Optimization and management of solar and wind production for standalone microgrid: a Moroccan case study

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ABSTRACT

The increasing demand for sustainable and efficient energy solutions has prompted extensive research into optimizing renewable energy sources in microgrid systems. This paper focuses on optimizing renewable energy sources within a standalone microgrid using particle swarm optimization (PSO) as the sole algorithm. The microgrid model proposed integrates photovoltaic (PV), wind, battery storage, and serves a load represented by an agricultural firm. Real-world data from Agdz in Ouarzazate, Morocco, is utilized for analysis. The primary objective is to minimize excess production from PV and wind sources when the battery reaches full charge. This research addresses the increasing demand for sustainable energy solutions by emphasizing a single optimization technique, PSO, for achieving a balanced and efficient energy generation system. The study aims to closely align energy production with load demand to reduce wastage and ensure a reliable energy supply within the microgrid. The evaluation is conducted based on the ability of the PSO algorithm to diminish the gap between total energy production and load demand. The use of the PSO algorithm resulted in a 30% reduction in excess energy, effectively mitigating unnecessary energy wastage when the battery is fully charged. This outcome highlights the algorithm's capacity to adapt and optimize energy production from primary sources to precisely align with the specific requirements of the load.

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1. INTRODUCTION

Microgrids are self-sufficient autonomous electrical systems designed to supply power to remote locations, critical infrastructure, and isolated communities not easily connected to the main electrical grid. They consist of various energy sources like batteries, wind turbines, solar panels, and backup generators, along with energy management and control technologies [1]. Emerging as an innovative solution for energy needs in remote and underserved areas, microgrids enable the use of renewable energy, reducing reliance on fossil fuels, and offering a sustainable alternative to traditional grids [2]. They are particularly useful for powering remote communities, essential facilities like hospitals and data centers, providing energy during emergencies, and lowering energy costs in rural regions [3]. As a result, microgrids are gaining traction in areas with high energy prices, limited infrastructure, or unstable electrical networks, making them a crucial focus for research in energy technology and policy [4]. Benefits of microgrids include improved power quality, reliability, and cost savings for remote areas. They enhance energy security by providing backup power during outages and contribute to climate change mitigation by reducing fossil fuel dependency and greenhouse gas emissions [5]. Ongoing efforts aim to improve microgrid design, management, and integration of renewable energy sources through advanced energy management systems, energy storage solutions, and grid-forming technologies to boost efficiency and reduce costs [6]. Preview study [7], a mixed-integer linear programming (MILP) model is introduced to optimize energy and reserve management in an independent microgrid powered by renewable sources, aiming to minimize costs while addressing energy production uncertainties. Similarly, [8] uses a genetic algorithm to minimize overall costs and incorporates demand response in a microgrid setting. Preview study [9], both genetic algorithm and particle swarm optimization (PSO) are applied to achieve an optimal configuration for a grid-connected hybrid system, with a focus on cost minimization. The study in [10] uses genetic algorithms and particle swarm optimization to optimize the sizing of renewable generation units in an isolated microgrid, considering cost and peak demand constraints. According to [11], MATLAB/Simulink and particle swarm optimization are used to demonstrate efficient power flow in a diverse microgrid model, leading to significant transmission loss reduction during battery charging and discharging. Benydir *et al.* [12] has tackled a crucial issue in microgrid optimization by concentrating on the efficient allocation of energy from renewable sources to meet load demand and reduce energy wastage, employing particle swarm optimization and genetic algorithm techniques [13].

This study makes a unique contribution in order to optimize the power production in microgrids by concentrating on the efficient allocation of energy from renewable sources to minimize energy waste and meet load demand. Unlike previous research, which focuses mainly on cost minimization and optimal sizing, our study addresses the critical issue of avoiding unnecessary energy surplus. By evaluating only, the performance of PSO, we emphasize its effectiveness in achieving optimal energy utilization. Utilizing real-world data from Agdz in Ouarzazate, Moroccan region with significant solar and wind potential [14]. This research extends beyond conventional optimization methods, offering insights into effective strategies for improving microgrid operation and maximizing renewable energy use while minimizing waste [15].

This paper is structured as follows: i) Section 1, we present the proposed microgrid and its components, including photovoltaic (PV) and wind sources, battery storage, and the load represented by an agricultural firm; ii) Section 2 offers an overview of particle swarm optimization (PSO), providing readers with a clear understanding of the algorithm's principles and mechanisms; iii) Section 3, we present the simulation results derived from the implementation of PSO in our microgrid system. This section showcases the practical implications of employing PSO to optimize power production, specifically addressing the reduction of excess energy when the battery is fully charged; Finally iv) Section 4, in the conclusion, we summarize the key findings and limitations of our study, emphasizing the effectiveness of PSO in enhancing microgrid operation and renewable energy utilization while minimizing wastefulness.

2. THE PROPOSED METHOD

The microgrid studied in this paper includes photovoltaic panels and wind turbines as the main renewable energy sources, with a battery storage system shown in Figure 1. This standalone microgrid is designed to meet the energy needs of an agricultural firm in Agdz, Morocco. It provides a reliable energy supply using the area's available solar and wind resources.

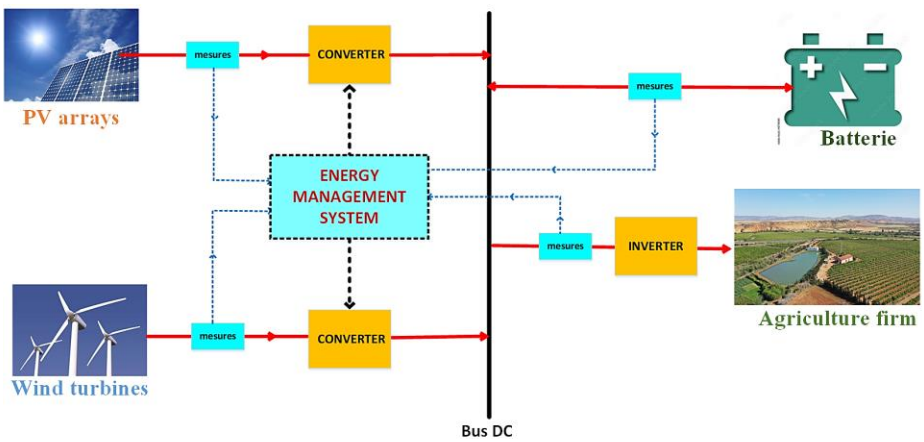

Figure 1. Microgrid studied

In this study, our attention is not directed towards the converters and power electronics of the microgrid. Instead, our primary focus lies in the management and optimization of power production from renewable energy sources. Table 1 presents the microgrid parameters.

Table 1. Microgrid parameters

Components	Parameters	Values
Photovoltaic	Rated max power	279 W
	Current at Pmax	8.59 A
	Voltage at Pmax	31.44 V
	Short circuit current	9.03 V
	Open circuit voltage	38.45 V
	Operating temperature range	-45+85 °C
	Cell technology	Polycrystalline
Wind turbine	Rated max power	15 kW
	Blade radius R	2 m
	Multiplication ratio G	2
	Air density ρ	1.25 Kg/m^2
Battery	Ref	APCNEW 150-12 GEL
	Voltage regulation for floating use	13.5 V–13.8 V
	Initial current	45 A
	Capacity	50 Ah

2.1. Proposed management strategy

The proposed management strategy for energy flow in the standalone microgrid is based on regulating the energy flow according to the level of the battery. This strategy ensures that the energy generated by the PV system and the wind turbine is stored in the battery during periods of low demand and is used to supply power during periods of high demand or when renewable energy sources are not available. The proposed strategy's objective is to optimize the utilization of renewable energy sources while also guaranteeing the protection of the batteries from any damage [16].

Balancing power in the microgrid is essential, especially under varying power generation from renewable sources. Overcharging or excessive discharging of batteries is a major cause of battery explosions. Therefore, controlling the battery's state of charge (SOC) is crucial for safe operations. In this study, we use SOC values in our energy management strategy. Figure 2 illustrates the energy management approach employed, which is based on SOC, the power produced, and the power demanded [17]. The system operates in five modes: Mode 1 charges the batteries while meeting firm demand when renewable energy (PV and wind) is sufficient. Mode 2 uses battery power to compensate for shortfalls when renewable energy is inadequate. Mode 3 relies entirely on battery power when no renewable energy is available. Mode 4 disconnects fully charged batteries to protect them when renewable energy is abundant. Mode 5 disconnects the firm when no renewable energy is produced, and the batteries are not charging [18].

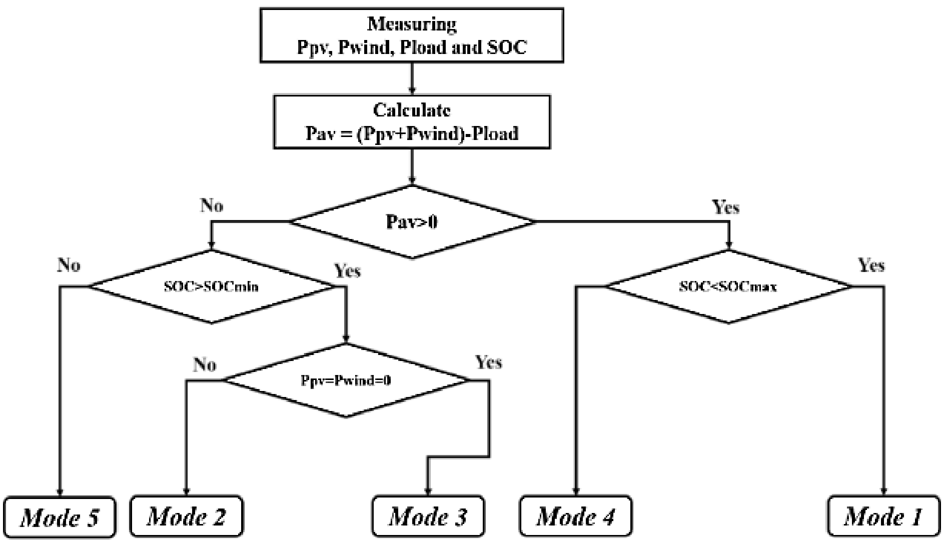

Figure 2. Flow chart of the energy flow regulation

2.2. Particle swarm optimization (PSO)

Particle swarm optimization (PSO) is a nature-inspired algorithm that mimics particle behavior in a search space to find optimal solutions, with particles adjusting positions based on personal and global best-known positions [19]. The algorithm updates each particle's velocity by considering the best solutions at both individual and global levels, influenced by two coefficients, α_1 and α_2, which represent trust in personal experience and collective information, respectively. These coefficients, combined with random values $x_1$and x_2, introduce stochastic effects from cognitive and social behaviors [12].

$$V_i(k+1) = V_i(k) + \alpha_1 x_1\left(pbest_i^k - p_i^k\right) + \alpha_2 x_2\left(gbest_i^k - p_i^k\right) \quad (1)$$

The second equation updates the position, with each particle modifying its location based on the recently determined velocity.

$$p_i^{k+1} = p_i^k + V_i^{k+1} \quad (2)$$

The parameters of position and velocity are interdependent; the velocity is influenced by the position, and the position is influenced by the velocity [20]. We can illustrate the moving particle in Figure 3. In this study, we use PSO to optimize power production from renewable sources, matching power generation with firm demand in our system [21]. Table 2 presents the PSO parameters employed in our study.

Figure 4 presents the PSO flowchart of a process. The algorithm begins by initializing particles with random positions and velocities within a search space. Each particle's fitness is then evaluated using a predefined fitness function [22]. The particles' velocities and positions are updated based on their personal best (pbest) and the global best (gbest) solutions found. This iterative process continues until the convergence of the fitness value to zero and reaches the maximum number of iterations [23].

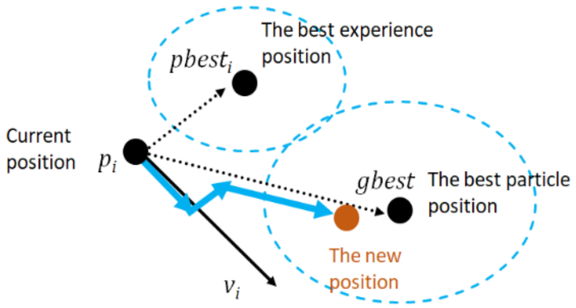

Figure 3. Moving particles

Table 2. PSO parameters

Parameters	Value
Swarm size	300
Maximum iterations	100

2.3. Fitness function

The objective function (fitness) used in this study for PSO algorithm can be expressed as (3).

$$f(x) = \sum_{i=1}^{24} \varphi\left|P_{g,i} - P_{d,i}\right| \quad (3)$$

According to 030),f(x) represents the fitness score of a solution, where $P_{g,i}$ is the total power generated by renewable sources and $P_{d,i}$ is the power demand for each hour i from 1 to 24. The weight φ indicates the importance of matching power generation with demand, with higher weights reducing deviations. This fitness function evaluates PSO solutions by measuring the difference between generated power and demand over 24 hours, summing the absolute differences for each hour. The PSO algorithm iteratively seeks to minimize this fitness value towards zero, optimizing power distribution to closely align generation with demand and minimize surplus or deficit [24].

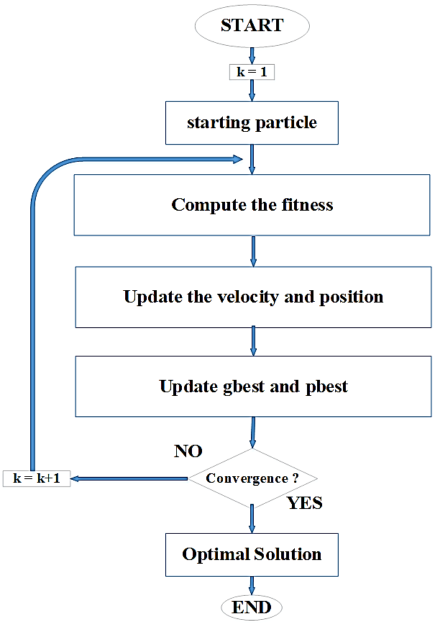

Figure 4. Flowchart of PSO

3. RESULTS AND DISCUSSION

In this section, we perform a comprehensive analysis of the outcomes obtained from applying our PSO method. We begin by presenting the profiles of irradiance and wind speed within the historical era referred to as Agdez, situated in Ouarzazate, Morocco. Following this, we showcase the generated output of both photovoltaic systems and wind turbines over a span of five days, as depicted in Figure 5 [25]. Figure 6 shows the power consumption profile for a farming establishment in Agdez over five consecutive days. It clearly shows when the agricultural firm's electricity demand peaked at 6.5 kW and when it dropped to as low as 1 kW. This graph provides valuable insights into the firm's energy consumption patterns, helping to identify peak usage periods and enabling more efficient energy management strategies. Figure 7 shows the power flow within the microgrid.

The proposed management strategy successfully managed the power flow over 5 days. The maximum PV power reached 10 kW, and the wind turbine produced up to 14 kW. However, at times during the day, the combined power from these sources fell below the firm's demand. In such cases, the batteries supplied the necessary power, indicated by the negative battery power value, meaning the power flowed from the batteries to the load.

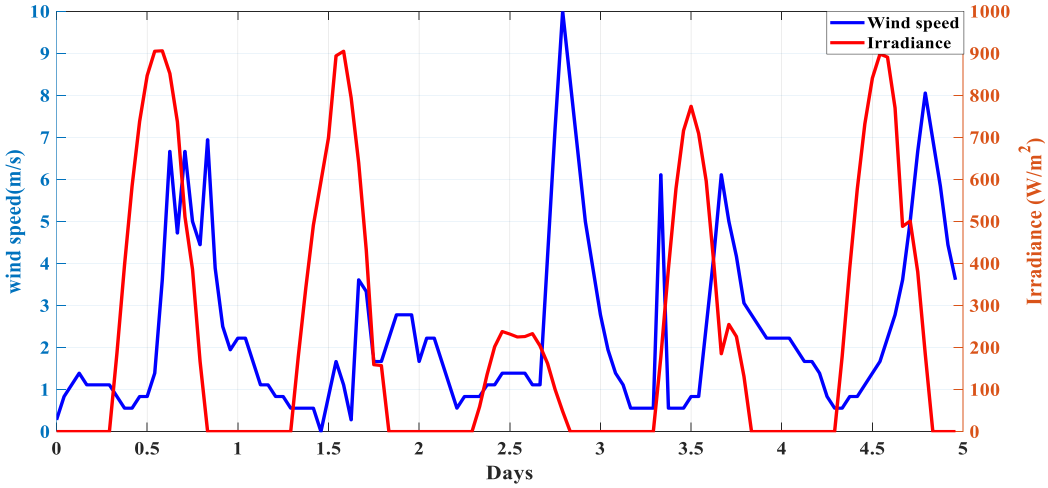

Figure 5. Wind speed and irradiance profile

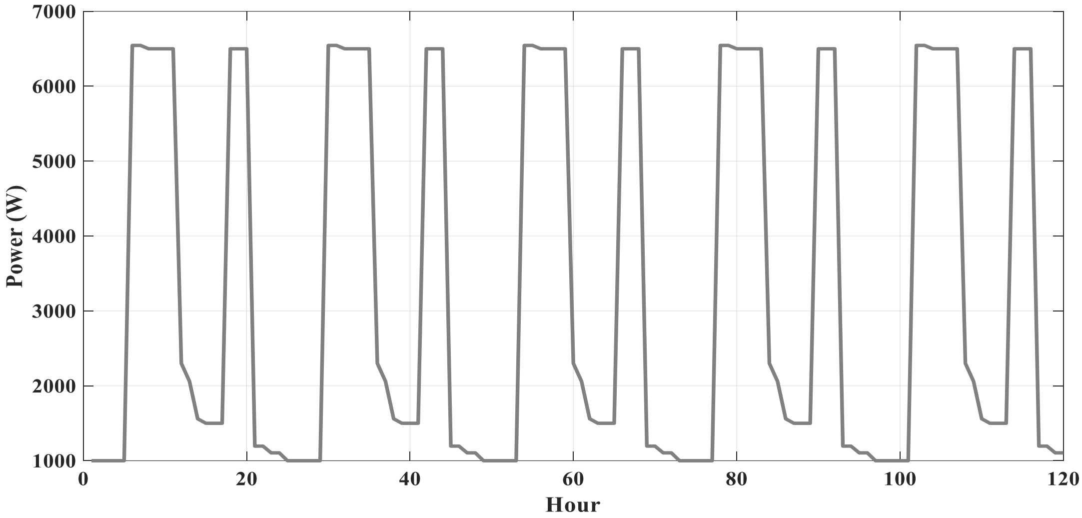

Figure 6. Load profile

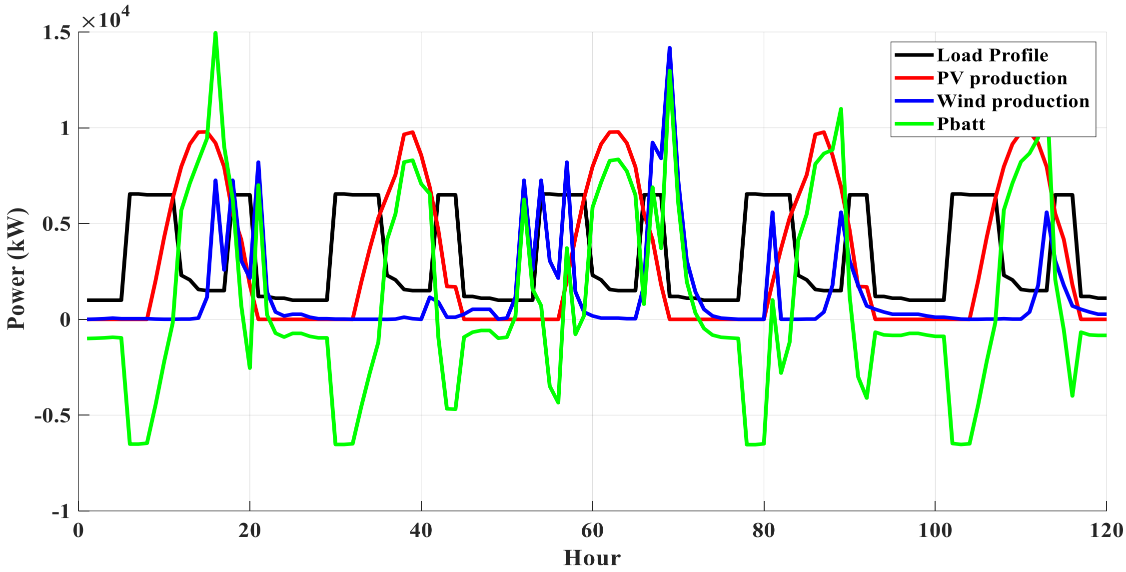

Figure 7. Power flow in the microgrid

In Figure 8, the comparison between total production and load demand is presented. It becomes evident that the microgrid exhibits notable instances of power surplus and shortage over time. Our algorithm, incorporating particle swarm optimization (PSO), is designed to address and optimize this issue. The outcomes of this optimization process are illustrated in Figure 9, revealing how the algorithm effectively mitigates the power surplus and shortage problems. Figure 10 illustrates the success of particle swarm optimization (PSO) in optimizing power production within a microgrid, particularly in managing battery performance. Before optimization, instances of power production surpassing demand led to the battery, reaching high power levels 14 kW. However, after optimization, this excess power was effectively reduced, resulting in the battery operating at a more efficient 8 kW. These results can benefit the battery in several ways. Firstly, the optimization process ensures that the battery operates within a more controlled and efficient range of power, specifically reduced from 14 to 8 kW. This optimization helps prevent extreme charging and discharging cycles, which can contribute to a longer lifespan for the battery. Secondly, by avoiding excessive power levels that exceed demand, the battery is subjected to less stress and strain. Figure 11 summarizes the comparison between the total production with the power battery before and after optimization.

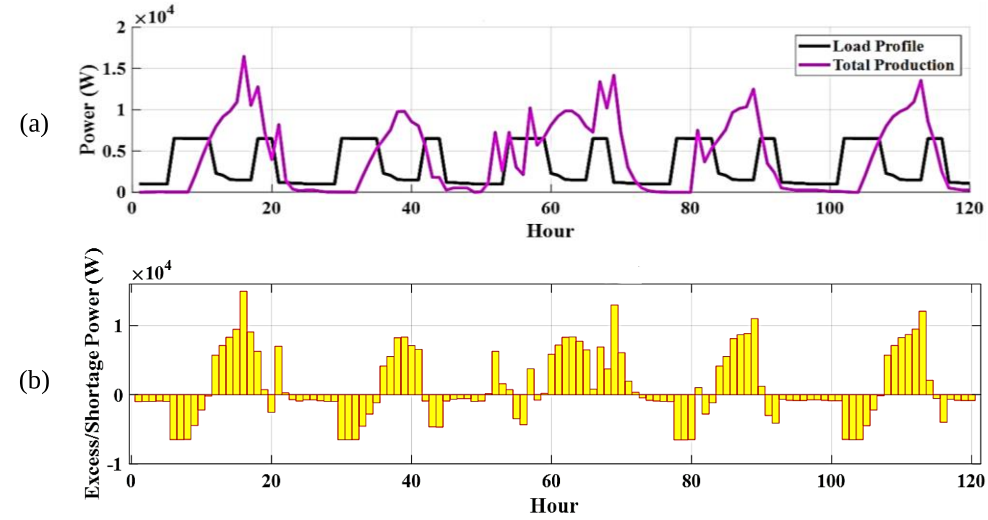

Figure 8. Total production: (a) and the excess/shortage power and (b) before optimization

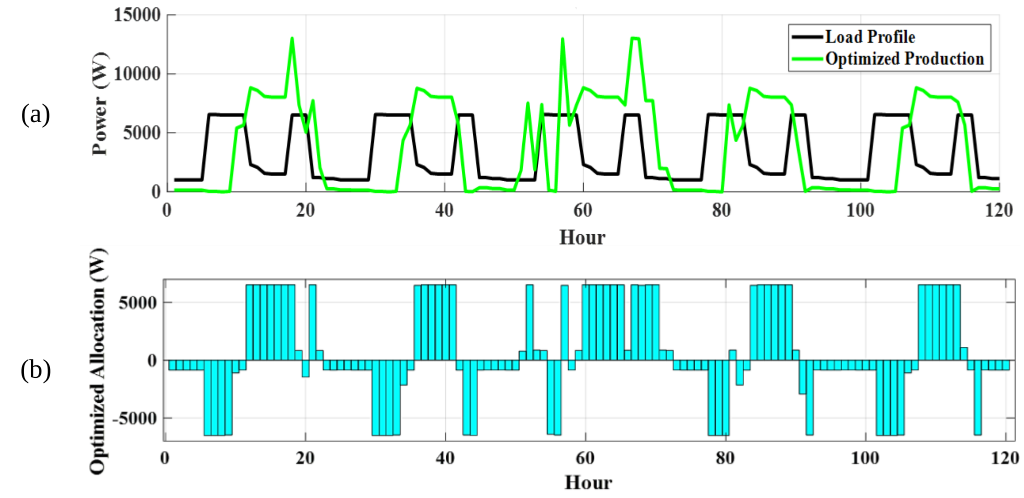

Figure 9. Total production: (a) and the excess/shortage power and (b) after optimization

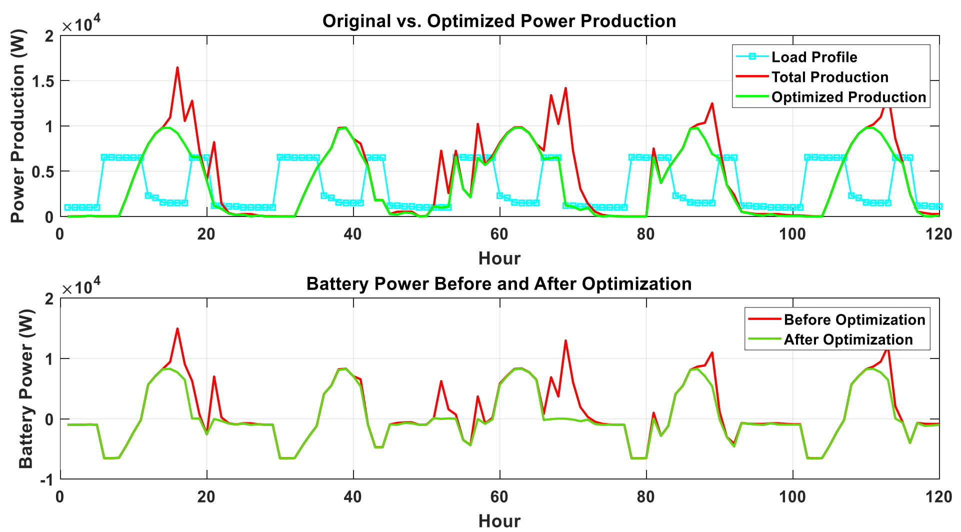

Figure 10. Total production and battery power before and after optimization

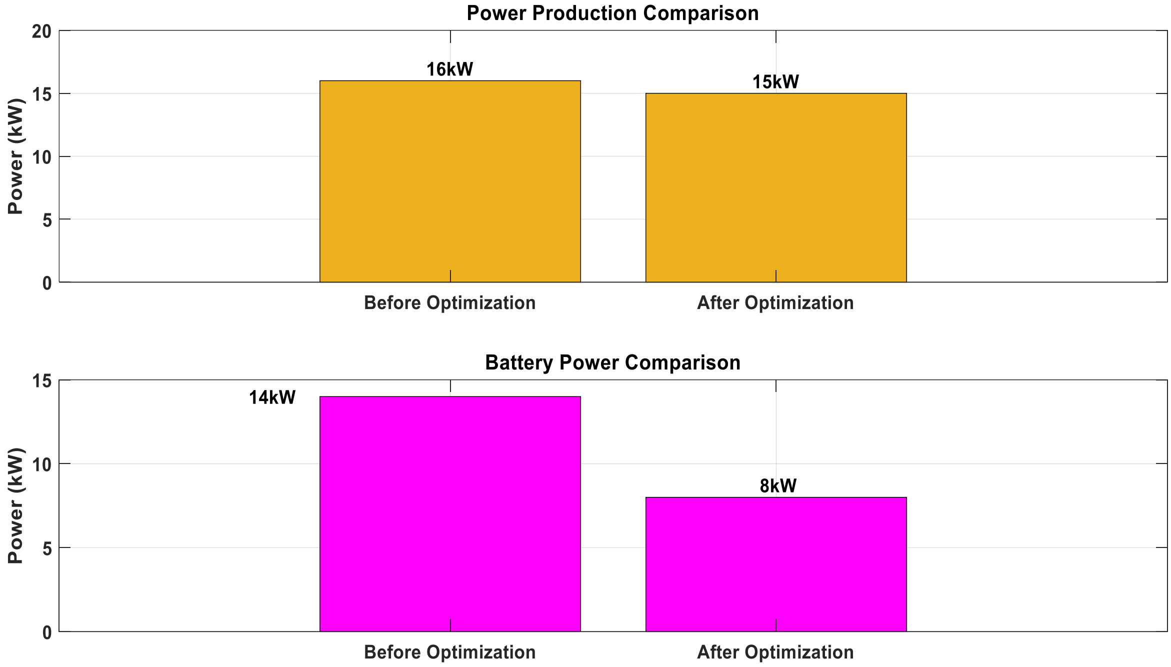

Figure 11. Summary of comparison before and after optimization

4. CONCLUSION

In conclusion, this study demonstrates the effectiveness of particle swarm optimization (PSO) in enhancing our microgrid system. Prior to optimization, power generation from solar panels and wind turbines exhibited significant fluctuations, resulting in inefficiencies and a combined 35% wastage and shortage of total power generated. The application of the PSO algorithm substantially improved the system by aligning power generation more closely with actual electricity demand. Post-optimization, the power range was reduced to 13-15 kilowatts, reducing inefficiencies to around 10% of the total power generated. Moreover, the optimization positively impacted the battery's lifespan by preventing extreme charging and discharging cycles, contributing to the overall sustainability of the energy system. The paper's contribution lies in successfully addressing power imbalance challenges, enhancing efficiency, and promoting sustainable energy use. However, there are some limitations to this work that can be addressed in future research. The study focuses solely on the PSO algorithm, potentially overlooking other optimization techniques that could yield better or more robust results in different scenarios. The effectiveness of the PSO algorithm was evaluated based on specific data sets for solar and wind power generation, and its performance may vary with different data inputs or under different environmental conditions. Overall, this study gives a strong starting point for improving microgrid optimization, providing useful insights and paving the way for future advancements in energy management and sustainability.

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