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Comprehensive Guide to Microgrid Design: Application and Background Insights

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Abstract. Nowadays, it has become increasingly imperative to pursue energy systems independent of centralized production, instead by employing decentralized resources such as renewable energy and responding promptly to localized demands, as microgrids exemplify. The concept of microgrids presents a promising solution to the challenges posed by traditional grid systems, offering resilience, sustainability, and efficiency. Despite the growing interest in microgrids, achieving their full potential requires a deep understanding of their diverse structures and design considerations. This paper contributes to the existing body of knowledge by thoroughly exploring various studied microgrid structures, conducting qualitative assessments to discern their strengths and weaknesses, and ultimately proposing a robust framework for designing and implementing microgrids in real-world scenarios. Through the analysis of a case study, this research aims to shed light on the most effective strategies for leveraging microgrids to meet the energy needs of modern societies while promoting sustainability and resilience.

Key words. Microgrids, rural energy solutions, sustainable design, remote area electrification, renewable energy integration.

1. Introduction

Microgrids (MGs) have become central to discussions about electrical networks in contemporary discourse. Their localized and decentralized nature marks a departure from traditional centralized power systems. This shift is driven by their ability to utilize distributed generation, primarily sourced from renewable resources [1]. Sustainability and resilience are inherent in MGs and underscore their importance in future electrical networks [2].

MG design hinges on carefully considering multiple components, each vital to enhancing overall system performance. The urgency of MG design arises from the imperative to fully exploit distributed energy resources, notably renewable sources. Unlike conventional power systems, MGs require a nuanced comprehension of the optimal sizing of their components to guarantee smooth integration and operational efficiency [3].

Designing a MG involves a comprehensive, meticulous planning process beyond mere hardware selection. The multifaceted nature of MG design requires a slight approach to selecting and sizing components such as generation units, storage systems, and load management mechanisms. The goal is to strike a delicate balance, ensuring efficient energy utilization while accommodating the dynamic nature of renewable resources.

The design philosophy of MGs centers on cooperative management. A well-designed MG is characterized by an intricate energy transition process, where various components synergistically operate to meet the energy demands of the local community or facility. Cooperative management facilitates optimal resource utilization, minimizes wastage, and ensures the stability and reliability of the MG [4].

By delving into the intricacies of MG configurations, this study shows pathways for tailoring MGs to meet specific energy demands, enhance sustainability, and bolster resilience across diverse settings. Its aim is not merely to catalog existing designs but to synthesize a coherent and actionable guide bridging the gap between theoretical research and practical application.

Through an exhaustive examination of diverse MG structures informed by a rich tapestry of scholarly work, this document seeks to equip stakeholders—from engineers to policymakers—with the knowledge and tools necessary to navigate the complexities of MG development. This highlights the need for a holistic approach to making MG systems efficient, reliable, and adaptable to keep up with the evolving demands of the energy landscape in which we live. This approach must incorporate technical, economic, environmental, and social considerations.

Moreover, this paper demonstrates how to effectively leverage the insights provided in this guide to apply them in real-world scenarios. A qualitative case study illustrates translating theoretical underpinnings into actionable strategies, ensuring readers grasp the principles behind MG design and how to implement these concepts in tangible projects to achieve sustainable and resilient energy solutions.

The paper is organized as follows. Section 2 presents all available categorizations related to MG design, and a qualitative comparison of the options offered for each category is outlined. Then, Section 3 presents the selection of the most suitable design for establishing MG potential in a rural area as an example of the data examined in the previous sections. Finally, some conclusions are drawn in Section 4.

2. Microgrids Classifications and Qualitative Assessment

In the domain of MGs, a diverse array of scholarly research exists, encompassing a variety of themes, reflecting the rise of diverse MGs and a growing demand for resilient energy solutions [5]. However, the plethora of MG options prompts questions about deployment criteria. Understanding the reasons behind this diversity and the decision-making process is vital for energy stakeholders. This section delves into the various classifications proposed for MGs, the factors driving this variety, and the criteria guiding deployment decisions, aiming to offer insights into energy system design and implementation.

Figure 1 presents a diagram that illustrates the various MG classifications based on different criteria.

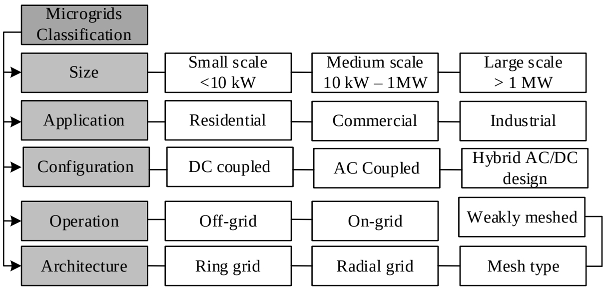

Figure 1. Classification of MGs from several perspectives.

The decision between off-grid and on-grid MGs relies on location, energy needs, budget, and environmental considerations. Off-grid MGs offer energy independence and resilience, while on-grid MGs provide grid integration and scalability.

Reliability, fault tolerance, scalability, and operational complexity are crucial in determining a suitable MG architecture. Ring grids offer high redundancy and resilience, while radial grids are simpler and better suited to less critical applications. Mesh-type grids, including weakly meshed configurations, provide superior redundancy and self-healing capabilities, making them ideal for mission-critical and large-scale applications.

Figure 2 illustrates diverse options for energy generation [6]. Renewables offer advantages like environmental sustainability, long-term cost stability, and resilience to fuel price fluctuations. However, their intermittent nature challenges MG integration, necessitating energy storage and grid management solutions. Non-renewables, while more reliable, have significant environmental and economic drawbacks, emphasizing the importance of transitioning to cleaner energy sources.

Notably, various energy generation options can be combined within MG systems.

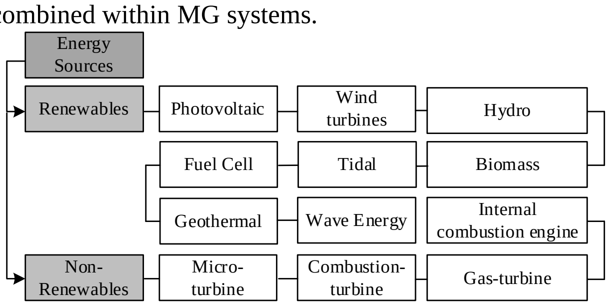

Figure 2. Different options for energy generation.

The generation side merges with various energy storage components [7] and sophisticated demand loads [8], distinguished by their energy consumption carriers and importance. Figures 3 and 4 represent options for energy storage systems and load segmentation types, respectively.

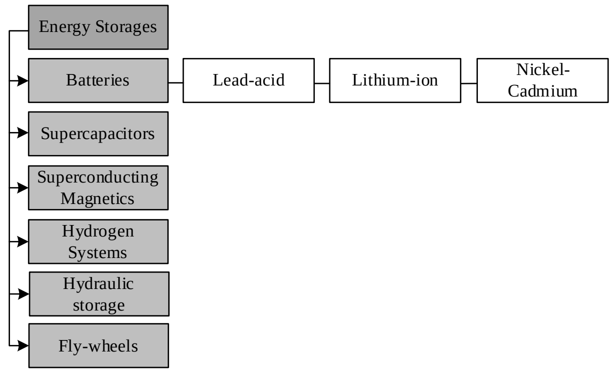

Figure 3. Various energy storage options.

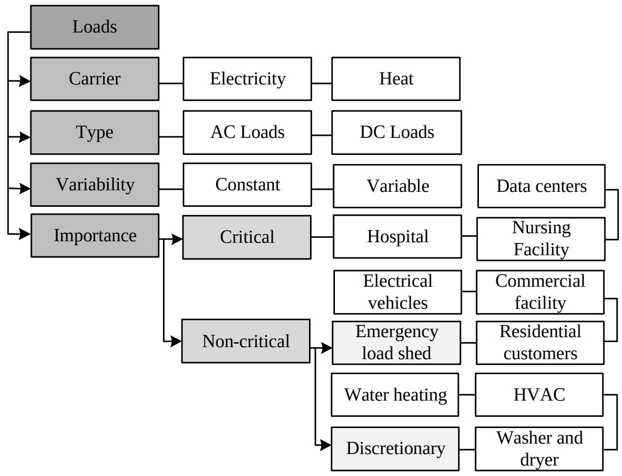

Figure 4. Load classifications.

Different energy storage technologies have unique strengths and weaknesses. Batteries offer flexibility and high energy density but may have durability and safety issues. Supercapacitors provide high power and a long lifespan but store less energy than batteries. Superconducting magnets and flywheels offer high power and almost unlimited lifespans but can be costly and have limited capacity. The choice of energy storage technology depends on factors such as energy requirements, response speed, lifespan, and budget.

Batteries have varied characteristics, benefits, and limitations, making them apt for diverse applications [9]. Lead-acid batteries are economical and dependable but offer restricted energy density and cycle life. Lithium-ion batteries boast high energy density, swift charging capabilities, and prolonged cycle life, albeit requiring sophisticated safety protocols. Nickel-cadmium batteries demonstrate exceptional durability and reliability and are suitable for extensive applications. Battery type selection hinges on energy needs, spatial limitations, weight restrictions, and cost factors.

Categorizing loads by electrical or thermal nature, AC or DC operation, and variability involves understanding their energy usage patterns and operational needs. Loads may operate steadily or vary over time. This understanding is essential for designing and optimizing energy systems to enhance efficiency and reliability. Furthermore, the demand-side management concept, especially demand response programs, has been the subject of significant research [10]. Figure 5 presents various demand-side management strategies.

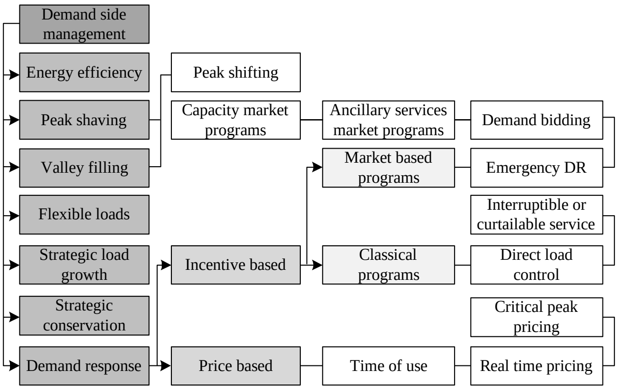

Figure 5. Various demand-side management strategies.

Many studies focus on the operational aspects of MGs, specifically examining various control strategy classifications [11], as shown in Figure 6.

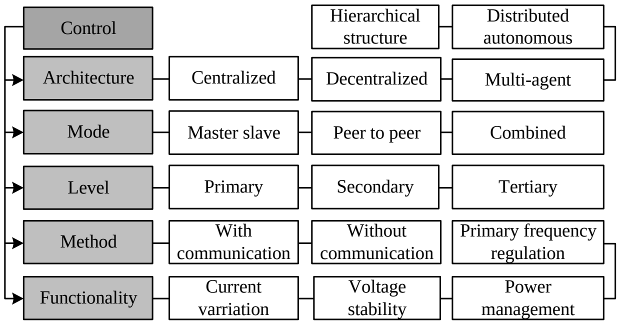

Figure 6. Different classifications of control strategies for MGs.

Centralized control ensures precise management of current variation, voltage stability, and power distribution. Decentralized strategies enhance adaptability and resilience locally by distributing decision-making. Using multi-agent control, autonomous agents can collaborate on decision-making through collaborative decision-making. Distributed control enables autonomous management of individual elements, promoting flexibility. Hierarchical control organizes functionalities into tiers for coordinated operation. Based on the system complexity and performance requirements, hybrid approaches are often preferred when developing MG systems to ensure comprehensive functionality.

Various techniques are used in MGs sizing and energy managing methods [12], as shown in Figures 7 and 8, respectively. There is considerable interest in using multi-criteria methods to find optimal solutions for both MG design and synergic management. This highlights the need for comprehensive strategies that address multiple facets of MG operation.

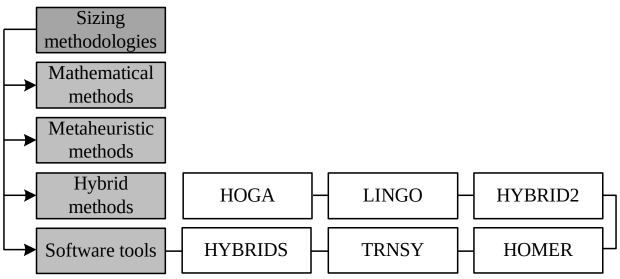

Figure 7. Different methods and software of MG sizing.

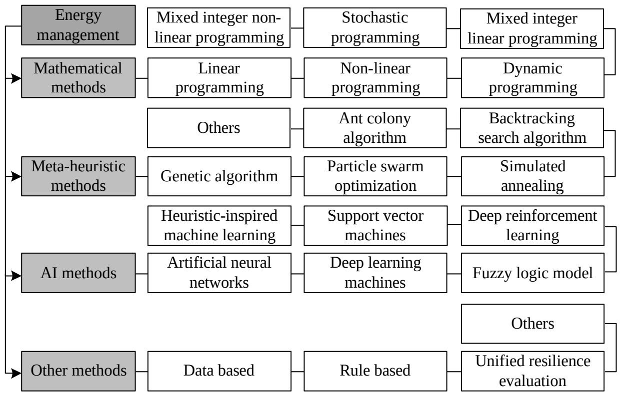

Figure 8. Various typical methods of energy management.

Generally, mathematical optimization offers precise solutions but needs help with scalability. Meta-heuristic algorithms provide efficient solutions but do not guarantee optimality. AI techniques like machine learning forecast energy consumption but may lack interpretability. Rule-based programming offers real-time decision-making but may lack flexibility. Selection depends on problem complexity, resources, and desired optimality, with hybrid approaches promising improved performance.

When comparing meta-heuristic optimization methods, evaluating their strengths, weaknesses, and applicability across diverse problem domains is crucial [13]. Genetic Algorithms (GAs) emulate natural selection, evolving solutions through mutation, crossover, and selection. GAs are versatile for complex search spaces but may encounter premature convergence and high computational overhead. Simulated annealing (SA) mimics metallurgical annealing, exploring the solution space with probabilistic acceptance of worse solutions to avoid local optima. SA is robust for rugged landscapes but requires careful parameter tuning and may converge slowly. Particle Swarm Optimization (PSO). simulates social behavior, adjusting particle positions based on best solutions, yet it may converge prematurely and need more diversity. Ant colony optimization (ACO) models ant foraging behavior, which is effective for combinatorial problems but demands computational resources. Differential evolution (DE) iteratively improves solutions and is robust for high-dimensional problems but may struggle with multimodal functions and noise. Comparison entails factors like convergence speed, solution quality, scalability, robustness, and ease of implementation, tailored to specific optimization problem characteristics.

The literature on MGs explores a range of economic, technical, and reliability goals within various constraints [14], as shown in Figures 9 and 10. These goals are studied both individually and collectively, sometimes focusing on a single objective, and other times on multiple objectives. Many studies aim to provide solutions to specific parts of the issue, often limited by simplified assumptions like focusing on a single goal or using deterministic inputs. Such objectives can include technical goals (e.g., minimizing losses), power quality goals (e.g., voltage stability), economic goals (e.g., cost reduction), or environmental goals (e.g., reducing emissions) and involve different types of data. However, this approach frequently overlooks other important objectives and aspects.

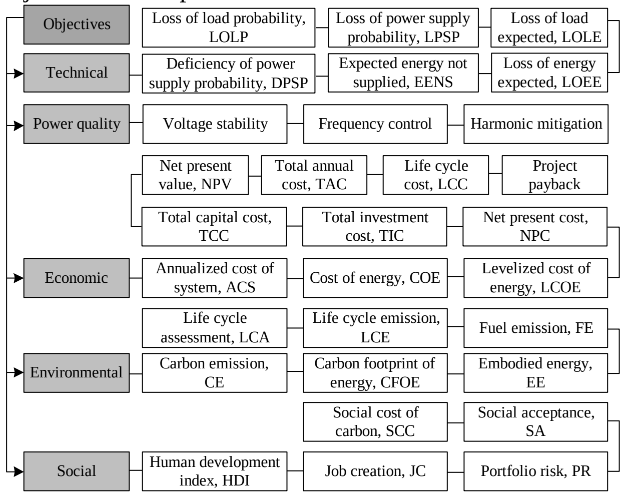

Figure 9. Energy planning objectives in MGs.

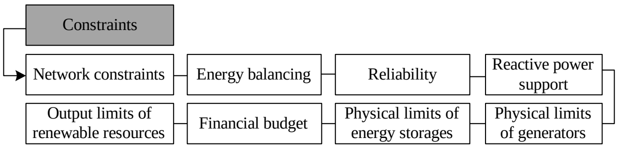

Figure 10. Constraints identified within MG systems.

Achieving balance in MG design is key to optimizing both system efficiency and societal benefits, encompassing technical integration and stability, economic cost-effectiveness, environmental sustainability, and social inclusivity. The approach necessitates comprehensive planning and collaboration to meet these diverse objectives, focusing on leveraging advanced technologies, efficient energy management, emission reduction, renewable integration, and community involvement. This holistic strategy aims to create intelligent, sustainable, and equitable MG systems, ensuring a balanced consideration of technical, economic, environmental, and social factors for future MG development.

Finally, Figure 11 presents the classification of various data types relevant to MG systems.

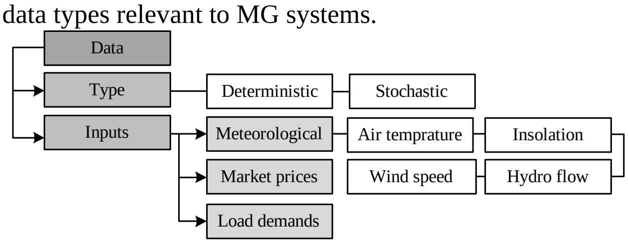

Figure 11. Classification of data types presented in MGs.

This section analyzed MGs, focusing on their types, operation, and goals, and discussed the technical, economic, and operational factors in MG design. Next, it assessed the methods' strengths and weaknesses, offering an in-depth evaluation of their use in MG analysis to guide informed MG design and implementation decisions.

3. Case Study, Optimal Framework Selection

This study examines the introduction of a MG focusing on the potential for photovoltaic (PV) generation, as highlighted in a previous study [15]. Now, all its power demands are met by the main-grid network. The goal is to explore the feasibility of integrating a MG to meet the community's specific energy needs and improve its electricity supply's resilience, considering economic efficiency improvements.

The proposed MG will be based on the existing energy consumption pattern and designed consequently. Hence, the MG, presented for a medium-scale, mainly residential application, is an on-grid, AC-coupled radial grid (Figure 1).

Given the region ample solar radiation and wind resources, the MG aims to leverage these renewable sources, reducing reliance on fossil fuels (Figure 2).

The batteries are needed alongside renewable sources for energy storage to ensure continuous power supply during low renewable energy generation periods, enhancing MG stability and reliability. Hence, the study also considers incorporating energy storage, with battery storage identified as the most efficient option despite high initial costs. Lead-acid batteries are selected for their cost-effectiveness (Figure 3).

Based on the rural area demand, all load carriers are AC power electricity, exhibit variable characteristics, are non-critical, and are designated for residential use (Figure 4).

The MG schematic is shown in Figure 12.

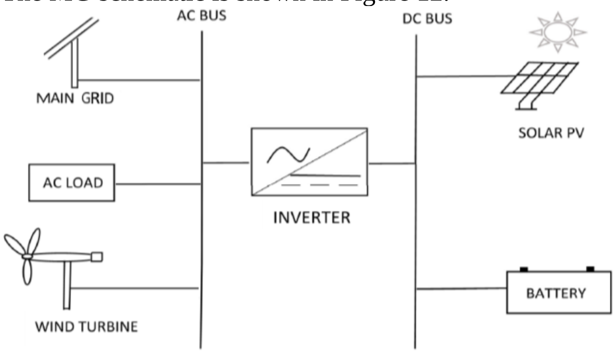

Figure 12. The schematic of the supposed MG.

In this structure, the goal is to design the system by finding the appropriate size of equipment based on geographical conditions and load demands. Due to the extensive search space and the high computational complexity, utilizing heuristic optimization algorithms seems rational (Figure 7). Among these algorithms, the PSO appears more suitable than others due to its high exploration capability. PSO is particularly advantageous for optimization problems characterized by high-dimensional search spaces and non-linear, non-convex objective functions. Its simplicity, ease of implementation, and ability to quickly converge to near-optimal solutions make it popular for various optimization tasks, including those encountered in MG optimal sizing.

This process is enabled by implementing a tailored energy management system (EMS) through the mentioned PSO algorithm. In other words, within the inner loop of the EMS, optimal performance is achieved at each time step. Subsequently, in the outer loop, the information from the EMS is utilized to determine the optimal sizing of the equipment to accomplish the objectives of interest.

By utilizing the solar panel model, the surface area of the panels, solar radiation, and air temperature at each time step, the energy produced by the solar panels is calculated. The wind turbines' energy is also calculated using the wind turbine model, the blades' surface area, and wind speed at each step. The difference between the total energy produced by these two generation resources and the load demand at each time step determines the energy that needs to be either charged or discharged by the battery. Indeed, the limited amount of energy that can be charged or discharged by the battery at each step depends on the specifications of the utilized battery model, the number of batteries, and the state of charge at each step.

It is noteworthy that in this structure, in cases where there is no generation, and the battery conditions are such that they cannot respond to the load, the demand for the load will inevitably be met through the upstream network. Additionally, when there is no load demand and the battery bank is fully charged, the generated energy will be transferred to a dump load. This load can be utilized for water heating and similar applications.

In the considered MG system, solar panels and wind turbines consistently operate in the direction of energy generation, while load demand consumes energy. The battery bank, therefore, serves as the sole component capable of interacting bidirectionally. Consequently, only one control variable, the battery power at each time step, is influenced by system conditions. Hence, all system-governing equations can be rewritten based on battery power. Under these circumstances, establishing a rule-based system under a look-up table could be optimal for energy management (Figure 8). The advantages of this EMS include simplicity, high responsiveness, and performance closely resembling real-time operation.

In this context, three variables—namely, the surface area of solar panels, the surface area of wind turbines, and the number of batteries—are initialized by the PSO algorithm. In this scenario, at each time step, the energy charged or discharged by the batteries is calculated from the difference between the energy produced by the generation units and the load demand. Upon completing the computations for all time steps within the study horizon, it becomes possible to calculate various technical criteria. One such criterion that reflects the level of reliability is the deficiency of the power supply probability (DPSP) metric (Figure 9), offering a clear indicator of its ability to meet demand effectively. It is defined as the sum of the values of unmet load demands in different sub-intervals to the sum of the total demand required in the entire time horizon as Eq (1).

$$DPSP = \frac{\sum_{t=1}^{T} DPS(t)}{\sum_{t=1}^{T} P_{Demand}(t)} \qquad (1)$$

Regarding Eq (1), T denotes the study period horizon. DPS stands for Deficiency of Power Supply, which indicates the inadequacy of sufficient energy supply in meeting demand at a particular time step.

Using system variables, it is also feasible to calculate the system's total capital cost (TCC), including initial costs, replacement costs, and maintenance costs over the project's lifespan (Figure 9). TCC criterion has been opted for due to its comprehensive assessment of overall investment expenses, encompassing initial and ongoing costs.

In this context, the PSO algorithm aims to find a system configuration that minimizes TCC criteria while ensuring that the DPSP remains below a specified threshold. In other words, the algorithm iteratively explores the search space of possible configurations of solar panels, wind turbines, and battery bank quantity to identify the optimal mix that meets economic constraints and reliability requirements (Figure 10). By adjusting the parameters and updating the positions of particles within the swarm, the PSO algorithm aims to converge toward a solution that balances minimizing costs and maximizing reliability, as indicated by the DPSP.

In this condition, the input data includes air temperature, solar radiation, wind speed, and load demand, which could be deterministic or stochastic (Figure 11). As mentioned before, the system variables consist of the surface area of solar panels, the swept area by the blades of wind turbines, and the number of batteries in the battery bank.

Many scenarios can be analyzed when the methodology is applied to the selected case study. As a result of this analysis, different optimal sizes are obtained depending on the target DPSP chosen. Table I shows the optimal sizes of components and the related costs considering two different DPSP levels.

Table I. – Optimal results based on different DPSP values.

Sce.	1	2
DPSP (%)	0	0.1
A_{PV} (m²)	17554	12912
A_{WT} (m²)	2927	2366
$N_{Battery}$ (#)	46368	8528
MG Cost (×10⁶ $)	17.434	6.964
Grid Purchase (×10⁶ $)	0	0.754
TTC (×10⁶ $)	17.434	7.718

Table I presents that the storage volume has been dramatically downsized by increasing DPSP from 0% to 10%. This reduction significantly decreases the system TCC, which is slightly dependent on the main grid. Compared to the first scenario, the second scenario shows a reduced renewable unit production and storage transaction volume while increasing network participation. The analysis of these scenarios can be used to obtain the optimal design.

Table II summarizes the MG components energy values for both scenarios on a typical day using optimal sizes according to Table I.

Table II. – Results in a typical day.

Sce.	1	2
PV (kWh)	5198.95	3824.14
WT (kWh)	558.86	451.75
Battery_Ch (kWh)	4697.64	3310.12
Battery_Disch (kWh)	2093.82	1334.30
Grid Supply (kWh)	0.00	853.93
Energy Demand (kWh)	3154	

According to Table I, in the second scenario, compared to the first scenario, there is a reduction in the energy output of PVs and WTs, as indicated in Table II. However, with a significant decrease in the size of the storage unit, energy input and output to/from the battery have decreased, leading to increased reliance on the grid.

To better understand the scenarios, the hourly energy balance on the typical day has been presented in Figure 13.

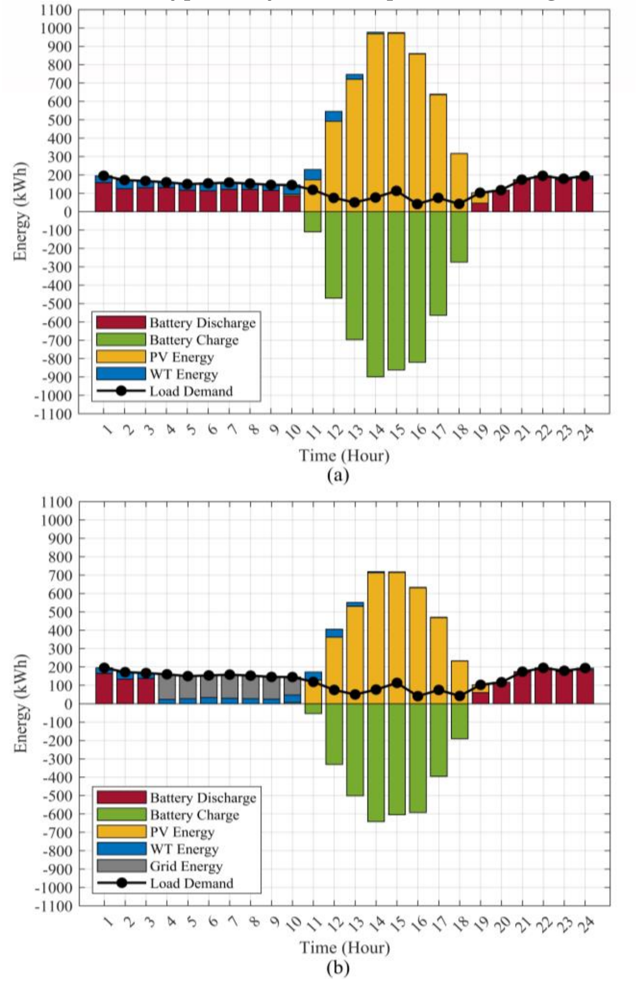

Figure 13. The schematic of the supposed MG. (a) DPSP equals 0%, (b) DPSP equals 10%.

Utilizing the PSO to optimize MG configuration offers a promising avenue for cost-effective solutions with ensured reliability. By dynamically adjusting system variables, PSO aims to minimize TCC while keeping DPSP below a set threshold. This approach enables efficient energy resource management, supporting sustainable and resilient energy solutions in response to evolving demands. Further research and development in optimization techniques can significantly enhance energy management practices in MG, promoting a sustainable and resilient energy future.

4. Conclusions

The present paper has explored MG structures from various perspectives, mainly focusing on aspects of designing a MG. Following this examination, a comprehensive analysis of the differences between these structures was conducted, presenting the brief advantages and disadvantages of each. With an understanding of these structures, the most suitable framework for a case study was proposed. The targeted MG is situated in a specific location where, considering the geographical conditions, type, and magnitude of demand, the optimal arrangement of the MG, EMS, and optimization algorithm for elements sizing, along with technical and economic constraints and objectives, were investigated. While the extensive scope of the topics presented in the initial sections was not fully addressed in the MG study, future research endeavors will delve into extensive quantitative analyses of the targeted MG, further advancing our understanding in the field. Additionally, obtaining the global optimal design will be an exciting outcome in future works.

Acknowledgement

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