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PSO-driven optimal sizing of a hybrid system for enhanced renewable energy integration in Algerian buildings

Optymalne wymiarowanie hybrydowego systemu na podstawie PSO w celu zwiększenia integracji energii odnawialnej w budynkach algierskich

Abstract. *This study investigates the application of the Particle Swarm Optimization for optimally sizing a hybrid renewable energy system in the Zenata region of West Algeria. A case study using real-world data is conducted to determine the best combination of PV panels, wind turbines, and batteries. The results demonstrate that the PSO algorithm effectively identifies the optimal configuration within approximately thirty iterations. The identified configuration features a dominant reliance on PV, highlighting the potential of solar energy as a cost-effective and reliable energy supply solution for buildings in Algeria.*

Streszczenie. *W niniejszym badaniu zbadano zastosowanie optymalizacji roju cząstek do optymalnego określania wielkości hybrydowej energii odnawialnej w regionie Zenata w zachodniej Algierii. Przeprowadzono studium przypadku z wykorzystaniem danych rzeczywistych w celu określenia najlepszej kombinacji paneli fotowoltaicznych, turbin wiatrowych I akumulatorów. Wyniki pokazują, że algorytm PSO skutecznie identyfikuje optymalną konfigurację w ciągu około trzydziestu iteracji. Zidentyfikowana konfiguracja charakteryzuje się dominującym poleganiem na PV, co podkreśla potencjał energii słonecznej jako opłacalnego I niezawodnego rozwiązania w zakresie zasilania budynków w Algierii.*

Keywords: Investment cost, hybrid power systems, optimal configuration, particle swarm optimization
Słowa kluczowe: Koszt inwestycji, hybrydowe systemy zasilania, optymalna konfiguracja, optymalizacja roju cząstek

1. Introduction

Electric power is vital for sustainable development, driving social, economic, and environmental progress. However, the growing global demand for electricity necessitates a shift towards cleaner energy sources to mitigate climate change. Renewable energy sources, such as solar and wind, offer promising alternatives, known by their abundance and low environmental impact [1,2]. Recognizing this potential, the Algerian government has embarked on an ambitious program to promote renewable energy integration across various sectors, including buildings, transportation, and industry [3,4]. Integrating renewable energy sources into the building sector can significantly reduce reliance on the national grid and contribute to a more sustainable energy system.

Given Algeria's abundant solar resources, particularly in regions like the Sahara, the integration of solar energy into the building sector presents a significant opportunity. Algeria boasts the highest solar potential in the Mediterranean, with an annual average solar irradiance of 2,500 kWh/m² [5]. However, the intermittent nature of these sources, characterized by fluctuations in solar irradiance and wind speed, poses challenges for system reliability and performance. Hybridizing renewable energy sources, such as combining PV and wind power, can mitigate these challenges by enhancing the system reliability [6,7].

Effective hybrid energy systems (HES) design requires accurate sizing based on in-depth knowledge of local renewable energy resources and load demand characteristics [8,9]. Metaheuristic optimization algorithms, such as Particle Swarm Optimization (PSO), offer a powerful approach to address this complex optimization problem. PSO, inspired by the social behavior of bird flocks, effectively explores the solution space to identify optimal system configurations while handling multiple constraints and non-linear relationships inherent in HES design [10,11].

To demonstrate the practical application of the PSO algorithm, a case study is conducted on a private enterprise in the Zenata region, West Algeria. The company aims to install a hybrid PV-wind-battery system to power its administrative building. This study utilizes real-world meteorological data and load profiles to determine the optimal system configuration using the PSO algorithm, minimizing the cost of electricity while ensuring reliable power supply. The rest of this paper is structured as follows: Section 2 outlines the methodology, which includes the problem formulation and a presentation of the output power profiles for the HES generators. Additionally, a brief description of the optimization method is provided. Section 3 presents and discusses the results of the optimal sizing technique. Finally, Section 4 concludes the paper with key findings, and future research directions.

2. Materials and methods

This study investigates the optimal sizing of a hybrid renewable energy system for a case study in the Zenata region, West Algeria. The proposed energy system is designed according to the region's significant potential (solar and wind energy). It is a low-power system intended to supply the administrative unit of the limited liability company. The site's dominant energy resources primarily determine the structure of the hybrid system that meets the load power requirements. To overcome the intermittency challenges of solar and wind energy, the company owners aimed to use a storage system instead of combustion generators to comply with the National Climate Plan on reducing greenhouse gas emissions. Figure 1 illustrates the architecture of the selected hybrid system.

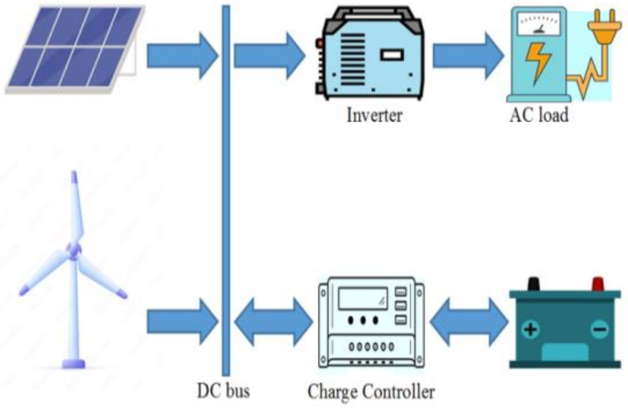

Fig. 1. Structure of the proposed hybrid system

To accurately assess system behavior along the measurement period, hourly output power profiles for the PV and WT generators were determined based on meteorological data from the region. These profiles account for the intermittent nature of renewable energy sources, considering factors such as solar irradiance, wind speed, and temperature. The integration of these pre-determined power profiles with the battery energy storage system enables the evaluation of system performance and the optimization of system components using the PSO algorithm.

The wind potential in Algeria, while relatively low compared to solar photovoltaic, represents a significant renewable energy resource. This study integrates both PV and wind power to leverage the complementary nature of these resources and enhance system reliability. This combination offers a significant environmental advantage compared to hybrid systems incorporating microturbines, which often rely on fossil fuels and contribute to greenhouse gas emissions. The storage system addresses the intermittency of renewable sources, ensuring reliable power supply without environmental impact [12-14]. The sizing and operation of each generator must consider variations in load and renewable sources to optimize the use of these generators and minimize the investment cost as much as possible while meeting the load demand [12,15].

2.1 Problem Formulation

This study investigates the optimal sizing of a hybrid renewable energy system for a private enterprise in the Zenata region, West Algeria. The system is designed to supply the energy needs of a small administrative building with an estimated peak demand of 9.5kW. Given the region's abundant solar resources and the availability of wind energy, the system integrates PV panels and WT, complemented by a battery energy storage system.

This study utilized input-output power models to estimate the electricity generation of PV panels and wind turbines. These models relied on measured meteorological data, including solar irradiation, temperature, and wind speed. To ensure accurate estimations, the study incorporated manufacturer-provided data on each generator's rated values and technical specifications [16]. Generator selection was based on two key criteria for the technical specifications and economic factors. It is necessary to identify commercially available generators that met the economic criterion of best value for money. Additionally, a crucial technical consideration involved matching the generators' rated voltage and current with the corresponding specifications of the used converters.

Table 1. Specifications of the selected components

PV panel					
Rated power	Rated voltage	Cell Size	Efficiency	Price (€)	Lifetime
300W	40.7 V	156.75mm x156.75mm	20.4 %	134.02	25 years
Three-bladed wind turbine					
Rated power	Rated voltage	Starting speed	Rated speed	Price (€)	Lifetime
1000W	48 V	2 m/s	11 m/s	138.83	5 years
Battery					
Capacity	Rated voltage	DOD	Efficiency	Price (€)	Lifetime
5 kWh	48 V	80%	95%	2690.9	10 years
Inverter					
Rated power	Rated voltage	Output Voltage	Efficiency	Price (€)	Lifetime
10kW	48 V	220-240V	94%	609.47	6 years

To achieve the research objectives, which include minimizing the cost of electricity while ensuring reliable power supply, the system's performance is evaluated using the Loss of Power Supply Probability (LPSP) technique. LPSP is employed to assess the system's ability to meet the load demand under various operating conditions. This technique helps create a set of feasible configurations, where each configuration represents a specific combination of PV panels, wind turbines, and battery capacity. The LPSP parameter quantifies the probability of having an imbalance between the electricity supply and the load. For this study, the probability of loss of power supply is set to zero, ensuring continuous and reliable power supply for the administrative building [6,17].

Given the list of technically and commercially suitable devices and the meteorological measurements from the case study site, the Particle Swarm Optimization algorithm was used to size the PV, wind, and storage systems optimally. The PSO technique has proven to be a practical algorithm for solving optimization problems in various fields, including function optimization. It is computationally efficient and requires minimal time to converge [18].

The LPSP technique serves to create a set of feasible configurations, where each configuration represents a specific combination of N_{PV} of PV panels, N_{WT} of wind turbines, and N_{bat} of batteries [19]. This technique ensures that the system can meet the load demand with the specified level of reliability. From this set of feasible configurations, the PSO algorithm searches for the optimal combination that minimizes the cost of electricity while ensuring a reliable power supply.

2.2 Output power profiles of HES generators

To accurately assess system performance and optimize system components, it is crucial to establish the hourly output power profiles of the photovoltaic and wind generators. This requires utilizing accurate meteorological data from the site, including solar irradiance, wind speed, and temperature, in conjunction with appropriate mathematical models for each component [14, 17].

A. Profile of the of PV generator output power

For determining the hourly output power of the PV panel, the characteristic equations governing solar panel operation were employed [17]. Considering the impact of temperature and irradiance on cell efficiency, the output power curve for the selected PV module was generated. Figure 2 illustrates the hourly output power of the selected PV panel based on the measured meteorological data from the site.

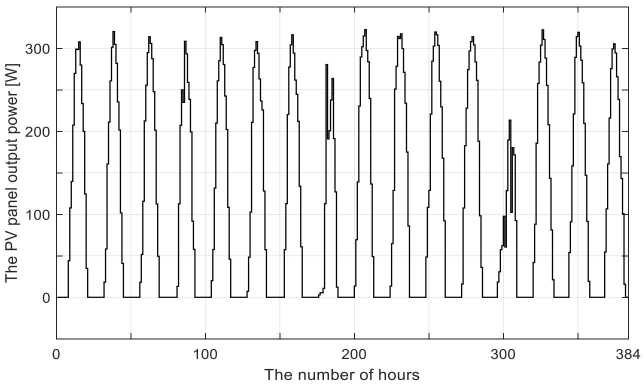

Fig. 2. Hourly output power of the selected PV panel

B. Profile of the wind turbine output power

Determining the wind turbine output power requires accurate wind speed data from the site. Manufacturers provide power curves based on extensive experimental measurements, which are specific to each turbine model [6]. Using these power curves and the measured wind speed, the hourly output power of the selected wind turbine was determined. Figure 3 illustrates the hourly distribution of the extracted power for the selected wind turbine.

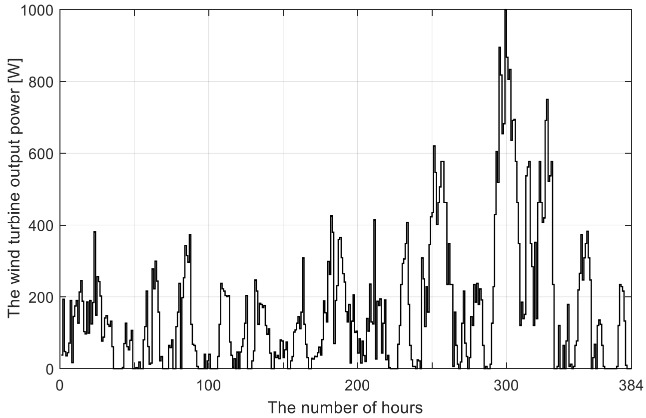

Fig. 3. Hourly output power of the selected wind turbine

C. Profile of the load demand

The generated power should be used efficiently to meet the load demand and improve the reliability of the HES system. The hourly load profile of the administrative building is primarily influenced by the daytime consumption of the administrative activities and the night-time consumption of irrigation and lighting. The load profile (Fig. 4) shows the significant activity during working hours (daytime), with a steady distribution of consumption in the evening and night, primarily due to lighting and irrigation.

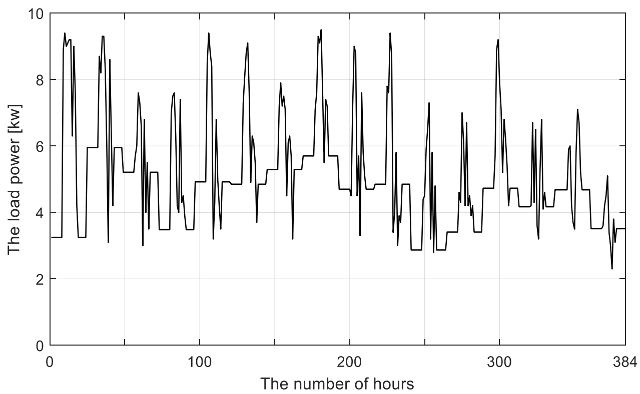

Fig. 4. Hourly power demand before and after shifting

D. Modeling of the storage system

The ability to charge and discharge the battery bank enables the absorption of excess power from renewable sources, which can be released when needed. This ability helps prevent power outages and ensures the load receives a reliable energy supply. If the total output power of generators is greater than the load demand, the storage system is consequently in the charging process, and the amount of energy of the battery bank will increase as follows [17,20]:

(1) $$E_{bat}(k) = E_{bat}(k-1) + \left[E_{PV}(k)\right] + E_{WT}(k) - \frac{E_{load}(k)}{\eta_{inv}}$$

However, when the total output power of generators is less than the load demand during discharging operation, the amount of energy in the battery bank will decrease in the following manner:

(2) $$E_{bat}(k) = E_{bat}(k-1) + \left[\frac{E_{load}(k)}{\eta_{inv}} - E_{PV}(k) - E_{WT}(k)\right]\eta_{bat}$$

where: $E_{PV}(k)$, $E_{WT}(k)$ – the output energy of PV and WT generators respectively at the hour *'k'*, $E_{load}(k)$ – the load demand at the hour *'k'*, η_{inv}, η_{bat} – the efficiencies of the inverter and the battery bank charging/discharging controller respectively.

The battery bank's state of charge *'SOC(k)'* is the percentage of stored energy compared to its maximum storage capacity and is given by [20,21]:

(3) $$SOC(k) = \frac{E_{bat}(k)}{C_{bat} \times V}$$

where: V – the voltage of the battery bank, C_{bat} – the full capacity of the battery bank

Maintaining a healthy State of Charge is critical for battery life and performance. Operating outside the ideal range (equation 4) can accelerate degradation and pose safety risks due to excessive heat and pressure generation [22].

(4) $$SOC_{\min} \le SOC(k) \le SOC_{\max}$$

2.3 The optimization cost function

The primary objective of this study is to minimize the overall investment cost associated with the operation of the hybrid energy system while ensuring an uninterrupted power supply to meet the demand of the administrative building. To achieve this, an optimization cost function is formulated, which incorporates various components of the system's economic and operational characteristics. The investment cost considers the cost of purchasing and installing the various components of the hybrid system (all generators, converters and storage unit), the maintenance cost for each element, and the cost of component replacement that has a lifetime less than the global system life [17, 23].

(5) $$f = C_b + C_m + C_r$$

where: C_b – the cost of acquiring and installing each hybrid system component, including photovoltaic panels, wind turbines, energy storage batteries, charge controllers, and inverters. It is variable and depends on the number of components and its specifications.

C_m – The operating and maintenance costs of the hybrid system. These costs encompass the cumulative expenses incurred in running and maintaining each system component.

C_r – the cost of renewing or substituting components whose lifespan is less than the reference period to safeguard continuous operation.

The objective function is minimized by finding the optimal number of generators and storage units while ensuring that all constraints are met, especially in satisfying load demand [8]. In this work, the reference period was set equal to the lifespan of the photovoltaic panels. A linear approach was used to determine the salvage value of the other components. Consequently, the salvage value is proportional to the component's lifespan. When the replacement cost differs from the initial cost, the salvage value is calculated based on the replacement cost rather than the original capital cost.

The primary constraint for our system is ensuring a zero probability of loss of power supply. In other words, the total output power from all photovoltaic generators, all wind turbines, and the battery system must always equal the load demand [6,17]. The balance equation (6) is directly linked to equations (1) and (2) given above. In these equations, the storage system power is either positive or negative, depending on whether the batteries are charging or discharging.

(6) $$P_{load}(k) = N_{PV} P_{PV}(k) + N_{WT} P_{WT}(k) + N_{bat} P_{bat}(k)$$

where: $P_{bat}(k)$ – the power that can be delivered or absorbed by each one of batteries at the hour *'k'*, $P_{load}(k)$ – the load demand power at the hour *'k'*.

2.4 Optimization method

The PSO technique is an evolutionary computation algorithm inspired by the social behavior of swarms, such as flocks of birds or schools of fish. The PSO is recognized for its computational simplicity and rapid convergence when searching for the global optimum. Two key concepts in the PSO framework must be considered: particles and swarms. In analogy with evolutionary computation paradigms, a swarm is akin to a population, while a particle represents an individual within that population [13,24,25].

Each particle navigates through a multidimensional search space where its position is adjusted based on its own past experiences as well as those of its neighbors. Specifically, each particle maintains a memory of its best-known personal position. This is the best personal position it has encountered since the beginning of the optimization process. In addition to personal experience, each particle is informed of the best-known positions within its neighborhood or the global swarm. Particles tend to move towards this "best local or global position," representing the best solution discovered by all the particles in the swarm throughout the optimization process [10].

The PSO algorithm proceeds through the following steps (Fig. 5):

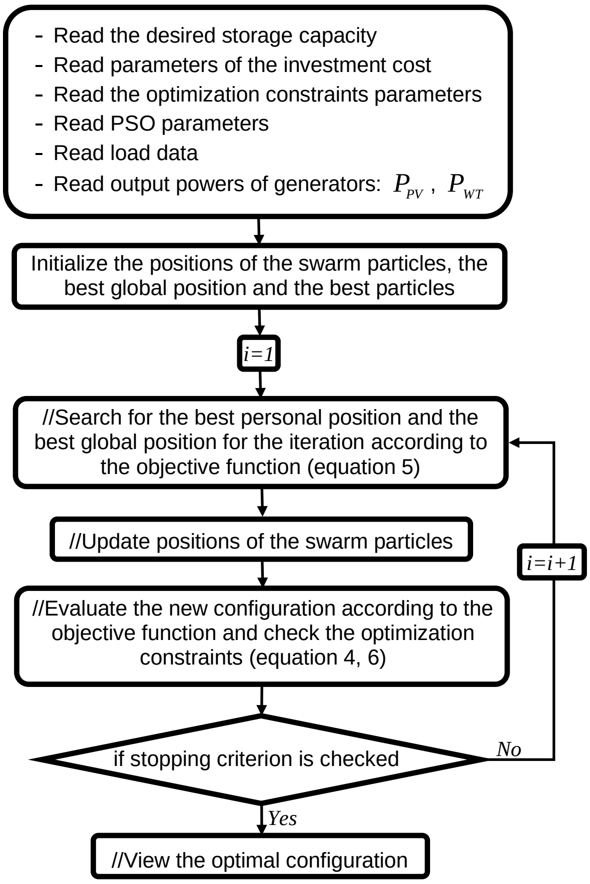

Fig. 5. Flowchart for search procedure of the optimal configuration

Initialization: A swarm of particles is randomly initialized within the bounds of the decision variables (Numbers of PV panels, WT, and batteries). Each particle's initial position is a candidate solution to the optimization problem.

Evaluation: Each particle's fitness is assessed by calculating the optimization cost function as defined previously, considering the initial investment, operational costs, maintenance, and reliability.

Update Mechanism: Each iteration, particles update their velocities and positions based on their personal best positions and the global best position found by the entire swarm. The update equations guide the particles' movement through the solution space, enabling exploration and exploitation of promising areas.

Iteration: This process is iteratively repeated for a set number of iterations or until convergence criteria are met, such as when the change in the global best position falls below a defined threshold.

Final Output: The algorithm concludes with the optimal configuration of solar panels, wind turbines, and storage capacity that minimizes the cost function while satisfying all operational constraints.

By leveraging the strengths of the PSO algorithm, the optimal configuration of the hybrid energy system can be efficiently identified, ensuring not only cost efficiency but also the reliability and sustainability of energy supply tailored to the specific demands of the administrative building.

3. Results and discussions

In the context of hybrid renewable energy system sizing, a range of artificial intelligence techniques have been explored, each with distinct characteristics. In contrast to deterministic methods, AI approaches like Genetic Algorithms (GA), Particle Swarm Optimization, and Simulated Annealing (SA) provide flexible solutions for complex optimization problems. Among these, PSO distinguishes itself through its simplicity of implementation, rapid convergence, and high precision, making it a particularly suitable choice for HRES sizing. As noted, PSO navigates the optimization landscape efficiently, avoiding the rossoverr and mutation operations characteristic of GA, and effectively addressing local optimization challenges, a significant advantage over methods like GA and SA. As evidenced by comparative analyses in existing literature [8, 26, 27, 28], PSO demonstrates a competitive edge against GA and other methods in terms of balancing solution quality and computational load. While other AI methods, such as Ant Colony Optimization, Artificial Bee Colony, Harmony Search, and Cuckoo Search (CS), also show promise, with CS potentially achieving higher accuracy and faster convergence than PSO in some cases, PSO's inherent ability to efficiently handle continuous optimization problems, as demonstrated in studies focusing on minimizing the cost of energy [25, 28, 29], positions it as a leading method for achieving techno-economic optimality. This literature review highlights PSO's ability to achieve a good balance between accuracy and computational efficiency, which justifies its selection for this study. Overall, while the choice of sizing method depends on the specific needs of the HRES project, PSO stands out as one of the most effective and reliable methods for optimizing system performance, balancing accuracy and efficiency in complex environments.

This study examined the impact of the number of photovoltaic panels and wind turbines on the total investment cost of a hybrid renewable energy system while maintaining a constant capacity for the storage system (18 batteries providing a full day of autonomy for the system). The optimization process was characterized by a gradient color representation, as depicted in the accompanying figures. The evolution of the best global position throughout the optimization process transitioned from blue at the initial iterations to red upon achieving convergence.

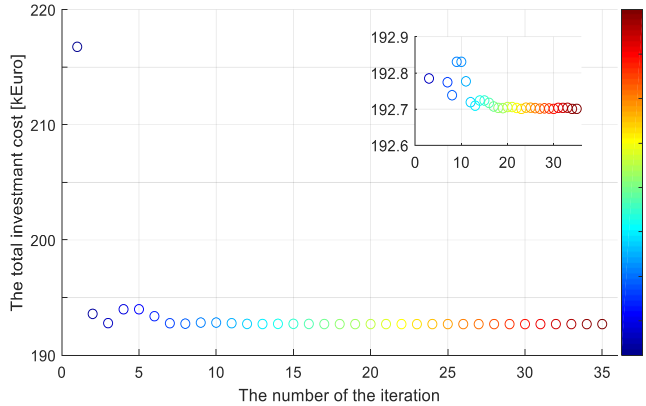

Fig. 6. Progression of the total investment cost as a function of the iteration number along the optimization process

Figure 6 showcases the evolution of the objective function (total investment cost), reflecting the total investment cost along the optimization process. The convergence was assessed after approximately 35 iterations, indicating a rapid and effective optimization process. The final investment cost of the hybrid system was determined to be €192,700 over its lifespan, yielding a cost of energy of €0.1725 per kWh. While this cost may seem relatively high, it could be considered affordable for Algerian companies, particularly given the islanded nature of the system and its limited power generation, which is especially crucial in off-grid locations.

Throughout the optimization, the PSO algorithm consistently improved the objective function with each iteration. However, it encountered instances where some solutions violated constraints related to the number of PV panels and/or the number of wind turbines. Such occurrences necessitated adjustments to ensure feasibility, resulting in temporary increases in the objective function in certain cases. It highlights the importance of robust constraint handling in optimization algorithms to prevent infeasible solutions.

Figure 7 illustrates the adjustments in the number of solar panels during the optimization process. Initially, the higher quantities of PV panels resulted in overestimated investment costs. Nevertheless, the algorithm gradually converged to the optimal number of PV panels that corresponded to the most cost-effective design. As seen in Figure 8, the relationship between investment cost and the number of PV panels indicates an evident point of minimization, concluding that the optimal design involves 52 PV panels, the configuration yielding the lowest investment cost.

Figure 9 demonstrates how the algorithm refined the number of wind turbines throughout the iteration process. Initial iterations featured configurations with an excessive number of wind turbines, contributing to inflated investment costs. However, similar to the convergence process observed with PV panels, the algorithm ultimately identified the optimal number of wind turbines necessary to minimize investment costs, as evidenced in Figure 10. The optimal configuration for our hybrid system is thus concluded to include 5 wind turbines.

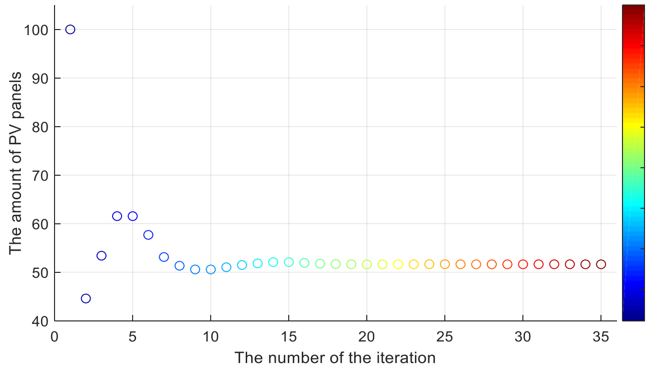

Fig. 7. Progression of amount of PV panels along the optimization process

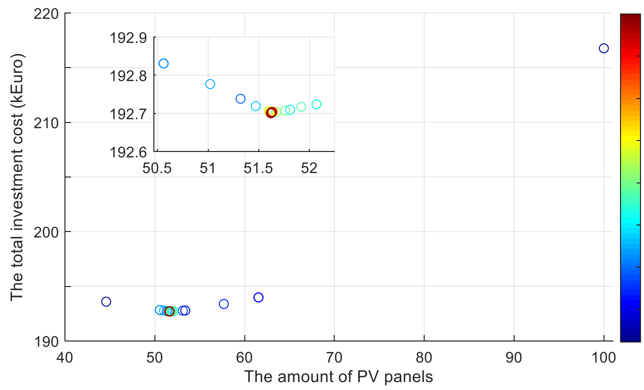

Fig. 8. Progression of amount of wind turbines and the total cost along the optimization process

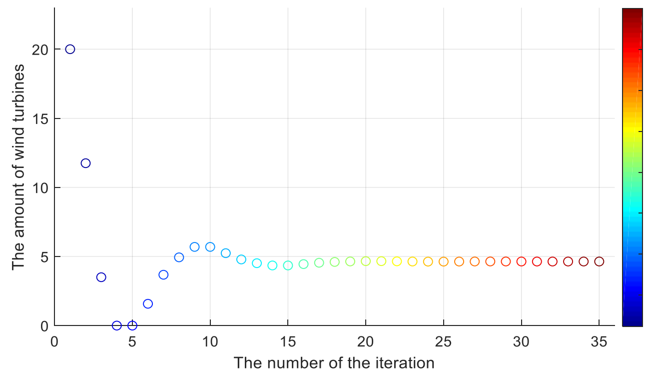

Fig. 9. Progression of amount of wind turbines along the optimization process

The PSO algorithm resulted in a configuration dominated by photovoltaic, confirming that PV solar energy is the most competitive at this site. Whereas wind energy is known to be competitive, our site's low to moderate wind speeds prevent the turbine from reaching its optimal operating speed. The obtained optimal cost was relatively high and was unattractive to Algerian companies. Since the system is islanded and has reduced power, the investment cost can be considered affordable, especially in remote areas.

To visually illustrate the nature of the optimization landscape and to support that the PSO algorithm converged efficiently to the global optimum, Figure 11 is presented. The 3D-curve depicts the variation of the investment cost as a function of the number of wind turbines and the number of PV panels. Notably, the curve exhibits a distinct parabolic shape, characterized by a single, well-defined minimum point. This parabolic trend provides compelling evidence that the optimization space is devoid of multiple local minima, thereby minimizing the risk of PSO becoming trapped in suboptimal solutions.

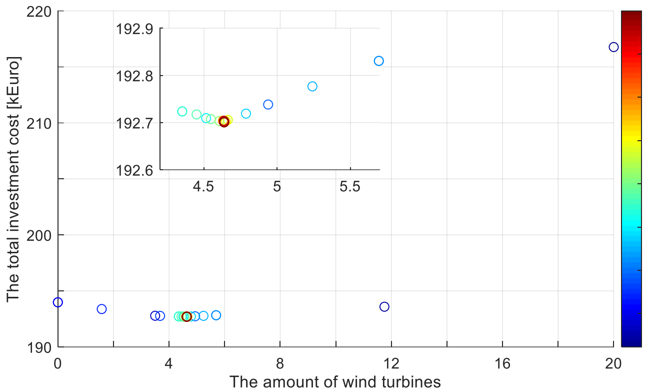

Fig. 10. Progression of the investment cost as a function of the amount of wind turbines along the optimization process

Conclusion

This study successfully developed and applied a Particle Swarm Optimization method for the optimal sizing of a hybrid renewable energy system to supply the administrative building of a limited liability company in Algeria. The PSO algorithm demonstrated rapid convergence, achieving an optimal system configuration of 52 PV panels and 5 wind turbines within approximately 35 iterations. This configuration resulted in a total investment cost of €192,700 over the system's lifespan, with a cost of energy of €0.1725 per kWh. The PSO algorithm's performance was notable, efficiently navigating the optimization landscape and avoiding local minima, as evidenced by the parabolic trend in the investment cost surface. The optimized system configuration predominantly relies on PV energy, reflecting the region's high solar irradiance and the competitive advantage of PV in this context. The obtained cost of energy, while seemingly high, is considered affordable for Algerian comp'nies, especially in off-grid locations, given the system's limited power generation and the benefits of energy independence. This study provides a practical framework for integrating renewable technologies in Algeria, aligning with the country's sustainable energy initiatives. Future work could explore alternative storage technologies and larger-scale applications to further optimize investment costs and enhance energy output. Additionally, applying PSO for load shifting and management energy sources for this case study may enhance the system's long-term economic viability.

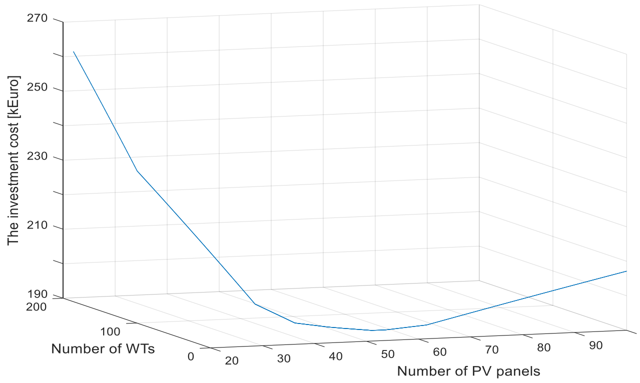

Fig. 11. Visual representation of investment cost optimization Space relative to PV panel and wind turbine sizing

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