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A Novel Hybrid Imperialist Competitive Algorithm–Particle Swarm Optimization Metaheuristic Optimization Algorithm for Cost-Effective Energy Management in Multi-Source Residential Microgrids

Ssadik Charadi [1,2,*], Houssam Eddine Chakir [3], Abdelbari Redouane [4], Abdennebi El Hasnaoui [4] and Brahim El Bhiri [2]

[1] Electronics Power and Control Team, Mohammadia School of Engineers (EMI), Mohammed V University, Rabat 10000, Morocco
[2] SMARTiLab, Moroccan School of Engineering Sciences (EMSI), Rabat 10000, Morocco
[3] EEIS-Lab, ENSET Mohammedia, Hassan II University, Casablanca 20000, Morocco
[4] Electromechanical Department, Ecole des Mines de Rabat (ENSMR), Rabat 10000, Morocco
* Correspondence: charadi.ssadik@gmail.com

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Abstract: The integration of renewable sources and energy storage in residential microgrids offers energy efficiency and emission reduction potential. Effective energy management is vital for optimizing resources and lowering costs. In this paper, we propose a novel approach, combining the imperialist competitive algorithm (ICA) with particle swarm optimization (PSO) as ICA-PSO to enhance energy management. The proposed energy management system operates in an offline mode, anticipating data for the upcoming 24 h, including consumption predictions, tariff rates, and meteorological data. This anticipatory approach facilitates optimal power distribution among the various connected sources within the microgrid. The performance of the proposed hybrid ICA-PSO algorithm is evaluated by comparing it with three selected benchmark algorithms, namely the genetic algorithm (GA), ICA, and PSO. This comparison aims to assess the effectiveness of the ICA-PSO algorithm in optimizing energy management in multi-source residential microgrids. The simulation results, obtained using Matlab 2023a, provide clear evidence of the effectiveness of the hybrid ICA-PSO algorithm in achieving optimal power flows and delivering substantial cost savings. The hybrid algorithm outperforms the benchmark algorithms with cost reductions of 4.47%, 14.93%, and 26% compared to ICA, PSO, and GA, respectively. Furthermore, it achieves a remarkable participation rate of 50.6% for renewable resources in the energy mix, surpassing the participation levels of the ICA (42.88%), PSO (40.51%), and GA (38.95%). This research contributes to the advancement of power flow management techniques in the context of multi-source residential microgrids, paving the way for further research and development in this field.

Keywords: imperialist competitive algorithm; particle swarm optimization; photovoltaic; wind turbine; energy flow management; microgrids; residential applications; cost-effectiveness

1. Introduction

1.1. Problem Statement and Motivation

The increasing global demand for clean and sustainable energy solutions has led to the rapid development of residential microgrids (MGs) [1]. These localized power systems integrate renewable energy sources (RESs), energy storage systems (ESSs), and grid connectivity to provide reliable and efficient electricity supply to residential communities [2]. The management of power flows in such MGs is critical to ensuring optimal utilization of available resources, minimizing operating costs, and enhancing system reliability [3].

In recent years, optimization techniques have emerged as effective tools for power flow management in MGs [4]. These techniques aim to find the best operating conditions that balance the generation, consumption, and storage of electricity within the MG [4]. Among various optimization methods, both the ICA and PSO have shown great potential in efficiently exploring the solution space and converging towards near-optimal solutions [4–6]. The ICA is known for its ability to effectively explore diverse solution spaces and find globally optimal solutions, while the PSO algorithm excels at exploiting local search capabilities and converging towards near-optimal solutions.

Shaheen et al. [7] proposed the gorilla troops optimization technique (GTOT) for multi-objective optimal power flow in electric power systems (EPSs). The GTOT emulates gorilla group behaviors, achieving efficient solutions for cost, losses, and pollutants optimization. Evaluation on standard and practical EPSs demonstrated the GTOT's effectiveness. Xu et al. [8] suggested a hierarchical energy management system for multi-source multi-product microgrids, combining traditional scheduling with a hierarchical control structure. This system efficiently manages thermal, gas, and electrical systems on different time scales, enhancing microgrid operation and interactions among energy sources. Roy et al. [9] introduced the RFCRO hybrid algorithm, combining random forest and coral reefs optimization, to optimize energy flow management in grid-connected microgrids. The algorithm targeted cost reductions by optimizing multiple fitness functions simultaneously, showcasing the potential of hybrid techniques for efficient microgrid power flow management. Moradi et al. [10] developed an optimization technique for photovoltaic–wind hybrid systems with battery storage in microgrids. Their approach aimed to enhance energy efficiency, minimize costs, and reduce environmental impact by employing predictive data and multi-objective optimization, including a demand response program. Abdelkafi et al. [11] proposed an assisted management strategy for a standalone multi-source power system, including wind and photovoltaic generators, a super-capacitor, and a diesel generator. The strategy aimed to optimize power flow, increase reliability, and protect the energy storage system's longevity. Simulation results confirmed its effectiveness in achieving efficient energy production and consumption balance.

On the other hand, Chen et al. [12] proposed a hybrid ICA-PSO algorithm for solving the complex multi-area economic dispatch problem. This approach combines the advantages of the ICA and PSO. The algorithm was effective in optimizing power system economic load dispatch, especially in large-scale scenarios, surpassing recent methods. Ghodrati et al. [13] combined the ICA and PSO for global optimization. The hybrid approach introduces an 'Independent' country type to enhance collaboration and uses swarm intelligence from PSO. The method's performance is evaluated against benchmark functions and compared with standard PSO and ICA algorithms. Idoumghar et al. [14] proposed a hybrid ICA–PSO algorithm for mono-objective and multi-objective problems. It combines the ICA and PSO, enhancing exploration, maintaining diversity, and improving solutions. The algorithm outperforms benchmark functions in optimizing different problems.

Moreover, several studies have focused on various aspects of energy flow management in multi-source MGs [15–17]. One common approach is the use of metaheuristic optimization techniques to achieve efficient power flow allocation and resource utilization. These techniques include GAs [18–21], PSO [22–24], and the ICA [5,25–28]. They aim to optimize the allocation of power generation, storage, and consumption within the MG, considering factors such as demand fluctuations, RES availability, and storage capacity.

Furthermore, researchers have investigated the integration of RESs, such as photovoltaic (PV) and wind turbine systems (WTS) into residential MGs [29–31]. PV and WTS have gained significant attention due to their environmentally friendly nature and potential for reducing dependency on the main power grid. Studies have explored strategies for maximizing PV and WTS energy utilization, minimizing grid dependency, and managing the intermittency of RESs through storage systems [32,33]. Recent studies on energy management in MGs, employing a variety of metaheuristic methods, are summarized in Table 1.

Table 1. Recent research on metaheuristic methods for energy management in MGs.

Authors	Reference	Year	Approach	Objectives
Dong et al.	[34]	2019	CHP	Reduce the system operation costs and the CO_2 emissions cost, improve system flexibility
Noreña et al.	[35]	2019	PSO-SA	Reduce the cost of the energy purchased to the utility grid
Adel et al.	[36]	2020	MOPSO	Reliability, cost of energy, and GHG reduction
Kaveh et al.	[5]	2020	ICHHO	Improve efficiency, and robustness
Hemant et al.	[37]	2020	GA	Improve energy consumption
Singh et al.	[38]	2020	ABC-PSO	Minimize the levelized cost of electricity
Cristian et al.	[39]	2021	PSO	Meet the energy demand in a MG
Ming et al.	[40]	2021	ICA	Minimize makespan, total tardiness, and total energy consumption
Abaeifar et al.	[41]	2022	IWLS-TLBO	Reduce the overall costs of the system
Güven et al.	[42]	2022	HFGA	Minimize the annual system costs and meet the energy demand reliably
Dey et al.	[43]	2022	WOA-SCA	Minimize the generation cost
Vignesh et al.	[44]	2023	GA	Reduce the grid purchase cost and battery degradation cost

Our algorithm introduces a novel hybrid ICA-PSO approach for offline energy flow management in multi-source microgrids, drawing inspiration from the latest developments in the field. The novelty of our choice lies in its uncharted potential within this specific context. Our distinctive formulation takes on the intricacies posed by diverse energy sources, consumption patterns, and tariff rates. Concentrating on the offline mode, we tackle real-world energy management complexities with a focus on predictive planning. Notably, our algorithm delivers swift execution times, a benefit facilitated by the synergy of hybridization.

1.2. Contributions

This paper presents a comprehensive study on the optimization of power flow management in residential MGs using the hybrid ICA-PSO algorithm.

The main contributions of this article can be summarized as follows:

- The proposal of a novel hybrid metaheuristic algorithm, named ICA-PSO, for optimizing microgrid energy management, which combines the exploration capabilities of the ICA with the exploitation capabilities of PSO.
- Development of a comprehensive model that considers the balance between energy demand and generation, as well as the constraints associated with power generation and ESS units.
- A showcase of the system's ability to effectively manage and maintain the ESS's state of charge (SOC).
- A comparison of the participation of renewable energies in the total energy generation within the MG using benchmark algorithms.
- The investigation of the ICA-PSO algorithm's performance in minimizing overall cost, and its performance compared with benchmark algorithms.

1.3. Article Organization

To support our research, we conduct a review of the existing literature on metaheuristic-based optimization techniques for power flow management in MGs. The literature review provides valuable insights into the current state of the art, identifies research gaps, and establishes the significance of our proposed approach.

The remaining sections of this paper are structured as follows: Section 2 provides a comprehensive overview of the materials and methods utilized in this research, including a detailed description of the MG components and the optimization methodology employed. In Section 3, we present the simulation results and conduct a thorough performance analysis, comparing the performance of the ICA-PSO hybrid algorithm with benchmark methods and showcasing the achieved cost savings. Section 4 offers a concise discussion of the simulation findings. Finally, Section 5 concludes the paper by summarizing the key contributions of this study and underscoring the significance of our proposed approach.

2. Materials and Methods

2.1. Description of MG Components

In this section, we will delve into the various components of the microgrid (MG) that collaboratively ensure a smooth and dependable power supply. The PV system harnesses sunlight to generate electrical energy, serving as a RES. The MG also incorporates a WTS to harness wind energy, and an ESS is employed to store excess energy and balance power supply and demand within the MG. Loads represent the electrical devices and appliances that consume power, such as residential appliances and lighting systems. The MG is connected to the main power grid, enabling the import or export of electricity and ensuring a dependable power supply. Power conversion and control devices, including AC/DC converters, facilitate efficient power transfer and control between different components. A control and monitoring system oversees the MG's operation, optimizing power flow and ensuring system performance. Together, these components enable the MG to effectively generate, store, and distribute electrical energy, contributing to a sustainable and reliable power infrastructure.

Figure 1 illustrates the configuration and interconnection of the MG components mentioned above, showcasing how they work together to enable efficient and reliable power supply.

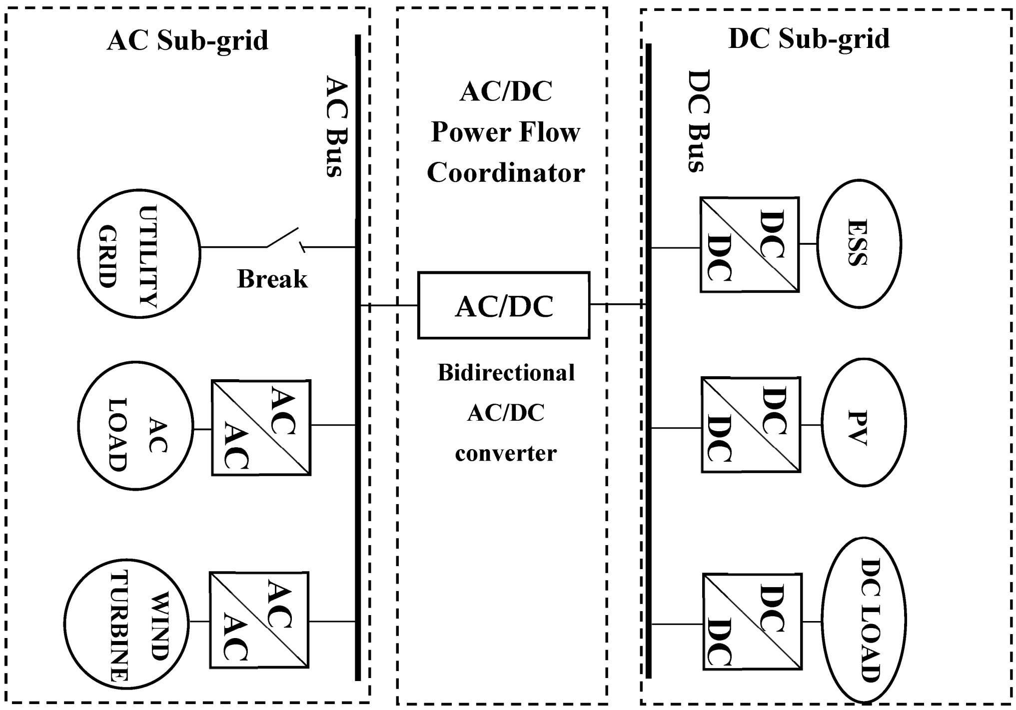

Figure 1. Proposed multi-source residential MGs.

2.2. Formulation of the Energy Flow Optimization Problem

2.2.1. Objective Function

The objective function aims to minimize the operating costs while ensuring reliable and efficient energy flow. It typically considers factors such as the cost of grid electricity and the ESS State of health (SOH) variation. The objective function may also incorporate environmental factors, such as carbon emissions, to promote sustainability. Equation (1) represents the objective function, which captures the optimization criteria for the energy flow management in a MG. Nomenclature provides the abbreviations used in this equation.

$$Min\ f(X) = \sum_{0.33h}^{24h} C_{ESS}\Delta SOH + C_{Grid}P_{Grid} + C_{\ CO_2} \tag{1}$$

2.2.2. Power Balance Equation

The power balance equation ensures that the total power generated is equal to the total power consumed by the loads and stored in the ESS. Equation (2) represents the balance equation, which ensures the equilibrium between power generation, power consumption, and ESS within the MG. By satisfying this equation, the MG operates in a stable and self-sustaining manner, ensuring that the power supply matches the power demand at all times. The abbreviations used in the equation are defined in Nomenclature.

$$P_{PV}(t) + P_{WTS}(t) + P_{Grid}(t) = P_{Load}(t) + P_{ESS}(t) \tag{2}$$

2.2.3. Power Generation Limits

The power generation limits are addressed through several equations in this section. Equation (3) outlines the restrictions for the main power grid, encompassing both its upper and lower power output bounds. Additionally, Equation (4) imposes constraints on the PV system, defining its maximum power generation capacity with consideration for factors such as solar intensity and system efficiency. Equation (5) further establishes limitations for the WTS, incorporating factors like wind speed and turbine specifications to determine the maximum attainable power output from the wind resource. The abbreviations employed in these equations are detailed in Nomenclature for reference.

$$P_{Grid\_min}(t) \leq P_{Grid}(t) \leq P_{Grid\_max}(t) \tag{3}$$

$$0 \leq P_{PV} \leq P_{PVmax} \tag{4}$$

$$0 \leq P_{WT} \leq P_{WTmax} \tag{5}$$

2.2.4. ESS Constraints

Given their role as storage entities, batteries are governed by specific constraints related to charging, discharging, and ESS capacity. Equation (6) delineates the range within which the SOC of the ESS must be maintained within the multi-source MG. Equation (7) further enforces limitations on the rate of SOC change, preventing abrupt variations. Moreover, Equation (8) safeguards the ESS's overall well-being and operational effectiveness over time. The abbreviations utilized in these equations are elaborated in Nomenclature for clarity.

$$SoC_{min} \leq SoC(k) \leq SoC_{max} \tag{6}$$

$$\Delta SoC_{min} \leq \Delta SoC(k) \leq \Delta SoC_{max} \tag{7}$$

$$SoH(k) \geq SoH_{min} \tag{8}$$

2.3. *A Hybrid ICA-PSO Optimization Algorithm*

2.3.1. Hybrid ICA-PSO Approach: Formulation

The optimization algorithm employed in this study is a hybrid approach combining the ICA and the PSO, referred to as ICA-PSO. The hybrid ICA-PSO algorithm is utilized to optimize the power flows in residential MGs, aiming to minimize operating costs and enhance system performance.

Figure 2a presents a flowchart illustrating the classic ICA algorithm, depicting the sequential steps involved in the algorithm. Figure 2b shows a flowchart specifically designed for the proposed hybrid ICA-PSO algorithm. This flowchart represents the modified steps and the integration of the PSO technique within the ICA framework.

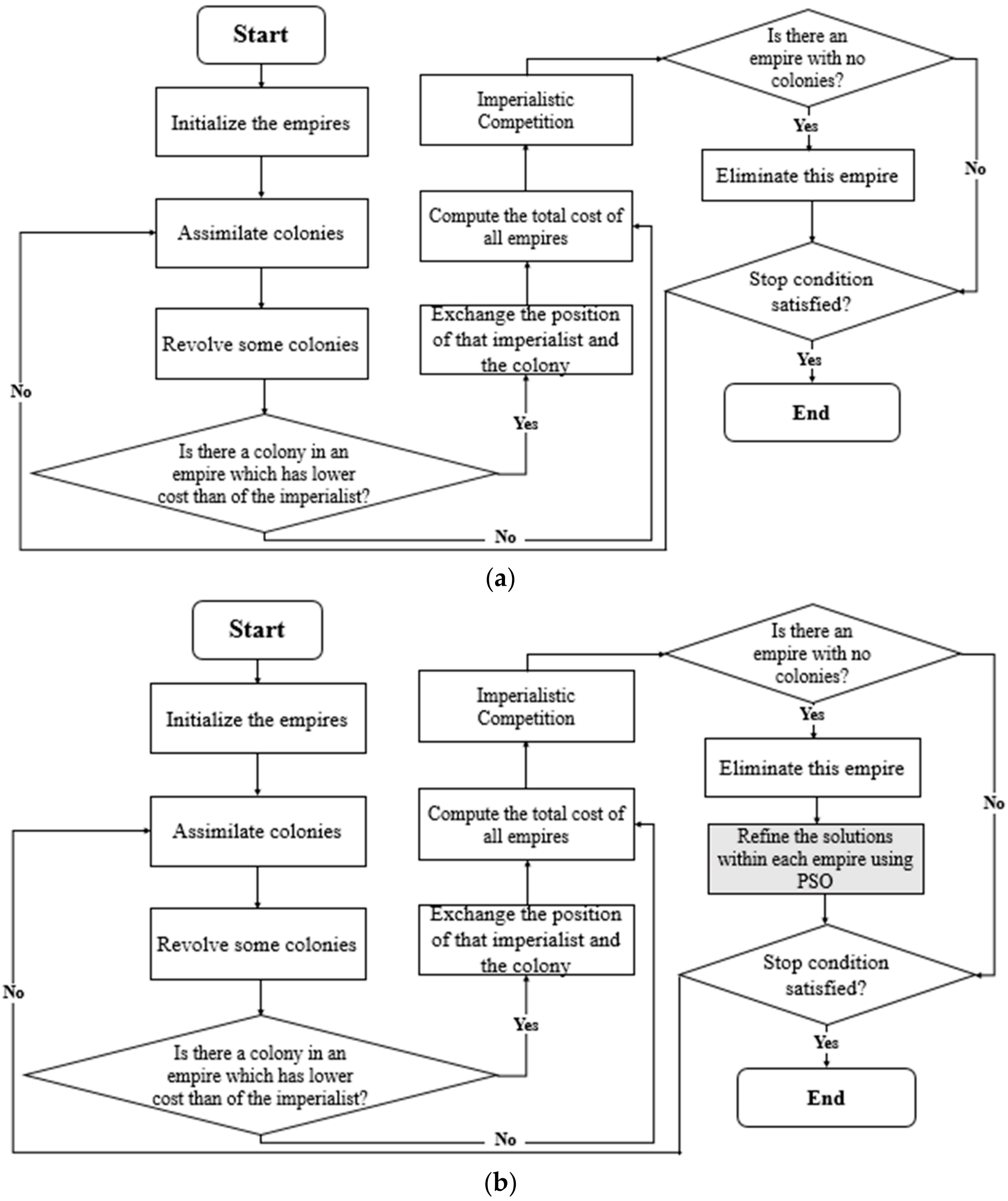

Figure 2. (**a**): Flowchart of classic ICA algorithm. (**b**): Flowchart of proposed hybrid ICA-PSO algorithm.

The main steps of the proposed hybrid algorithm include:

Step 1: Initialization step, where random solutions are generated within the search space. These solutions represent the initial empires in the algorithm.

Step 2: Assimilation phase, where colonies move towards imperialist states in different directions. This step allows for the exploration of the solution space and the identification of potential optimal solutions. Figure 3a visually illustrates the formation of initial empires in the hybrid ICA-PSO algorithm. It showcases the distribution of colonies around the respective imperialists, highlighting the initial configuration of the algorithm.

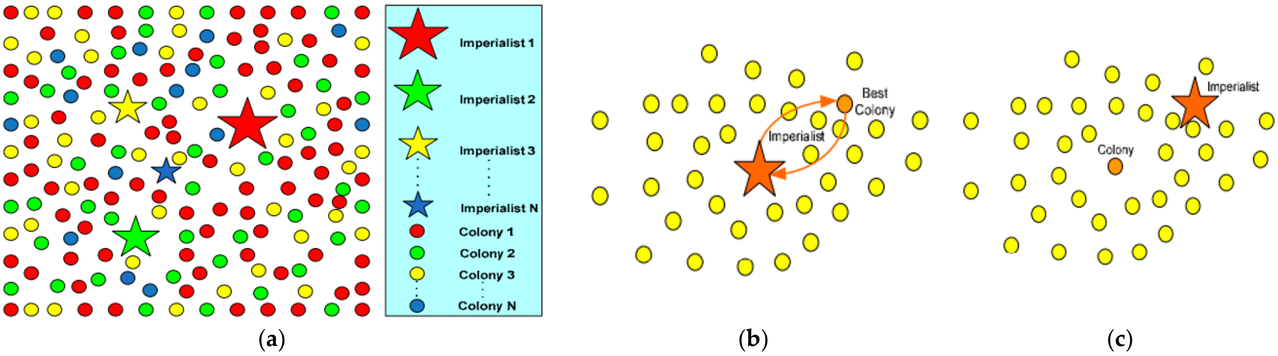

Figure 3. Dynamics of empires: initial composition, position exchange, and post-position-exchange state [45]. (**a**) Formation of initial empires. (**b**) Position exchange: empires and colonies switching roles. (**c**) Resulting configuration: post-position-exchange state.

Step 3: The revolution phase takes place, introducing random changes in the characteristics of some countries within the empires. This step adds diversity to the search process and helps in escaping local optima. Figure 3b demonstrates the exchange of positions between colonies and imperialists. It illustrates the process where a colony with a superior position replaces the existing imperialist, aiming to improve the overall solution quality.

Step 4: The algorithm incorporates imperialistic competition, where all imperialists compete to possess colonies from each other. This competition enhances the exploration and exploitation of the solution space, leading to improved optimization results. Figure 3c showcases the positions of empires and colonies after the exchange, demonstrating the impact of competition on the distribution of solutions.

Step 5: To refine the solutions and enhance their accuracy, the hybrid ICA-PSO algorithm incorporates a local search technique using PSO. This technique allows for the fine-tuning of solutions within each empire, improving the convergence towards optimal solutions.

Step 6: The hybrid ICA-PSO algorithm iteratively repeats these steps until a stopping condition is met, such as reaching a maximum number of iterations or achieving a desired level of convergence. At the end of the algorithm, the optimal power flows that minimize operating costs and enhance system performance are obtained.

The rationale for adopting the hybrid ICA-PSO algorithm in microgrid optimization lies in its ability to navigate the intricacies of multi-source energy systems. By capitalizing on the global exploration strengths of the ICA and the local optimization proficiency of PSO, the algorithm tackles challenges associated with efficient power distribution, resource utilization, and cost-effectiveness within microgrids.

2.3.2. Hybrid ICA-PSO Approach: Advantages

In our study, we have chosen a hybrid ICA-PSO approach to solve the power flow optimization problem. Unlike existing methods, the ICA-PSO algorithm has a special advantage: it can handle various types of objective functions and constraints, whether they are linear or not, differential or not, convex or concave, and so on. Additionally, it does not require a specific math solver from the start.

How well this approach works depends on how we choose the "discretization step". Smaller steps lead to higher-quality optimal solutions, but they also need more computing power and memory. It is like finding the balance between obtaining the best results and using more resources. Even though choosing the right step can be tricky sometimes, the ICA-PSO method remains superior here because we are not trying to perform the optimization in real time; we are planning the best solution for day N based on what happened on the previous day, N − 1.

3. Simulation Results

3.1. Simulation Setup

The performance evaluation of the proposed hybrid ICA-PSO-based power flow optimization approach was conducted through simulations using a Dell OptiPlex 7070 Workstation. The workstation was equipped with 16 GB of RAM memory and an Intel(R) Core (TM) i7-9700 CPU, operating at 3 GHz. The simulations were carried out in MATLAB 2023a, utilizing a time step of 20 min, which corresponds to 72 samples per day. This rigorous evaluation aimed to assess the algorithm's effectiveness in optimizing energy utilization and load management in residential MGs. It is important to note that the PV and WTS cost was considered as zero or free of charge.

Regarding the assumption of zero cost for PV and WTS sources, it is important to note that this simplification was initially made to streamline the analysis and prioritize the optimization process itself. However, the assumption's potential impact on the results should be acknowledged. While this assumption facilitates the focus on optimization of outcomes, we recognize that in real-world scenarios, actual costs associated with PV and WTS sources significantly influence the economic feasibility of the proposed solutions. Therefore, in future research, the consideration of realistic costs for these sources will be crucial to provide a more accurate depiction of the cost-effectiveness of the optimization results.

The results obtained from the simulations are thoroughly discussed, providing valuable insights into the performance and practical applicability of the hybrid ICA-PSO-based system.

Table 2 provides an overview of the control parameters employed in the simulation for the hybrid ICA-PSO and benchmark optimization algorithms.

Table 2. Control parameters used in different algorithms.

Parameters	PSO	GA	ICA	ICA-PSO
Population size	100	100	100	100
Imperialist number	-	-	10	-
Dimension of the problem	6	6	6	6
Maximum number of iterations	2000	2000	2000	2000
Inertia weight	0.5	-	-	0.5
Cognitive coefficient	1	-	-	1
Weighting factor	2	-	-	-
Social coefficient	1	-	-	1
Revolution rate	-	-	0.1	0.1
Assimilation coefficient	-	-	0.5	0.5
Crossover rate	-	0.5	-	-

3.2. Simulation Results and Analysis

3.2.1. Simulation Results

In the simulation, the load profile considered is representative of a residence with 100 apartments in France [46]. Figure 4 presents the load profile of the considered neighborhood, showcasing the daily variation in electricity consumption. The load profile represents the pattern of electricity demand throughout a typical day, capturing the peak and off-peak periods of usage.

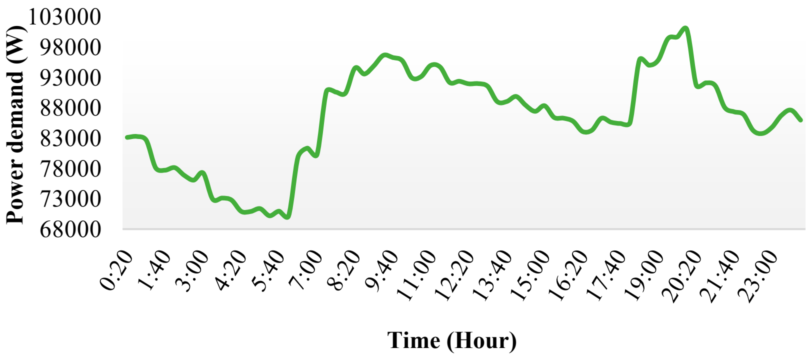

Figure 4. Daily active demand load.

The simulation results presented in this study provide valuable insights into the performance of our hybrid ICA-PSO algorithm in a multi-source MG system. Figure 5 illustrates the active power balance of the MG, showcasing the effectiveness of our ICA-PSO-based algorithm in ensuring a stable and optimized power distribution among the various sources. To evaluate the overall performance of our algorithm, Figure 6 compares the daily SOC of the MG system using our hybrid ICA-PSO algorithm and comparing with benchmark algorithms. The results demonstrate the superior performance of our algorithm, as it achieves higher and more consistent SOC levels throughout the day. Figure 7 provides a comprehensive comparison of the daily cost evolution between our hybrid ICA-PSO-based algorithm and benchmark algorithms. The results clearly indicate the cost-saving potential of our algorithm, as it consistently outperforms the benchmark algorithms in achieving cost reductions. Table 3 presents the daily energy participation of each MG element using our hybrid ICA-PSO algorithm. It showcases the contributions of different elements to the overall energy mix and highlights the efficient utilization of available resources facilitated by our algorithm. For a broader perspective on the energy mix, Figure 8 compares the energy source contributions of different algorithms. Our hybrid ICA-PSO algorithm demonstrates its capability to significantly increase the participation of renewable resources in the energy mix, surpassing the performance of benchmark algorithms.

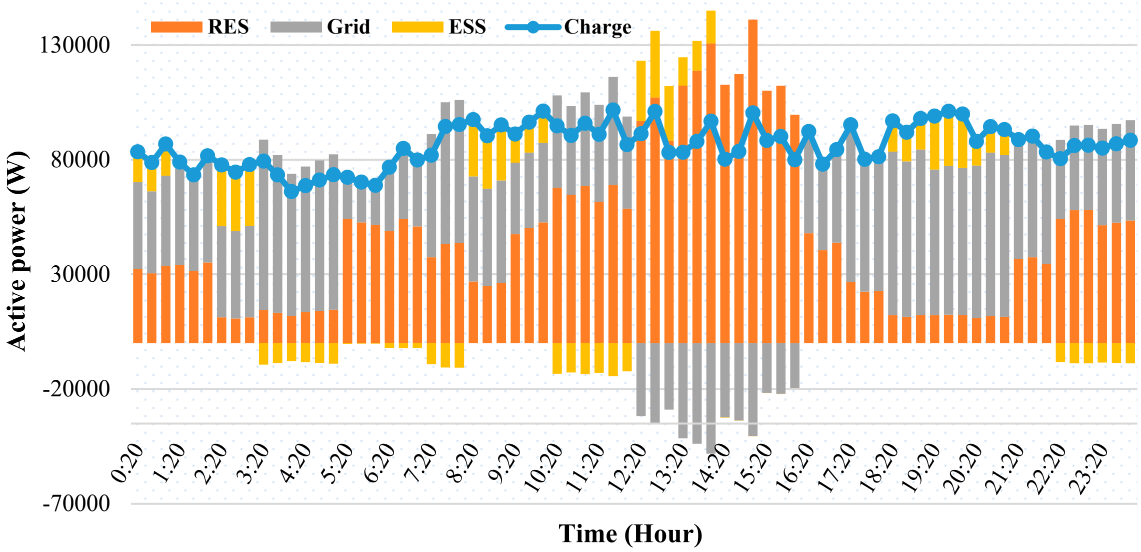

Figure 5. Active power balance of multi-source MG with ICA-PSO-based algorithm.

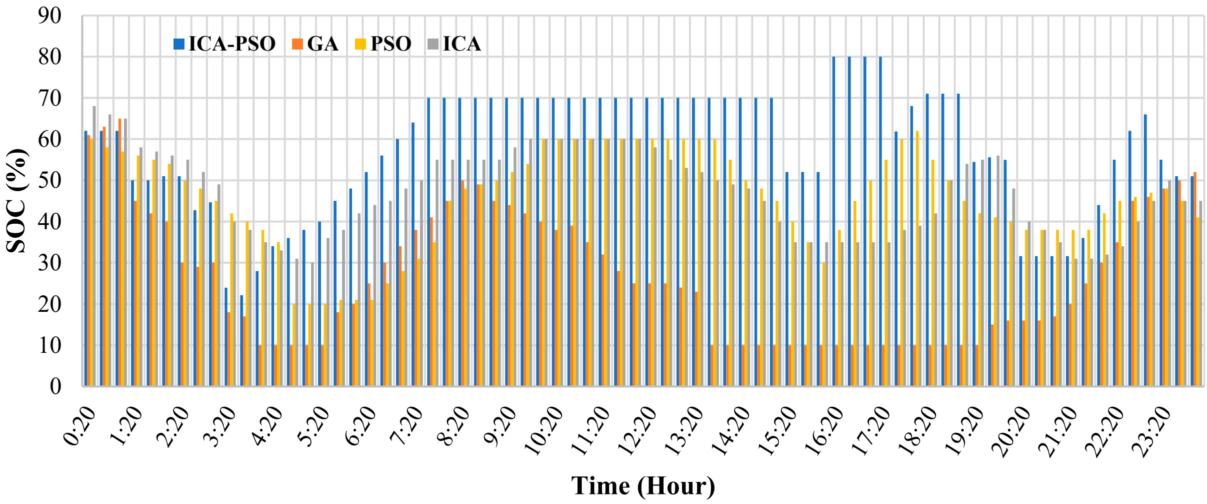

Figure 6. Comparison of daily SOC between hybrid ICA-PSO-based algorithm and benchmark algorithms.

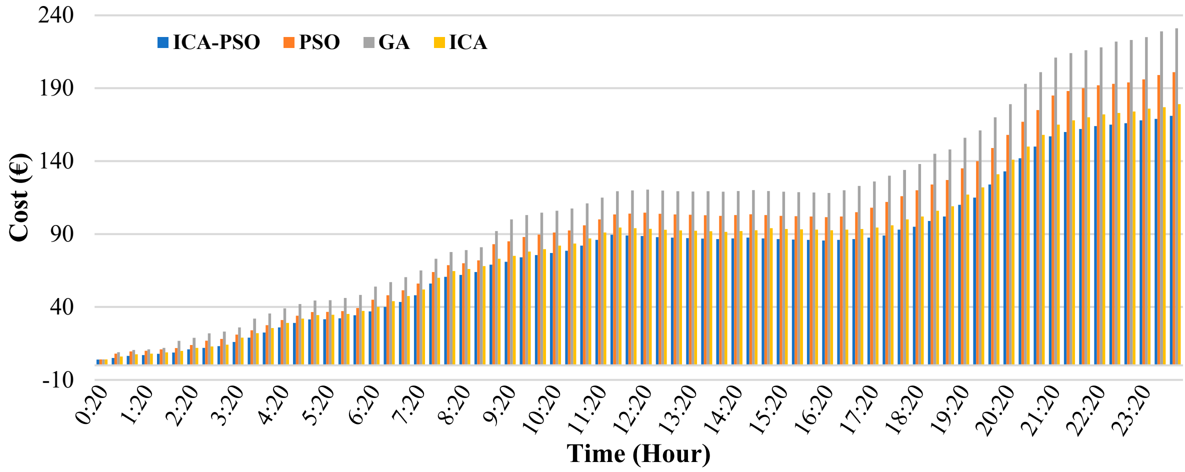

Figure 7. Comparison of daily cost evolution between hybrid ICA-PSO-based algorithm and benchmark algorithms.

Table 3. The daily energy (kWh) participation of each MG element using hybrid ICA-PSO algorithm.

Hour	RES		ESS	Grid	Hour	RES		ESS	Grid
	PV	WTS				PV	WTS		
1	0	32.1	13.2	37.7	13	87.2	10.2	26.4	−31.98
2	0	33.6	0	44.38	14	91.2	29.4	13.2	−44.5
3	0	11.1	26.4	39.22	15	88	35.7	−0.14	−35.51
4	0	13.2	−8.62	68.37	16	82.4	24.9	−0.06	−21.08
5	0	14.1	−8.62	65.59	17	33.6	10.5	0	40.8
6	0	52.8	−0.24	17.88	18	24	0	0	61.53
7	0	51.3	−2.12	31.32	19	12	0	13.2	70.4
8	0	41.4	−10.15	59.32	20	0	12.3	23.5	64.18
9	12.8	13.2	24	44.34	21	0	11.4	10.97	69.46
10	28.8	21.3	13.2	32.93	22	0	36.3	0	51.12
11	42.4	24.6	−13.2	39.91	23	0	56.7	−8.62	36.2
12	54.4	8.7	−13.2	43.18	24	0	52.5	−8.62	42.91

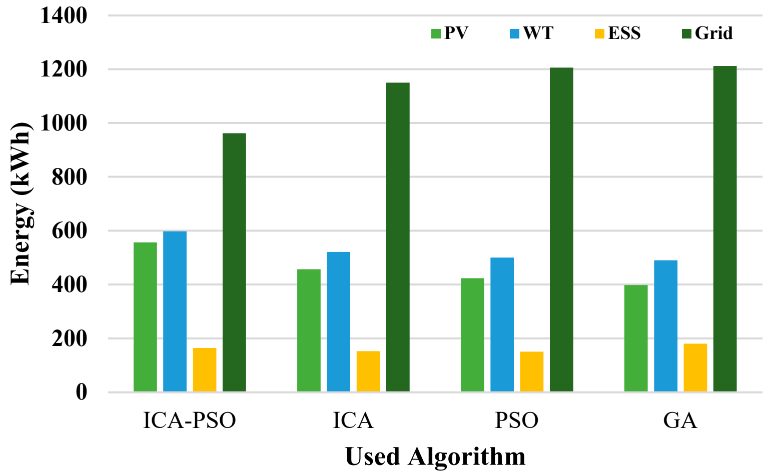

Figure 8. Comparison of energy source contributions in the energy mix for different algorithms.

These simulation results provide empirical evidence of the effectiveness and superiority of our hybrid ICA-PSO algorithm in achieving optimal power balance, cost reductions, and enhanced utilization of renewable resources within the MG system.

3.2.2. Statistical Analysis of Numerical Results

We assess the performance of our hybrid algorithm through the utilization of four widely recognized benchmark functions. Subsequently, we conduct a comparative analysis between the outcomes generated by our algorithm and those derived from the benchmark methods (PSO, ICA, and GA).

An examination of the numerical results presented in Table 4 reveals the following findings:

Table 4. Statistical analysis to compare different algorithms.

Test Function	GA	PSO	ICA	ICA-PSO
f_1 : Sphere [47]	1.5167×10^{-19}	0.81904×10^{-8}	7.87423×10^{-3}	2.1556×10^{-27}
f_2 :Michalewicz [48]	−7.0378	−7.0377	−7.03778	−7.03756
f_3 :Ackley [47]	3.8703	1.9476	2.164×10^{-2}	8.9834×10^{-14}
f_4 : Rastrigin [47]	5.772	3.324	0.905	1.5069×10^{-7}

- All three algorithms effectively address the f_1 problem, with our algorithm achieving the most optimal solutions.
- The f_2 problem is accurately solved by all algorithms, although the ICA-PSO hybrid algorithm exhibits a slightly superior performance compared to the other algorithms.
- In the case of highly multimodal functions such as Ackley's and Rastrigin's, the ICA-PSO hybrid algorithm demonstrates a clear superiority over the other algorithms.

4. Discussion

4.1. Power Balance

Figure 5 depicts the balance of active power within the residential MG, showcasing the close alignment between power generation and demand. The plot clearly demonstrates that the generated power effectively meets the system's active power requirements, ensuring a balanced and reliable operation. This observation underscores the successful management and control of power flow within the MG, where power generation is carefully coordinated to meet consumption needs. The results presented in Figure 5 validate the efficient regulation of active power supply, thereby maintaining a stable and sustainable energy supply within the MG.

4.2. Improved SOC

Figure 6 illustrates a comparison of the SOC of the ESS between the hybrid ICA-PSO algorithm and the benchmark algorithms. The results clearly demonstrate that the hybrid ICA-PSO algorithm outperforms the other algorithms in terms of adaptability and efficiency in maintaining the SOC of the ESS. By effectively utilizing a wider range of the storage system's capacity, the hybrid ICA-PSO algorithm ensures optimal energy management and facilitates the efficient integration of RESs into the overall power system. These findings highlight the superior performance of the hybrid ICA-PSO algorithm in effectively utilizing and managing the ESS, leading to enhanced system performance and reliability.

The adaptability of the hybrid ICA-PSO algorithm enables it to dynamically adjust the charging and discharging rates of the ESS based on the fluctuating energy generation and consumption patterns. This adaptability allows for efficient balancing of power supply and demand, minimizing energy wastage and maximizing the utilization of available resources.

Moreover, the hybrid ICA-PSO algorithm's efficient management of the ESS's SOC contributes to the overall stability and reliability of the MG. By maintaining the SOC within an optimal range, the algorithm ensures a steady power supply to meet the energy demands of the residential community.

4.3. Participation of RESs in the MG Energy Mix

The simulation results presented in Table 3 provide hourly energy contributions of each component in the MG over a day. The results show that when using our hybrid ICA-PSO algorithm, the participation of RESs in the energy mix reaches a significant level of 50.6%. This demonstrates the effectiveness of our algorithm in maximizing the utilization of available RESs within the MG.

To further evaluate the performance of our algorithm, Figure 8 provides a comparison between our approach and benchmark algorithms. The results clearly indicate the superiority of our algorithm, as the participation levels achieved with the ICA, PSO, and GA are only 42.88%, 40.51%, and 38.95%, respectively.

These findings emphasize the efficiency and positive impact of our hybrid ICA-PSO algorithm on integrating renewable resources into the MG's energy mix. They underscore the importance of algorithm selection in ensuring optimal participation of RESs, thereby promoting the sustainability and resilience of the MG.

These results reinforce the importance of leveraging RESs, such as PV and WTSs, in meeting the energy needs of residential communities. By maximizing the utilization of renewables and optimizing their integration into the MG, a more sustainable and cost-effective energy system can be achieved.

4.4. Cost Savings and Financial Benefits

The cost evolution demonstrated in Figure 7 illustrates the superior cost efficiency of the hybrid ICA-PSO algorithm compared to both the ICA and PSO. In terms of cost savings, the hybrid ICA-PSO algorithm achieves a remarkable 4.47% (2920 EUR/year) improvement over the ICA and a substantial 14.93% (10,950 EUR/year) improvement over PSO. Additionally, when compared to the GA algorithm, the hybrid ICA-PSO algorithm achieves an impressive cost reduction of 26% (21,900 EUR/year).

The findings highlight the significant advantage of the hybrid ICA-PSO algorithm in reducing costs in power generation systems. Its optimization capabilities in power generation and storage operations effectively balance power supply and demand, minimizing wastage and maximizing RES utilization. As a result, substantial cost reductions are achieved over time. Implementing the hybrid ICA-PSO algorithm offers significant financial benefits and improves economic viability in multi-source MGs.

Overall, these findings, summarized in Table 5, underscore the superiority of the hybrid ICA-PSO over the benchmark algorithms in terms of cost savings, adaptability, and energy efficiency. The ICA-PSO algorithm outperforms the benchmark algorithms, achieving significant reductions in operating costs and demonstrating higher adaptability in maintaining the SOC of the ESS. These advantages highlight the economic and sustainability benefits of implementing the ICA-PSO algorithm in residential MGs.

Table 5. Comparison of performance metrics between ICA and GA Algorithms.

Performance Metrics	ICA	PSO	GA	ICA-PSO
Daily Cost	EUR 179	EUR 201	EUR 231	EUR 171
SOC preservation	Moderate efficiency in maintaining SOC of ESS	Limited preservation of SOC	Low preservation of SOC	Higher efficiency in maintaining SOC of ESS
Energy mix participation	Provides a strong participation of RESs	Ensures a moderate participation of RESs	Shows a relatively low participation of RESs	Efficiently maximizes participation of RESs

4.5. Limitations and Challenges

While the results presented in the previous sections demonstrate the effectiveness of the hybrid ICA-PSO algorithm in addressing various aspects of energy management in multi-source residential microgrids, it is important to acknowledge certain limitations and challenges inherent to this approach.

4.5.1. Assumption of Perfect Forecasting

One of the underlying assumptions of the algorithm is the availability of accurate forecasts for energy generation, consumption, and weather conditions. However, real-world scenarios often involve uncertainties and variations that can impact the reliability of these forecasts. Imperfect forecasts might lead to suboptimal decisions, affecting the overall performance of the algorithm. Incorporating robust predictive models and strategies to handle uncertainty could enhance the algorithm's resilience in unpredictable situations.

4.5.2. Scalability and Complexity

The algorithm's complexity may increase as the scale of the microgrid and the number of integrated energy sources grow. This could potentially affect computational efficiency and optimization time, especially for larger systems. Addressing scalability challenges and optimizing computational efficiency will be crucial to ensure the algorithm's applicability to diverse microgrid scenarios.

4.5.3. Parameter Tuning

As with many optimization algorithms, the performance of the hybrid ICA-PSO algorithm can be influenced by the choice of algorithmic parameters. Finding the right combination of parameters for different microgrid configurations might require iterative experimentation. Automated parameter tuning techniques or sensitivity analysis can aid in optimizing the algorithm's performance for specific cases.

4.5.4. Generalization to Dynamic Scenarios

The current implementation of the hybrid ICA-PSO algorithm assumes an offline energy management mode, based on historical data and forecasts. Adapting the algorithm to dynamic real-time scenarios, where energy generation and consumption patterns fluctuate rapidly, could pose challenges. Developing strategies to handle dynamic scenarios and integrating real-time data could be avenues for further research.

5. Conclusions

In this paper, we have investigated the application of a hybrid ICA-PSO algorithm for optimizing energy flow management in a multi-source residential MG. The results demonstrated the superiority of the hybrid algorithm in achieving cost savings and enhancing the overall performance of the MG. By considering multiple energy sources, including PV panels, WTSs, and ESSs, the proposed hybrid ICA-PSO algorithm effectively balanced power generation, consumption, and storage, leading to efficient resource utilization and reduced operating costs.

The comparison with benchmark algorithms underscores the hybrid ICA-PSO algorithm's superiority, yielding notable cost reductions and significantly promoting the integration of renewable resources into the energy mix. Additionally, the algorithm enhances energy storage system state-of-charge management and overall energy efficiency.

However, it is important to acknowledge that no solution is without limitations. The complexities of real-world scenarios, varying weather conditions affecting renewable energy generation, and inherent uncertainties in demand forecasting might pose challenges to the algorithm's performance. While our current study emphasizes the algorithm's advantages, it is equally crucial to consider its limitations and potential challenges in practical applications.

Our findings contribute substantively to the domain of residential microgrid energy management. By showcasing the hybrid ICA-PSO algorithm's prowess in achieving economic viability and sustainability, this study imparts crucial insights into the design of intelligent and resilient energy systems. Looking ahead, avenues for further exploration encompass refining the algorithm to encompass factors like demand response mechanisms and real-time pricing. Additionally, extending the algorithm's scalability to encompass larger microgrid systems and a wider array of energy sources holds promise.

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Nomenclature

C_{ESS}	Energy storage system cost (EUR)
SoH	State of health of ESS (%)
SoC	ESS state of charge (%)
C_{Grid}	Grid cost (EUR)
C_{CO_2}	CO_2 emissions penalties (EUR)
P_{PV}	Power generated by the photovoltaic system (W)
P_{WTS}	Power generated by the wind turbine system (W)
P_{Grid}	Power imported from the grid (W)
P_{Load}	Power consumed by the loads within the MG (W)
P_{ESS}	Power stored in the ESS (W)

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