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Development and analysis of scheduling strategies for utilizing shared energy storage system in networked microgrids

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ABSTRACT

The proliferation of microgrid installations has led to the emergence of networked microgrids, where individual microgrids are interconnected to maximize their benefits and assist the grid. Each individual microgrid in a networked microgrid is equipped with renewable energy sources. To address the intermittent and variable nature of renewable energy sources, energy storage systems are integrated into individual microgrids or networked microgrids. However, implementing energy storage systems for each microgrid can be expensive and space-consuming. To mitigate these challenges, the concept of shared energy storage system is introduced and applied to networked microgrids. This paper presents a comprehensive study focusing on cost minimization of networked microgrids through scheduling strategies, for the effective deployment of shared energy storage systems. Various approaches based on supply–demand imbalance, time-of-use prices, forecasted generation, and load considerations are investigated. The proposed strategies are implemented in two topologies: a networked microgrid framework with independent energy storage system and a networked microgrid framework with shared energy storage system. The networked microgrid framework topology consists of three interconnected microgrids. Numerical results indicate that the scheduling strategies lead to substantial cost savings, with up to 25.58% reduction in operating costs achieved through the incorporation of shared energy storage systems and intelligent scheduling strategies. These findings enhance the reliability and practical applicability of the proposed approaches for optimizing networked microgrid operations.

1. Introduction

Microgrids (MGs) have emerged as an effective framework for localizing power generation and consumption through the interconnection of Distributed Energy Resources (DERs) and loads within an electrical boundary. Each MG can operate in grid-connected mode and islanded mode. In MGs, MG Central Controller (MGCC) is deployed to coordinate the DERs and load within an MG. The MGCC is responsible for the management of MG operations under various conditions. MGCC serves as the central point for communication and control of resources. MGs provide a range of services that can benefit both the MG and the grid in terms of economics, security, and clean energy. Since the integration of MGs into the electrical grid has progressed, Networked Microgrids (NMGs) concept has attracted a lot of interest. The IEEE standard 1547.4 [1] demonstrated that modeling major power grids by a network of interconnected MGs considerably improves network reliability, sustainability, and resilience. NMGs are interconnected MGs that can operate independently or in parallel with the grid. In an NMG framework, each MG can generate and store its own energy using renewable or traditional sources. The MGs can employ various types of Energy Storage Systems (ESS), such as batteries, flywheels, etc. NMGs assist the grid with energy management, frequency regulation, voltage regulation, etc. NMGs with interconnected MGs can provide these services more efficiently and effectively than standalone MGs. NMG framework allows MGs to increase profits by trading energy with other MGs or the grid [2,3]. Individual MGs in the NMG framework can share energy resources and services with other interconnected MGs [2]. The practice of exchanging power between NMGs and/or between MGs and the main grid is referred to as "energy trading''. It enables the effective use of resources and can aid in balancing demand and supply within the NMG framework. By trading energy within the NMG framework, participants can avoid costly transmission fees and other charges associated with purchasing power from the main grid. This leads to lower energy costs for both producers and consumers in the NMG. Different architectures are proposed for energy trading in NMGs, such as centralized, decentralized, hybrid, hierarchical, and market-based.

NMGs incorporate ESS as a crucial element due to the variable and intermittent nature of RES in each MG. The incorporation of ESS

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into MGs results in lower operational costs, enhanced resilience and stability, reduced maximum demand, environmental benefits, and augmented participation in demand response programs [4,5]. Nonetheless, the integration of ESS requires significant space and comes at a high cost. Also, ESS such as Battery Energy Storage Systems (BESS) have a limited life span and need to be replaced after a certain number of charging–discharging cycles or a specified lifespan. To overcome these disadvantages and bring new economic opportunities, the concept of shared economy has been introduced for ESS, known as Shared ESS (SESS). In SESS, multiple users invest in or combine, to operate the ESS, allowing them to charge and discharge the ESS according to their needs [6]. SESS has a large capacity that enables users to often charge and discharge while also utilizing energy stored by other users as an additional energy source, in turn reducing the electricity price [7]. According to [4], SESS can be implemented through both direct and indirect approaches. In the direct approach, external ESS is implemented or the Individual ESS (IESS) are interconnected with each other. In an indirect approach, IESS shares only the stored energy and cannot share the capacity. In [4], SESS is classified as: a) community ES b) cloud ES c) virtual ES.

In [8], a probabilistic optimization approach for scheduling NMGs is proposed, under conditions of uncertainty. In the proposed Energy Management System (EMS), the BESS is charged/discharged within the MGs. The BESS is utilized to maintain the generation and load balance in NMGs and decrease the cost to customers. A three-stage approach for resilience-constrained scheduling of NMGs, which includes the utilization of the BESS to support the scheduling decisions is proposed in [9]. In the proposed method, the second stage involves the development of a scheduling plan that takes into account the identified contingency scenarios. In [10], a two-stage robust optimization model is proposed for the scheduling of DERs in MGs of the NMG framework considering uncertainties and outages. The BESS is charged/discharged based on energy balance or in the event of an outage. In [11], the ESS is utilized to maintain energy balance and provide backup power in case of sudden power failures or outages. In [12], the BESS is utilized to improve the resiliency of NMGs against real-time failures by providing a backup power supply, load shifting, renewable energy integration, and voltage regulation. In [13], the ESS is utilized to facilitate distributed Peer-to-Peer (P2P) trading among MGs in an active distribution network. It allows MGs to manage their energy supply and demand better. A hybrid ESS is utilized to optimize the economic schedule for NMGs in [14]. The BESS is used for long-term energy storage, while the super-capacitor ESS is used for short-term energy storage and rapid response to load changes. In [15], ESS in each MG of NMG framework are coordinated through a centralized dispatch algorithm that takes into account the state of the ESS in all MGs. The dispatch algorithm determines the optimal charging/discharging schedules for each ESS, based on the current state of the MG and the predicted energy demand and RES generation.

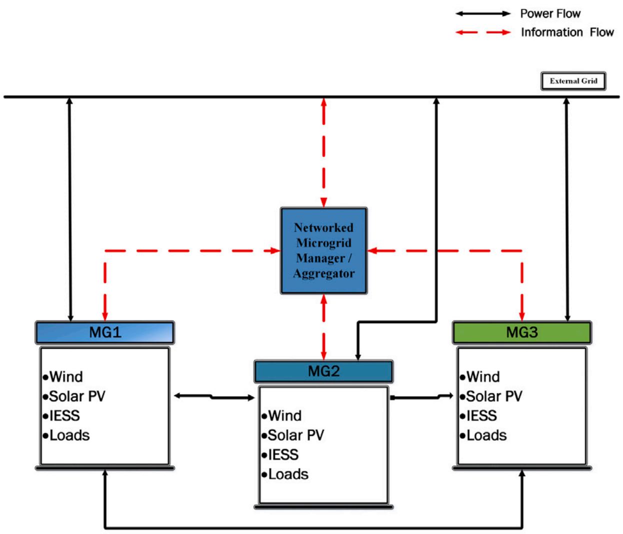
Literature on the utilization of SESS in various forms for different households, buildings, apartments, and communities is abundant. However, research on the application of SESS for NMGs is limited. In [16], a day-ahead economic optimal dispatch model for a cluster of MGs with an SESS is proposed. The scheduling algorithm considers the energy demand and supply of the MGs, the capacity of the SESS, the P2P transaction prices, and the electricity grid constraints to optimize the usage of SESS. In [17], an optimal dispatch model for NMG with an SESS is proposed while considering uncertainties in RES and load forecasting. A day-ahead bidding strategy to schedule the usage of a cloud ESS serving multiple heterogeneous MGs in the electricity market is proposed in [5]. The MGs are assumed to make long-term and short-term agreements with cloud ESS, which is considered a retailer among MGs and the electricity market. A bi-level optimization problem formulation for coordinating the operation of MGs with cloud ESS is proposed in [18]. The upper-level problem is formulated as a cloud ESS scheduling problem, while the lower-level problem is formulated as an optimal power flow problem for each MG. A bi-level optimization problem is proposed in [19], where cloud ESS coordinates the energy exchange among the MGs. The cloud ESS operator acts as a coordinator among the MGs and the grid. This trade is performed based on information collected from the CESS operators of different MGs.

The literature presented above examines the diverse applications of ESS in improving the performance of NMGs. However, there is a lack of existing literature that specifically compares the utilization of ESS or the scheduling of ESS, such as in IESS and SESS, under different conditions. This research paper aims to address this gap by conducting a comparative analysis of scheduling strategies to optimize the utilization of IESS and SESS in NMGs for the day-ahead market. The strategies proposed for NMGs with IESS are based on load imbalance, TOU prices, or a combination of both. For NMGs equipped with SESS, strategies described in IESS are implemented. Additionally, a new strategy is proposed based on forecasted generation and load, during different TOU periods. This study also addresses energy trading within the NMG, where a reciprocal trade approach is considered. Moreover, the paper introduces a novel method for determining the energy exchange prices within NMG considering total generation and load in an NMG, FIT, and TOU price. In this work, the evaluation of various strategies, determination of energy trading prices, and energy trading within NMG and the grid are conducted with the objective of minimizing the overall operating cost of NMGs.

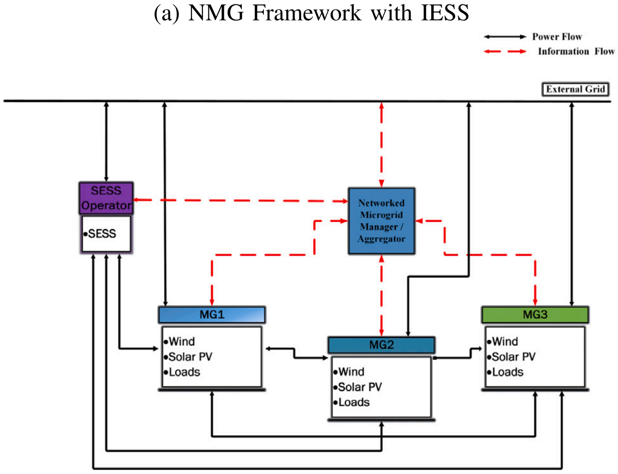
In Section 1 the NMG framework is introduced, and the utilization of ESS in NMGs for achieving various objectives is given. Section 2 addresses the research objective and the constraints associated with it. This section provides insights into the energy trading framework considered in the study and details the formulation used to calculate energy trading prices. Section 3 presents an in-depth analysis on the different strategies proposed in this work for the optimal utilization of IESS and SESS in NMGs. Additionally, this section provides system data considered in this study. Finally, it discusses the results obtained from implementing the strategies. In Section 4, the paper concludes by summarizing the results obtained from the research.

2. Problem formulation

The main objective of this research, is to minimize the overall operating cost of NMG. To achieve this goal, the study focuses on two key aspects: day-ahead optimal scheduling of IESS and SESS in NMGs, as well as energy trading within the NMG. The scheduling aspect involves considering various factors such as RES power output and load demand within NMG, and TOU pricing from the external grid. By optimizing the scheduling of IESS and SESS based on these parameters, cost minimization is achieved. The energy trading within NMG depends on excess and deficit energy at a particular hour for each MG. This means that if a particular MG has an excess of energy beyond its load requirements during a certain hour, it can trade that surplus energy with other MGs that may be facing a deficit or higher demand. The energy trading mechanism enables NMGs to balance demand and supply, optimize resource utilization, and lead to cost minimization. The formulation of energy trading prices is based on several factors, including Feed-in Tariffs (FIT), and TOU pricing from the grid, as well as load and generation within the NMG system. By considering these variables and formulating appropriate energy trading prices, the research aims to facilitate efficient and economically viable energy exchange for the NMG. The NMG framework, incorporating both IESS and SESS, is illustrated in Fig. 1. Each MG within the NMG consists of various components, including loads, RES such as solar PV, wind turbines, and ESS. The MGCC of each MG communicates information about excess and deficit energy to the NMG manager/aggregator. The NMG manager/aggregator decides the amount of energy to be traded among the MGs. The MGs can share energy among themselves using dedicated power lines. In both the cases, the MGs have the option to



(a) NMG Framework with IESS



(b) NMG Framework with SESS

Fig. 1. NMG framework with IESS and SESS.

trade energy with the grid, and the ESS can also engage in energy trading with the grid.

For NMG framework with IESS, as shown in Fig. 1(a), each MG is equipped with its own individual ESS. The NMG framework with SESS is depicted in Fig. 1(b), where the ESS is shared among the MGs. In this framework, MGs trade energy with the SESS through dedicated lines. The SESS operator/SESS acts as an individual player and has an independent decision-making system.

2.1. Objective function

The objective is to minimize the total operating cost of the NMG system. The operating cost includes:

- the operation and maintenance cost of RES in each MG.
- the cost of energy traded with the grid.
- the cost of energy traded within NMG.
- the cost of energy traded with ESS.

The objective function is given below in Eq. (1).

$$Min\,C = \sum_{i=1}^{MG} C^{i}_{OM} + C^{i}_{G,TD} + C^{i}_{N,TD} + C^{i}_{ESS} \tag{1}$$

Where C, represents the total operation cost of NMG, C^{i}_{OM}, is the Operation and Maintenance (O&M) cost of RES in MG_i, $C^{i}_{G,TD}$, is the cost of energy trading with the grid by MG_i, $C^{i}_{N,TD}$, is the cost of energy traded within NMG by MG_i, C^{i}_{ESS}, is the cost of energy exchanged with ESS by MG_i, MG is the total number of MGs in NMG.

2.1.1. Operation and maintenance (O&M) cost

The O&M is the cost associated for operating and maintaining the RES. The O&M cost of the RES in each MG_i is given in Eq. (2).

$$C^{i}_{OM} = \sum_{t=1}^{T} \rho^{i,t}_{PV}.P^{i,t}_{PV} + \rho^{i,t}_{WT}.P^{i,t}_{WT} \tag{2}$$

Where $\rho^{i,t}_{PV}$, is the (O&M) cost of PV, $P^{i,t}_{PV}$, is the power generated by PV in MG_i at time t, $\rho^{i,t}_{WT}$, is the (O&M) cost of WT, $P^{i,t}_{WT}$ is the power generated by WT in MG_i at time t, T is the total number of operated hours.

2.1.2. Cost of energy traded with grid

In instances when the load exceeds the generation, the MG_i purchases power from the grid because IESS/SESS or NMG trading cannot supply the deficit energy. When generation exceeds load, the MG_i sells the extra energy to the grid after charging IESS/SESS and/or NMG trading. The cost for energy traded by each MG_i with the grid is given in Eq. (3).

$$C^{i}_{G,TD} = \sum_{t=1}^{T} \rho^{i,t}_{b,G}.P^{i,t}_{b,G} - \rho^{i,t}_{s,G}.P^{i,t}_{s,G} \tag{3}$$

Where $\rho^{i,t}_{b,G}$, is the electricity price at which MG_i buy electricity from the grid, $P^{i,t}_{b,G}$, the amount of energy bought by MG_i from the grid at time t, $\rho^{i,t}_{s,G}$, is the electricity price at which MG_i sell electricity to the grid, $P^{i,t}_{s,G}$, the amount of energy sold by MG_i to the grid at time t.

2.1.3. Cost of energy traded within NMG

The MGs with excess/deficit energy trade energy within the NMG to satisfy the load and minimize the cost. The cost for energy traded by each MG_i within in the NMG is given in Eq. (4).

$$C^{i}_{N,TD} = \sum_{t=1}^{T} \rho^{i,t}_{b,N}.P^{i,t}_{b,N} - \rho^{i,t}_{s,N}.P^{i,t}_{s,N} \tag{4}$$

Where $\rho^{i,t}_{b,N}$, is the electricity price at which MG_i buy electricity from the NMG, $P^{i,t}_{b,N}$, the amount of energy bought by MG_i from the NMG at time t, $\rho^{i,t}_{s,N}$, is the electricity price at which MG_i sell electricity to the NMG, $P^{i,t}_{s,N}$, the amount of energy sold by MG_i to the NMG at time t.

2.1.4. Cost of energy traded with ESS

In the NMG framework with SESS, the SESS operates as an individual entity and sells/buys the energy to/from NMG or the grid based on the proposed strategy. The cost for energy exchanged by each MG_i with ESS is given in Eq. (5).

$$C^{i}_{ESS} = \sum_{t=1}^{T} \rho^{i,t}_{b,ESS}.P^{i,t}_{b,ESS} - \rho^{i,t}_{s,ESS}.P^{i,t}_{s,ESS} \tag{5}$$

Where $\rho^{i,t}_{b,ESS}$, is the electricity price at which MG_i buy electricity from ESS, $P^{i,t}_{b,ESS}$, the amount of energy bought by MG_i from ESS at time t, $\rho^{i,t}_{s,ESS}$, is the electricity price at which MG_i sell electricity to ESS, $P^{i,t}_{s,ESS}$, the amount of energy sold to MG_i from ESS at time t.

2.2. Constraints

The objective considered in this work should satisfy the power balance in each MG and ESS charging/discharging constraints.

2.2.1. Power balance

At any time ‘t’, the sum of power generated in MG_i must balance the power consumption as shown in Eq. (6). The power generation in the MG_i consists of power generated by RES within MG_i, power bought from the grid or NMG, and discharging of IESS/power bought from the SESS. The power consumption in MG_i consists of the load in MG_i, power sold to the grid or NMG, and charging of IESS/power sold to the SESS.

$$P_{PV}^{i,t} + P_{WT}^{i,t} + P_{b,G}^{i,t} + P_{b,N}^{i,t} + P_{b,ESS}^{i,t} = P_{L}^{i,t} + P_{s,G}^{i,t} + P_{s,N}^{i,t} + P_{s,ESS}^{i,t} \tag{6}$$

Where $P_L^{i,t}$, is the load in MG_i at time t.

2.2.2. Energy storage system (ESS)

The energy capacity of ESS at a particular hour depends on discharged/charged power given by Eq. (7). The energy in the ESS is limited by Eq. (8). The charging and discharging power constraints for the ESS at a particular time are given by Eqs. (9)–(10).

$$ESE_i^t = ESE_i^{t-1} + \left(P_{s,ESS}^{i,t} * \eta_c * \Delta(t) - \frac{P_{b,ESS}^{i,t}}{\eta_d} * \Delta(t) \right) \tag{7}$$

$$ESE_i^{min} \leq ESE_i^t \leq ESE_i^{max} \tag{8}$$

$$P_{s,ESS}^{min} \leq P_{s,ESS}^{i,t} \leq P_{s,ESS}^{max} \tag{9}$$

$$P_{b,ESS}^{min} \leq P_{b,ESS}^{i,t} \leq P_{b,ESS}^{max} \tag{10}$$

Where η_c and η_d represent the charging and discharging efficiency of the ESS, $\Delta(t)$ is the period for which ESS is charging or discharging, i.e., 1 h.

2.3. Energy trading formulation

The energy trading formulation in this paper is built upon our previous work presented in [20]. According to [20], based on the load and generation conditions within the MG, the load imbalance is calculated at a given hour ‘t’. In the NMG framework with the IESS, after calculating the load imbalance, the IESS is scheduled. After satisfying the load and scheduling IESS, the MGs with excess energy act as sellers. The excess energy with seller MGs is shown in Eq. (11). On the contrary, those with a deficit in energy act as buyers. The deficit energy with buyer MGs is given in Eq. (12). The calculation of load imbalance, scheduling of IESS in MG, and calculation of excess/deficit energy in MG are performed by corresponding MGCC. All the MGs acting as sellers are represented in a set S. Whereas all the MGs acting as buyers are represented by the set B.

$$MG_{i,sur}^t = (P_{PV}^{i,t} + P_{WT}^{i,t} - (ESE_i^{t-1} + P_{s,ESS}^{i,t} * \eta_c * \Delta(t)) - P_L^{i,t}) \geq 0 \,\forall\, i \in S \tag{11}$$

$$MG_{i,sur}^t = (P_{PV}^{i,t} + P_{WT}^{i,t} + \left(ESE_i^{t-1} - \frac{P_{b,ESS}^{i,t}}{\eta_d} * \Delta(t) \right) - P_L^{i,t}) < 0 \,\forall\, i \in B. \tag{12}$$

Where $MG_{i,sur}^t$ represent the surplus energy at time t for MG_i, where the surplus energy can be positive for sellers and negative for buyers. ESE_i represents the energy in the ESS for MG_i.

In the NMG framework with the SESS, the MGCC decides the excess and deficit energy in the corresponding MG after calculating the load imbalance within MG. The MGs with excess energy, after satisfying the load, act as sellers and are represented in a set S. The excess energy with seller MGs is given in Eq. (13). Similarly, the MGs with deficit energy are considered buyers and are represented in a set B. The amount of deficit energy with buyer MGs is given in Eq. (14). After calculating the excess and deficit energy, MGs participate in energy trading within NMG along with SESS.

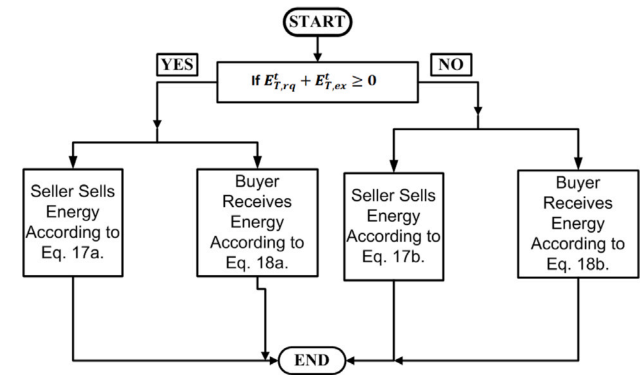


Fig. 2. Flowchart for energy trading among MGs.

$$MG_{i,sur}^t = (P_{PV}^{i,t} + P_{WT}^{i,t} - P_L^{i,t}) \geq 0 \,\forall\, i \in S \tag{13}$$

$$MG_{i,sur}^t = (P_{PV}^{i,t} + P_{WT}^{i,t} - P_L^{i,t}) < 0 \,\forall\, i \in B. \tag{14}$$

The total amount of excess/deficit energy with seller MGs and buyer MGs is given in Eqs. (15)–(16), respectively.

$$E_{T,ex}^t = \sum_{i=1}^{S} (MG_{i,sur}^t) \tag{15}$$

$$E_{T,rq}^t = \sum_{i=1}^{B} (MG_{i,sur}^t) \tag{16}$$

In the reciprocal approach [20], the amount of excess energy supplied by seller MG is given in Eq. (17), whereas the amount of energy received by the buyer MG is given by Eq. (18). The trading within NMG between sellers and buyers as per the reciprocal approach is depicted in flowchart as shown in Fig. 2.

$$P_{s,N}^{i,t} = \begin{cases} \left(\frac{-MG_{i,sur}^t}{E_{T,ex}^t} \right) * E_{T,rq}^t & if(E_{T,rq}^t + E_{T,ex}^t \geq 0) \\ MG_{i,sur}^t & if(E_{T,rq}^t + E_{T,ex}^t < 0) \end{cases} \tag{17}$$

$$P_{b,N}^{i,t} = \begin{cases} MG_{i,sur}^t & if(E_{T,rq}^t + E_{T,ex}^t \geq 0) \\ \left(\frac{-MG_{i,sur}^t}{E_{T,rq}^t} \right) * E_{T,ex}^t & if(E_{T,rq}^t + E_{T,ex}^t < 0) \end{cases} \tag{18}$$

In the NMG framework with IESS, the excess energy with seller MGs, after trading among the MGs, is sold to the grid, as given in Eq. (19). On the other hand, in case there is demand for power after the settlement of trade in the NMG then the amount of deficit energy required by the buyer MGs is bought from the grid as given in Eq. (20).

$$P_{s,G}^{i,t} = MG_{i,sur}^t - P_{s,N}^{i,t} \tag{19}$$

$$P_{b,G}^{i,t} = MG_{i,sur}^t - P_{b,N}^{i,t} \tag{20}$$

In the NMG framework with the SESS, excess/deficit energy of the MGs is exchanged with SESS. The deficit energy with buyer MGs is traded with SESS following energy trading among MGs and vice-versa, according to Eqs. (17)–(18). When trading energy with NMGs, the SESS must adhere to the constraints given in Eqs. (8)–(10). The amount of energy sold to the grid after energy trading among MGs and exchange of energy with SESS is given by Eq. (21). Similarly, the amount of

Table 1
NMG framework parameters [16].

Parameters	Value
T	24 h
Δ	1 h
$\rho_{PV}^{i,t}$	0.025 RMB/(kWh)
$\rho_{WT}^{i,t}$	0.029 RMB/(kWh)
η_c	0.98
η_d	0.98
ESE_i^{min}	$0.02.Cap_{ESS}$
ESE_i^{max}	Cap_{ESS}
$P_{s,ESS}^{min}$, $P_{b,ESS}^{min}$	$0.02.Cap_{ESS}$
$P_{s,ESS}^{max}$, $P_{b,ESS}^{max}$	$0.25.Cap_{ESS}$

energy bought from the grid after energy trading among MGs and exchange of energy with SESS is given by Eq. (22).

$$P_{s,G}^{i,t} = MG_{i,sur}^{t} - P_{s,N}^{i,t} - P_{s,ESS}^{i,t} \tag{21}$$

$$P_{b,G}^{i,t} = MG_{i,sur}^{t} - P_{b,N}^{i,t} - P_{b,ESS}^{i,t} \tag{22}$$

The energy traded among the MGs is limited by the tie line capacity and the technical parameters are also considered from [21] respectively. It is assumed that all the MGs are having the capability of controlling the voltage magnitude and the angle at the PCC.

2.4. Energy trading price formulation

According to [16,22], the motivation for the prosumers/MGs to participate in the energy trading among them is to minimize the electricity bills and maximize the profits of individuals. For this, energy trading prices among MGs should follow the relation in Eq. (23).

$$FIT \leq \rho_{b,N}^{i,t}, \rho_{s,N}^{i,t} \leq TOU^{t} \tag{23}$$

In [22], surplus vs demand-based pricing is used and an aggregated supply-to-demand ratio is considered and in [16], the load to renewable energy generation ratio in an MG, and the Feed-in-Tariff (FIT) are considered as factors for determining the prices of energy trading in an NMG. In this work, all the factors are considered. The electricity price for trading is proposed to be based on the total generation and load in an NMG, FIT, and TOU price as in Eq. (24).

$$\rho_{b,N}^{i,t}, \rho_{s,N}^{i,t} = FIT + \left((TOU^{t} - FIT) * \left(\frac{P_L^{N,t}}{P_L^{N,t} + P_G^{N,t}} \right) \right) \tag{24}$$

Where $P_L^{N,t}$, is the total load in NMG at hour 't', $P_L^{G,t}$ is the total generation in NMG at hour 't', TOU^t is the TOU price for hour 't'.

3. System data and results

This work investigates a series of case studies aimed at maximizing the economic operation of NMG. The case studies involve different strategies based on supply–demand imbalances, TOU prices, forecasted generation, and loads. The developed strategies are investigated in two distinct NMG frameworks: the NMG framework with IESS topology and the NMG framework with SESS topology. MATLAB is employed to evaluate all these cases. The NMG framework studied in this research comprises of three MGs, interconnected with each other as depicted in Fig. 1. Each MG includes PV and WT generation as well as loads in addition to IESS or SESS in the above frameworks. Fig. 3 displays the TOU price, representing the selling price of electricity by the grid to the MGs, and the FIT data, which indicates the price at which the grid purchases energy from the MGs for the NMG framework considered. As can be observed from Fig. 3, the TOU price is classified into three periods: off-peak, intermediate, and peak periods. The operational parameters of the NMG framework are detailed in Table 1.

In the context of this research paper, power flow analysis serves as an indispensable tool for comprehensively understanding the dynamics of the system. Power flow is important for assessing and implementing the different strategies applied for energy trading.

Table 2
Energy trading in NMG.

Cases	MGs	NMG (kW)		Grid (kW)		SESS (kW)	
		Sold	Bought	Sold	Bought	Sold	Bought
Case 1	MG1	NA	NA	453.2	858.09	NA	NA
	MG2			314.09	3087.22		
	MG3			1665.1	60.49		
Case 2	MG1	36.32	277.85	416.9	580.24	NA	NA
	MG2	11.69	443.75	302.4	2643.47		
	MG3	673.6	0	1000.43	60.49		
Case 3	MG1	13.15	219.05	1.7	209.44	NA	NA
	MG2	11.69	351.4	148.23	584.74		
	MG3	545.6	0	1066.7	0		
Case 4	MG1	13.6	599.35	767.31	997.99	NA	NA
	MG2	11.7	779.24	849.22	3833.76		
	MG3	1350.64	0	1126.17	338.38		
Case 5	MG1	36.32	361.78	0	453.99	415.2	42.31
	MG2	11.69	443.75	5.79	1503.14	289.59	1140.32
	MG3	673.59	0	58.97	60.49	847.06	0
Case 6	MG1	36.32	361.78	0	550.88	416.02	29.36
	MG2	11.69	443.75	5.79	2007.1	296.6	636.38
	MG3	673.59	0	58.97	60.49	941.45	0

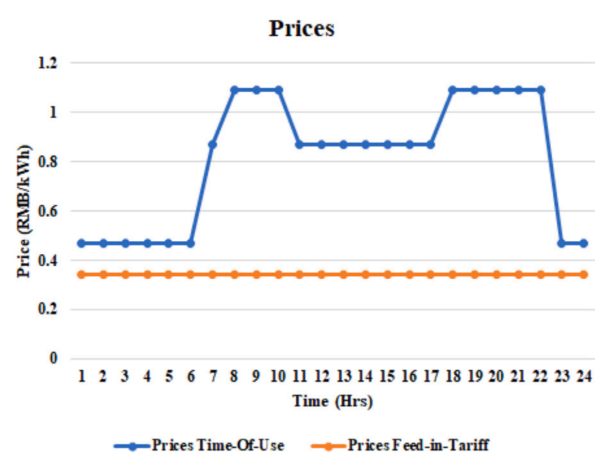
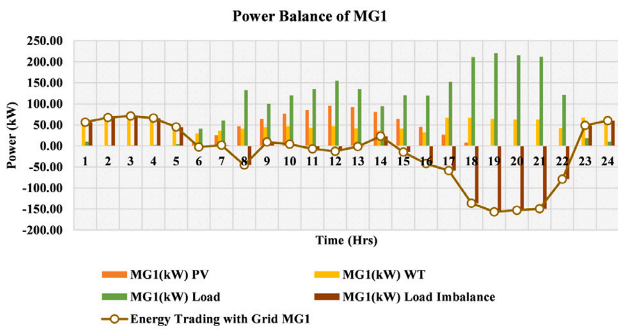


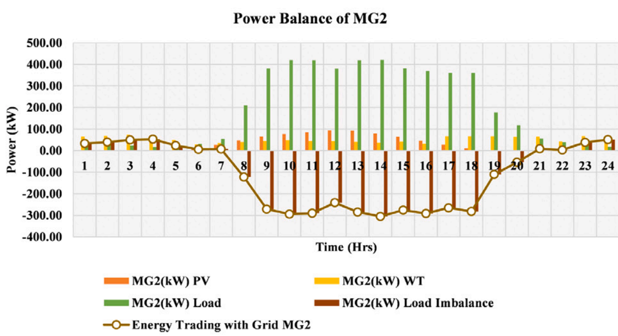
Fig. 3. TOU and FIT prices [16].

3.1. Case 1: ESS and energy trading both excluded

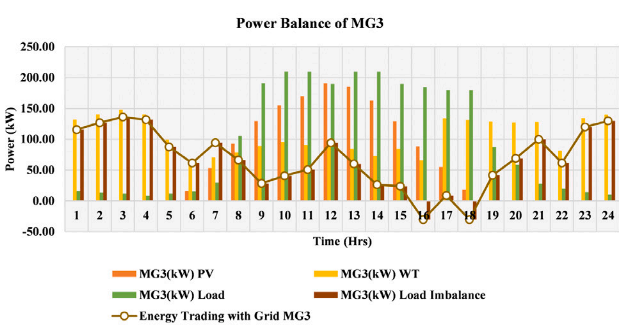
In this case, the IESS/SESS is excluded, and energy trading among MGs is not considered. However, MGs can trade energy with the grid and it is considered for all cases. As there is no IESS/SESS, the excess or deficit energy in the individual MG is directly traded with the grid. The MGs can sell any surplus energy they generate to the grid and purchase energy from the grid to meet their deficits. The power balance of individual MGs within NMG is depicted in Fig. 4. In this case, MG_1 generates excess energy during 00:00–04:00, 07:00, 09:00–10:00, 14:00, and 22:00–23:00 h, while experiencing a deficit energy during the remaining hours. Similarly, MG_2 generates excess energy during 00:00–06:00 and 20:00–23:00 h and encounters a deficit of energy during other hours. MG_3 generates excess energy during 00:00–14:00, 16:00, and 18:00–23:00 h, while facing deficit energy during the remaining hours. The total amount of energy traded in NMG for all cases is given in Table 2.



(a) Power Balance in MG_1 for Case 1

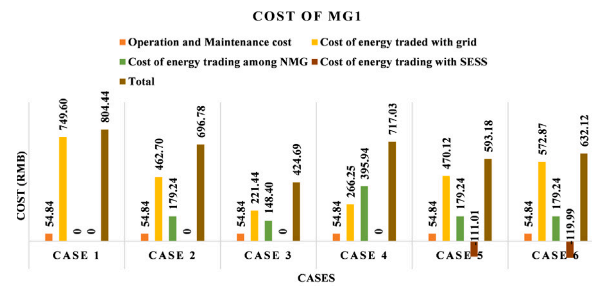


(b) Power Balance in MG_2 for Case 1

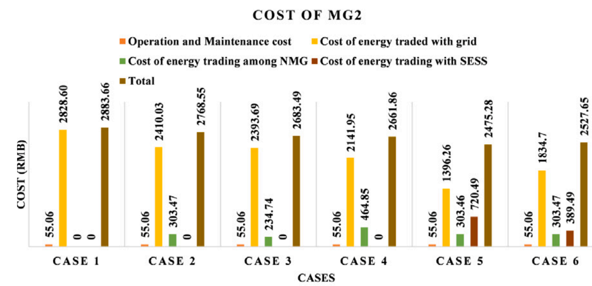


(c) Power Balance in MG_3 for Case 1

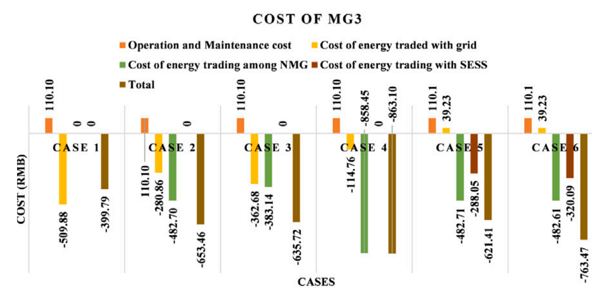
Fig. 4. Power balance in NMG for case 1.



(a) Operation Cost of MG_1



(b) Operation Cost of MG_2



(c) Operation Cost of MG_2

Fig. 5. Total operating of individual MGs.

3.2. Case 2: IESS/SESS excluded with included energy trading

The IESS/SESS is not considered while energy trading among MGs is allowed. In case 2, considering energy trading among MGs allows the balancing of excess or deficit energy within MGs in NMG. This is achieved by following the energy trading formulation described in Eqs. (17) and (18). The energy trading mechanism enables the seller MGs to trade surplus energy with the buyer MGs or the main grid. Similarly, buyer MGs can satisfy any deficit after energy trading among MGs in NMG. The energy trading strategy among MGs and with the grid is depicted as a flowchart in Fig. 6. The individual MGs will have excess and deficit energy during the same hours as in case 1. In this case, the MGs participate in energy trading within NMG during the hours as provided in Table 4. The individual MGs trade with the grid during the following hours: MG_1: 00:00–04:00, 06:00–07:00, 10:00–12:00, 14:00–23:00, MG_2: 00:00–19:00, 22:00–23:00, MG_3: 00:00–06:00, 15:00, 17:00, 22:00–23:00.

3.3. Case 3: Integration of load imbalance-based IESS scheduling and energy trading

In this case, each MG is equipped with IESS, and energy trading among the MGs is considered. The IESS is charged when an MG generates excess energy and discharges the energy when there is a deficit i.e. based on load imbalance, as shown in Fig. 7. The capacity of the IESS is divided according to the maximum load of each respective MG, with a total capacity of 4000 kWh. The IESS capacity in the respective MGs is 1000 kWh, 2000 kWh, and 1000 kWh. After scheduling the IESS, the excess and deficit energy in MGs is traded within NMG and with the grid as shown in Fig. 6. The IESS in the corresponding MGs i.e. MG_1, MG_2, and MG_3 charges and discharges during the following hours as mentioned in Table 3. The MGs participate in energy trading within NMG during the following hours as mentioned in Table 4.

3.4. Case 4: Integration of load imbalance and TOU-based IESS scheduling and energy trading

In this case, IESS in each MG is scheduled based on both TOU prices and load imbalance. During the off-peak period, the IESS is charged from both the MG and the grid, while it discharges during the peak period to both the MG and the grid. In the intermediate

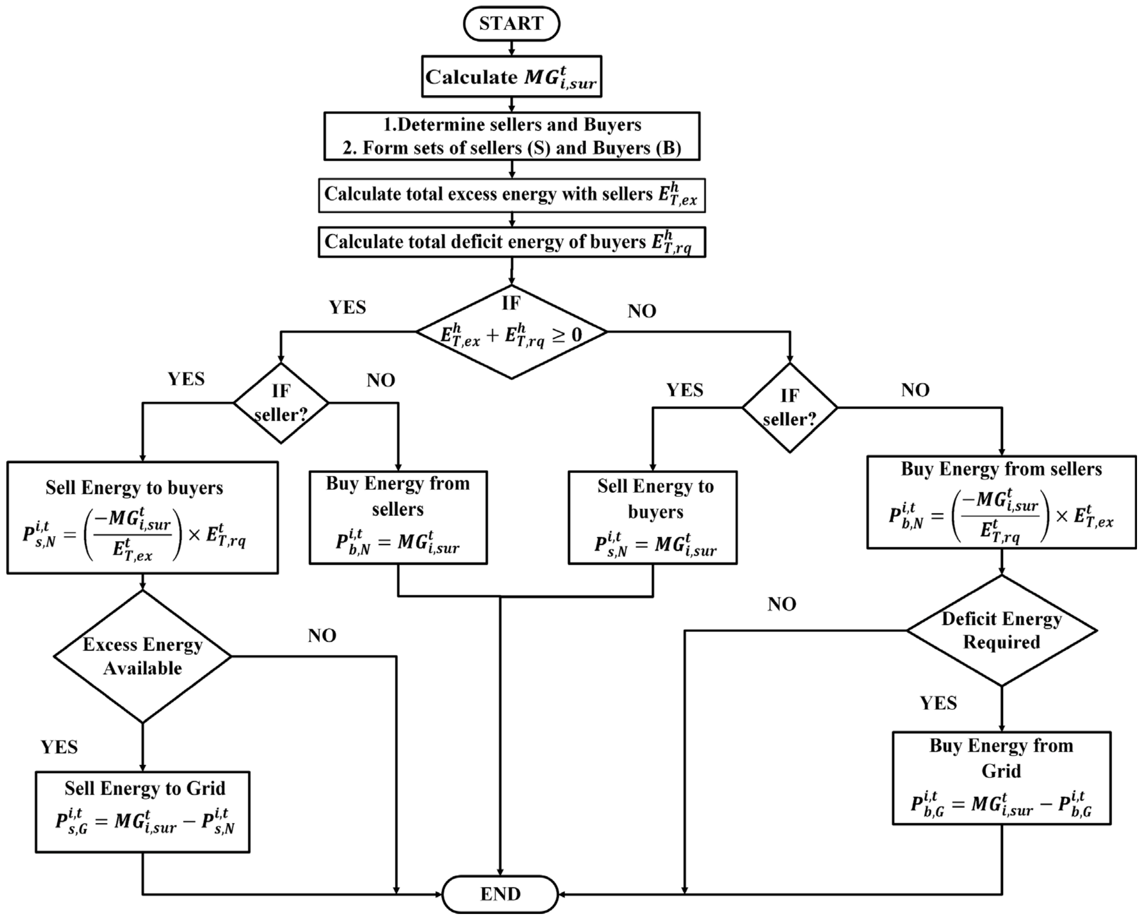


Fig. 6. Flowchart for energy trading in NMGs.

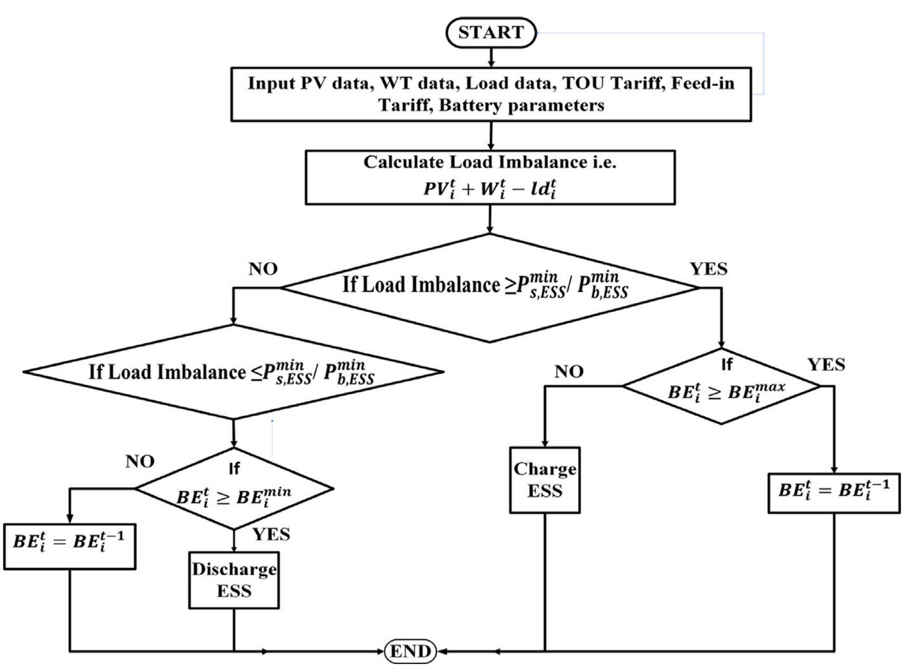


Fig. 7. Flowchart for scheduling of IESS based on load imbalance.

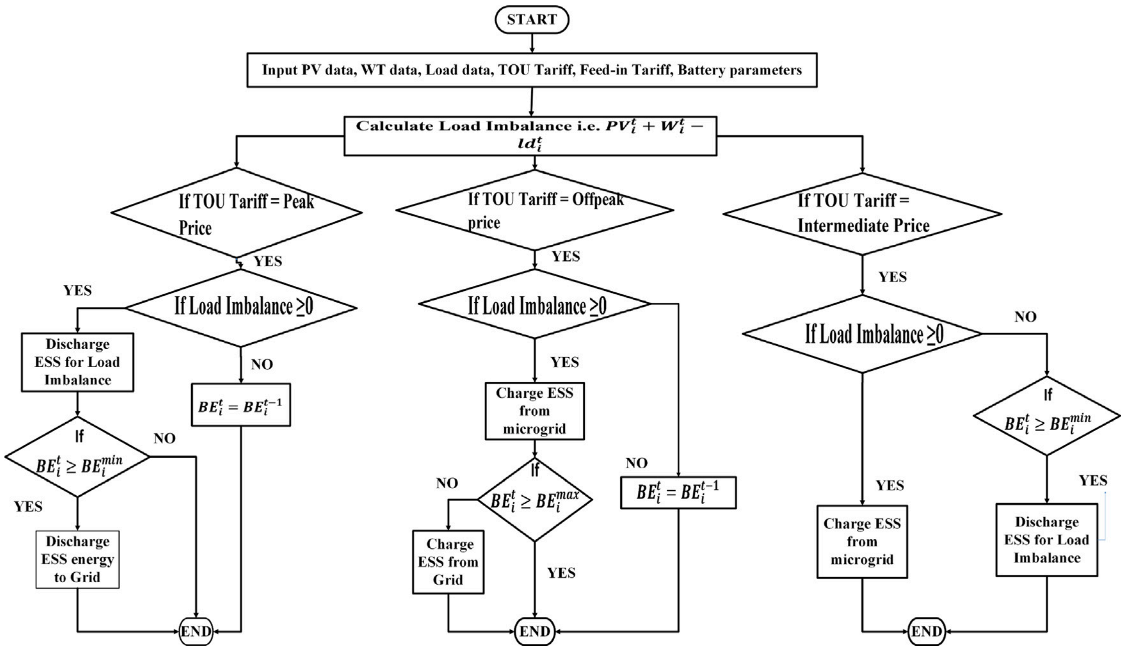


Fig. 8. Flowchart for scheduling of IESS based on load imbalance and TOU.

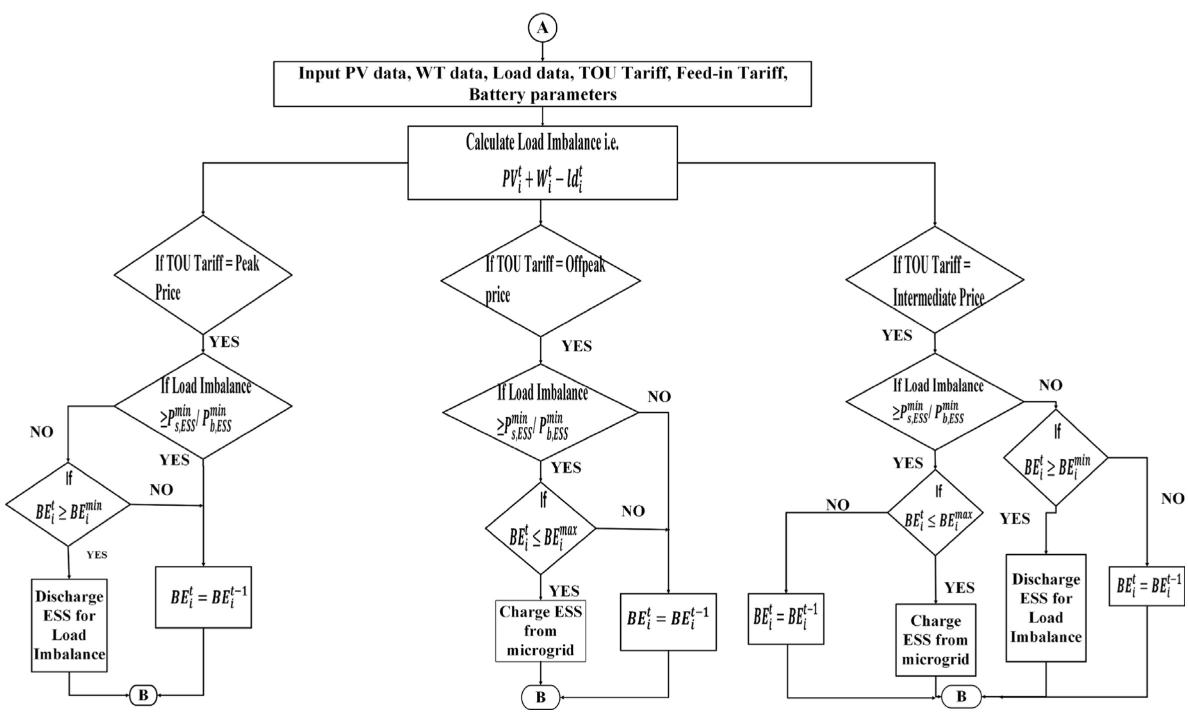


Fig. 9. Flowchart for scheduling of SESS based on proposed strategy (Level-1).

period, the charging/discharging of IESS is determined based on the load imbalance specific to each individual MG. The strategy of IESS scheduling is depicted in Fig. 8. The IESS adheres to the constraints outlined in Eqs. (8)–(10) during charging and discharging. Additionally, energy trading among MGs is considered after the IESS scheduling. The IESS charging and discharging schedule in the corresponding MGs is mentioned in Table 3. The MGs participate in energy trading within NMG during the following hours as mentioned in Table 4.

3.5. Case 5: Integration of load imbalance-based SESS scheduling and energy trading

In this case, the ESS is scheduled based on the TOU pricing and the load imbalance similar to case 3. SESS is introduced in NMG and IESS is removed from individual MGs. The SESS competes as an individual player along with other MGs in the energy market. Firstly, in this case, we calculate the excess energy and deficit energy based on load imbalance for each MG in the NMG. After calculating the excess and

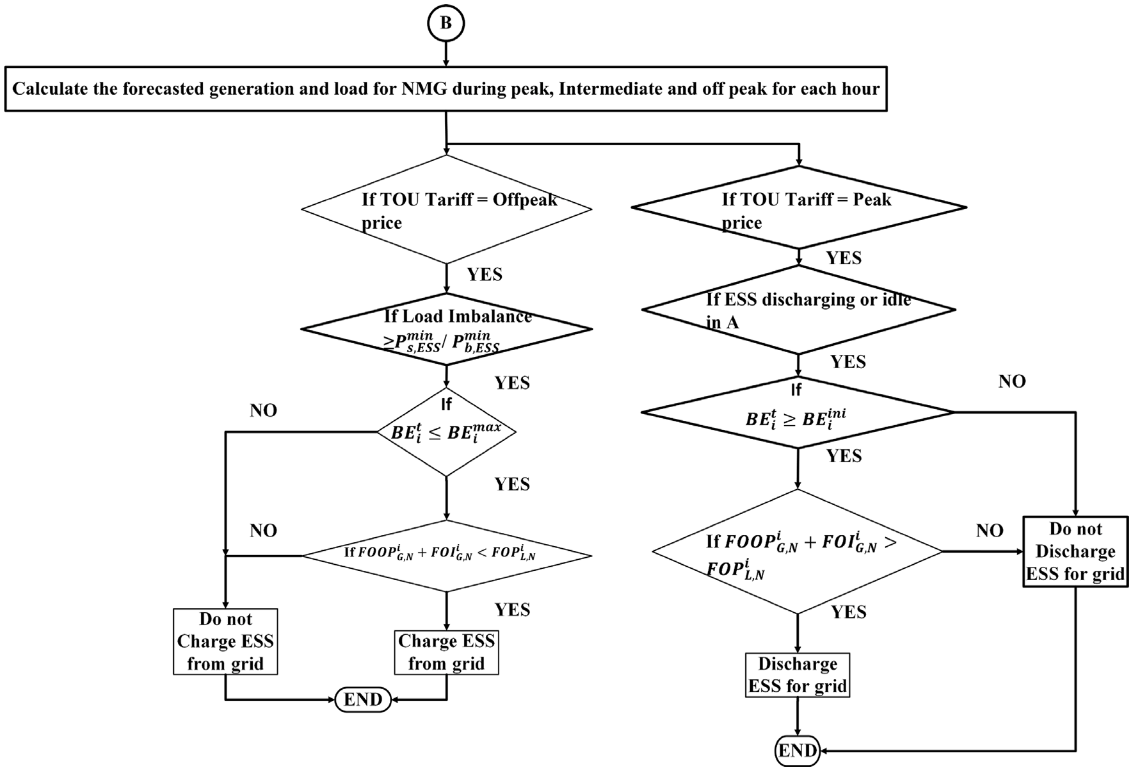


Fig. 10. Scheduling of SESS based on proposed strategy (Level-2).

Table 3
Charging and discharging schedule of IESS and SESS for proposed cases.

Cases	Charging			Discharging			Idle		
	MG1	MG2	MG3	MG1	MG2	MG3	MG1	MG2	MG3
Case 1	NA	NA	NA	NA	NA	NA	NA	NA	NA
Case 2	NA	NA	NA	NA	NA	NA	NA	NA	NA
Case 3	00:00–04:00, 13:00, 22:00–23:00	02:00–03:00, 23:00	18:00–19:00	07:00, 15:00–18:00	07:00–08:00	15:00, 17:00	05:00–06:00, 08:00–12:00, 14:00, 19:00–21:00	00:00–01:00, 04:00–06:00, 09:00–22:00	00:00–14:00, 16:00, 20:00–23:00
Case 4	00:00–03:00, 13:00, 22:00–23:00	00:00–03:00, 22:00–23:00	10:00–14:00, 22:00–23:00	07:00–09:00, 15:00–17:00	07:00–11:00.	07:00–09:00, 15:00, 17:00–18:00.	04:00–06:00, 10:00–12:00, 14:00, 18:00–21:00	04:00–06:00, 12:00–21:00	00:00–06:00, 16:00, 19:00–21:00
Case 5	00:00–04:00, 06:00, 22:00–23:00			07:00–12:00			05:00, 13:00–21:00		
Case 6	00:00–04:00, 06:00, 22:00–23:00			07:00–10:00.			05:00, 10:00–21:00		

Table 4
Energy trading schedule among MGs in NMG.

Cases	Hours
Case 1	NA
Case 2	5:00, 07:00–14:00, 16:00, and 18:00–21:00
Case 3	05:00, 08:00–14:00, 16:00–17:00, and 19:00–21:00.
Case 4	00:00–03:00, 05:00, and 16:00–21:00
Case 5, Case 6	05:00, 07:00–14:00, 16:00, and 18:00–21:00

deficit energy, the energy is traded among the NMGs. Subsequently, the remaining excess/deficit energy with NMG is traded with SESS. The capacity of SESS is considered as 4000 kWh. The scheduling of SESS i.e. charging, discharging, and idle period is shown in Table 3. The MGs participate in energy trading within NMG during the following hours as mentioned in Table 4.

3.6. Case 6: SESS scheduling incorporating forecasted generation, load, TOU prices, and energy trading

In this case, a two-level strategy is developed, taking into account various factors such as forecasted generation and load, Time-of-Use (TOU) price, and load imbalance. The SESS is considered an individual player in the energy market and can trade with NMG and the grid. It is assumed that the forecasted generation and load are accurate. The two-level strategy operates as follows: In the first stage, the power imbalance for each MG is calculated. Based on this calculation, the excess and deficit energy are determined for the seller and buyer MGs, respectively. Energy trading is then carried out within the NMG. Additionally, depending on the TOU price and the excess/deficit energy within the NMG, the SESS is either charged or discharged, as depicted in the flowchart shown in Fig. 9. In the second stage, the forecasted generation and load, for each level of TOU (peak, intermediate, and off-peak periods) are evaluated using Eqs. (25)–(30). In this stage, the

Table 5
Profit of SESS in Case 5 and Case 6.

Case	MG_1 (RMB)	MG_2 (RMB)	MG_3 (RMB)	Grid (RMB)	Total (RMB)
Case 5	−111.01	303.46	−288.05	NA	−95.60
Case 6	−119.99	389.49	−320.09	358.96	308.37

Table 6
Operation costs of each MG and NMG in proposed cases.

Case	MG_1 (RMB)	MG_2 (RMB)	MG_3 (RMB)	NMG (RMB)
Case 1	804.44	2883.65	−399.78	3288.32
Case 2	696.78	2768.55	−653.46	2811.87
Case 3	424.69	2683.49	−635.72	2472.46
Case 4	717.03	2661.86	−863.10	2515.79
Case 5	593.18	2475.28	−621.41	2447.05
Case 6	632.12	2527.65	−763.47	2206.75

proposed strategy intelligently determines whether it is more advantageous to charge the SESS using the grid's power or to utilize the energy stored in the SESS to meet the load demand during specific time periods. For this, we determine the forecasted generation and load in different TOU periods i.e. Off peak, Intermediate, and Peak periods. This is achieved by summing up the generation and load for the remaining hours within each respective period. The step-by-step process of this stage is depicted as a flowchart in Fig. 10.

$$FOOP^{h}_{G,N} = \sum_{t=h}^{T} P^{i,t}_{PV} + P^{i,t}_{WT} \; if \; (TOU = off-peak) \tag{25}$$

$$FOOL^{h}_{L,N} = \sum_{t=h}^{T} P^{i,t}_{L} \; if \; (TOU = off-peak) \tag{26}$$

$$FOI^{h}_{G,N} = \sum_{t=h}^{T} P^{i,t}_{PV} + P^{i,t}_{WT} \; if \; (TOU = Intermediate) \tag{27}$$

$$FOI^{h}_{L,N} = \sum_{t=h}^{T} P^{i,t}_{L} \; if \; (TOU = Intermediate) \tag{28}$$

$$FOP^{h}_{G,N} = \sum_{t=h}^{T} P^{i,t}_{PV} + P^{i,t}_{WT} \; if \; (TOU = Peak) \tag{29}$$

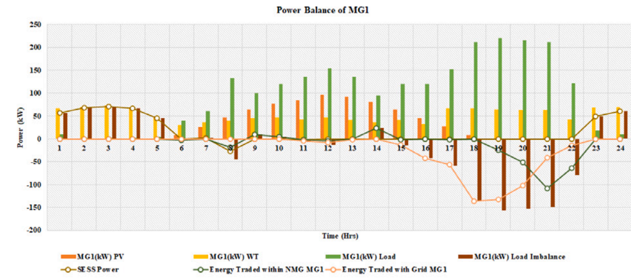
$$FOP^{h}_{L,N} = \sum_{t=h}^{T} P^{i,t}_{L} \; if \; (TOU = Peak) \tag{30}$$

Where, $FOOP^{h}_{G,N} \& FOOL^{h}_{L,N}$ are the forecasted off-peak generation and load for the corresponding hour h in NMG, $FOI^{h}_{G,N} \& FOI^{h}_{L,N}$ are the forecasted intermediate generation and load for the corresponding hour h in NMG, $FOP^{h}_{G,N} \& FOP^{h}_{L,N}$ are the forecasted peak generation and load for the corresponding hour h in NMG.

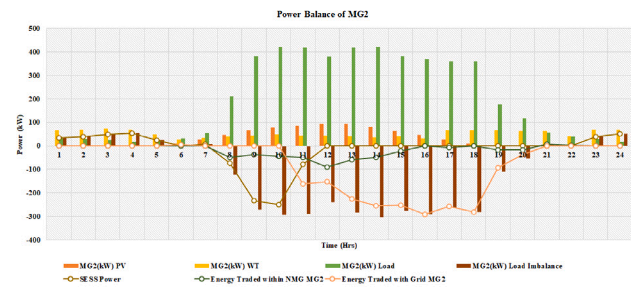
The scheduling of SESS i.e. charging, discharging, and idle period is shown in Table 3 and power balance in individual MGs is shown in Fig. 11. The total profit for SESS after trading with MGs in NMG and the grid is 358.96 (RMB). Table 5 shows the profit generated by SESS in case 5 and case 6. The profit earned by SESS from MGs is nullified while calculating the total cost of NMG, whereas the profit generated by trading with the grid results in the reduction of the overall cost. The operating cost of each individual MG, SESS, and total NMG is demonstrated in Figs. 5 and 12.

3.7. Discussion

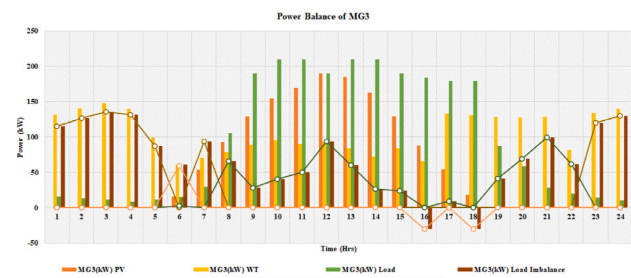
In the above cases, different strategies and scenarios are examined to evaluate the operating costs of NMG. A comparison table for the operation costs of all the strategies is presented in Table 6 and Fig. 12. In cases involving IESS/SESS (Cases 3, 4, 5, and 6), the operating costs of individual MGs are typically lower, indicating potential revenue generation. From Table 6, introducing IESS/SESS and incorporating energy trading within MGs typically results in cost savings for individual MGs and the whole NMG. Strategies that consider TOU pricing and load imbalances, in addition to IESS/SESS and energy trading, tend to optimize the operating costs of NMG more effectively. The two-level strategy with SESS (Case 6) demonstrates the potential of a holistic approach by considering multiple factors, including forecasted generation and load, TOU prices, and load imbalance, resulting in cost-effective energy management.



(a) Power Balance in MG_1 for Case 6



(b) Power Balance in MG_2 for Case 6



(c) Power Balance in MG_3 for Case 6

Fig. 11. Power balance in NMG for case 6.

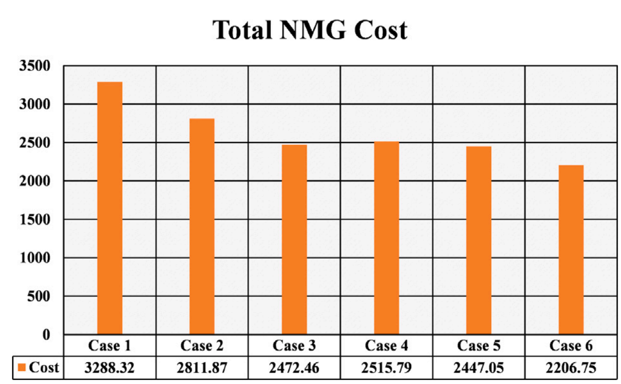


Fig. 12. Comparison of total operation cost of NMG.

4. Conclusion

In this work, a comparative analysis of scheduling strategies for the utilization of IESS/SESS in NMGs is studied. The scheduling strategies considered a number of factors, including load imbalances, TOU pricing, forecasted generation and load, and energy trading. The application of these strategies for the assessment of the operational costs of NMGs provides valuable insights into the efficacy of proposed strategies. Integration of IESS/SESS played a vital role in reducing load imbalances and optimizing energy consumption, resulting in cost savings. Energy trading mechanism enabled MGs to share excess energy and jointly address energy deficits, thereby enhancing operating cost reduction. In a case-by-case comparison, we observed that excluding energy storage and energy trading (case 1) often leads to higher costs for both individual MGs and the NMG whole. Introducing energy trading among MGs (case 2) provided cost savings by 14.48%, but more significant improvements were seen when combining energy storage with trading. The incorporation of intelligent scheduling strategies that consider load imbalance and TOU prices in IESS (cases 3 and 4) reduces the operating cost of NMGs by 24.81% and 23.49% respectively in comparison to case 1. The implementation of SESS considering load imbalance and TOU pricing (case 5) reduces the operating cost of NMGs further by 25.58%. The proposed two-level strategy (case 6) considers forecasted generation, load, TOU pricing, and energy trading, leading to a significant reduction in the operating cost by 32.89%.

Future research should focus on optimizing scheduling strategies in NMGs using advanced algorithms, exploring blockchain integration for decentralized energy trading, and understanding regulatory impacts on shared energy storage adoption. Additionally, implementing cooperative and non-cooperative approaches for determining pricing that satisfies all participating entities is crucial.

CRediT authorship contribution statement

Lokesh Vankudoth: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Altaf Q.H. Badar:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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