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Negawatt-Driven Sustainable Energy Management Based-on Nanomaterial-Enhanced Batteries

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ABSTRACT

With the dramatic increase of energy demand around the world, it has become a necessity to monitor and optimize energy consumption to conserve its use and decrease carbon emissions. This paper presents a comprehensive analysis of MicroGrids (MGs) that encompass a diverse array of energy sources, including renewable energy, Diesel Generators (DGs), and Battery Storage Systems (BSS). In this study, critical constraints are addressed such as distributed generator limits and grid power exchange. Moreover, the potential integration of nanomaterials within BSS to enhance energy efficiency and achieve Negawatt energy are explored. The main objectives are to evaluate the performance of various energy system configurations, with a specific focus on nanomaterial-enhanced batteries, and identify the optimal strategy to minimize operating costs while maximizing Negawatt energy production. By considering technical, economic, and environmental factors, this research aims to provide valuable insights into sustainable and efficient Microgrid solutions for future energy management.

1. Introduction

This study underscores the essential role that MicroGrids (MGs) play in ensuring a reliable energy supply through the integration of diverse energy sources and loads [1-3]. In today's context, the development of intelligent and robust grids prioritizing environmental sustainability, cost efficiency, and safety is crucial to harness the full potential of multiple energy resources [4-8]. Our primary objective is to address technical, economic, and environmental challenges within MGs, with a specific focus on curbing carbon emissions and greenhouse gases.

To achieve this, we delve into various MG configurations, spanning renewable energy sources, Diesel generators, and energy storage systems. Effective energy management plays a pivotal role in optimizing solutions and driving down costs throughout the MG lifecycle. By modelling PV systems, wind turbines, battery energy systems, and diesel generators, we enable the evaluation of diverse

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system setups. Our analysis centres on minimizing operational expenses and emissions by identifying the most efficient MG configuration that achieves minimal economic and environmental costs. Accordingly, we conduct three distinct system studies, each centring on different energy sources.

In the first study, we explore comprehensive integration of the grid, Renewable Energy Sources (RESs), diesel generators, and battery storage systems to meet load demand. The second study prioritizes RESs, diesel generators, and battery storage systems, with the grid as an auxiliary option. The third study exclusively relies on grid supply for load demand. Throughout these analyses, the pivotal role of the Micro Grids Central Controller (MGCC) becomes evident, as it monitors cost dynamics and facilitates informed decision-making to minimize operational costs and emissions.

Furthermore, our investigation probes the integration of nanomaterials into Lead-Acid (LA) batteries, aiming to enhance their performance within microgrid contexts and realize the concept of Negawatt Energy (NE). NE encapsulates energy saved through efficient energy management practices, translating to reduced energy wastage and a diminished environmental footprint [9,10]. This underscores the significance of optimizing energy consumption and waste reduction for sustainability and cost-effectiveness [11-20]

The integration of nanomaterials into LA batteries is anticipated to bolster energy storage capacity, charging/discharging rates, and overall efficiency, thereby enhancing NE and elevating system effectiveness. The evaluation of these nanomaterial-enhanced batteries and their implications on overall microgrid system performance are discussed in-depth, including a thorough analysis of the Negawatt energy concept in each case. These evaluations yield insights into achieved energy savings and the effectiveness of distinct energy management strategies.

The paper follows a logical structure. Section 2 details system configuration and objective function, while Section 3 expands on the proposed system data, detailing specifics about the grid, RESs, diesel generators, and battery storage systems. In Section 4, case studies and simulation results are presented, appraising performance of diverse system configurations and their economic and environmental impacts. Finally, Section 5 concludes the study by summarizing key findings and discussing broader implications.

2. Microgrid Configuration and Optimization Objectives with Nanomaterial-Enhanced Battery Storage (NEBS)

The integration of nanomaterials into battery technology has resulted in significant advancements in power and energy management systems. The integration of nanomaterials has been observed to enhance the performance and efficiency of the lead-acid battery by approximately 5-20%, as supported by the research findings from [21-28].This remarkable enhancement is attributed to the unique properties and characteristics of nanomaterials, which allow batteries to achieve higher power and capacity ratings.

The technical, economical, and environmental illustration of installing the Nanomaterial-Enhanced Battery Storage (NEBS) to the microgrids are considered and studied in this section. The microgrids constructed from conventional thermal diesel generators sources, integrated with renewable energy resources and NEBSs as shown in Figure 1. Photovoltaic (PV) systems and Wind Turbine (WT) generators represent the renewable energy resources. The microgrids' energy generation sources and loads are controlled through the MGCC.

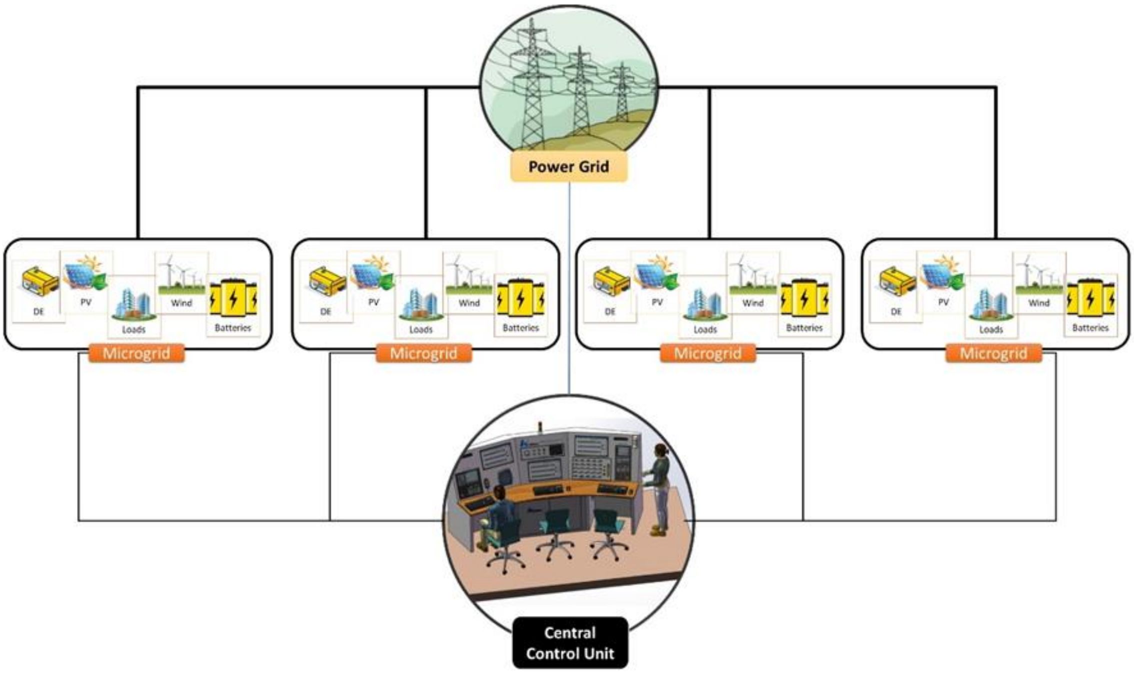

Fig. 1. The proposed system of multi-microgrids integrated with the nanomaterial-enhanced battery storage

2.1 The System Cost Function

The system time dependent-Cost Function ($CF_{Sys}(t)$) formula consists of three main parts, which are technical cost function ($CF_{tech}(t)$), economical cost function ($CF_{econ}(t)$), and environmental cost function ($CF_{envir}(t)$) as illustrated in Eq. (2). The proposed power system is constructed of different power generation conventional and renewable sources incorporated with the NEBS, the main grid, the loads. So, the overall system Cost Function (CF_{Sys}) is the summation of the three-cost function main parts of all the power system components which are the main grid, the diesel generators, PV systems, WT generation, and NEBS as shown in Eq. (1).

$$
\begin{aligned}
CF_{Sys}(t) &= CF_{tech}(t) + CF_{econ}(t) + CF_{envir}(t) \\
&= \textstyle\sum_{t=1}^{T}([C_{Gr}(t) + C_{PV}(t) + C_{WT}(t) + C_{start}(t) + C_{shut}(t) + C_{c-NEBS}(t)] + [\,C_{OM-DG}(t) + \\
&\quad C_{OM-PV}(t) + C_{OM-WT}(t)] + [\textstyle\sum_{i=1}^{N_{DG}} p_f \times c_{em}^{i} \times P_G^{i}(t) \times t]\,) \\
&= \textstyle\sum_{t=1}^{T}([p_{Gr} \times P_{Gr}(t) + p_{PV} \times P_{PV}(t) + p_{WT} \times P_{WT}(t) + C_{start}(t) + C_{shut}(t) + C_{c-NEBS}(t)] + \\
&\quad [\,p_{DG}(\frac{P_{DG}(t)}{\eta_{DG}}) + C_{OM-PV}(t) + C_{OM-WT}(t) + C_{OM-NEBS}(t)] + [\textstyle\sum_{i=1}^{N_{DG}} p_f \times c_{em}^{i} \times P_G^{i}(t)]\,)
\end{aligned}
\tag{1}
$$

$$C_{start} = p_{DG-st} \times \max\Big(0, \big(i_{DG}(t) - i_{DG}(t-1)\big)\Big) \tag{2}$$

$$C_{shut} = p_{DG-sh} \times \max\Big(0, \big(i_{DG}(t-1) - i_{DG}(t)\big)\Big) \tag{3}$$

$$C_{c-NEBS} = (p_{NEBS-P} \times P_{NEBS}) + (p_{NEBS-E} \times E_{NEBS}) \tag{4}$$

$C_{Gr}(t)$, $C_{PV}(t)$, $C_{WT}(t)$, and $C_{c-NEBS}(t)$ are the time-variant technical cost of the main grid, photovoltaic, wind turbine generation and NEBS respectively (in \$). The technical cost includes the different sources capital costs, the technical aspects costs, and the constraints penalty. $C_{start}(t)$ and

$C_{shut}(t)$ are the start-up and shut-down costs of the diesel generators respectively (in \$). $C_{OM-DG}(t)$, $C_{OM-PV}(t)$, and $C_{OM-WT}(t)$ are the operation and maintenance costs of the diesel generator, PV, and WT respectively which represent the time-variant economical cost of the system (in \$). Each power source in the studied system is indicated by certain number and their total number is N_{DG} . $P_G^i(t)$ is the time-variant power generation of the different power sources and storage system (in kW). B is the penalty factor of CO2 emissions (in \$/kgCO2), while c_{em}^i is the emission coefficient of each power generation source (in kgCO2/kWh). $P_{Gr}(t)$, $P_{PV}(t)$, $P_{WT}(t)$, $P_{DG}(t)$, and P_{NBES} are the main grid, PV, WT, diesel generator, and NEBS delivered power (in kW) respectively, while NEBS energy capacity (in kWh) is presented by E_{NBES}. p_{Gr}, p_{PV}, p_{WT}, p_{DG}, and p_{NEBS-P} are the cost coefficient of main grid, PV, WT, and NEBS power consumption (in \$/kW) respectively. p_{DG-st} and p_{DG-sh} are the penalty coefficient of the diesel generator start-up and shutdown (in \$) respectively, while p_{NEBS-E} is the cost coefficients of the NEBS energy (in \$/kWh). All optimization procedures will be executed numerically for precise quantitative evaluation. This approach ensures a rigorous assessment of the impact of various factors on the energy management system.

2.2 The System Constraints

The targeted achievement is to minimize the system cost function with respect to fulfil the maximum benefit of the system with optimal technical conditions considering some operating constraints as illustrated in Eq. (5) to Eq. (10).

$$\sum P_{sys-delivered} = \sum P_{sys-consumed}$$

$$P_{DG}(t) + P_{PV}(t) + P_{WT}(t) \pm P_{Gr}(t) \pm P_{NEBS}(t) = P_{Load}(t) \tag{5}$$

$$P_{DG-min}(t) \leq P_{DG}(t) \leq P_{DG-max}(t) \tag{6}$$

$$P_{PV-min}(t) \leq P_{PV}(t) \leq P_{PV-max}(t) \tag{7}$$

$$P_{WT-min}(t) \leq P_{WT}(t) \leq P_{WT-max}(t) \tag{8}$$

$$P_{Gr-min}(t) \leq P_{Gr}(t) \leq P_{Gr-max}(t) \tag{9}$$

$$SOC_{NEBS-min} \leq SOC_{NEBS}(t) \leq SOC_{NEBS-max} \tag{10}$$

$SOC_{NEBS-min}$, $SOC_{NEBS-max}$ are the minimum and maximum limits of the NEBS State of Charge (SOC) respectively.

3. System Configuration and Components

This section provides an in-depth overview of the configuration and components of the studied system. The system encompasses a combination of diesel generators, renewable energy sources (such as wind and solar installations), and a battery storage system. Through meticulous elucidation, the functionality and distinctive roles of each component within the system will be expounded upon, fostering a comprehensive comprehension of the overall system architecture.

3.1 Distributed Generation and Grid Power Capacity

Table 1 presents the capacities and characteristics of the distributed generation units and grid power sources. It provides essential information on the power limitations, operation, and maintenance costs, as well as the start-up and shut-down costs associated with each unit.

Table 1
Power limitations and costs of distributed generators and grid sources [17]

Unit	Max. power (kW)	Min. power (kW)	Bid ($/kWh)	Operation and maintenance cost ($/kWh)	Start-up/shut-down cost ($)
WT	15	-	1.72	0.24	0
PV	25	-	2.8	0.19	0
DG	100	5	1.32	0.59	0.96
Grid	40	- 40	variable	NA	NA

3.2 Nanomaterial-Enhanced Lead-Acid Battery Storage System

As previously mentioned, the integration of nanomaterials has been observed to enhance the performance and efficiency of the lead-acid battery by approximately 5-20% [21]. Based on these enhancements, a new calculation has been applied to the data from [22], considering an approximate of 15% improvement brought about by nanomaterial integration. Table 2 displays the modified key parameters of the nanomaterial-enhanced lead-acid battery storage system, including capital power and energy costs, annual maintenance cost per kW, and efficiency.

Table 2
Nanomaterial-enhanced lead-acid battery storage system: power and energy costs

Battery	Capital power cost ($/kW)	Capital energy cost ($/kWh)	Annual maintenance cost ($/kW)	Eff (%)
LA-NM: Lead-Acid Battery with Nanomaterial Enhancement	170	170	42.5	80.5

3.3 Battery System Cycles with Varying Depth of Discharge

Table 3 presents the battery system cycles for the nanomaterial-enhanced Lead-Acid (LA-NM) battery, considering Different Depths of Discharge (DDOD). It is worth noting that the battery system itself remains unchanged even with the incorporation of nanomaterials.

The purpose of evaluating the battery system cycles with varying DDOD levels is to assess its performance and longevity under different operating conditions. The addition of nanomaterials in the battery enhances its characteristics and improves overall performance, such as energy storage capacity, charging and discharging rates, and efficiency. However, the fundamental structure and components of the battery system remain unaltered.

Table 3
Battery system cycles with different depth of discharge

Battery	DDOD	NC
LA-NM	100	350

3.4 Environmental Impact Charges

Emissions occur because of the combustion of coal fuel in thermal generators. However, for renewable energy sources such as wind and photovoltaic, there are no penalties imposed for CO_2 emissions (B = 0 \$/ton CO_2). In contrast, a penalty factor 'B' ranging from 10 to 15 \$/tonCO_2 is typically applied to other emission sources [28]. The emission factors of CO_2 for various distributed energy resources are provided in Table 4, offering valuable insights into their environmental impact, and contributing to informed decision-making in energy management strategies.

Table 4
CO_2 emission factors for various distributed energy resources

Energy resources	Fuel oil	Wind	Solar
CO_2 emission factor (ton/kWh)	$8.93\text{x}10^{-4}$	$21.0\text{x}10^{-6}$	$6.00\text{x}10^{-6}$

3.5 Aggregate Demand and Energy Market Rate

The visual representation of hourly forecast values for total load demand and market price in Figures 2 and 3 offers valuable insights into energy consumption patterns and pricing dynamics, enabling the identification of peak demand periods, price fluctuations, and opportunities for energy optimization. The maximum load typically occurs between 10 am and 12 pm, peaking at around 90 kW, with prices reaching 5 cents during this period and dropping to 2 cents for lower demand. Figure 2 complements this by highlighting renewable energy source outputs throughout the day, aiding effective energy management. Stakeholders can use this data to inform energy procurement, trading strategies, and demand response measures, leading to optimized energy usage and cost reduction, ultimately enhancing the sustainability and efficiency of microgrid systems.

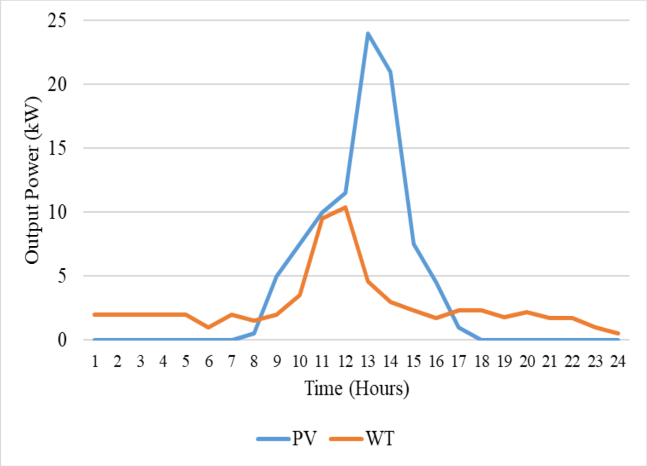

Fig. 2. Wind and solar system power profile [22]

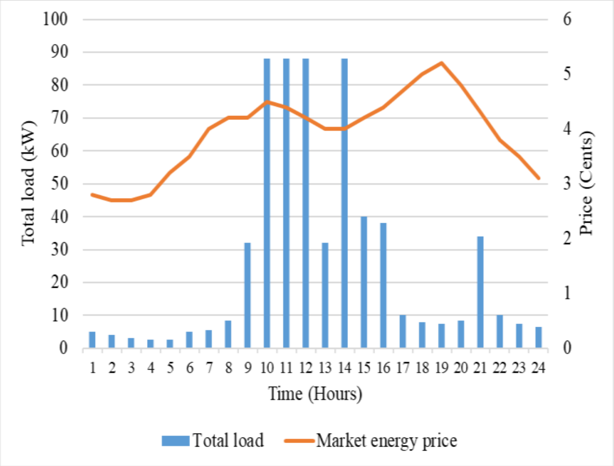

Fig. 3. Dynamic variation of market energy price and load demand throughout the day [22]

4. Case Studies and Simulation Results

In this paper, three distinct case studies are implemented and compared using MATLAB software to identify the optimal energy management system that minimizes overall cost and to calculate the total Negawatt energy. A detailed flowchart illustrates the proposed system is depicted in Figure 4. In the first case study, all available energy resources, including diesel generators, renewable resources, Lead-Acid Battery with Nanomaterial Enhancement, and the main grid, are considered to meet the load demand. This comprehensive approach allows for the evaluation of various energy sources and their potential cost-saving benefits. The second case study focuses on utilizing the energy resources of diesel generators, renewable resources, and batteries storage system to satisfy the load requirements. The main grid is utilized as a backup source only if these resources prove insufficiency. This scenario aims to assess the feasibility of relying primarily on renewable and stored energy. In the third case study, the main grid is the sole energy source utilized to meet the load demand. This case explores the cost implications and feasibility of relying solely on grid power.

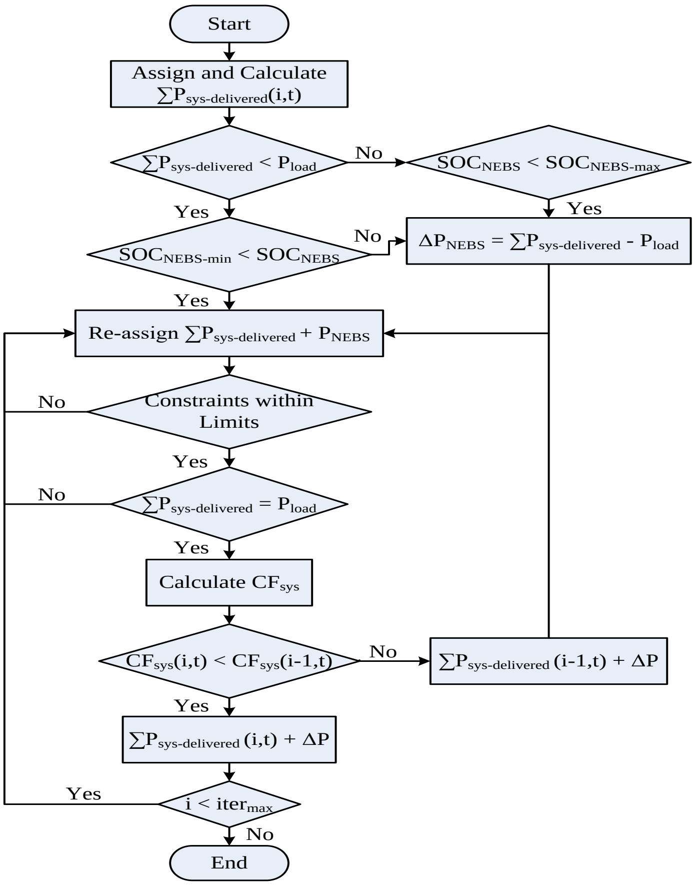

Fig. 4. Flowchart of the optimized energy management system with Negawatt energy integration

To establish a robust connection between the optimization algorithm obtained numerically and the showcased case studies, the integration of the algorithm into the simulation model drove decision-making processes and shaped outcomes. The optimization algorithm played a central role, dynamically influencing the MicroGrid Central Controller (MGCC) throughout the simulation. Prior to each case study, the algorithm's parameters were meticulously fine-tuned to align with specific study objectives: minimizing costs and achieving the Negawatt energy concept. Over the simulation timeline, the algorithm seamlessly engaged with the MGCC, offering real-time insights and actionable recommendations. It directed energy source scheduling, formulated load management strategies, and managed battery storage operations, all with the overarching goal of optimizing economic and environmental performance. The algorithm's impact on decision-making was profound, guiding the optimal allocation of resources, energy generation, and distribution. This intricate orchestration incorporated dynamic factors like energy demand, renewable resource availability, and system constraints.

The simulation outcomes offer in-depth and meaningful insights into various aspects of the three case studies, including their environmental impact, cost-effectiveness, and load profile, as clearly illustrated in Figures 5 to 12. Based on the simulation results, Case Study 1 demonstrates a considerable reliance on the main grid, resulting in a comparatively lower Negawatt Energy output when compared to the other cases.

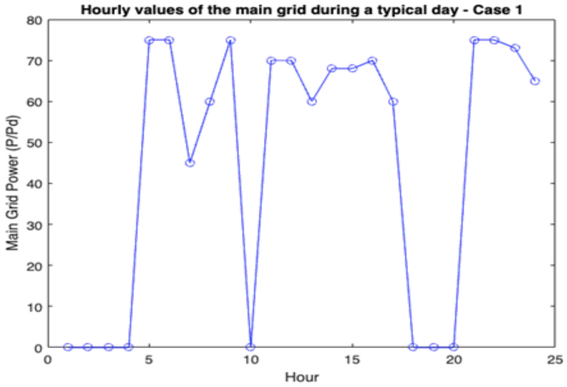

Fig. 5. Main grid consumption

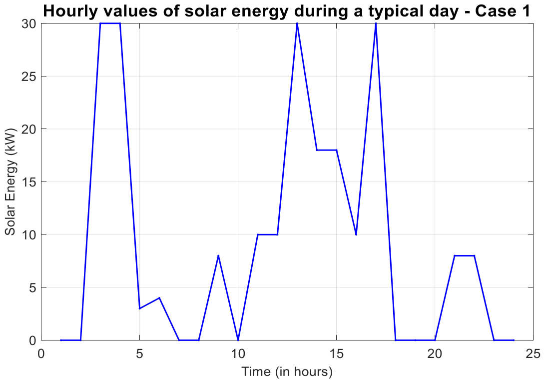

Fig. 6. Solar energy consumption for case one

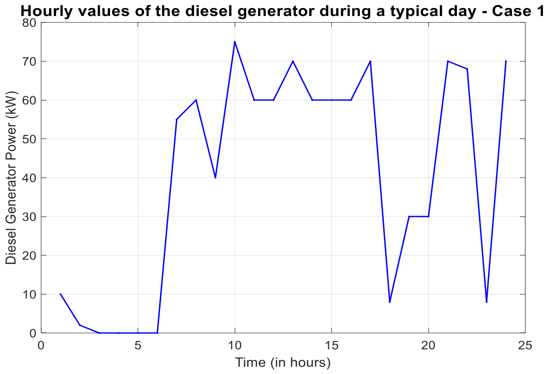

Fig. 7. Diesel engine consumption for case study one

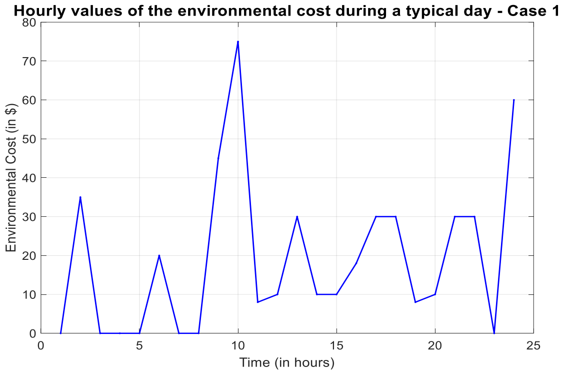

Fig. 8. Environmental cost per day

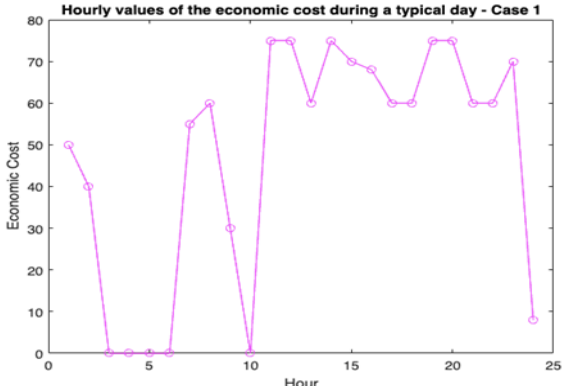

Fig. 9. Economic cost for a day for case one

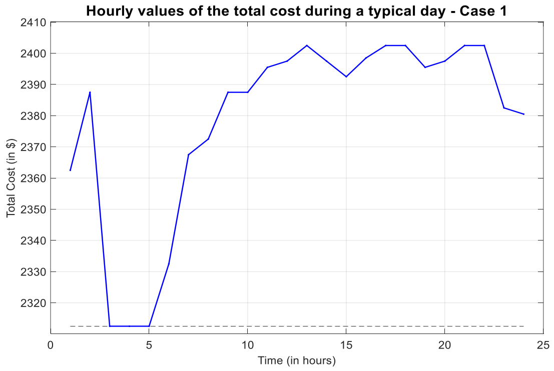

Fig. 10. Hourly value of total cost during the day case 1

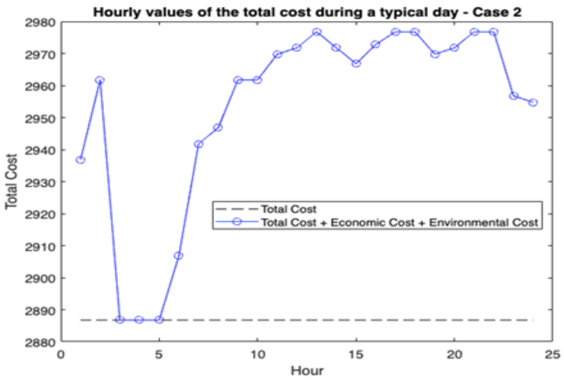

Fig. 11. Hourly value of total cost during the day case 2

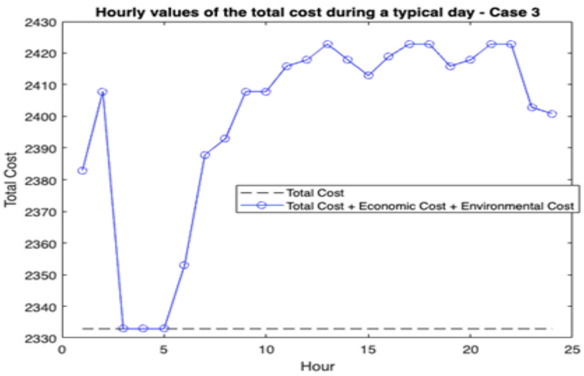

Fig. 12. Hourly value of total cost during the day case 3

Despite its cost advantage, as indicated in Figure 13, the findings suggest that insufficient emphasis on energy efficiency and conservation measures may hinder the achievement of sustainable outcomes. On the other hand, Case Study 2 strategically integrates solar energy, wind energy, and diesel generators to achieve the highest Negawatt Energy output, showcasing exemplary energy conservation practices as shown in Figure 14.

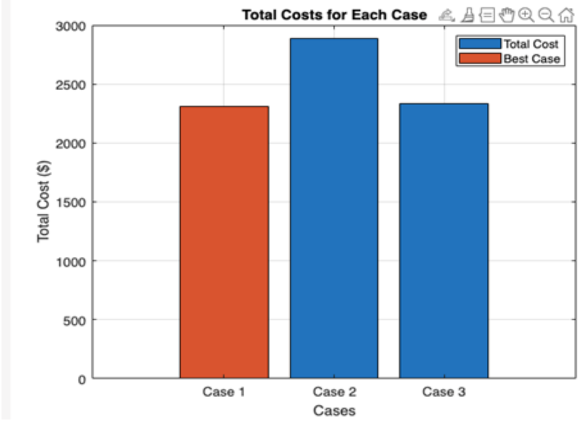

Fig. 13. Total cost comparison of the three cases study

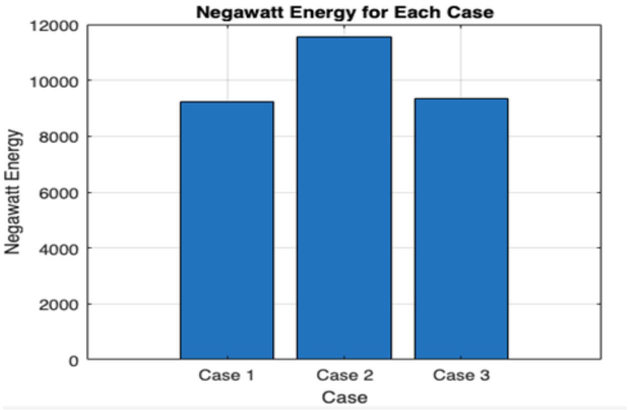

Fig. 14. Negawatt energy of the three cases study

Conversely, Case Study 3 predominantly relies on the main grid, leading to a competitive total cost but possibly lower energy efficiency due to a limited emphasis on conservation measures. In alignment with the objective of highlighting the fundamental innovations and contributions of this research, a comprehensive case study was conducted. This study involved a direct comparison of the proposed technique against the widely utilized Conventional Load Prioritization method, which holds prominence in the literature. This meticulous comparison forms a compelling showcase of the effectiveness and superiority of the approach in optimizing energy management within Microgrid systems. By leveraging simulation results across three distinct case studies, a vivid depiction of the total cost outcomes for each method is offered, yielding a tangible understanding of their distinct performances. Furthermore, in response to the call for experimental validation, the exploration extended to Software-in-the-Loop (SIL) simulation, specifically in contrast with the renowned Advanced Load Balancing method. The integration of SIL simulation in evaluating the advanced load balancing technique introduces an additional layer of validation and insight, thereby reinforcing its real-world applicability. The amalgamation of performance presentation, comparative case study, and SIL simulation collectively underscores the significant contributions of this research in the domain of optimizing Microgrid energy management.

Proceeding to the visual aids, Figure 15 offers a graphical contrast of the total costs among the proposed technique, Conventional Load Prioritization, and Advanced Load Balancing methods. This visualization unveils the proposed approach's prowess in achieving notable cost reductions, underscoring its financial viability as it provides the lowest total cost among them approximately 2300,2700,2450. For a deeper insight, Figure 16 delves into the specifics of Negawatt Energy, presenting a detailed breakdown of values.

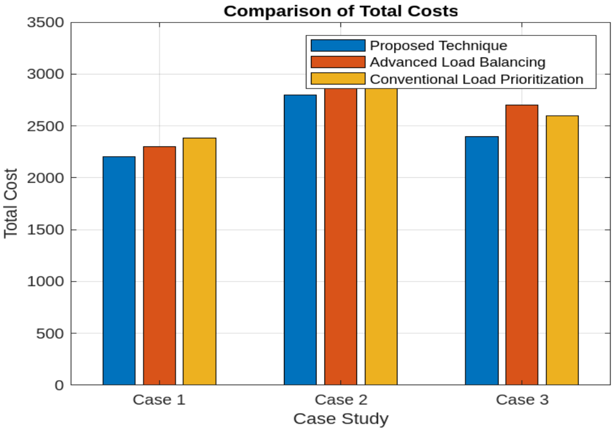

Fig. 15. Comparison of several classical & PT

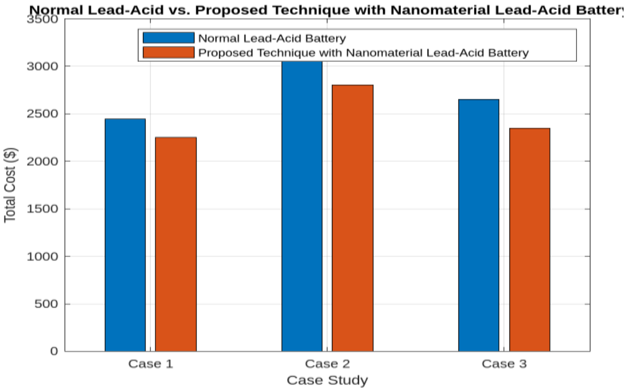

Fig. 16. Normal battery vs nanomaterial

The exact values are shown in Table 5. This comprehensive perspective enables a more thorough grasp of the performance distinctions among the techniques.

Table 5
Comparative Negawatt Energy Values for Different Methods

Method	Case 1 (Approx.)	Case 2 (Approx.)	Case 3 (Approx.)
Proposed Technique	9000	13000	9500
Advanced Load Balancing Method	8000	10000	9000
Conventional Load Prioritization Method	8500	11000	9200

Now, turning to Figures 17 and 18, these visuals offer insights into the total cost outcomes of the proposed technique with a nanomaterial-enhanced battery and a normal Lead-Acid (LA) battery. Figure 17 shows how integrating nanomaterials can lead to substantial cost savings, demonstrating its potential economic benefits as the cost have been reduced approximately to 2300,2700,2450. Meanwhile, Figure 18 provides a detailed comparison of the energy efficiency gains associated with the nanomaterial-enhanced battery, emphasizing its significance. The detailed values are shown in Table 6.

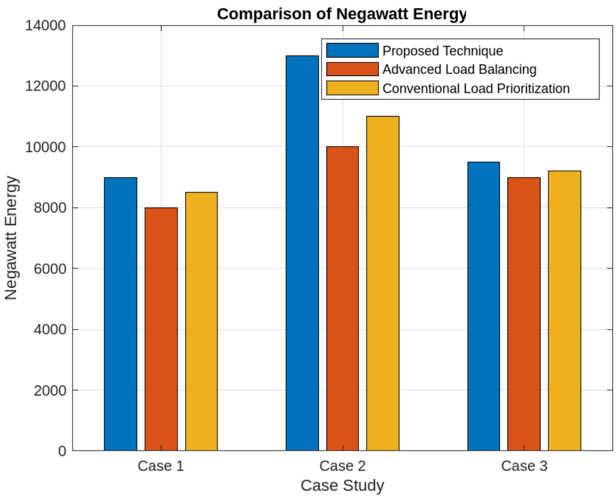

Fig. 17. Negawatt comparison of several classical & PT

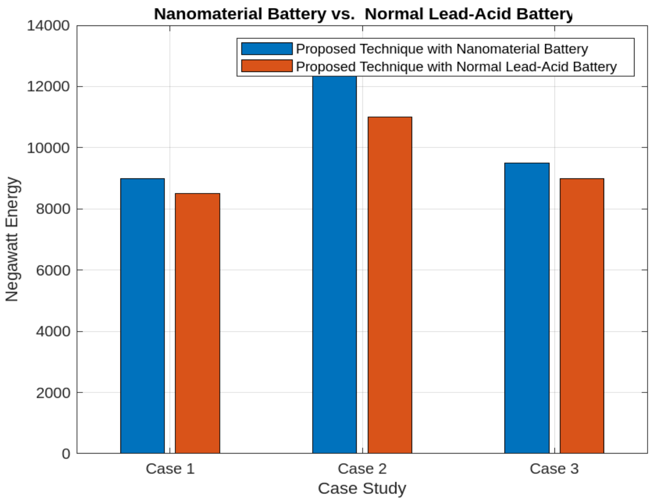

Fig. 18. Negawatt Comparison Normal battery vs nanomaterial

Table 6
Comparison of Negawatt Energy Values for Proposed Technique with Nanomaterial Battery and Normal Lead-Acid (LA)

Case	Proposed Technique (with nanomaterial battery)	Proposed Technique (normal LA battery)
1	≈9000	≈8500
2	≈13000	≈11000
3	≈9500	≈9000

In conclusion, the careful examination of simulation outcomes reinforces the prominence of Case Study 2 as a harmonious and effective energy utilization strategy, well-positioned to achieve significant advancements in both environmental sustainability and cost-effectiveness. Nevertheless, it's crucial to acknowledge the limitations of this work. This research, while promising for microgrid energy management, may not fully capture the intricacies and variability of every real-world microgrid scenario. Comprehensive validation through real-world experiments and the consideration of additional factors, such as extreme weather events and grid-scale integration, will be necessary to fully assess its robustness and adaptability. In summary, the combination of rigorous simulations, detailed case studies, and insightful visual representations highlights the effectiveness of this proposed technique. It holds the potential to transform microgrid energy management, offering cost-efficiency and environmentally responsible energy optimization practices.

5. Conclusions

This research emphasizes the importance of optimal economic and environmental energy management solutions for Microgrids through comprehensive case studies. These studies seek to minimize costs and improve decision-making by the MicroGrid Central Controller (MGCC), aligned with the Negawatt energy concept. Case Study 1 highlights cost-efficient load generation optimization and the advantageous incorporation of Nanomaterial adjustments in the lead-acid (LA) battery, achieving Negawatt Energy and promoting efficient energy management with reduced environmental impact. Case Study 2 underscores the significance of energy-efficient configurations, exemplified by its superior Negawatt Energy outcomes. Acknowledging the absence of constraint discussion, future endeavours will integrate emerging technologies like blockchain and artificial intelligence to enhance energy management. Validation through real-world tests and feedback is crucial. Moreover, exploration into system scalability and alternative energy storage technologies will provide further insights into advancing microgrid energy optimization. Ultimately, this study underscores the urgency of embracing sustainable practices for a greener future.

Acknowledgement

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