓	✓	✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are openly available in this article.

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BIOGRAPHIES OF AUTHORS

Manal Kouihi received her Engineering degree in Electrical Engineering and Renewable Energy from ENSET Mohammedia, Hassan II University, in 2019. She is currently pursuing a Ph.D. in renewable energy at the ENSAM school, within the LCCPS Laboratory at Hassan II University, Casablanca, Morocco. Her research specializes in the hybridization of wind and solar energy, focusing on optimization of system sizing and energy management. She can be contacted at email: manal.kouihi-etu@etu.univh2c.ma or manal.kouihi@gmail.com.

Mohamed Moutchou received his Ph.D. degree in 2015 from the Mohamed V University of Rabat in Electrical Engineering. Since 2016, He has been a Professor of Electrical Engineering at the School of Arts and Crafts of Casablanca, Morocco (ENSAM), where he continued developing his research on motor driver and control, and photovoltaic/wind energy. His recent research interests are energy quality (power filtering), energy recovery for IOT and Industry 4.0. He is responsible of the Laboratory of Electronic components and conception in ENSAM-Casablanca. Since 2017, he is the general secretary of the Association of connected objects and smart systems, domiciled at ENSAM. Since 2022, he has been the Associate Director of the Research Laboratory of Complex Cyber Physical Systems and a permanent member of the research team of smart control, diagnostic, and renewable energy. He can be contacted at email: mohamed.moutchou@univh2c.ma.

Abdelhafid Ait Elmahjoub is a research professor in Electrical Engineering at ENSAM Casablanca. Doctor aggregated professor in Industrial Automation and Computer Science. University Habilitation in Electrical Engineering. Head of the research team: smart control, diagnostic, and renewable energy. Member of the Jury of the National Electrical Engineering Aggregation Competition. Coordinator of the management of intelligent electrical systems. Coordinator of a professional degree in industrial automation and electrical systems. Field of research: control of power converters, renewable energies, and intelligent systems. He can be contacted at email: aitelmahjoub@gmail.com.