

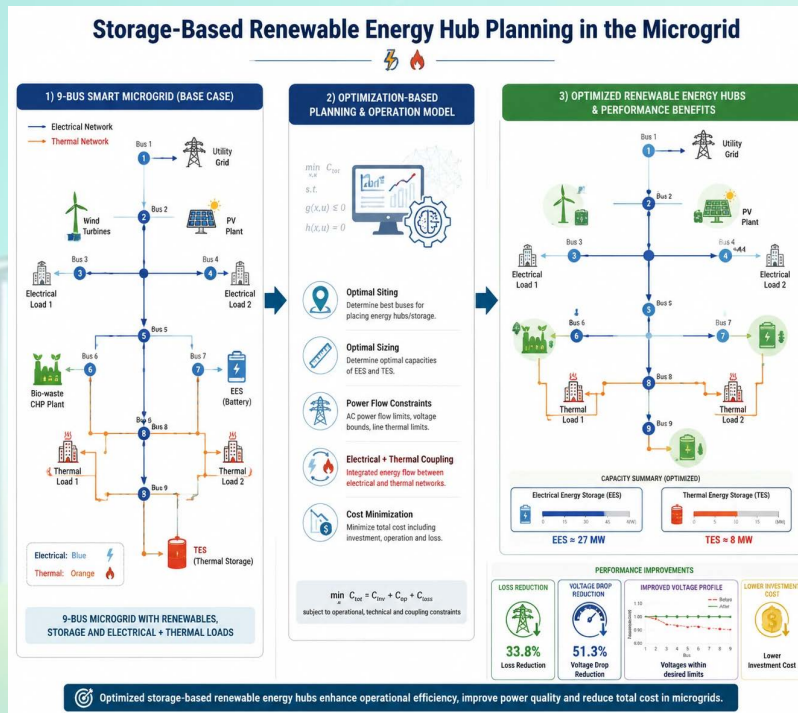
Storage-based Renewable Energy Hubs Sitting and Sizing in the Microgrid

Ehsan Akbari

Highlights

- ❖ Identifying the most optimal locations for deploying EHs within electrical and heating networks,
- ❖ Determining the ideal sizing (capacity) for renewable sources and both electrical and thermal storage solutions within EHs,
- ❖ Designing a renewable hub model capable of managing both active and thermal power simultaneously, and
- ❖ Introducing a combined heat and power (CHP) based BU model for the simultaneous generation of electricity and heat within EHs.

Graphical Abstract



Use your device to scan and read the article online



Citation

E. Akbari," Storage-based Renewable Energy Hubs Sitting and Sizing in the Microgrid," *Journal of Green Energy Research and Innovation*, vol. 3, no. 2, pp. 1-10, 2026.

<https://doi.org/10.61186/jgeri.3.2.1>

© Author





Online ISSN: 3041-9018

Journal of Green Energy Research and Innovation

Journal Homepage: www.jgeri.araku.ac.ir

Storage-based Renewable Energy Hubs Sitting and Sizing in the Microgrid

Ehsan Akbari *

Department of Electrical Engineering, Mazandaran University of Science and Technology, Babol, Iran.

ARTICLE INFO

Keywords:

Allocation and sizing,
Bio-waste unit,
Microgrid,
Optimal planning-operation,
Renewable energy hub.

Article History:

Received: 04 May 2025;
Revised: 09 June 2025;
Accepted: 30 June 2025.

Article type:

Research Article

* **Corresponding authors**

E-mail address
e.akbari@ustmb.ac.ir (E. Akbari)

ABSTRACT

Renewable energy hubs have the potential to significantly improve the technical performance of microgrids while reducing environmental pollutants. This is achieved through efficient energy management within the hubs and determining their optimal capacities and placements in the energy network. This article focuses on the planning and operation of renewable energy hubs integrated with storage systems in microgrids. The objective is to minimize the overall costs related to building resources and storage facilities within these hubs. Key constraints addressed include power flow equations, operational limitations, and the planning-operational model of the hubs. The innovation of this approach lies in combining a comprehensive planning-operation model for renewable energy hubs with the implementation of a bio-waste unit model. The numerical results underscore the effectiveness of this strategy, demonstrating improvements in microgrid performance through efficient hub planning and operation. Specifically, the optimal planning process achieved the lowest construction costs for the hubs, while the optimal operation led to substantial reductions in energy losses and voltage drops within the microgrid by approximately 33.8% and 51.3%, respectively, in comparison with traditional power flow analysis. In this condition for the used case study, the planning cost of EHs is M\$46.43.

1. Introduction

Extensive research has been carried out on the planning and operational management of energy hubs (EHs), reflecting their growing importance in integrated energy systems and modern microgrids. Energy hubs serve as key infrastructures capable of coordinating multiple energy carriers, like electricity, heating, and cooling, while improving overall system flexibility and efficiency. In this context, numerous studies have investigated different modeling approaches to enhance the performance, reliability, and economic viability of EHs. Reference [1] presents a stochastic two-stage optimization model developed to deal with the operational scheduling of EHs under uncertainty. In this framework, electricity and heat storage devices are incorporated to increase operational flexibility. The model explicitly considers uncertainties associated with electrical, heating, and cooling load demands, besides the variability of power generation from wind systems (WSs). Furthermore, demand response (DR) and integrated demand response (IDR) programs are integrated into the operational strategy, allowing the system to adjust consumption patterns in response to supply variations and market conditions. This integration enables a more adaptive and resilient operational structure for the EH. In reference [2], a sustainable long-term planning methodology is proposed for the design of EHs with high penetration of renewable energy sources (RESs). The proposed hubs are capable of simultaneously supplying electrical, heating, and cooling loads while incorporating dedicated storage units for electricity, thermal energy, and cooling energy. To improve planning accuracy, the study considers uncertainties related to load demands and photovoltaic (PV) generation output. The planning problem is formulated as a dynamic optimization model covering a 15-year horizon, allowing decision-makers to evaluate long-term investment strategies and operational performance under evolving system conditions.

Reference [3] investigates the role of stochastic optimization in facilitating the participation of EH-based systems in energy markets. In this work, demand response programs (DRPs) are incorporated into the optimization framework to provide additional operational flexibility. The results demonstrate that the implementation of DRPs can significantly reduce the operational costs of microgrids (MGs). Moreover, these programs contribute to shifting energy consumption from peak-demand periods to off-peak intervals, thereby smoothing the load curve and improving overall system efficiency and stability. A stochastic scheduling approach to multi-EH systems was proposed [4], where the coordinated operation of EHs and distribution networks is addressed. The proposed approach integrates renewable energy sources, uncertain operational parameters, DRPs, and environmental emission considerations into a unified optimization framework. By simultaneously considering these factors, the model enhances the operation of the integrated energy system while promoting more sustainable and environmentally conscious operation. Finally, reference [5] focuses on hydrogen-based micro-EHs, highlighting the growing role of hydrogen technologies in future energy infrastructures. The study emphasizes the integration of hydrogen storage systems alongside IDR mechanisms to improve operational flexibility and energy management. By incorporating hydrogen as an energy carrier and storage medium, the proposed framework supports cleaner energy utilization and provides additional pathways for balancing supply and demand within micro-scale energy systems.

In reference [6], the EH system consists of a WS, PV, and electric vehicles (EVs) that engage in energy exchange within energy and reserve markets. This system incorporates energy, thermal, and gas DRP. However, effectively managing the balance between energy demand and generation remains challenging due to the unpredictable nature of these units. Reference [7] introduces a double-step stochastic model that addresses EH operations in the context of day-ahead and real-time electricity markets. This model adeptly handles uncertainties related to demand fluctuations, RES outputs, and real-time electricity price variations. To minimize the risk of elevated operational costs under unfavorable conditions, the model integrates a value-at-risk (VaR) metric as a risk management tool. A hybrid linear programming-reinforcement learning approach for the optimal supervision of EHs is explored in [8]. Meanwhile, reference [9] focuses on managing energy flow within flexible EHs connected to the main grid. The proposed scheme integrates electricity and heating networks, combining RES, storage systems, and a centralized hub acting as a coordinator. The study decreases the operational costs of these interconnected grids by adopting an ideal power flow model and tailored formulations for flexible EHs. The problem formulation takes into account uncertainties in demand levels, electricity and heat costs, and renewable electricity availability. An unscented transformation method is employed to simplify the problem, enabling faster computation of optimal solutions. Reference [10] delves into energy management for electricity and heating networks, emphasizing the role of renewable EHs in enhancing network flexibility through dynamic pricing services. These EHs include RES, BUs, ESS, and responsive demand mechanisms. BUs provide combined electricity and heat generation. The primary objective is to narrow the gap between network energy costs and the revenue generated from the hub's flexibility. The analysis incorporates optimal power flow constraints, including equality and inequality conditions, as well as restrictions on network flexibility. Furthermore, it considers the operational models of energy generation units, storage systems, and responsive demand within EHs, alongside flexibility modeling for the hub itself. A novel energy hub management strategy is introduced in [11], which combines unified plug-in EV-based demand response with energy storage systems through a hybrid methodology. Meanwhile, [12] presents a two-layer optimization framework for managing energy between two energy hubs. These hubs are operated as a virtual energy hub (VEH) to supply heat, water, and power demands, while also participating in the thermal market and accommodating additional loads within the upstream distribution system's hosting capacity. In [13], a new approach is proposed to tackle complex challenges linked to energy hubs, with a particular focus on addressing issues related to energy transmission and generation within gas and power grids.

Previous research highlights notable gaps in the planning and operation of EHs. Most studies, as reflected in references [3-13], focus on investigating the integration of EHs within various energy networks. These studies primarily explore the selection of appropriate locations and dimensions for EHs. Subsequently, they analyze how the strategic management of energy resources impacts the operational performance of these networks. It is worth noting that the optimal placement and sizing of EHs significantly enhance network operation conditions. However, this subject was explored in few studies, such as [1-2]. Several studies, including [1-8], extensively incorporate renewable energy sources (RESs) like wind and solar. Additionally, bio-waste (BUs) were shown to generate gas from environmental waste, which is then converted into electrical energy, offering a promising solution for reducing environmental pollution. The incorporation of combined heat and power (CHP) within BU can further enable simultaneous production of electricity and heat. Consequently, integrating EHs into energy networks could accelerate the transition to RESs. Despite this potential, only a few researchers, as indicated in [9-10], have addressed this topic comprehensively.

This paper proposes a strategy to address existing research gaps by integrating renewable EHs into MGs utilizing storage solutions. Electric energy production within EHs is realized by integrating various systems, including WS, PV, and BU. Additionally, BU contributes to thermal energy production. EHs are equipped with EES and thermal energy storage (TES) functionalities. This method minimizes the cost of constructing resources and storage elements that constitute an EH. The constraints associated with this task include the planning and operational framework for renewable generation units and storage systems within the EH structure, along with the optimal power flow model of the MG. Upon analyzing prior research and the proposed solution, several innovations are highlighted: 1) Identifying the most optimal locations for deploying EHs within electrical network, 2) Determining the ideal sizing (capacity) for RESs and both electrical and thermal storage solutions within EHs, 3) Designing a renewable hub model capable of managing both active and thermal power simultaneously, and 4) Introducing a CHP based BU model for the simultaneous generation of electricity and heat within EHs.

This paper introduces a comprehensive strategy aimed at bridging the existing research gaps in the planning and operation of renewable-based EHs integrated into MGs. The proposed framework emphasizes the combined use of renewable generation, storage technologies, and bio-waste-based cogeneration to achieve a more efficient and sustainable energy ecosystem.

Within the proposed structure, electric energy generation inside each EH is realized through the integration of multiple renewable subsystems, including WSs, PV units, and a BU. In addition to electricity production, the BU plays a dual role by also contributing to thermal energy generation, thereby enhancing the energy conversion efficiency and supporting CHP operation.

Each EH is further equipped with two key storage components: EES and TES. The inclusion of these elements provides the flexibility required to manage temporal variations in renewable generation and energy demand, ensuring more stable and reliable microgrid performance.

This strategy minimizes the cost associated with constructing and installing the necessary RESs and storage facilities that constitute the EH. To achieve this, the optimization process incorporates both planning and operational constraints, encompassing the technical limits of renewable generation units, the dynamic behavior of storage systems, and the optimal power flow (OPF) model governing the MG's operation. This integrated approach ensures that economic efficiency is achieved without compromising system reliability or network stability.

A detailed comparison with previous research highlights several key innovations introduced by this study:

1. Optimal siting of energy hubs – developing an effective methodology for identifying the most appropriate installation locations of EHs within the microgrid to minimize network losses and improve voltage stability.
2. Optimal sizing of components – determining the ideal capacities of RESs and both electric and thermal energy storage units to balance cost and performance.
3. Dual-domain energy management – designing a renewable hub model capable of jointly managing electrical and thermal power flows, to boost coordination and efficiency of the energy conversion processes.
4. Bio-waste-based CHP modeling – introducing an innovative CHP model derived from a bio-waste unit (BU) to enable the simultaneous production of electricity and thermal energy within each EH, supporting cleaner and more sustainable system operation.

Through this integrated planning–operation approach, the paper provides a robust framework for the deployment of storage-based renewable EHs, contributing to the advancement of sustainable microgrid development and offering a realistic pathway toward optimized energy system design.

In [Section 2](#), the planning and operation of EHs will be outlined. [Section 3](#) will then present the details of the problem data. [Section 4](#) discusses the numerical results obtained from various research scenarios, and finally, the conclusions are addressed in [Section 5](#).

2. Formulation

Scheme of this paper is based on [Figure 1](#).

A) Objective function: [Equation \(1\)](#) presents the objective function of minimizing the cost of constructing RESs and storage facilities within the EHs [14]. This objective reflects the planning-oriented nature of the model, in which optimal decisions regarding the installation and capacity of system components are determined to achieve an economically efficient EH structure.

More specifically, the first three terms in this function represent the investment costs of installing BU, WS, and PV systems. Each of these terms is calculated by multiplying the quantity of installed units and the investment cost of a single unit [14]. This formulation allows the optimization model to find the most appropriate combination and quantity of renewable generation resources within the EHs.

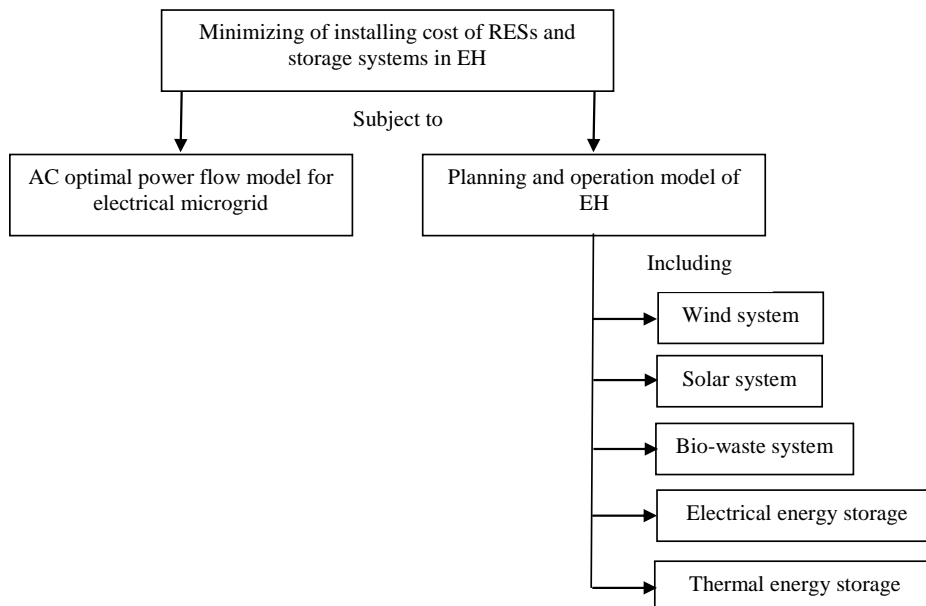


Figure 1. Planning of EH in the electrical MG.

The fourth and fifth terms of the objective function correspond to the installation costs of EES and TES, respectively. In these terms, the total cost is obtained by multiplying the storage capacity by the unit cost of storage with a capacity of 1 MWh. By incorporating these components into the objective function, the model simultaneously optimizes both renewable generation resources and storage capacities in the EHs, ensuring that the overall system configuration achieves the minimum possible investment cost while satisfying the operational and network constraints of the MG.

$$Cost = \sum_e c_B n_{Be} + c_W n_{We} + c_V n_{Ve} + c_E \bar{E}_{Ee} + c_T \bar{E}_{Te} \quad (1)$$

B) Planning and operational constraints of the EH: The subsequent Equations (2)-(20) outline the performance and planning model for RES and storage systems. Equations (2) and (3) address the active and heat power flow within the hub. Active power of the EH, from the MG's perspective, is achieved by summing the power generation of BU, WS, PV, and EES, while deducting the power consumed by passive loads and EES. In the thermal domain of the EH, BU and TES in discharge mode supply the required heat power for loads, while TES in charge mode absorbs energy. The planning-operational model for BUs is presented through Equations (4)-(6) [14]. Equation (4) provides the active power output calculation for BU farms, which involves factors such as the number of BUs, their efficiency, the methane content in production gas, low heating value (LHV), and output gas derived from eco-friendly waste. It is assumed that BUs utilize CHP technology, allowing simultaneous heat and electricity generation. Equation (5) involves the heat power generated by BUs as a component of their active power. Equation (6) defines the maximum number of BUs allowable in the EH system. The operational constraints for WS are defined in Equations (7)-(8) [15]. Equation (7) calculates the total active power of WSs within the EH system. This study identifies four operating zones based on wind output power and wind speed interactions: (1) below cut-in speed, where WS produces no active power; (2) between cut-in and nominal speeds, where power output increases linearly with wind speed; (3) between nominal and cut-out speeds, where power output is constant at nominal levels to avoid mechanical damage; and (4) above cut-out speed, where WS halts operations to prevent damage. Equation (8) addresses the maximum number of WS units that can be installed in the EH. The planning-operation model for PV systems is detailed in Equations (9)-(10) [15]. Equation (9) calculates PV active power output based on system count, efficiency, surface area, and received radiation. Equation (10) limits the number of PV installations permissible in the EH. The EES model is described through Equations (11)-(14) [16]. Equations (11)-(12) address charging and discharging rate limitations of EES. Equation (13) prevents simultaneous charging and discharging states. Equation (14) specifies how total energy stored in EES is computed by adding initial energy to the charging power while subtracting discharging power. Planning constraints for EES are defined in Equation (15), limiting its installed capacity within the EH. The TES operation-planning model is outlined in Equations (16)-(20). This model closely resembles that of EES but substitutes active power with heat power considerations.

$$P_{EH e,h,s} = P_{Ve,h,s} + P_{We,h,s} + P_{Be,h,s} + (P_{DCH e,h,s} - P_{CH e,h,s}) - P_{Ce,h,s} \quad \forall e, h, s \quad (2)$$

$$H_{Be,h,s} + (H_{DCH e,h,s} - H_{CH e,h,s}) - H_{Ce,h,s} \quad \forall e, h, s \quad (3)$$

$$P_{Be,h,s} = n_{Be} \eta_B \rho_{CH4} LHV_{CH4} G_{Be,h,s} \quad \forall e, h, s \quad (4)$$

$$H_{Be,h,s} = \frac{(1 - \eta_B) \eta_H}{\eta_B} P_{Be,h,s} \quad \forall e, h, s \quad (5)$$

$$n_{Be} \in \{1, 2, \dots, \bar{n}_B\} \quad \forall e \quad (6)$$

$$P_{We,h,s} = \begin{cases} 0 & v_{c-in} \leq v_{e,h,s} \leq v_{c-out} \\ n_{We} P_R \frac{v_{e,h,s} - v_{c-in}}{v_r - v_{c-in}} & v_{c-in} \leq v_{e,h,s} \leq v_r \\ n_{We} P_R & v_r \leq v_{e,h,s} \leq v_{c-out} \end{cases} \quad \forall e, h, s \quad (7)$$

$$n_{We} \in \{1, 2, \dots, \bar{n}_W\} \quad \forall e \quad (8)$$

$$P_{Ve,h,s} = n_{Ve} \eta_V A_V I_{Ve,h,s} \quad \forall e, h, s \quad (9)$$

$$n_{Ve} \in \{1, 2, \dots, \bar{n}_V\} \quad \forall e \quad (10)$$

$$0 \leq P_{CH e,h,s} \leq \frac{\bar{E}_{Ee}}{\tau_{EC}} \quad \forall e, h, s \quad (11)$$

$$0 \leq P_{DCH e,h,s} \leq \frac{\bar{E}_{Ee}}{\tau_{ED}} \quad \forall e, h, s \quad (12)$$

$$P_{CH e,h,s} P_{DCH e,h,s} = 0 \quad \forall e, h, s \quad (13)$$

$$\alpha_E \bar{E}_{Ee} \leq \chi_E \bar{E}_{Ee} + \sum_{\tau=1}^h \left(\eta_{EC} P_{CH e,h,s} - \frac{1}{\eta_{ED}} P_{DCH e,h,s} \right) \leq \bar{E}_{Ee} \quad \forall e, h, s \quad (14)$$

$$0 \leq \bar{E}_{Ee} \leq E_{Ee}^{UP} \quad \forall e \quad (15)$$

$$0 \leq H_{CH\ e,h,s} \leq \frac{\bar{E}_{Te}}{\tau_{HC}} \quad \forall e, h, s \quad (16)$$

$$0 \leq H_{DCH\ e,h,s} \leq \frac{\bar{E}_{Te}}{\tau_{HD}} \quad \forall e, h, s \quad (17)$$

$$H_{CH\ e,h,s} H_{DCH\ e,h,s} = 0 \quad \forall e, h, s \quad (18)$$

$$\alpha_H \bar{E}_{Te} \leq \chi_H \bar{E}_{Te} + \sum_{\tau=1}^h \left(\eta_{HC} H_{CH\ e,h,s} - \frac{1}{\eta_{HD}} H_{DCH\ e,h,s} \right) \leq \bar{E}_{Te} \quad \forall e, h, s \quad (19)$$

$$0 \leq \bar{E}_{Te} \leq E_{Te}^{UP} \quad \forall e \quad (20)$$

C) Model of electrical MG: The optimal power flow constraints within an MG are represented in Equations (21) through (27) [17-18]. These equations describe the electrical network behavior and ensure that power flow within the MG operates in a technically feasible and secure manner. The AC power flow model for the MG is defined by Equations (21)-(24), which establish the balance between active and reactive power at the electrical buses of the network. These equations also determine the active and reactive power flows through the electrical distribution lines, ensuring that generation, demand, and network losses are properly balanced at each bus [17-18]. By modeling both active and reactive power interactions, this formulation provides an accurate representation of the electrical behavior of the MG. Equations (25)-(27) further represent the operational limitations of the MG. In particular, Equation (25) considers the allowable limits of voltage magnitude at each bus in order to maintain system stability and acceptable power quality levels. Equation (26) addresses the limits on the magnitude of apparent power transmitted through the distribution lines, preventing thermal overloading of the network conductors. Finally, Equation (27) specifies the permissible boundaries for the apparent power flowing through the distribution substation, ensuring that the substation operates within its rated capacity and maintains reliable interaction between the MG and the upstream grid [17,18].

$$P_{ES\ n,h} + \sum_e J_{En,e} P_{EH\ e,h} + \sum_l I_{EL\ n,l} P_{EL\ n,l,h} = P_{C\ n,h} \quad \forall n, h \quad (21)$$

$$Q_{ES\ n,h} + \sum_l I_{EL\ n,l} Q_{EL\ n,l,h} = Q_{C\ n,h} \quad \forall n, h \quad (22)$$

$$P_{EL\ n,l,h} = G_{EL\ n,l} (V_{n,h})^2 - V_{n,h} V_{l,h} \{G_{EL\ n,l} \cos(\beta_{n,h} - \beta_{l,h}) + B_{EL\ n,l} \sin(\beta_{n,h} - \beta_{l,h})\} \quad \forall n, l, h \quad (23)$$

$$Q_{EL\ n,l,h} = -B_{EL\ n,l} (V_{n,h})^2 + V_{n,h} V_{l,h} \{B_{EL\ n,l} \cos(\beta_{n,h} - \beta_{l,h}) - G_{EL\ n,l} \sin(\beta_{n,h} - \beta_{l,h})\} \quad \forall n, l, h \quad (24)$$

$$V_{LO} \leq V_{n,h} \leq V_{UP} \quad \forall n, h \quad (25)$$

$$\sqrt{(P_{EL\ n,l,h})^2 + (Q_{EL\ n,l,h})^2} \leq \bar{S}_{EL\ n,l} \quad \forall n, l, h \quad (26)$$

$$\sqrt{(P_{ES\ n,h})^2 + (Q_{ES\ n,h})^2} \leq \bar{S}_{ES\ n} \quad \forall n, h \quad (27)$$

3. Problem Data

The method was assessed on a 9-bus MG depicted in Figure 2. The MG operates with a base power of 1 MVA and a base voltage of 1 kV, as reported in [9]. In this system, Bus 1 is considered the reference bus, where the voltage magnitude is fixed at 1 p.u. and the voltage angle is set to zero radians. The technical characteristics of the distribution lines, substations, active loads, and reactive peak loads are provided in [9] and are used as the basis for modeling the electrical network. The allowable range for voltage magnitudes in the system is considered between 0.9 and 1.1 p.u., ensuring acceptable operating conditions for the MG. The hourly electrical load values are determined by multiplying the maximum load by the corresponding hourly load factor, while the daily load factor profile used in this study is obtained from [19]. This approach enables the model to represent realistic daily variations in electricity demand. Data related to RESs, as well as specifications of electricity and thermal storage systems, are taken from [14-15]. These references also provide the daily profiles for wind speed rates, solar radiation rates, and BU gas rates [14-15,19]. The hourly values for wind speed, solar radiation, and BU gas are calculated by multiplying their respective maximum values by the corresponding hourly rate, allowing the model to capture the temporal variability of renewable resources. In this section, EHs are assigned to buses 2-9, enabling distributed integration of renewable resources and storage units across the MG. It is assumed that the load of each hub represents 50% of the total hub load. Additionally, each EH is designed to supply a thermal load with a peak value of 0.2 MW. The daily heat load profile is obtained from [14-15,19], while the combined thermal demand of all EHs is limited to a maximum of 0.8 MW, ensuring that the thermal energy supply remains within the operational capacity of the system.

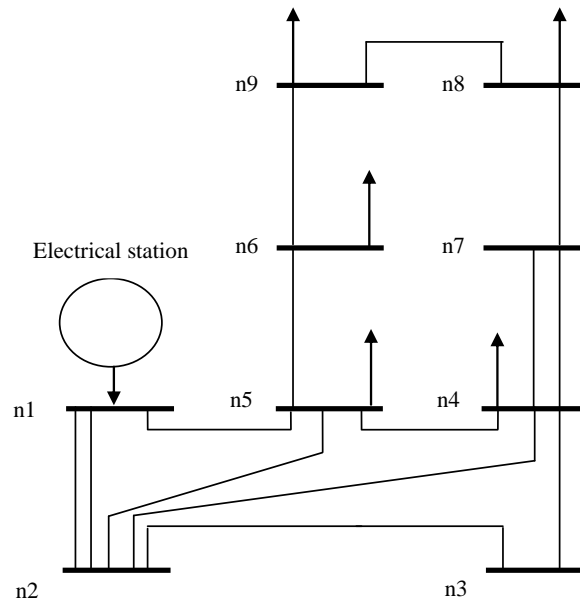


Figure 2. Test MG [9].

4. Results

The approach was implemented according to the problem formulation of Sections 2 and 3 using the GAMS optimization platform. The developed mathematical model, including the objective function and all planning and operational constraints, was coded and executed within this environment. Subsequently, the BONMIN solver was adopted to find the solution of the optimization problem [20]. BONMIN is particularly suitable for handling mixed-integer nonlinear programming problems, which arise due to the presence of nonlinear power flow equations and integer decision variables related to the installation of system components.

After solving the model, the obtained numerical results were analyzed under several different scenarios to assess the performance of the proposed scheme. The main findings and outcomes obtained from these scenarios can be summarized as follows.

A) Planning Status of EHs in Electricity and Heating Grids

The optimal placement of the selected EHs within the MG is illustrated in Figure 3. According to the obtained planning results, three hubs that are solely responsible for electricity generation are installed at buses 2, 5, and 9. These hubs operate as distributed electrical generation units and contribute to meeting the electrical demand of the network without providing thermal energy. In addition, four hybrid hubs that are capable of producing both electrical and thermal energy simultaneously are deployed at buses 4, 6, 7, and 8. The hybrid configuration enables these hubs to support the MG not only through electricity generation but also by supplying the thermal energy required by the system.

As discussed in Section 3, the total thermal power demand of the system is 0.8 MW. Since each EH with thermal capability can provide up to 0.2 MW of heat power, a minimum of four such hubs is necessary to fully satisfy the overall heat requirement. Consequently, the installation of four hybrid EHs ensures that the aggregated thermal production capacity reaches the required 0.8 MW level. This arrangement enables the system to reliably meet the thermal load while maintaining a distributed structure for heat supply, which improves flexibility and reduces dependence on a single thermal source.

From the spatial distribution of the hubs, it can be observed that EH6 and EH7 are located at buses that are electrically farther from the reference bus (bus 1). This placement is deliberate and follows common principles in distribution network planning. In most MG power flow analyses, buses that are located at larger electrical distances from the reference bus are more susceptible to voltage drops due to line impedances and load concentration. Installing generation units at these remote buses introduces local power support, which reduces the amount of power that must be transmitted from the upstream network. As a result, the voltage magnitude at these buses can be improved and the overall voltage profile of the MG becomes more uniform. This local generation support also contributes to enhancing voltage stability and mitigating the risk of excessive voltage deviations during system operation.

The remaining hubs are installed at buses where the connecting distribution lines have relatively higher transmission capacities. Selecting such locations ensures that the electrical power injected by the hubs can be effectively transferred through the network without overloading the lines or violating their thermal limits. This consideration is particularly important when multiple distributed generation units operate simultaneously, as improper placement could lead to congestion in certain branches of the MG. By positioning the hubs in areas with adequate line capacity, the network is able to absorb the generated power more efficiently, thereby maintaining secure operation conditions.

Overall, the obtained placement strategy reflects a balanced approach that simultaneously considers thermal demand satisfaction, electrical network constraints, and voltage support requirements. Through the coordinated installation of purely electrical hubs and hybrid hubs across different buses of the MG, the system benefits from improved operational flexibility, enhanced voltage regulation, and more efficient utilization of the distribution infrastructure. This strategic configuration ultimately contributes to strengthening the overall operational performance and reliability of the MG.

Figure 3 illustrates the size of RES installations and electricity and heat storage components within selected EHs, specifically hubs EH1 through EH7. BU and TES are absent in hubs 1, 3, and 7, as these hubs primarily serve to provide electrical energy. This is because BU and TES are important factors in thermal energy management. These hubs rely on WS and PVs as renewable sources, in addition to EES. In hubs EH1, EH3, and EH7, the number of WSs exceeds that of PVs because, based on findings [14-15], a WS with the same capacity as a PV can generate more energy. Additionally, the installation cost of a 1 MW WS is lower than that of a PV of equal size. Among these three hubs, hub EH1 features the highest number of renewable installations since it is connected to bus 2 (as noted in Figure 3), where the distribution line capacity is substantial. Conversely, hub EH7, connected to bus 9, has fewer renewable resources due to the comparatively lower distribution line capacity associated with bus 9. The size of EES in a hub correlates directly with the number of installed RES. If the number of renewables in a hub is high, the EES capacity is significant; otherwise, it remains smaller. Essentially, EES capacities are designed so that their charging rates align closely with the peak power output of the renewables, enabling them to store an amount of energy equivalent to the maximum output of the renewable systems. BU and WS are installed in hubs EH2, EH4, EH5, and EH6. As BUs also contribute to thermal energy provision, their numbers in these hubs surpass those of WSs. Hubs EH2 and EH4 have more renewable resources compared to hubs EH5 and EH6 due to the higher distribution line capacities connected to hubs EH2 and EH4. Meanwhile, the TES size remains consistent across hubs EH2, EH4, EH5, and EH6.

Table 1 presents a detailed breakdown of the installation costs for renewable and storage components at each hub, along with the total installation cost, as defined by the cost function in Equation (1). The data clearly shows that the installation costs of BUs significantly surpass those of WSs, while WSs have higher construction costs compared to PVs. This is explained by Figure 3, which indicates that the number of installed BUs is highest, while PV installations are the lowest. Additionally, BU units are priced higher than WS and PV units on a per-unit basis.

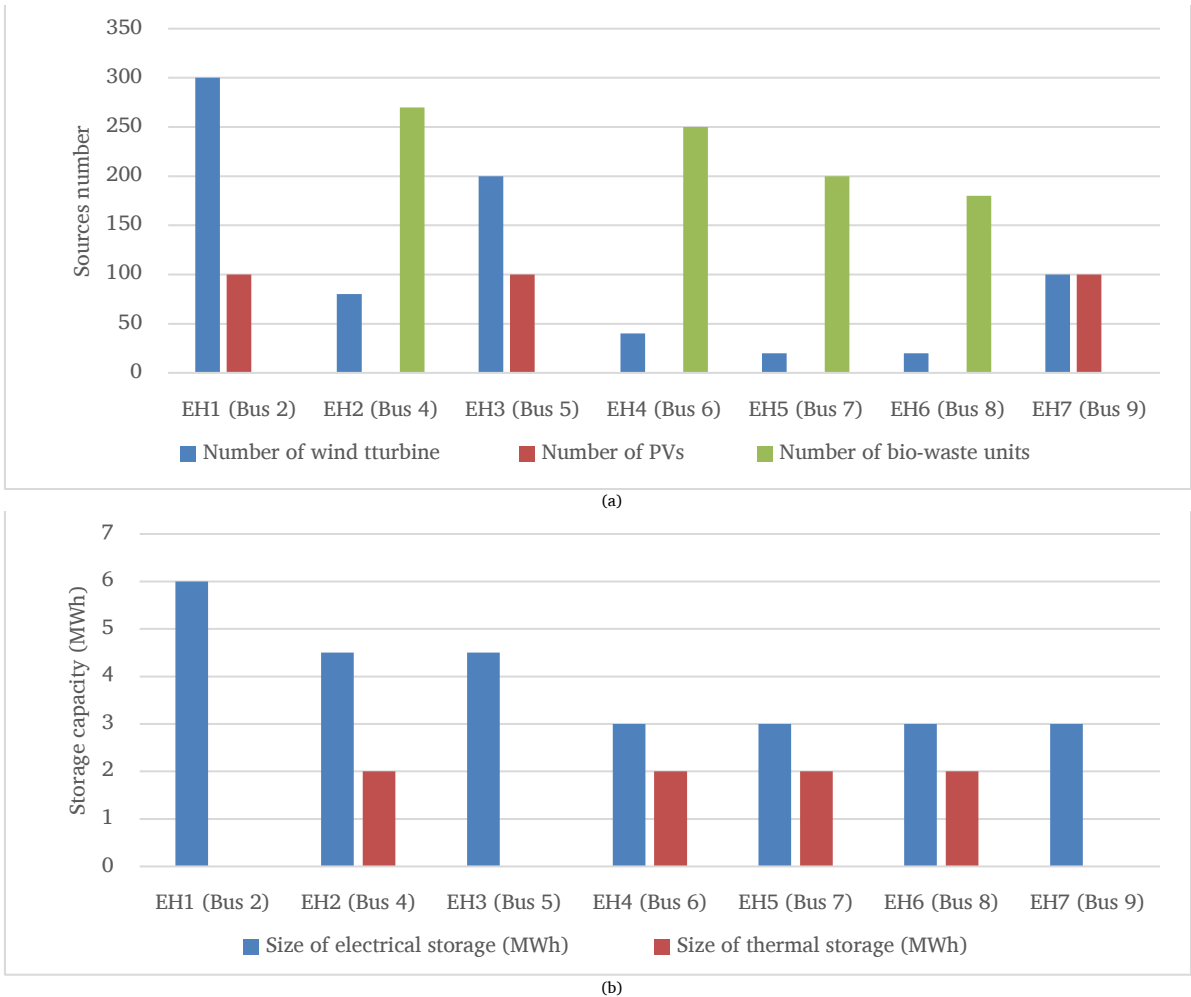


Figure 3. Size of, a) sources, and b) storages in the optimal location of EHs.

Figure 3 further reveals that the installed capacity for EES is approximately 27 MW, whereas TES capacity stands at about 8 MW. Based on references [14-15], the unit cost of EES is greater than that of TES, meaning EES incurs higher installation costs among storage systems. Ultimately, the total installation cost for the proposed scheme amounts to approximately M\$46.43.

B) Analysis of the operational status of the electric and heating networks reveals the performance indicators presented in Table 2. These indicators include energy loss (EL), maximum voltage drop (MVD), and maximum overvoltage (MOV), which are evaluated for two different conditions: load flow analysis (Case I) and the proposed design (Case II). In Case I, a conventional load flow study is performed for the MG without the installation of EHs. In contrast, Case II considers the complete optimization framework represented by model (1)-(27), where EH planning and operational constraints are incorporated into the system. The comparison between these two cases allows the effectiveness of the proposed scheme to be clearly evaluated. According to the results, Case I exhibits the highest values of energy loss and voltage drop within the network. However, when the proposed design is applied in Case II, both EL and MVD are significantly reduced, while only a small amount of overvoltage is introduced, equal to 0.011 p.u. Under this improved configuration, the energy loss in the electrical network decreases by approximately 33.8% $((3.673 - 2.432)/3.673)$. In addition, the maximum voltage drop is reduced by about 51.3% compared with the results obtained from the basic power flow analysis. Furthermore, the overvoltage observed in Case II remains well within the acceptable operational limit of 0.1 p.u. $(1.1 - 1)$. This confirms that the proposed planning and operational strategy not only improves the efficiency of the MG by reducing network losses and voltage drops, but also maintains the voltage profile within safe and reliable operating boundaries.

5. Conclusion

The research focused on identifying the most suitable locations and capacities for renewable EHs that are integrated with both electrical and thermal energy storage systems within an MG. The primary aim was to reduce the overall expenditure related to the installation of renewable generation units as well as the associated storage infrastructures in these energy hubs. In this context, the minimization of the total investment and deployment cost was defined as the main objective function of the optimization problem. To properly represent the interactions between the distribution network and the energy hubs, the objective function was developed in conjunction with the optimal power flow equations of the MG. In addition, the planning and operational characteristics of the EHs were incorporated into the formulation. By combining these elements, a comprehensive modeling framework was established that simultaneously captures the operational behavior of the MG and the strategic planning aspects of the EHs, enabling coordinated decision-making for both network operation and hub deployment. The numerical results demonstrated that the optimal strategy involved installing EHs at buses located farther from the reference bus in order to reduce the risk of significant voltage drops in the network. At the same time, some EHs were connected to buses closer to the reference bus, where a higher number of power transmission lines are available. This configuration helps reduce energy losses in the MG by taking advantage of stronger network connectivity at those buses. Therefore, the placement of EHs was performed in a balanced manner to improve both voltage profile and energy efficiency in the system. Among the renewable sources considered in the study, the BU had the highest installation rate because it is the only unit responsible for providing thermal energy within the network. In contrast, the number of WS units installed was higher than that of PV units. This difference is mainly due to the lower unit cost of WS compared with PV, which makes WS more economically attractive in the optimization process. The sizing of storage systems was also closely related to the number of renewable generation units installed in the EHs. In fact, an increase in the number of renewable power sources led to a proportional increase in the required storage capacity. Consequently, the capacities of EES and TES expanded as the renewable generation capacity increased, ensuring proper energy balancing and operational flexibility in the hubs. The proposed planning and energy management approach for EHs significantly improved the operational performance of the MG. In comparison with conventional load flow studies, the proposed design reduced energy losses by approximately 33.8% and decreased maximum voltage drops by about 51.3%. These results confirm the effectiveness of integrating renewable EH planning with MG operational constraints. The scheme enables the selection of the most suitable locations for integrating EHs into electrical networks. Second, it optimizes the sizing and capacity of RES as well as electrical and thermal storage systems within EHs. Third, it develops a renewable EH model capable of efficiently managing both active and thermal power simultaneously. Fourth, it implements a CHP to BU model that allows the simultaneous production of electricity and heat within EHs. In the proposed design, renewable resources and load demand inherently involve uncertainties. Therefore, stochastic, probabilistic, or robust modeling approaches should be considered in order to accurately represent these uncertainties. In the present paper, deterministic models were used for renewable generation and load demand. However, incorporating uncertainty modeling is considered as an important direction for future work in the proposed design.

Table 1. Installing cost (10^3 \$) of sources and storages in the selected EHs.

Energy hub	Location	WS	PV	BU	EES	TES	Total cost (103 \$)
EH1	Bus 2	4500	2000	0	360	0	6860
EH2	Bus 4	1200	0	8100	270	100	9670
EH3	Bus 5	3000	2000	0	270	0	5270
EH4	Bus 6	600	0	7500	180	100	8380
EH5	Bus 7	300	0	6000	180	100	6580
EH6	Bus 8	300	0	5400	180	100	5980
EH7	Bus 9	1500	2000	0	180	0	3680
Total cost (\$)		11400	6000	27000	1630	400	46430

Table 2. Value of operation indices of network.

Variable	EL (MW)	MVD (p.u.)	MOV (p.u.)
Case I	3.673	0.111	0
Case II	2.432	0.054	0.011

Nomenclature

Indices

e	Energy Hub (EH)
h	Operation hours
l	Auxiliary index corresponding to bus
n	Bus

Variables

\bar{E}_E	The installed capacity of electric energy storage (EES) in EH (MWh)
\bar{E}_T	The installed capacity of thermal energy storage (TES) in EH (MWh)
H_B	Heat power of bio-waste unit (BU) (MW)
H_{CH}	Heat power of TES in charge mode (MW)
H_{DCH}	Heat power of TES in discharge mode (MW)
n_B	Installed number of BUs in EH
n_V	Installed number of photovoltaics (PV) in EH
n_W	Installed number of wind systems (WS) in EH
P_B	Active power of BU (MW)
P_{CH}	Active power of EES in charging mode (MW)
P_{DCH}	Active power of EES in discharge mode (MW)
P_{EH}	Active power of EH from the microgrid's viewpoint (MW)
P_{EL}	Active power flow in the electric distribution line (MW)
P_{ES}	Active power flow in the electrical distribution substation (MW)
P_V	Active power of PVs (MW)
P_W	Active power of WS (MW)
Q_{EL}	Reactive power flow in the electric distribution line (MVar)
Q_{ES}	Reactive power flow in the electrical distribution substation (MVar)
V	Voltage magnitude (p.u.)
β	Voltage angle (rad)

Parameters

A_V	Area of PV (m^2)
B_{EL}	Susceptance of electric distribution line (p.u.)
c_B	The cost of installing a BU in EH (\$)
c_E	Installation cost of EES with a capacity of 1 MWh (\$/MWh)
c_T	Installation cost of TES with a capacity of 1 MWh (\$/MWh)
c_V	The cost of installing a PV in EH (\$)
c_W	The cost of installing a WS in EH (\$)
E_E^{UP}	Maximum installable size of EES in EH (MWh)
E_T^{UP}	Maximum installable size of TES in EH (MWh)
G_B	Gas emission from environmental waste (m^3)
G_{EL}	Conductivity of electrical distribution line (p.u.)
H_C	Heat load (MW)
I_{EL}	Incidence matrix of distribution lines and buses
J_E	Incidence matrix of EH and bus
I_V	Solar radiation (kW/m^2)
LHV_{CH4}	Low heat volume (kW/m^3)
\bar{n}_B	Maximum installable number of BUs in EH
\bar{n}_V	Maximum installable number of PVs in EH
\bar{n}_W	Maximum installable number of WSs in EH
P_C	Active load (MW)
P_R	Nominal active power of WS (MW)
Q_C	Reactive load (MVar)
\bar{S}_{EL}	Maximum apparent power flow in the electrical distribution line (MVA)
\bar{S}_{ES}	Maximum apparent power flow in the electrical distribution substation (MVA)
v	Wind speed (m/s)
v_{c-in}	Cut-in wind speed (m/s)
v_{c-out}	Cut-out wind speed (m/s)
V_{LO}	Minimum voltage magnitude (p.u.)
v_r	Nominal wind speed (m/s)
V_{UP}	Maximum voltage magnitude (p.u.)
α_E	The ratio between the least and highest energy storage of EES
α_H	The ratio between the least and highest energy storage of TES
χ_E	The ratio between the initial energy and the highest energy storage of EES
χ_H	The ratio between the initial energy and the highest energy storage of TES
η_B	The efficiency of the electrical sector of BU
η_{EC}	EES efficiency in charging mode
η_{ED}	EES efficiency in discharge mode
η_H	Efficiency of the thermal sector of BU
η_{HC}	TES efficiency in charging mode
η_{HD}	TES efficiency in discharge mode
η_V	PV efficiency
ρ_{CH4}	Percentage of methane in BU gas
τ_{EC}	Charging period in EES
τ_{ED}	Discharge period in EES
τ_{HC}	Charge period in TES
τ_{HD}	Discharge period in TES

References

- [1] S. Mansouri, A. Ahmarinejad, et al., "A Multi-Stage Joint Planning and Operation Model for Energy Hubs Considering Integrated Demand Response Programs," *International Journal of Electrical Power & Energy Systems*, vol. 140, 108103, 2022.
- [2] H. A. Honarmand, and S. M. Rashid, "A Sustainable Framework for Long-Term Planning of the Smart Energy Hub in the Presence of Renewable Energy Sources, Energy Storage Systems and Demand Response Program," *Journal of Energy Storage*, vol. 52, 105009, 2022.
- [3] W. Jiang, X. Wang, H. Huang, D. Zhang, and N. Ghadimi, "Optimal Economic Scheduling of Microgrids Considering Renewable Energy Sources Based on Energy Hub Model Using Demand Response and Improved Water Wave Optimization Algorithm," *Journal of Energy Storage*, vol. 55, 105311, 2022.
- [4] V. Thang, T. Ha, Q. Li, and Y. Zhang, "Stochastic Optimization in Multi-Energy Hub System Operation Considering Solar Energy Resource and Demand Response," *International Journal of Electrical Power & Energy Systems*, vol. 141, 108132, 2022.
- [5] H. Zhang, Y. Chen, K. Liu, and S. Dehan, "RETRACTED: A Novel Power System Scheduling Based on Hydrogen-Based Micro Energy Hub," *Energy*, vol. 251, 123623, 2022.
- [6] E. Mokaramian, H. Shayeghi, F. Sedaghati, A. Safari, and H. H. Alhelou, "An Optimal Energy Hub Management Integrated EVs and RES Based on Three-Stage Model Considering Various Uncertainties," *IEEE Access*, vol. 10, pp. 17349–17365, 2022.
- [7] A. R. Jordehi, "Two-Stage Stochastic Programming for Risk-Aware Scheduling of Energy Hubs Participating in Day-Ahead and Real-Time Electricity Markets," *Sustainable Cities and Society*, vol. 81, 103823, 2022.
- [8] A. Ghadertootoonchi, M. Moeini-Aghaie, and M. Davoudi, "A Hybrid Linear Programming-Reinforcement Learning Method for Optimal Energy Hub Management," *IEEE Transactions on Smart Grid*, vol. 14, no. 1, pp. 157–166, 2023.
- [9] X. Zhang, X. Yu, X. Ye, and S. Pirouzi, "Economic Energy Management of Networked Flexi-Renewable Energy Hubs According to Uncertainty Modeling by the Unscented Transformation Method," *Energy*, vol. 278, 128054, 2023.
- [10] E. Akbari, S. F. Mousavi Shabestari, S. Pirouzi, and M. Jadidoleslam, "Network Flexibility Regulation by Renewable Energy Hubs Using Flexibility Pricing-Based Energy Management," *Renewable Energy*, vol. 206, pp. 295–308, 2023.
- [11] A. Karthikeyan, and V. Arun, "Enhancing Energy Hub Management with Unified Plug-In Electric Vehicle Based Demand Response and Energy Storage Systems," *Journal of Energy Storage*, vol. 108, 114997, 2025.
- [12] Y. Pezhmani, and N. Rezaei, "Risk-Averse Energy Management of a Water-Heat-Power Virtual Energy Hub Considering Hosting Capacity and Volt-VAR Control of Distribution Network," *Energy*, vol. 318, 134949, 2025.
- [13] L. Yan, X. Deng, and J. Li, "Integrated Energy Hub Optimization in Microgrids: Uncertainty-Aware Modeling and Efficient Operation," *Energy*, vol. 291, 130391, 2024.
- [14] M. R. Jokar, S. Shahmoradi, et al., "Stationary and Mobile Storages-Based Renewable Off-Grid System Planning Considering Storage Degradation Cost Based on Information-Gap Decision Theory Optimization," *Journal of Energy Storage*, vol. 58, 106389, 2023.
- [15] A. Maleki, and A. Askarzadeh, "Optimal Sizing of a PV/Wind/Diesel System with Battery Storage for Electrification to an Off-Grid Remote Region: A Case Study of Rafsanjan, Iran," *Sustainable Energy Technologies and Assessments*, vol. 7, pp. 147–153, 2014.
- [16] A. Azarhooshang, D. Sedighzadeh, and M. Sedighzadeh, "Two-Stage Stochastic Operation Considering Day-Ahead and Real-Time Scheduling of Microgrids with High Renewable Energy Sources and Electric Vehicles Based on Multi-Layer Energy Management System," *Electric Power Systems Research*, vol. 201, 107527, 2021.
- [17] M. Roustaei, and A. Kazemi, "Multi-Objective Stochastic Operation of Multi-Microgrids Constrained to System Reliability and Clean Energy Based on Energy Management System," *Electric Power Systems Research*, vol. 194, 106970, 2021.
- [18] A. Rohani, M. Abasi, A. Beigzadeh, M. Joorabian, and G. B. Gharehpajian, "Bi-level Power Management Strategy in Harmonic-polluted Active Distribution Network Including Virtual Power Plants," *IET Renewable Power Generation*, vol. 15, no. 2, pp. 462–476, 2021.
- [19] Z. Qu, C. Xu, F. Yang, F. Ling, and S. Pirouzi, "Market Clearing Price-Based Energy Management of Grid-Connected Renewable Energy Hubs Including Flexible Sources According to Thermal, Hydrogen, and Compressed Air Storage Systems," *Journal of Energy Storage*, vol. 69, 107981, 2023.
- [20] M. R. Bussieck, and A. Meeraus, "General Algebraic Modeling System (GAMS)," *Applied Optimization*, pp. 137–157, 2004.

Declaration of competing interest

The author declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the author.

Bibliography



Ehsan Akbari received the B.Sc. degree in Electrical Power Engineering from Mazandaran University, Babolsar, Iran, in 2009 and M.S. degree in Electrical Power Engineering from Mazandaran University of Science and Technology, Babol, Iran, in 2014. He received Ph.D. in Electrical Power Engineering from Isfahan University of Technology, Isfahan, Iran in 2022. He is now a Assistant Professor at Department of Electrical Engineering, Mazandaran University of Science and Technology, Babol, Iran. He is the author of 25 books and more than 355 papers in reputed journals and conferences and won six patents in his research fields. He has obtained five provincial scientific and technological progress awards. His main areas of research are power quality, flexible AC transmission systems (FACTS), application of power electronics in power systems, power electronics multilevel converters, smart grids, control of grid-connected converters, fault location, distributed generation, energy storage systems, micro-grids, voltage stability, electrical machines, special electrical machinery, HVDC systems, harmonics, reactive power control using hybrid filters and renewable energy systems.

Email: e.akbari@ustmb.ac.ir

ORCID: [0000-0002-53185673](https://orcid.org/0000-0002-53185673)

Contribution Statement: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Roles/Writing - original draft, Writing-review & editing.