A Local Transactive Energy Market for Microgrids Considering Techno-Economic Interactions With Distribution System

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In landscape transitions toward smart neighborhood microgrids (MGs), local transactive energy markets provide promising opportunities for energy management. However, besides the positive features, this would be a bit of a challenging task due to a prompt proliferation of distributed energy resources (DERs). To tackle these issues, this study aims to design an efficient local market for energy transactions between residential and commercial loads within neighborhood MGs, with a focus on enhancing economic and technical objectives. The integration of DERs such as energy storage systems (ESS), photovoltaic (PV) systems, and plug-in hybrid electric vehicles (PHEV) would facilitate energy management optimization processes. Subsequently, in the proposed model, data interactions are conducted between the MGs and the distribution system operator (DSO). In this way, not only the MGs' energy consumption costs are minimized but also the distribution system load profile deviation (LPD) would be diminished, too. Meanwhile, the effect of varying electricity tariffs is also explored on the net profit of the DSO. The developed models are mathematically implemented in general algebraic modeling system (GAMS) and surveyed in different simulation studies. The results indicate that through the proposed model, a constant minimum cost of energy consumption of MGs could be maintained while simultaneously enhancing the LPD by approximately 25%.

Keywords: *Neighbourhood microgrids (MGs), Local market design, Transactive energy, Techno-economic interactions, Distribution system operation*

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1. Introduction

1.1. Motivation

The optimization of energy management in neighborhood microgrids (MGs), encompassing smart homes and commercial loads, is a promising opportunity for techno-economic operational enhancements [1]. These features would occur through a local market design for neighborhood MGs enabling transactive energy management interactions. Meanwhile, it is imperative to devise energy management systems which would account for the energy consumption of smart homes within neighborhood MGs and regulate power interactions between them. To effectively manage energy in systems hosting multiple MGs under distinct ownership, besides the developed market framework which aims to minimize energy consumption costs, possible interactions with distribution system operator (DSO) focused on enhancing load profile curve (LPD) would provide further values. This framework should incentivize demand-side participation in energy management [2-3]. The smart home, as a representation of modern technology penetration in residential areas, facilitates the control of energy efficiency and consumption for consumers [4-5]. In the context of neighborhood MGs, commercial and residential loads exhibit distinct electricity consumption patterns. The home energy management (HEM) system can establish a connection between smart home equipment within the Internet of Things (IoT) framework, enabling the optimal utilization of household electrical appliances to curtail electric energy consumption costs. Furthermore, this system can engage in marketplace activities by sharing surplus energy availability from each smart home through data sharing for potential sale to other homes/consumers within the MGs [6-7]. Commercial loads typically encompass energy-intensive operations such as those found in office buildings, retail establishments, restaurants, and industrial facilities. These loads tend to exhibit greater consistency throughout the day and may experience peak demand periods during business hours [8]. The differences in electricity consumption between commercial and residential loads are significant, driven by their distinct operational needs. Residential loads are simpler, primarily servicing electrical appliances and lighting, resulting in a consistent usage pattern that peaks in the evenings when families are home. In contrast, commercial loads, found in retail and business environments, are more complex, featuring multiple circuits and varied consumption trends influenced by factors like operational hours, equipment demands, and energy management practices. This complexity often leads to increased energy use during busy afternoon shopping times, necessitating advanced energy management strategies to improve efficiency and reduce costs.

The penetration of modern technologies and the IoT has propelled a growing interest in the concept of efficient and economic operation of commercial and residential loads. Leveraging smart systems and cutting-edge technologies, smart homes and smart commercial loads can intelligently manage their energy consumption. With the establishment of communication infrastructure, energy transactions between commercial and residential loads can be facilitated based on cloud computing platforms [10-12]. Effective MGs transactive energy management necessitates the integration of various components, including distributed energy resources (DERs), energy storage systems (ESS), plug-in hybrid electric vehicle (PHEV), and demand response strategies [13]. These components interact with one another and with the grid, forming a dynamic interconnected system that requires meticulous planning and control strategies [14].

DSOs are dedicated to modernizing distribution systems through the incorporation of advanced communication, control, and monitoring technologies to enhance efficiency and flexibility. They oversee the deployment of smart grid technologies, encompassing sensors, automation systems, data analytics, and grid management software to monitor and regulate power flows while integrating DERs both on its side and MGs' sides [15-17]. While both MG operators (MGOs) and DSOs are involved in managing aspects of DERs and system operations, MGOs focus specifically on operating individual neighborhood MGs. In contrast, DSOs are responsible for optimizing the broader distribution system by integrating smart grid technologies and managing interactions between diverse DERs, residential, and commercial loads [18-19]. Figure 1 outlines the connections between DSO and MGOs within neighborhood MG frameworks, highlighting the energy and data exchanges. Each MG encompasses a heterogeneous array of residential and commercial loads, each demonstrating distinct energy consumption behaviors. Information from these loads is relayed to the DSO via a cloud-integrated IoT platform, thereby enabling real-time data exchanges. The DSO sends the management directives and pricing signals towards the MGOs, thereby enhancing the optimization of energy distribution. Loads are classified into fixed, shiftable, and DERs, with advanced technologies facilitating demand-side engagement for both residential and commercial stakeholders. A resilient communication infrastructure enables these interactions, fostering dynamic energy management that adapts to variable tariffs while assuring grid technical and economic advantages.

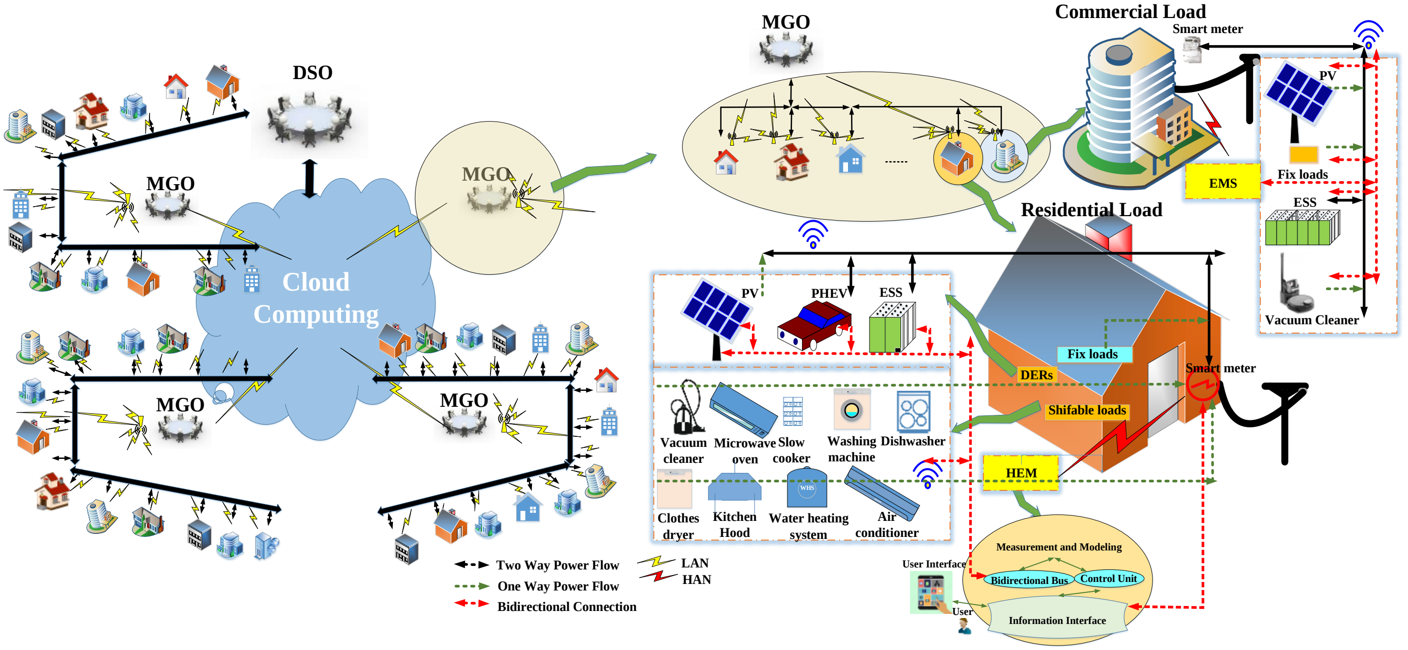

Fig. 1. Energy and data interactions between DSO and MGOs.

Furthermore, the DSO distributes management directives and pricing signals to the MGOs utilizing cloud computing infrastructure. As mentioned, each residential and commercial load encompasses a variety of fixed loads, shiftable loads, and DERs such as ESS, photovoltaic (PV) systems, PHEV, water heating system (WHS), and air conditioning (AC) systems. Within this framework, complex energy interactions occur among all residential and commercial loads, as well as between neighborhood MGs. It is evident that the energy interactions between residential and commercial loads, influenced by fluctuating energy tariffs, necessitate an efficient energy management framework overseen by the DSO. In essence, the dynamic energy interactions and trading activities between MGOs and DSOs have the potential to foster collaborative efforts, optimize the utilization of DERs, and facilitate the transition towards a more adaptable and resilient energy grid. Through the utilization of cutting-edge technologies and local market mechanisms, MGOs and DSOs can generate value for themselves while contributing to the enhancement of sustainable and efficient grid operations [20]. Cloud computing can provide vital support to MGOs and DSOs by offering advanced data management solutions, remote monitoring capabilities, seamless integration of DERs, and robust cybersecurity measures. By harnessing the potential of cloud-based technologies, operators can elevate the efficiency and sustainability of their energy systems [21-22]. Consequently, energy management within a smart distribution system that integrates neighborhood MGs, MGOs, DSOs, commercial and residential loads, smart HEM systems, cloud computing infrastructure, and IoT technologies represents a demanded market-based approach towards optimizing energy utilization and assuring sustainable energy practices.

Local transactive energy markets play a crucial role in facilitating energy management within neighborhood MGs by enabling efficient energy transactions between residential and commercial loads. These markets incorporate DERs such as photovoltaic systems and energy storage, optimizing energy consumption, and reducing costs through dynamic pricing mechanisms. The integration of smart home technologies and IoT frameworks allows for real-time data sharing and interactions among various energy consumers, enhancing the overall efficiency of the MGs. Additionally, the collaboration between MGOs and DSO ensures that energy consumption profiles are optimized, leading to minimized load profile deviations and improved economic outcomes for all stakeholders involved. This cooperative approach fosters an adaptable energy grid, ultimately promoting sustainable energy practices within the distribution systems.

1.2. Literature Review

In recent years, there has been increasing interest among the researchers in the domain of energy management and marketplace of distribution systems and neighboring MGs. Paper [23] scrutinizes the scalability and performance of the communication infrastructure based on peer-to-peer (P2P) energy trading within a social MG. The developed P2P architecture encompasses five components: power grid, communication network, cloud management, block chain, and application. In this paper, the effects of energy exchanges among multiple MGs as well as the impact of DERs on improving the load curve of the distribution system, have been overlooked. In [24], the authors analyze the design of local energy markets, exploring their relationship with smart grid and MG applications and their contribution to sustainability in smart cities. This is accomplished through a comprehensive review addressing key features pertinent to the design of local energy markets while considering their connection with urban sustainability. While this paper examines energy stability in smart cities, it neglects the influence of communication infrastructure on energy interactions between residential and commercial loads. Additionally, the role of the DSO in facilitating energy interactions among various consumers and generating of profit for the distribution system has been disregarded; even though, this is essential for energy stability studies in smart cities. The authors in [25] have introduced the concept of internet of objects and shed light on the applications and domains impacted by this technology. The study also explores smart homes as one of the areas of application for the IoT, essential for social well-being, and examines the role of IoT as a technology infrastructure and building management system for smart grid. While this research considers energy management and cost reduction in smart homes, it does not account for the effect of energy interactions among smart homes. Furthermore, the existence of various MGs within a distribution system, along with the enhancement of economic and technical objectives and cloud-based energy interactions, has not been investigated. In [26], a smart home management system based on the IoT employing sensors, actuators, smartphones, web services, and microcontrollers is proposed. The system architecture addresses scenarios where devices are deactivated when not in use. Unlike existing frameworks, the proposed architecture makes the IoT system fully accessible via the internet and open source systems. However, it lacks the capability for energy interactions with MGs and other smart homes. This study focuses solely on energy management within a smart home, while interactions between smart homes could significantly alter energy planning strategies. Moreover, IoT-based energy management considered in this study could be managed differently by incorporating energy interactions and taking into account the technical and economic objectives of the distribution system. The model proposed in paper [27] develops the concept of cloud energy storage system (CESS) to offer public access to charging/discharging capacity for smart home owners. It also develops a simple yet viable CESS capacity sharing strategy for smart home energy interactions in MGs. However, it does not provide an efficient method for energy interactions between smart MGs. Although a new DER is utilized in this paper, which could greatly influence energy planning, its effect on improving the load curve of the distribution network has not been examined. On the other hand, optimal operation of CESS and the establishment of energy interactions among smart homes require communication infrastructure that is developed by the DSO at the network level. Therefore, the benefits derived from the presence of CESS for the DSO should also be considered. Paper [28] presents an optimal energy management model within a transactional energy management framework based on distributed optimization mechanisms for P2P energy trading using a new approach. This cooperative structure engages neighborhood MGs in a decentralized framework to reach a consensus that safeguards their privacy. However, the model does not consider energy interactions between smart homes or between MGs. Additionally, the impact of the presence or absence of DERs in smart homes on energy management task from the perspectives of the DSO, MGO, and smart home owners has not been evaluated.

1.3. Contributions

Considering the reviewed literature, some of the technical and economic shortcomings are still present calling the need for further research studies. This study, is hence, dedicated to develop a local transactive energy market for neighboring MGs with the following contributions:

i. **Developing an efficient market-based model for energy interactions of MGs:** Herein, the formulation of a comprehensive framework is targeted that enables energy trading and exchanges among diverse MGs. The proposed model will account for the heterogeneous energy demands of both residential and commercial loads within each MG, thereby optimizing resource allocation and enhancing overall energy efficiency.

ii. **Developing a mathematical model for DSO-MGOs energy interactions**: Here, a mathematical model that represents the dynamics of energy exchanges among DSO, MGOs, and smart homes is launched. Such a model facilitates the analysis of interactions, resource sharing, and the influence of these entities on energy pricing and availability.

iii. **Concurrent satisfaction of objectives from different players' perspectives**: This involves simultaneous optimization of economic objectives, such as cost reduction and profit maximization, with technical objectives, including LPD minimization. Accordingly, balanced and compromised decisions are taken in regard to all stakeholders.

1.4. Organization of the Manuscript

This study is organized as follows. The outlined strategic market-based approach and the relevant mathematical formulations are provided in Section 2. Afterwards, extensive simulation studies and investigations are provided in Section 3. Eventually, the concluding remarks are reported in Section 4.

2. Proposed Local Market for Neighborhood MGs and DSO Interactions

2.1. Main Framework

The proposed strategy for energy trading between the DSO and MGOs entails efficient smart HEM and MG energy management systems to facilitate the interactions of energy between commercial and residential loads. The strategy under consideration in this investigation unfolds in three distinct stages.

Stage 1: Data Gathering and Consumption Modification

In the initial stage, the energy management system assumes a vital function by acquiring real-time electricity prices from MGOs. Utilizing this pricing information, the energy management system modifies the energy usage of various appliances and DERs in both commercial and residential environments. These modifications result in distinct energy consumption patterns for each load, which are then communicated back to the MGOs. This aggregation of data enables MGOs to gain insights into overall consumption trends, thereby enhancing their ability to manage energy distribution efficiently.

Stage 2: Energy Profile Enhancement by DSO

The second stage sees the DSO refining the aggregated energy profiles received from the MGOs. The goal of this optimization process is to improve the LPD within the distribution network while keeping the overall energy consumption costs as low as possible across all loads. This stage is crucial for effectively balancing supply and demand, facilitating better integration of DERs, and lowering operational expenses.

Stage 3: Transmission of Optimized Consumption Plans

In the third stage, MGOs relay the optimized energy consumption plans developed by the DSO back to their respective commercial and residential energy management systems. This feedback loop allows MGOs to enable essential energy interactions, which may involve decreasing reliance on the main grid during peak demand times or when local generation capabilities are adequate.

This three-stage approach cultivates a more decentralized and efficient energy trading framework between DSOs and MGOs, improving both economic and technical metrics.

2.2. Mathematical Formulation

The implemented market-based computational framework for energy interactions comprises multiple MGs interconnected together which revolves around the minimization of energy expenditure costs during the operation intervals, denoted by (1).

$$Of_1 = Minimize\left\{Cost^{Distribution}\right\} = \sum_{m\in M} Cost_m^{Microgrid} \tag{1}$$

Here, $Cost^{Distribution}$ denotes the total cost of the distribution system, while $Cost_m^{Microgrid}$ represents the energy consumption cost of each neighborhood MG. With regard to the aforementioned mathematical equation, the energy consumption cost of each MG is modeled as follows.

$$Cost_m^{Microgrid} = \sum_{t\in T}\left[\begin{array}{l}\left(\begin{array}{l}Energy_{t,m}^{Residential}\times\\ Price_t^{Residential}\end{array}\right)+\\ \left(\begin{array}{l}Energy_{t,m}^{Commercial}\times\\ Price_t^{Commercial}\end{array}\right)\end{array}\right] \quad \forall Microgrid \tag{2}$$

Here, $Energy_{t,m}^{Residential}$ and $Energy_{t,m}^{Commercial}$ respectively indicate the energy consumption of residential and commercial loads. $Price_t^{Residential}$ and $Price_t^{Commercial}$ represent the electricity tariff for these loads, respectively. The energy consumption of residential and commercial loads is determined by the variance between purchased and sold energy at each time period. The following equations are considered.

$$\begin{aligned}Energy_{t,m}^{Residential} &= (Energy_{t,h}^{Buy}\times\rho_{t,h}^{Buy} -\\ &\quad Energy_{t,h}^{Sell}\times\rho_{t,h}^{Sell})\quad \forall Home\end{aligned} \tag{3}$$

$$\begin{aligned}Energy_{t,m}^{Commercial} &= (Energy_{t,c}^{Buy}\times\rho_{t,c}^{Buy} -\\ &\quad Energy_{t,c}^{Sell}\times\rho_{t,c}^{Sell})\quad \forall Commercial\end{aligned} \tag{4}$$

Here, $Energy_{t,h}^{Buy}$, $Energy_{t,h}^{Sell}$, $Energy_{t,c}^{Buy}$, and $Energy_{t,c}^{Sell}$ respectively denote the quantities of purchased and sold energy for residential and commercial loads in the time period t. $\rho_{t,h}^{Buy}$, $\rho_{t,h}^{Sell}$, $\rho_{t,c}^{Buy}$, and $\rho_{t,c}^{Sell}$ represent the binary values associated with the purchase and sale of residential and commercial loads, respectively. For instance, if the binary variable $\rho_{t,h}^{Buy}$ equals 1, it indicates that smart home h is in the energy purchasing mode at time t.

The secondary objective function of this study is to minimize the LPD associated with the distribution system. Consequently, the subsequent equation is formulated to represent this objective function. It is imperative to emphasize that in order to stimulate the involvement of residential and commercial loads in energy consumption regulation, the costs incurred in the primary objective function should not exceed during the second objective satisfaction. Thus, it is written as (5).

$$\begin{gathered}Of_2 = Minimize\left\{LPD^{Distribution}\right\} =\\ \sum_{t\in T}\left|\sum_{m\in M}\left[\begin{array}{l}\left(Energy_{t,m}^{Residential}\right)+\\ \left(Energy_{t,m}^{Commercial}\right)\end{array}\right] - E_{mean}^{Distribution}\right|\\ s.t\left\{\begin{array}{l}\left(\begin{array}{l}(Energy_{t,h}^{Buy}\times\rho_{t,h}^{Buy} -\\ Energy_{t,h}^{Sell}\times\rho_{t,h}^{Sell})\times\\ Price_t^{Residential} -\\ (Energy_{t,h}^{Residential}\times\\ Price_t^{Residential})^{*}\end{array}\right)\le 0 \quad \forall Home\\ \left(\begin{array}{l}(Energy_{t,c}^{Buy}\times\rho_{t,c}^{Buy} -\\ Energy_{t,c}^{Sell}\times\rho_{t,c}^{Sell})\times\\ Price_t^{Commercial} -\\ (Energy_{t,h}^{Commercial}\times\\ Price_t^{Commercial})^{*}\end{array}\right)\le 0 \quad \forall Commercial\end{array}\right.\end{gathered} \tag{5}$$

Here, * denotes the energy cost quantities for residential and commercial loads in the first objective function, serving as a constraint. $E_{mean}^{Distribution}$, mathematically defined in (6), represents the average energy consumption over the operation horizon, formulated to minimize LPD.

$$E_{mean}^{Distribution} = \frac{\sum_{t\in T}\sum_{m\in M}\left[Energy_{t,m}^{Residential} + Energy_{t,m}^{Commercial}\right]}{T} \tag{6}$$

It is necessary to consider that the energy transactions between commercial and residential loads necessitates oversight by the DSO. The differential tariff structures for energy consumption by these distinct load types require careful management by the DSO. For instance, a residential entity may seek to procure energy from a MG while a commercial entity may be engaged in selling surplus energy. Procurement of energy at elevated prices for residential loads is economically inefficient, while selling energy at reduced rates to commercial loads fails to incentivize active participation in energy management. Conversely, the sale of surplus energy from residential loads to commercial entities is viewed as a beneficial transaction for the DSO. Therefore, the financial impact of energy transactions between commercial and residential loads is quantified to ascertain the overall benefit or loss for the DSO.

The DSO's objective is to optimize its primary and secondary objective functions to maximize profitability from energy transactions between commercial and residential loads subject to varying electricity tariff structures. In line with the aforementioned considerations, the financial performance of the DSO stemming from these energy transactions is modeled as follows.

$$Maximize\left\{Profit^{DSO}\right\} = Benefit - Loss \tag{7}$$

$$Benefit = \sum_{h\in H} \left(Energy_{t,h}^{Sell} \times \rho_{t,h}^{Sell} - Energy_{t,h}^{Buy} \times \rho_{t,h}^{Buy}\right) \times Price_t^{Commercial} \quad \forall t \tag{8}$$

$$Loss = \sum_{c\in C} \left(Energy_{t,c}^{Sell} \times \rho_{t,c}^{Sell} - Energy_{t,c}^{Buy} \times \rho_{t,c}^{Buy}\right) \times Price_t^{Residential} \quad \forall t \tag{9}$$

The aggregate energy procurement by each of the residential and commercial loads within the time period t (denoted as $Energy_{t,h}^{Buy}$ and $Energy_{t,c}^{Buy}$) comprises two components. Specifically, $Energy_{t,h}^{Buy,DS}$ and $Energy_{t,c}^{Buy,DS}$ represent the total energy procurement by each residential and commercial load from the distribution system; while, $Energy_{t,h}^{Buy,MG}$ and $Energy_{t,c}^{Buy,MG}$ denote the total energy procurement from other loads shared within the distribution system by the residential and commercial loads. Consequently, this concept is modeled as follows.

$$Energy_{t,h}^{Buy} \times \rho_{t,h}^{Buy} = (Energy_{t,h}^{Buy,DS} + Energy_{t,h}^{Buy,MG}) \quad \forall Home,t \tag{10}$$

$$Energy_{t,c}^{Buy} \times \rho_{t,c}^{Buy} = (Energy_{t,c}^{Buy,DS} + Energy_{t,c}^{Buy,MG}) \quad \forall Commercial,t \tag{11}$$

Furthermore, the total energy procurement by each residential and commercial load can be modeled as follows, divided into two components. Specifically, $Energy_{t,h}^{Sell,DS}$ and $Energy_{t,c}^{Sell.DS}$ represent the aggregate energy procurement by each residential and commercial load from the upper distribution system, while $Energy_{t,h}^{Sell,MG}$ and $Energy_{t,c}^{Sell,MG}$ denote the total energy procurement shared with other commercial or residential loads within the distribution system. Consequently, this concept is modeled in the following manner.

$$Energy_{t,h}^{Sell} \times \rho_{t,h}^{Sell} = Energy_{t,h}^{Sell,DS} + Energy_{t,h}^{Sell,MG} \quad \forall Home,t \tag{12}$$

$$Energy_{t,c}^{Sell} \times \rho_{t,c}^{Sell} = Energy_{t,c}^{Sell.DS} + Energy_{t,c}^{Sell,MG} \quad \forall Commercial,t \tag{13}$$

Here, it is vital to consider the constraint that residential and commercial loads exhibit mutual exclusivity in their capacity to participate in either energy procurement or sales experiences during a discrete time interval. Hence, the inclusion of the following equation within the proposed model is necessary.

$$\begin{cases} \rho_{t,h}^{Buy} + \rho_{t,h}^{Sell} \le 0 & \forall Home,t \\ \rho_{t,c}^{Buy} + \rho_{t,c}^{Sell} \le 0 & \forall Commercial,t \end{cases} \tag{14}$$

It is clear that the sum of energy acquired within the distribution system by every load must be equivalent to the total energy dispensed within the distribution system by them within each time interval. Consequently, (15) is considered.

$$\sum_{h\in H} Energy_{t,h}^{Buy,MG} + \sum_{c\in C} Energy_{t,c}^{Buy,MG} = \sum_{h\in H} Energy_{t,h}^{Sell,MG} + \sum_{c\in C} Energy_{t,c}^{Sell,MG} \quad \forall t \tag{15}$$

The energy allocation model for residential and commercial loads in each time interval is defined by equations (16) and (17). It is essential to emphasize that ESSs are applicable to both residential and commercial loads, whereas the WHS and PHEV are exclusively considered for residential loads.

$$\begin{aligned} Energy_{t,h}^{Buy} \times \rho_{t,h}^{Buy} = {} & \overset{A}{Fix_{h,t}} + \overbrace{\sum_{j\in J}\left(shift_{h,j} \times \rho_{h,j,t}\right)}^{B} + \overbrace{(WHS_h \times \rho_{h,t}^{whs})}^{C} + \\ & \overbrace{\left(\frac{1}{\eta_h^{ess,ch}} \times \left(ESS_{h,t}^{ch} \times \rho_{h,t}^{ess,ch}\right)\right)}^{D} + \overbrace{\left(\frac{1}{\eta_h^{phev,ch}} \times \left(PHEV_{h,t}^{ch} \times \rho_{h,t}^{phev,ch}\right)\right)}^{E} - \\ & \overbrace{\left(\eta_h^{ess,dis} \times ESS_{h,t}^{dis,\text{home}} \times \rho_{h,t}^{ess,dis}\right)}^{F} - \overbrace{\left(\eta_h^{phev,dis} \times PHEV_{h,t}^{dis,\text{home}} \times \rho_{h,t}^{phev,dis}\right)}^{G} + \\ & \overbrace{(AC_h \times \rho_{h,t}^{AC})}^{H} - \overbrace{\left(PV_{h,t}^{\text{home}}\right)}^{I} \qquad \forall Home,t \end{aligned} \tag{16}$$

$$\begin{aligned} Energy_{t,c}^{Buy} \times \rho_{t,c}^{Buy} = {} & \overset{A}{Fix_{c,t}} + \overbrace{\sum_{j\in J}\left(shift_{c,j} \times \rho_{c,j,t}\right)}^{B} + \\ & \overbrace{\left(\frac{1}{\eta_c^{ess,ch}} \times \left(ESS_{c,t}^{ch} \times \rho_{c,t}^{ess,ch}\right)\right)}^{C} - \overbrace{\left(\eta_c^{ess,dis} \times ESS_{c,t}^{dis,commercial} \times \rho_{c,t}^{ess,dis}\right)}^{D} - \\ & \overbrace{\left(PV_{c,t}^{commercial}\right)}^{E} \qquad \forall Commercial,t \end{aligned} \tag{17}$$

Each equation is segmented into distinct components representing energy consumption for residential and commercial loads. In equations (16) and (17), component A signifies the constant load consumed by both types of loads, while component B represents the energy attributed to shiftable load. Component C in equation (16) illustrates the energy consumption of the WHS in residential loads. The energy required for charging and discharging ESS is denoted by components D and F, and the energy needed for charging and discharging PHEV is represented by components E and G, respectively. Additionally, the utilization of PV-generated power to fulfill the energy demands of residential and commercial loads is outlined by components I and E. Moreover, component H accounts for the energy consumption in the smart AC system designed for residential loads, exclusively.

It is imperative to note that a portion of optimally discharged energy from ESS and PHEV is allocated for consumption by residential and commercial loads, while another portion is designated for energy sales to other consumers. Therefore, supplementary equations (18)-(20) are integrated to model.

$$\begin{aligned} & ESS_{h,t}^{dis} = \\ & (ESS_{h,t}^{dis,\text{home}}) + (ESS_{h,t}^{dis,sell}) \quad \forall Home,t \end{aligned} \tag{18}$$

$$\begin{aligned} & ESS_{c,t}^{dis} = \\ & (ESS_{c,t}^{dis,commercial}) + (ESS_{c,t}^{dis,sell}) \quad \forall Commercial,t \end{aligned} \tag{19}$$

$$\begin{aligned} & PHEV_{h,t}^{dis} = \\ & (PHEV_{h,t}^{dis,Home}) + (PHEV_{h,t}^{dis,sell}) \quad \forall Home,t \end{aligned} \tag{20}$$

The mathematical model related to the energy sold in each time interval for each of the residential and commercial loads is modeled by equations (21) and (22).

$$\begin{aligned} & Energy_{t,h}^{Sell} \times \rho_{t,h}^{Sell} = (ESS_{h,t}^{dis,sell} \times \rho_{h,t}^{ess,dis}) + \\ & \quad (PHEV_{h,t}^{dis,sell} \times \rho_{h,t}^{phev,dis}) + PV_{h,t}^{sell} \qquad \forall Home,t \end{aligned} \tag{21}$$

$$\begin{aligned} & Energy_{t,c}^{Sell} \times \rho_{t,c}^{Sell} = (ESS_{t,c}^{dis,sell} \times \rho_{t,c}^{ess,dis}) \\ & \quad + PV_{t,c}^{sell} \qquad \forall Commercial,t \end{aligned} \tag{22}$$

Regarding the WHS, the permissible time interval for using this load is modeled based on the number of individuals in smart homes.

$$\sum_{t=on}^{t=off} \rho_{h,t}^{whs} = U^{whs} \qquad \forall Home \tag{23}$$

Here, t=on and t=off represent the start and stop times of using the WHS. The required operating time for the WHS, equals to the number of individuals in the home who will use it according to previous operation and is denoted by U^{whs}. In accordance with the above modeling, the binary index related to the WHS ($\rho_{h,t}^{whs}$), which is outside the specified working period, is equal to zero.

For responsive residential and commercial loads, the permissible time periods for using these shiftable loads are modeled as follows.

$$\begin{cases} \sum_{t=b_j}^{g_j} \rho_{h,j,t} = U_{j,h} & \forall Home,\, j \\ \sum_{t=b_j}^{g_j} \rho_{c,j,t} = U_{j,c} & \forall Commercial,\, j \end{cases} \tag{24}$$

Here, b_j and g_j respectively denote the start and stop times of using the shiftable responsive residential and commercial loads, respectively. $U_{j,h}$ and $U_{j,c}$ represent the required operating time for the j-th responsive residential and commercial loads. According to this model, the binary index related to each shiftable residential and commercial load that is outside the specified working interval is equal to zero.

To model the use of each household and commercial electrical appliance that starts operating without interruption and continues until the required time is over, time should be considered continuously. Equations (25) and (26) demonstrate the continuous use of household and commercial electrical loads.

$$\begin{cases} y_{h,j,t} - z_{h,j,t} = \rho_{h,j,t} - \rho_{h,j,t-1} & \forall Home,\, j,t \\ \sum_{t \in T} y_{h,j,t} = 1 & \forall Home,\, j \\ y_{h,j,t} + z_{h,j,t} \le 1 & \forall Home,\, j,t \end{cases} \tag{25}$$

$$\begin{cases} y_{c,j,t} - z_{c,j,t} = \rho_{c,j,t} - \rho_{c,j,t-1} & \forall Commercial,\, j,t \\ \sum_{t \in T} y_{c,j,t} = 1 & \forall Commercial,\, j \\ y_{c,j,t} + z_{c,j,t} \le 1 & \forall Commercial,\, j,t \end{cases} \tag{26}$$

Here, $y_{h,j,t}$, $z_{h,j,t}$, $y_{c,j,t}$ and $z_{c,j,t}$ are binary indices indicating the start and stop times of the j-th responsive residential and commercial loads. The binary variables $y_{h,j,t}$ and $y_{c,j,t}$ represent the time when the j-th responsive load is turned on, while $z_{h,j,t}$ and $z_{c,j,t}$ represent the time when it is turned off.

In the presented equations for ESS, it should be considered that ESS cannot be simultaneously in charging and discharging modes. Therefore:

$$\begin{cases} \rho_{h,t}^{ess,ch} + \rho_{h,t}^{ess,dis} \le 1 & \forall Home,t \\ \rho_{c,t}^{ess,ch} + \rho_{c,t}^{ess,dis} \le 1 & \forall Commercial,t \end{cases} \tag{27}$$

The state of charge (SOC) related to ESS for residential and commercial loads is taken into account to maintain the balance of charge and discharge of ESS as follows.

$$\begin{cases} SOC_{h,t}^{ESS} = \\ ESS_{h,0} + \sum_{p=1}^{t} \begin{pmatrix} \left(ESS_{h,p}^{ch} \times \rho_{h,p}^{ess,ch} \right) - \\ (ESS_{h,p}^{dis} \times \rho_{h,p}^{ess,dis}) \end{pmatrix} \forall Home,t \\ SOC_{c,t}^{ESS} = \\ ESS_{c,0} + \sum_{p=1}^{t} \begin{pmatrix} \left(ESS_{c,p}^{ch} \times \rho_{c,p}^{ess,ch} \right) - \\ (ESS_{c,p}^{dis} \times \rho_{c,p}^{ess,dis}) \end{pmatrix} \forall Commercial,t \end{cases} \tag{28}$$

The variables $SOC_{h,t}^{ESS}$ and $SOC_{c,t}^{ESS}$ represent the energy level available in the ESS for residential and commercial loads at the end of the time interval t. In this modeling, p is another index for that time interval. $ESS_{h,0}$ and $ESS_{c,0}$ denote the initial energy level in the ESS for residential and commercial loads at the beginning of the operation period.

The discharging rate related to the ESS in residential and commercial loads, as well as the capacity of the ESS to determine the SOC, is modeled based on the following equations for residential and commercial loads.

$$\begin{aligned} & \begin{cases} (ESS_{h,t}^{dis} \times \rho_{h,t}^{ess,dis}) - SOC_{h,t-1}^{ESS} \le 0 \\ SOC_{h,t}^{ESS} - ESS_{h}^{\max} \le 0 \end{cases} \quad \forall Home,t \\ & \begin{cases} (ESS_{c,t}^{dis} \times \rho_{c,t}^{ess,dis}) - SOC_{c,t-1}^{ESS} \le 0 \\ SOC_{c,t}^{ESS} - ESS_{c}^{\max} \le 0 \end{cases} \quad \forall Commercial,t \end{aligned} \tag{29}$$

The minimum and maximum allowable values for charging and discharging of the ESS in residential and commercial loads in each time interval are modeled as follows.

$$\begin{cases} ESS_{h,t}^{ch,\min} \le ESS_{h,t}^{ch} \le ESS_{h,t}^{ch,\max} \\ ESS_{h,t}^{dis,\min} \le ESS_{h,t}^{dis} \le ESS_{h,t}^{dis,\max} \end{cases} \forall Home,t$$
$$\begin{cases} ESS_{c,t}^{ch,\min} \le ESS_{c,t}^{ch} \le ESS_{c,t}^{ch,\max} \\ ESS_{c,t}^{dis,\min} \le ESS_{c,t}^{dis} \le ESS_{c,t}^{dis,\max} \end{cases} \forall Commercial,t \tag{30}$$

For modeling PHEV, similar equations to the above can be used. It should be noted that the battery of PHEV in smart homes cannot be in charging and discharging modes, simultaneously. Thus, the following equation is considered.

$$\rho_{h,t}^{phev,ch} + \rho_{h,t}^{phev,dis} \le 1 \qquad \forall Home,t \tag{31}$$

The SOC related to the PHEV battery in each time interval t is modeled as follows.

$$SOC_{h,t}^{PHEV} = PHEV_{h,0} + \sum_{p=1}^{t} \begin{pmatrix} \left(PHEV_{h,p}^{ch} \times \rho_{h,p}^{phev,ch} \right) \\ -(PHEV_{h,p}^{dis} \times \rho_{h,p}^{phev,dis}) \end{pmatrix} \quad \forall Home,t \tag{32}$$

Here, $SOC_{h,t}^{PHEV}$ represents the energy level of the PHEV at the end of the time period t, and $PHEV_{h,0}$ indicates the initial energy level of the PHEV at the beginning of the operation period.

It should be noted that the battery used in PHEV must be sufficiently charged in the time interval t-1 to be able to discharge to the required level in the time interval t. Therefore, the following equations are considered.

$$\begin{cases} (PHEV_{h,p}^{dis} \times \rho_{h,p}^{phev,dis}) \le SOC_{h,t-1}^{PHEV} & \forall Home, t \le GO_h \\ (PHEV_{h,p}^{dis} \times \rho_{h,p}^{phev,dis}) \le \begin{pmatrix} SOC_{h,t-1}^{PHEV} - \\ PHEV_{h,O-H} \end{pmatrix} & \forall Home, t \ge CB_h \end{cases} \tag{33}$$

Here, the PHEV related to smart home h leaves the home at time GO and returns to the home at time CB. Therefore, during this time period, it is outside the home and does not participate in energy management. $PHEV_{h,O-H}$ is the energy consumption of PHEV outside the smart home. The capacity of the PHEV battery before leaving home and for time intervals after entering the home is modeled as (34).

$$\begin{cases} (SOC_{h,t}^{PHEV} - PHEV_h^{max}) \le 0 & \forall Home, t \le GO_h \\ (SOC_{h,t}^{PHEV} - PHEV_{h,O-H} - \\ PHEV_h^{max}) \le 0 & \forall Home, t \ge CB_h \end{cases} \tag{34}$$

Here, $PHEV_h^{max}$ represents the maximum amount of energy that can be stored in the PHEV battery. Also, the required energy level for the PHEV battery outside the smart home must be available before leaving the home. This assumption is modeled in the following equation.

$$PHEV_{h,O-H} \le SOC_{GO_h-1}^{PHEV} \qquad \forall Home \tag{35}$$

The minimum and maximum acceptable levels of charging and discharging for PHEV in each time interval are modeled as follows.

$$\begin{cases} PHEV_{h,t}^{ch,\min} \le PHEV_{h,t}^{ch} \le PHEV_{h,t}^{ch,\max} \\ PHEV_{h,t}^{dis,\min} \le PHEV_{h,t}^{dis} \le PHEV_{h,t}^{dis,\max} \end{cases} \forall Home,t \tag{36}$$

The incident solar radiation at the specific geographical coordinates of the PV system installation site during discrete time periods is probabilistically characterized by a beta probability distribution function (PDF) that is informed by localized solar radiation data. The mathematical formulation pertaining to the PV system is elaborated in detailed in reference [21].

For the modeling of the AC system to regulate the temperature of smart homes in residential loads, it is specified that the smart AC system is only considered for residential loads. This is while, the commercial loads lack smart AC systems and are not controllable. In the case study of a summer day and for modeling purposes, the residential AC system is considered. $\rho_{h,t}^{AC}$ is a binary variable representing the operational status of the temperature regulation system for cooling the smart home within the time interval t-1. The associated equations, (37)-(38), are further elaborated.

$$\rho_{h,t}^{AC} = \begin{cases} 1 & \tau_t^{home} > \tau_{t,set}^{AC} \\ 0 & \tau_t^{home} \le \tau_{t,set}^{AC} - \tau^{margin} \\ \rho_{h,t-1}^{cooler} & otherwise \end{cases} \quad \forall Home \tag{37}$$

$$\tau_t^{home} = \tau_{t-1}^{home} + \begin{bmatrix} k_\theta^{room} \times \\ (\tau_{t-1}^{amb} - \tau_{t-1}^{home}) \end{bmatrix} + \begin{bmatrix} k_{human} \times n_{t-1}^{human} \times \\ (\tau_{human} - \tau_{t-1}^{home}) \end{bmatrix} + \left[k_{AC}^{eff} \times \tau_{AC}^{g} \times \rho_{h,t-1}^{\theta} \right] \quad \forall Home,t \tag{38}$$

Here, τ_t^{home} represents the temperature of the smart home within the time interval t-1, $\tau_{t,set}^{AC}$ represents the set cooling temperature within the time period t-1, τ^{margin} represents the cooling reduction constant, k_θ^{room} represents the thermodynamic constant of the room, and τ_{t-1}^{amb} represents the external ambient air within the time interval t-1. k_{human} represents the heat exchange constant between humans and the environment, n_{t-1}^{human} represents the number of individuals being present in the home within the time interval t-1, τ_{human} represents the body temperature of humans, k_{AC}^{eff} represents the AC system's thermal effectiveness coefficient, τ_{AC}^{g} represents the marginal value of performance temperature and cooling reduction constant, and eventually, $\rho_{h,t-1}^{\theta}$ represents the binary variable indicating the operational status of the AC system within the time interval t-1.

It is noteworthy that the energy supplied from the main distribution system to residential and commercial loads must be subject to energy injection constraints. The following equations accounts for these constraints.

$$\begin{cases} (Energy_{h,t}^{Residential} - \\ Energy_{h,t}^{Max,Residential}) \le 0 \qquad \forall Home,t \\ (Energy_{c,t}^{Commercial} - \\ Energy_{c,t}^{Max,Commercial}) \le 0 \qquad \forall Commercial,t \end{cases} \qquad \textbf{(39)}$$

Furthermore, another aspect to consider is the constraint on energy purchase and sale between the main distribution system and residential and commercial loads. The following equations represent the minimum and maximum allowable energy purchase and sale values modeled.

$$\begin{cases} \sum_{h \in H} \left((Energy_{t,h}^{Buy,DS}) + \sum_{c \in C} (Energy_{t,c}^{Buy,DS}) \right) \\ -Energy_t^{Max,Buy} \le 0 \\ \sum_{h \in H} \left((Energy_{t,h}^{Sell,DS}) + \sum_{c \in C} (Energy_{t,c}^{Sell,DS}) \right) \\ -Energy_t^{Max,Sell} \le 0 \end{cases} \qquad \forall t \qquad \textbf{(40)}$$

Here, $Energy_t^{Max,Buy}$ and $Energy_t^{Max,Sell}$ respectively denote the maximum allowable buy and sale amounts of energy from the distribution system for supplying and selling energy to residential and commercial loads within the time interval t.

3. Numerical Results

3.1. Input Data

In this investigation, a distribution system encompassing 400 smart residences and 4 commercial loads is under scrutiny. The system is segmented into four distinct neighborhood MGs, each comprising 100 smart homes as residential loads and one commercial load, with energy management scheduling occurring at half-hour intervals. Each neighborhood MG encompasses four categories of smart homes with varying proportions of units, each unit containing 8 shiftable electrical loads. Furthermore, the commercial loads exclusively feature a single type of shiftable electrical load. The commercial loads in the first to fourth neighborhood MGs consist of a 4-story organization with 20 retail spaces, a 3-story structure with 20 retail spaces, a single-level building with 40 retail spaces, and a 2-story building with 25 retail spaces, respectively. The residential loads encompass WHS, PV systems, PHEV, and ESS, while the commercial loads include ESS and PV systems. The number of smart residential and commercial loads in each neighborhood MG is explicated in Table 1. The prescribed time intervals for smart homes, regarding the inhabitants' comfort are delineated in Table 2. The optimum time intervals for the selection of each electric load are determined on the basis of the specified time intervals for each smart home. For instance, a residential load such as a washing machine functions within three distinct time slots amounting to a cumulative duration of one and a half hour. The energy consumption attributed to this apparatus is quantified at 1.5 kW per day, corresponding to 0.5 kW per segment. The prescribed time interval for the utilization of the vacuum cleaner, with due consideration for the comfort of proprietors of commercial loads, is revealed in Table 3. For instance, within the commercial load framework of MG 1, the vacuum cleaner necessitates an energy consumption of 5.5 kWh per day, to be deployed over a duration of 2.5 hours, corresponding to five distinct time intervals. This shiftable load entails an energy consumption of 1.1 kWh per period within each time period and is recommended to be activated from period 1 to 13.

Table 1. Distribution system's load.

MG	MG Load	Num.	MG	MG Load	Num.
1	Smart Home Type 1	%20	3	Smart Home Type 1	%30
	Smart Home Type 2	%30		Smart Home Type 2	%20
	Smart Home Type 3	%10		Smart Home Type 3	%20
	Smart Home Type 4	%40		Smart Home Type 4	%30
	Commercial 1	1		Commercial 3	1
2	Smart Home Type 1	%10	4	Smart Home Type 1	%40
	Smart Home Type 2	%10		Smart Home Type 2	%20
	Smart Home Type 3	%40		Smart Home Type 3	%30
	Smart Home Type 4	%40		Smart Home Type 4	%10
	Commercial 2	1		Commercial 4	1

The operation time interval for the WHS system, based on predetermined patterns by smart home residents, are displayed in the Table 4.

Table 2. Characteristics of shiftable household loads.

Energy consumption			Hour	Smart Home Type			
List	(kWh/ day)	(kWh/ period)		1	2	3	4
Washing Machine	1.5	0.5	1.5	16-48	20-48	25-44	16-48
Dish Washer	1	0.5	1	38-48	-	40-47	36-44
Clothes Dryer	1.4	0.7	1	-	-	1-20	3-30
Slow Cooker	1.2	0.4	1.5	20-35	18-25	-	18-38
Microwave	0.8	0.4	1	-	30-48	34-48	-
Vacuum Cleaner	0.9	0.3	1.5	-	1-48	1-48	1-48
Kitchen Hood	0.5	0.5	0.5	40-48	36-44	-	-
Coffee Mixer	0.5	0.5	0.5	15-20	40-48	32-40	-

Table 3. Specifications of the vacuum cleaner for commercial loads.

Commercial load	Energy consumption		Hour	Proposed intervals
	(kWh/day)	(kWh/period)		
1	5.5	1.1	2.5	1-13
2	6	1	3	1-13
3	5	1	2.5	1-13
4	6.5	1.3	2.5	1-13

Table 4. Proposed intervals for the WHS system.

Smart Home	Energy consumption	Proposed intervals
Type 1	0.55 kWh/period	33-44
		4
Type 2	0.65 kWh/period	28-48
		2
Type 3	0.55 kWh/period	38-48
		1
Type 4	-	-
		-

For example, within smart homes categorized as Type 1, the energy utilization of the WHS amounts to 0.55 kWh per period during intervals 33 to 44, necessitating the activation of the WHS system for four discrete time segments. Additionally, it is noteworthy that the WHS system is not factored into the design of smart homes classified as Type 4. Furthermore, the energy consumption of the AC system, installed to regulate indoor temperatures in smart homes over a summer day, is taken into consideration. The influence of the number of occupants on the AC system's operation is elucidated in Figure 2.

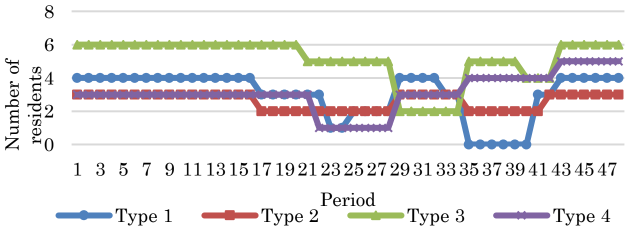

Fig. 2. Number of residents in smart homes.

Additional information such as the cooling set temperature in time period t, is equal to 250 C, the temperature reduction constant is equal to 10 C, and the thermodynamic constant of the room is equal to 0.1 C for all smart homes. Also, the outside air temperature in time period t-1, is shown in the Figure 3.

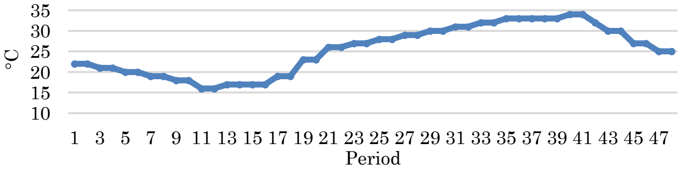

Fig. 3. Ambient temperature outside the smart home.

The heat exchange constant between humans and the environment is 0.005, the body temperature of humans is equal to 37°C, and the AC system's thermal efficiency coefficient, is equal to 0.9 and the temperature reduction constant is equal to 2.

The ESS type and capacity are consistent across all smart homes, albeit with varying initial charges. Notably, smart homes of type 3 are excluded from possessing ESSs, as they do not incorporate such systems. The ESS capacity for smart homes is considered 6.37 kWh. The maximum and minimum acceptable range for charging and discharging is 0.531 kWh/period and 0.133 kWh/period, respectively. Furthermore, the minimum charge and discharge rates for each time period are assumed to be 25% of the maximum charge and discharge rates. Also, the efficiency of ESS in considered 0.9. The initial charges of ESSs for smart homes type 1, type 2, and type 4 is considered 1.074, 1.596, and 2.356 kWh, respectively. The ESS type for commercial loads type 1 to type 4 is uniform, but with different capacities 300, 400, 350 and 390 kWh, respectively. Similarly, the initial charges of ESSs in commercial loads are 105, 120, 150, and 135 kWh, respectively. The maximum and minimum acceptable range for charging ad discharging is 50 kWh/period and 12.5 kWh/period, respectively. For commercial loads, the minimum charge and discharge rates for ESSs in each period are presumed to be 25% of the maximum charge and discharge rates. Also, the efficiency of commercial ESS in considered 0.95, 0.9, 0.95, and 0.9, respectively.

In this study, the presence of PHEVs is only assumed for residential loads, and for smart homes of type 2, PHEVs are not considered. The PHEV's capacity is considered 8.5 kWh. The maximum and minimum acceptable range for charging and discharging of PHEVs is 0.85 kWh/period and 0.2125 kWh/period, respectively. Similarly, the minimum charge and discharge rates for each time period are assumed to be 25% of the maximum charge and discharge rates. The efficiency of PHEV in considered 0.95. The initial charges of ESSs for smart homes type 1, type 3, and type 4 is considered 1.7, 1.7, and 0.92 kWh, respectively. The out of home time periods for each type of smart homes are considered 16-30, 22-28, and 16-34, respectively. Also, the required energy for PHEVs consumption in out of home is 4.30, 3.41, and 5.85 kWh, respectively.

The PV system considered for residential loads is uniform, with a generation capacity of 1 kW derived from four 250 W solar panels. An efficiency of 6.18% and an area of 6 m2 per home are assumed. For commercial loads 1 to 4, generation capacities of 25 kW, 25 kW, 28 kW, and 30 kW are respectively considered, with 100, 100, 120, and 112 solar panels of 250 W, respectively. Also, an efficiency of 6.18% and an area of 150 m^2, 150 m^2, 180 m^2, and 168 m^2 per commercial load are assumed.

Solar radiation is considered between time periods 11 to 38. Figures 4 and 5 illustrate the generation capacity from solar panels for residential and commercial loads within each time interval, considering sunrise to sunset and specified panel areas as per the modeling inputs. As depicted in Figure 5, the PV system's generation capacity varies among different commercial loads. For instance, in commercial load 3 (C3), a greater number of solar panels are utilized, resulting in a larger panel area and consequently higher production capacity compared to other commercial loads.

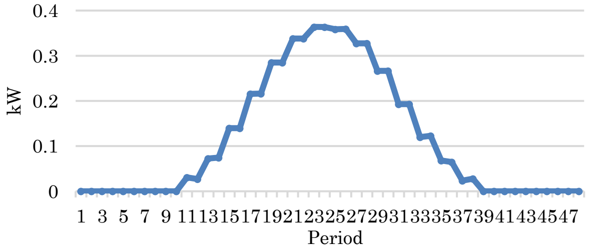

Fig. 4. Output power of residential PV system.

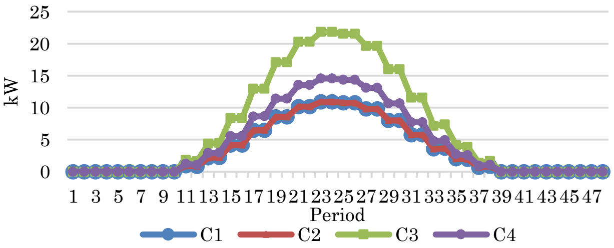

Fig. 5. Output power of commercial PV system.

The electricity tariffs for specific time intervals is distributed by the distribution system to the residential and commercial loads. The energy management system embedded within these loads strives to optimize the designated objective functions through energy transaction planning. Figure 6 provides a visual representation of the electricity tariffs across all time intervals within a day for residential and commercial loads. As depicted in this figure, disparities in energy consumption costs exist between residential and commercial loads, with the DSO aiming to enhance its profitability through energy trading activities.

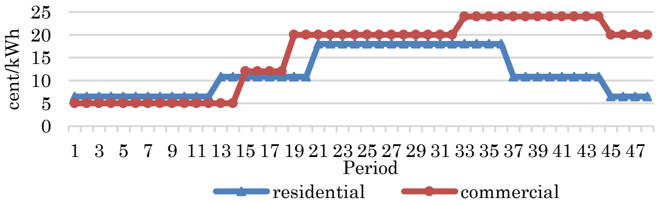

Fig. 6: Price tariff for residential and commercial loads.

Based on the presented model, each of the residential and commercial loads is also characterized by non-controllable fixed loads. In Figure 7, the total fixed loads of residential (R) and commercial (C) loads in each MG are compared. As evident in this figure, each commercial load has a higher fixed energy consumption.

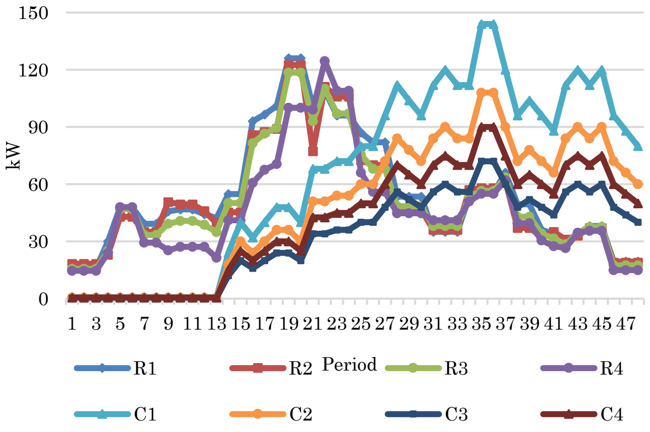

Fig. 7. Total fix loads of distribution system.

Ultimately, based on this figure, the fixed consumption load in each neighborhood MG indicating distinct energy consumption patterns.

3.2. Simulation Results

As the archived models in the literatures do not completely comply with each other in assumptions and model components, comparing the results of the proposed model with the existing literature would not be an accurate task; however, in the form of different sequential cases, the conducted study establishes an accurate study. The obtained results for these cases make it possible to establish a comparison platform and highlighting the performance success of the proposed model. In this section, simulation results are presented in two distinct cases with the aim of minimizing the daily energy consumption costs of all residential and commercial loads, as well as minimizing the LPD related to the distribution system operation. The obtained results are compared with each other and ultimately the benefit and loss experienced by the DSO as a consequence of energy interactions among loads is delineated. In case 1, energy management systems for residential and commercial loads endeavor to optimize the utilization of DERs and shiftable loads subsequent to receiving electricity tariff prices, while taking into account the primary objective function. In light of minimizing LPD while considering the minimum energy cost of existing loads in the distribution system obtained in case 1, an optimal solution is achieved in case 2. Fundamentally, based on the presented model, in order to optimize the secondary objective function, the primary objective function must be regarded as a constraint to prevent an increase in the cost of existing loads in the distribution system. Consequently, the minimum energy consumption cost for each type of residential and commercial load is determined and is consistent across both cases as reported in Table 5. According to this table, the value of the primary objective function, specifically the daily energy consumption cost of the total residential and commercial loads for each MG is determined. For instance, the total energy consumption cost of smart home type 1 in MG 1 is 37.7$. However, given that the number of smart home type 1 varies in other MGs, different values of the primary objective function are derived.

As indicated in this table, the computed LPD for case 2 stands at 3314.92, signifying an approximate 25% enhancement in LPD in comparison to case 1. Hence, it can be deduced that through a proper energy management within the distribution system can lead to the optimization of LPD associated with the distribution system, while concurrently minimizing the energy consumption expenses for all residential and commercial loads. LPD significantly impacts energy management strategies within MGs by influencing both operational efficiency and economic performance. High LPD can lead to increased costs for energy procurement and inefficient utilization of DERs, as it indicates a mismatch between energy supply and demand. This deviation necessitates the implementation of advanced demand response strategies to balance load and minimize costs. Effective management of LPD requires real-time data analytics and forecasting to optimize energy consumption patterns, which can be facilitated through IoT technologies.

Table 5. Optimum simulation results.

Distribution System Loads		COST ($)		Distribution System Loads		COST ($)	
MG1	Smart Home Type 1	37.77	877.737	MG3	Smart Home Type 1	56.66	486.0445
	Smart Home Type 2	102.63			Smart Home Type 2	68.42	
	Smart Home Type 3	27.00			Smart Home Type 3	54.01	
	Smart Home Type 4	139.82			Smart Home Type 4	104.87	
	Commercial 1	570.48			Commercial 3	202.06	
MG2	Smart Home Type 1	18.88	692.383	MG4	Smart Home Type 1	75.55	560.769
	Smart Home Type 2	34.21			Smart Home Type 2	68.42	
	Smart Home Type 3	108.03			Smart Home Type 3	81.02	
	Smart Home Type 4	139.82			Smart Home Type 4	34.95	
	Commercial 2	391.41			Commercial 4	300.80	
Total	2616.93 $						
LPD	Case 1	4451.42					
	Case 2	3314.92 (-25%)					

Table 6. AC system operation.

Home	Period
Type1	27-30-32-34-36-39-41-43-45
Type2	28-31-33-35-37-39-41-43-45
Type3	24-27-30-32-35-37-38-40-42-43-45
Type4	28-31-33-35-37-39-41-42-44-47

The derived optimal scheduling for the AC system remains consistent across both cases 1 and 2, owing to the negligible impact of objective function variation on its operation. This stability arises from the AC system's dependency on external factors such as ambient temperature, household occupancy, and various other parameters, as outlined in the provided model. The scheduling for the AC system corresponding to each category of smart home is reported in Table 6.

The residential loads' WHS are presented in Table 7, detailing the requisite time periods for each smart home. Notably, in MG 3, for smart home type 1 (h9), the optimal time periods for WHS system usage in case 1 are determined to be 37, 39, 41, and 42, and in case 2 are 39, 40, 43, and 44. Furthermore, this table reveals that the WHS system is not considered for smart home type 4 (h4-h8-h12-h16) in any of the MGs. The findings from Tables 6 and 7 lead to the inference that the commercial load disregards the presence of WHS and AC systems. Moreover, due to diverse energy consumption patterns in residential loads, distinct results are obtained for the utilization of WHS and AC systems.

Figures 8 to 12 depict the energy purchase and sale quantities of residential and commercial loads in case 2. These figures depict the time and amount of energy purchased from the grid, acquired from neighboring MGs by each residential or commercial load, and also the amount of energy sold, separately. For clarity, smart homes of types 1 to 4 in MG 1 are denoted as (h1, h2, h3, and h4), in MG 2 as (h5, h6, h7, and h8), in MG 3 as (h9, h10, h11, and h12), and in MG 4 as (h13, h14, h15, and h16). Additionally, commercial loads are denoted as (c1 c2, c3 and c4).

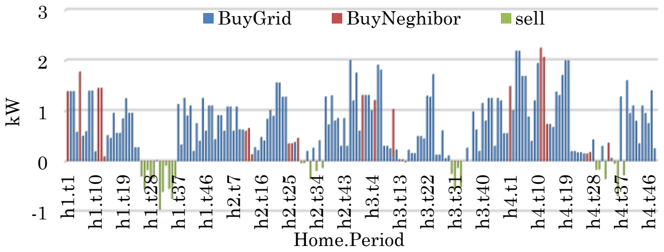

Fig. 8. Buying and selling energy for residential loads in MG 1-case2.

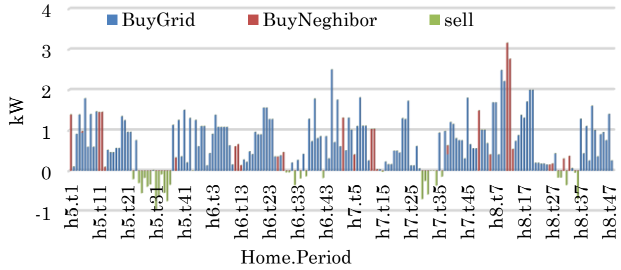

Fig. 9. Buying and selling energy for residential loads in MG 2-case2.

Table 7. WHS operation for residential loads.

MG 1			MG 2		
Smart Home	Period		Smart Home	Period	
	Case1	Case2		Case1	Case2
Type1 (h1)	t37	t37	Type1 (h5)	t39	t37
	t38	t39		t41	t39
	t42	t40		t43	t41
	t44	t41		t44	t43
Type2 (h2)	t46	t45	Type2 (h6)	t46	t45
	t47	t47		t48	t47
Type3 (h3)	t45	t46	Type3 (h7)	t46	t45
Type4 (h4)	-	-	Type4 (h8)	-	-
MG 3			MG 4		
Smart Home	Period		Smart Home	Period	
	Case1	Case2		Case1	Case2
Type1 (h9)	t37	t39	Type1 (h13)	t37	t37
	t39	t40		t39	t39
	t41	t43		t41	t40
	t42	t44		t42	t41
Type2 (h10)	t46	t45	Type2 (h14)	t45	t45
	t47	t47		t46	t46
Type3 (h11)	t45	t46	Type3 (h15)	t48	t48
Type4 (h12)	-	-	Type4 (h16)	-	-

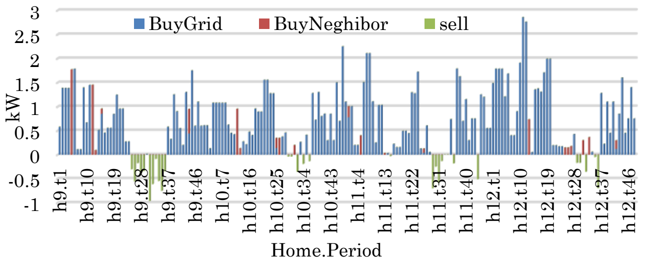

Fig. 10. Buying and selling energy for residential loads in MG 3-case2.

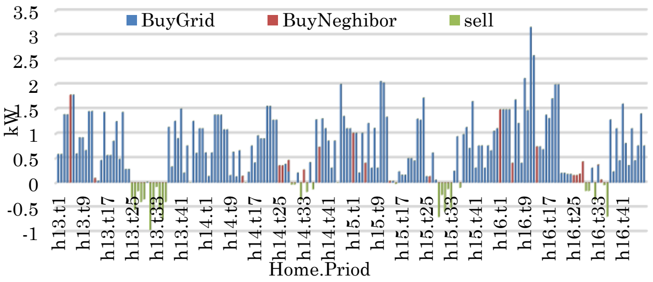

Fig. 11. Buying and selling energy for residential loads in MG 4-case2.

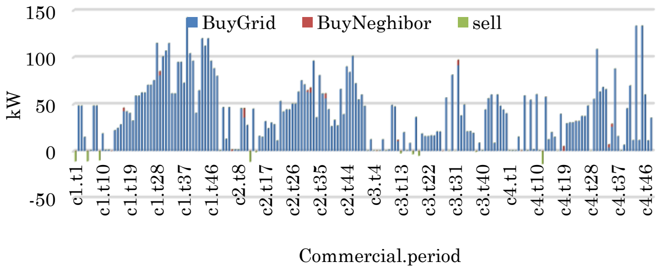

Fig.12. Buying and selling energy for commercial loads in case2.

The optimal charging and discharging of ESS for residential and commercial loads in case 2 are illustrated in Figures 13 to 17. These figures exemplify the optimal temporal occurrences and quantities for charging and discharging. Illustratively, during periods of peak electricity prices, ESS is matched with discharge scheduling, whereas during off-peak pricing, ESS is charging energy to ameliorate LPD for residential and commercial loads.

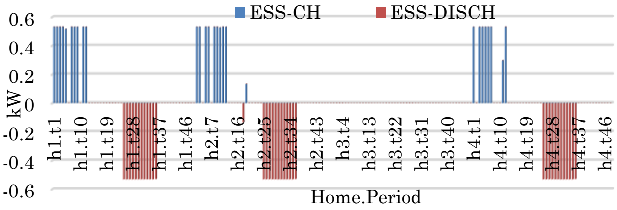

Fig.13. Optimum operation of ESSs for residential loads in MG 1-case 2.

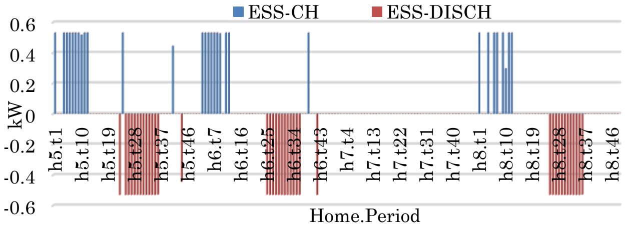

Fig. 14. Optimum operation of ESSs for residential loads in MG 2-case 2.

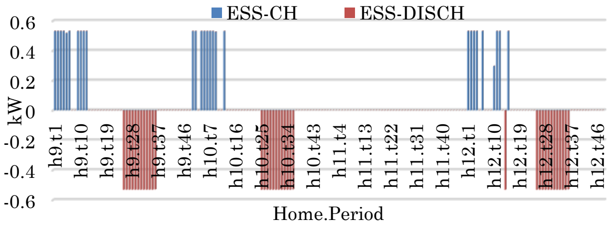

Fig. 15. Optimum operation of ESSs for residential loads in MG 3-case 2.

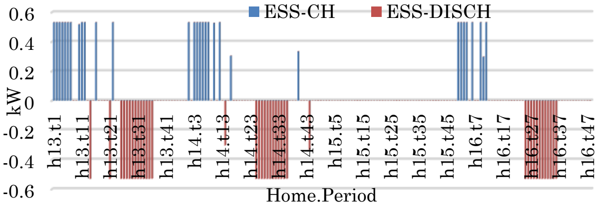

Fig. 16. Optimum operation of ESSs for residential loads in MG 4-case 2.

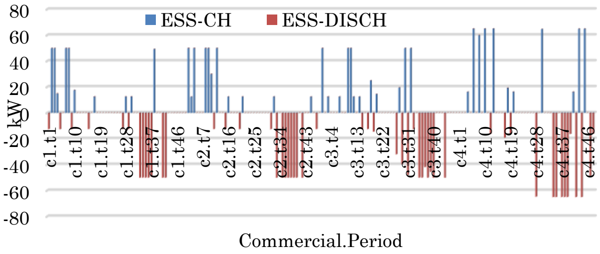

Fig. 17. Optimum operation of ESSs for commercial loads in case 2.

The Figures 18 to 21 demonstrate the obtained results in absence of ESS in smart homes of Type 3 (h3, h7, h11, and h15). Optimal charging and discharging patterns of PHEVs for various smart home types are depicted, highlighting the optimal timing and quantities for PHEV operations in case 2. Consistent with case 1, the integration of PHEVs in smart homes of Type 2 (h2, h6, h10, and h14) is not considered.

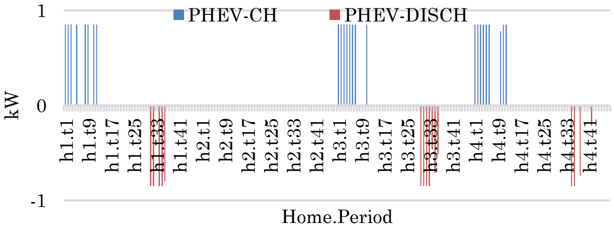

Fig. 18. Optimum Operation of PHEVs for residential loads in MG 1-case 2.

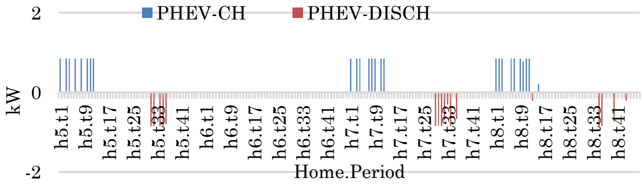

Fig. 19. Optimum Operation of PHEVs for residential loads in MG 2-case 2.

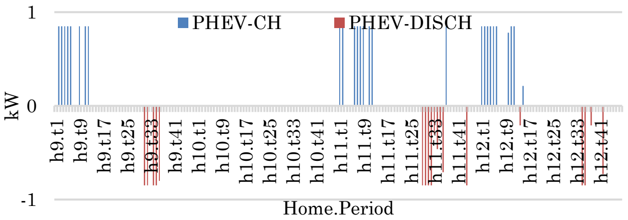

Fig. 20. Optimum Operation of PHEVs for residential loads in MG 3-case 2.

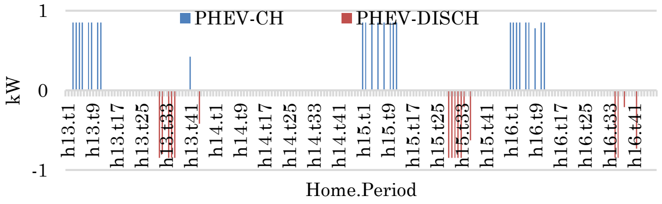

Fig. 21. Optimum Operation of PHEVs for residential loads in MG 4-case 2.

The scheduling of shiftable loads for residential and commercial purposes must be optimized within designated time frames. The utilization periods for these loads are outlined in Table 8 based on the modeling approach employed. Notably, the analysis includes eight types of shiftable loads for residential usage, while only one type is considered for commercial applications, as detailed in this table. Furthermore, certain shiftable loads specific to different smart home types are excluded from the study assumptions, as evident from this table.

The findings derived from the two cases demonstrate the feasibility of minimizing the LPD for both residential and commercial loads while maintaining a fixed energy consumption cost in case 2. This can be accomplished through the optimal utilization of DERs and residential and commercial loads. Notably, the results underscore the potential for energy interactions between residential and commercial loads. Given different electricity prices for distribution system's loads, the DSO must possess the capability to manage these energy interactions. Consequently, the benefit and loss incurred by the DSO due to the involvement of residential and commercial loads in energy interactions are scrutinized for both cases.

In case 1 and case 2, the benefit derived from energy transactions between residential and commercial loads amounts to -15,603.9 $ and 5,837.49 $, respectively. The negative benefit value in case 1 signifies a lack of benefit for the DSO. Furthermore, the loss for the DSO in case 1 and 2 totals 75.335 $ and -184.282 $, with the negative loss value in case 2 indicating an absence of loss for the DSO. Consequently, the overall profit for the DSO resulting from energy transactions between residential and commercial loads in case 1 and case 2 amounts to -15,679.2 $ and 6,021.772 $, respectively. The negative profit obtained for the DSO in case 1 indicates a lack of profit. Therefore, it can be inferred that in case 2, the DSO has the potential to generate profit by managing energy and establishing infrastructure for energy interactions between residential and commercial loads, thereby serving as a revenue source for the DSO.

Table 8. Optimum operation periods of shiftable loads in case2.

	Washing machine	Dishwasher	Cloth dryer	Slow cooker	Microwave	Vacuum cleaner	Kitchen Hood	Coffee mixer
h1	t46, t47, t48	t47,t48	-	t20,t21,t22	-	-	t45	t16
h2	t45, t46, t47	-	-	t18,t19,t20	t47,48	t1,t2,t3	t40	t46
h3	t41, t42, t43	t45,t46	t6,t7	-	t47,48	t1,t2,t3	-	-
h4	t45, t46, t47	t39,t40	t3,t4	t18,t19,t20	-	t9,t10,t11	t35	-
h5	t46, t47, t48	t47,t48	-	t20,t21,t22	-	-	t45	t19
h6	t45, t46, t47	-	-	t18,t19,t20	t47,48	t2,t3,t4	t40	t45
h7	t39, t40, t41	t45,t46	t6,t7	-	t47,48	t1,t2,t3	-	-
h8	t45, t46, t47	t40,t41	t11,t12	t18,t19,t20	-	t9,t10,t11	t35	-
h9	t45, t46, t47	t47,t48	-	t20,t21,t22	-	-	t45	t15
h10	t46, t47, t48	-	-	t18,t19,t20	t47,48	t10,t11,t12	t40	t47
h11	t38, t39, t40	t45,t46	t7,t8	-	t47,48	t6,t7,t8	-	-
h12	t46, t47, t48	t43,t44	t11,t12	t18,t19,t20	-	t2,t3,t4	t35	-
h13	t45, t46, t47	t47,t48	-	t20,t21,t22	-	-	t48	t16
h14	t45, t46, t47	-	-	t18,t19,t20	t47,48	t4,t5,t6	t40	t48
h15	t38, t39, t40	t46,t47	t10,t11	-	t47,48	t10,t11,t12	-	-
h16	t46, t47, t48	t41,t42	t11,t12	t18,t19,t20	-	t10,t11,t12	t35	-
c1	-	-	-	-	-	t9,t10,t11,t12,t13	-	-
c2	-	-	-	-	-	t2,t3,t4,t5,t6,t7	-	-
c3	-	-	-	-	-	t9,t10,t11,t12,t13	-	-
c4	-	-	-	-	-	t9,t10,t11,t12,t13	-	-

Note that the simulations are conducted using general algebraic modeling system (GAMS) as the modeling platform. Its capability to handle large-scale linear simulations enables researchers and operators to evaluate different energy management strategies effectively, leading to enhanced decision-making processes in MG operations and improved economics for both MGOs and DSOs.

4. Conclusions

Based on the findings of this study, it is imperative to incorporate optimal energy operation scheduling and demand-side participation in order to enhance the technical and economic objectives of future distribution systems. To achieve this, a market-based mechanism was developed for transactive energy interactions between neighboring MGs and the distribution system.

The present study meticulously scrutinized simulation results derived from introduced models in two distinct cases, employing pertinent tables and figures for thorough examination. Each outcome was meticulously analyzed and compared with others, revealing that energy interactions between residential and commercial loads within various MGs yield reduced energy consumption costs for all loads, improved LPD associated with the distribution system, and profit generation for the DSO through the establishment of energy trading infrastructures between residential and commercial loads. The findings reveal that in case 2, under the constraint of preserving the optimality of primary objective function, an improvement of approximately 25% in LPD for DSO is achieved. Put differently, both smart homes and commercial loads were strategically planned to minimize daily energy costs and LPD of the distribution system while ensuring profit generation for the DSO through energy interactions at varying prices.

The proliferation of DERs in local energy markets presents several challenges, as highlighted in the study. One significant challenge is the integration complexity of various DERs, such as ESS, PV systems, and PHEV, which requires sophisticated management and control strategies to ensure efficient operation within the MG. Additionally, there are regulatory and market barriers that can hinder the seamless participation of DERs in local energy markets, including inconsistent policies and lack of standardized frameworks for energy transactions. Furthermore, the interoperability between different technologies and platforms poses a challenge, as effective communication and data sharing among diverse systems are essential for optimizing energy management. Lastly, the economic viability of DER investments can be uncertain due to fluctuating electricity prices and market dynamics, which may prevent stakeholders from fully engaging in local transactive energy markets. These challenges necessitate robust solutions to enhance the operational efficiency and sustainability of neighborhood MGs.

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