Stochastic Operation Of Multi-Carrier Microgrid Leveraging Dynamic Price-Responsive Loads

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A microgrid is a smaller-scale power system that helps integrate distributed energy generation and maximize demand-side management utilization. This article analyzes the economic dispatch of a typical multi-carrier microgrid with price-responsive loads in an uncertain environment. Integrating multiple energy infrastructures under the multi-carrier microgrid is shown as an energy hub. This paper proposes a novel price-responsive load that integrates the final price of energy of demanded loads for multiple carriers with energy market price, site generations, and energy purchase. Also, the proposed price-responsive method is analyzed on two different DRP models to verify the model's effectiveness. The proposed multi-carrier microgrid is investigated considering the uncertainties in thermal and electrical loads, solar generations, and the electricity market. Previous investigations have optimized energy consumption from an infrastructure perspective without considering interactions. However, this study takes into account the interaction between energy system infrastructures in the presence of distributed energy generation and responsive loads. A series of simulations are conducted using GAMS to develop a model for a connected microgrid that incorporates electricity, district heat networks, and natural gas to supply multiple energy demands. Results show that the simultaneous operation of different energy carriers and utilization of price-responsive loads resulted in lower operating costs for smart distribution grids. Finally, the impact of uncertain parameters was assessed in the system, enhancing the optimal solution's trustworthiness.

Keywords: Economic dispatch; Demand response; Small-scale energy resources, multi-carrier microgrid.
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1. Introduction

Due to scientific advancement, there has been an increase in power consumption over the last several decades, while conventional devices have met fossil fuel constraints, community losses, and high financing expenses. To overcome the issue, increasing the use of renewable energy resources (RERs), for example, solar, wind turbine, and small-scale energy sources (SSER), has resulted in reliability improvement and strength expenditures discount through customers' engagement in demand response programs (DRPs) [1]. Moreover, increased use of SSERs might result in technical and non-technical issues for possible future issues of power systems [2].

Microgrid (MG) [3] is a rescue solution that addresses the existing distribution system difficulties and many energy infrastructure interconnections. As an alternative to large-scale power plants, MGs are expected to offer grid operators and customers greater energy utilization efficiency, enhanced power quality and local dependability, fewer power losses, and greener energy [4]. The microgrid subject was presented to overcome existing network difficulties and improve the system's performance. It is projected that the operation and control of the systems will be improved with these networks' consideration. An MG should be capable of reforming to the optimum state when a system malfunction has occurred [5]. Small-scale energy zones (SSEZs) or multi-carrier microgrids (MCMGs) are the energy carriers that make up microgrids.

Principal to the functioning of the multi-carrier microgrid is the optimum use of resources and components. In past research, the system operation with diverse energy facilities, e.g., natural gas, electricity, heat, etc., were investigated independently, which hindered the optimum operation. However, the greater effect of SSERs on gas usage has boosted energy carriers' use of network services [6]. To achieve this objective, the idea of an energy hub system was presented to introduce multi-carrier systems and explore the energy effect on others in a variety of forms [7]. The studies primarily concentrate on several operational topics, such as economic dispatch [8], power flow and optimum gas [9, 10], unit commitment [11, 12], and optimal coupling of energy carriers [13]. As an example of a structure for the EH, the MCMG has been examined in a few studies [14] to integrate different energies.

Nowadays, the optimal performance of different energy carriers is carried out individually, although most of the current energy foundations face deterioration. However, congested transmission networks and growth in demand have prompted researchers to investigate alternatives for future vitality management frameworks. Considering MCMGs as an energy hub system is one method for ensuring the effective exploitation of available foundations. It suggests that rather than examining various energy infrastructures individually, diversified energy infrastructures should be reviewed and operated on simultaneously [15].

The RERs uncertainty, e.g., solar irradiance and wind speed, was explored in [16]. Besides, the uncertainty of load was investigated in [17]. A modern procedure, using the Beta likelihood dispersion, for the era of the total request designs through modeling the energy utilization behaviour of a bunch of private buyers is displayed in [18]. A novel robust optimization approach is created to show multi-objective MG venture costs [19]. A show for ideal operations of an MG, counting generator planning choices, line network choices, control exchange between fundamental and MG, sun-powered vitality integration, and stockpiles, is created [20].

A two-stage, robust optimization system oversees the solar power uncertainty. At that point, a reformulation was made for the min-max issue to apply the Column-and-Constraint-Generation calculation. Reference [21] analyzes a household's present and future electricity demand at rural and urban domestic in the Province of Baluchistan in Pakistan for three years. The results confirm that RERs will supply the demand due to the greater potential of solar and wind.

Bellman's dynamic algorithm for optimal energy management in a standalone microgrid is presented [22]. The cost function consists of the cost of operations in generators and the cost of load shedding. The Pontryagin maximum fundamental is utilized by extracting five optimal points to handle the computational time of the dynamic algorithm. Reference [23] introduces an optimal generation dispatch in a microgrid considering the WT, generators, PV systems, storages, and plug-in EVs. The proposed optimization algorithm is computed utilizing hybrid differential and harmony search algorithms. The results show that microgrids are more stable considering storage systems and plug-in EVs. Several methods, such as scenario-based [24, 25], or sensitivity analysis [26], are utilized to handle uncertainties.

The purpose of [27] is to address the issue of economic dispatch in the shape of a multi-objective problem in which the operation cost is not the only consideration. However, the emission in considering plug-in EVs is included. Similarly, Zah et al. presented a multi-objective optimization in which the battery life cycles have been considered in the extracted model in the cost function [28]. Optimal management of the resources to respond to demands is the main problem in the operation of microgrids [29]. To realize this goal, smart grid facilities to distribute energy through small resources with a low price are considered [30]. A smart EMS is presented for residential demands to reduce electricity bills by suitable time-scheduling in the household devices [31]. In addition, the DR method is used to shave the peaks. The advantage of DRP, considering the local RERs, is the estimation of typical isolated hybrid microgrids [32]. Reference [33] investigates the hybrid method for rescheduling demand-side management and generation utilizing different DRPs in congestion management. The paper scrutinizes the effect of DRP and RER's uncertain output on different parameters of the power system. The behavior of the energy consumption from the customer's normal demand considering the electricity price changes can change by DRP utilizations. The DRPs are utilized to induce lower electricity consumption at times with high market prices or reliability jeopardy of the system [34]. In addition to the effect of different resources in the smart grids in the future, the idea of DRP will include a wide variety of loads. DRPs can be categorized into price-based and incentive-based programs [35]. A central control system in an energy hub system is used for control steps and peak shaving service [36]. The study in [37] pays attention to DRPs to prevent carbon emissions and load participation in spinning reserve markets. References [38] presented an optimal energy management of residential buildings to supply controllable and uncontrollable loads under uncertainty. Also, an optimal coalition operation of interconnected hybrid energy systems containing local energy conversion technologies, renewable energy resources, and energy storage systems has been presented in [39]. A hybrid interval-stochastic optimal operation framework of a multi-carrier microgrid in the presence of hybrid electric and hydrogen-based vehicles intelligent parking lot has been investigated in [40].

Considering the above-mentioned studies, a local price-responsive model for DRPs has not been extracted yet. In this regard, this study presents a price-responsive model for DRPs in a multi-carrier microgrid to reform the load's curve and also prevent excessive energy use during peak times. The proposed model integrates the final price of energy for responsive loads for multiple carrier systems, energy market tariffs, on-site generations, and energy purchases. The multi-carrier microgrid is pinpointed with CHP, boilers, photovoltaic, converters, and electrical and thermal storage units in grid-connected mode. The operational optimization of an MCMG is conducted to calculate the optimal strategy of an MCMG considering prevailing uncertainties, using the mixed-integer nonlinear programming (MINLP) model via GAMS software. Briefly, the main novation of this study is as follows:

- Integrating multiple energy infrastructures under the multi-carrier microgrid is shown as an energy hub.
- Proposing a novel price-responsive load that integrates the final price of energy of demanded loads for multiple carriers with energy market price, site generations, and energy purchase.
- Analyzing the proposed price-responsive method on two different DRP models to verify the model's effectiveness.
- The proposed multi-carrier microgrid is investigated considering the uncertainties in thermal and electrical loads, solar generations, and the electricity market.

In the following table a comparison between the contributions of this work with some past researches has been performed.

The remaining sections of the paper are categorized as follows: Section 2 presents a multi-carrier microgrid and its mathematical model. In Section 3, the results of simulations are provided and analyzed, and the conclusion is presented in Section 4.

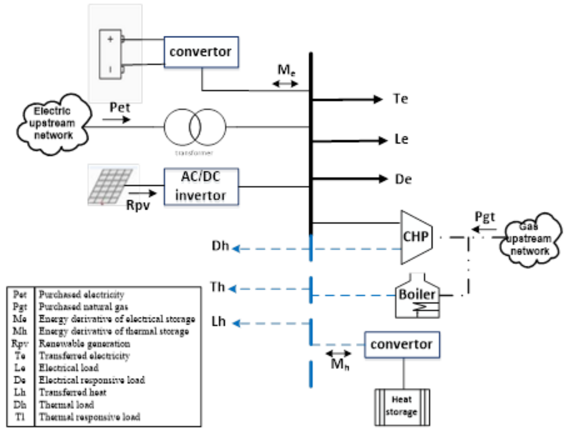


Fig. 1. The proposed MCMG structure

2. System model

An MCMG comprises a low-voltage or medium-voltage electrical network in addition to natural heat and natural gas networks. In other words, equipment, such as cogeneration, thermal exchanger transformers, and so on, may convert energy. In addition to converters, distributed energy resources (DERs) such as batteries and solar systems may provide a portion of demand and considerably influence energy cost reduction relative to the local energy costs of carriers. DRPs may increase the network's flexibility to meet demand at a particular time. As indicated in Figure 1, this article models a single-bus MCMG with equipment coordination to meet different energy needs for 24 hours. The MCMG network is linked to the gas and main electric grid, and it is believed that energy savings and conversion are possible.

2.1. MCMG system modeling

The MCMG discussed in this article motivates the energy-hub model illustrated in Fig. 1. The newly installed MCMG is linked to the main natural gas and power grids. The CHP, storage, and boilers are utilized only for supply or storage. Here, the solar system is also included, allowing the MCMG to sell excess power to the grid. It is also believed that price-responsive loads would flatten the curves of loads by transferring a portion of demand to off-peak times. The energy balancing model in the matrix's output and input hub ports is as follows:

Table 1. Comparison of main contributions between some important studies

Method	Contributions
Proposed method	- Integrating multiple energy infrastructures under the multi-carrier microgrid is shown as an energy hub. - Proposing a novel price-responsive load that integrates the final price of energy of demanded loads for multiple carriers with energy market price, site generations, and energy purchase. - Analyzing the proposed price-responsive method on two different DRP models to verify the model's effectiveness. The proposed multi-carrier microgrid is investigated considering the uncertainties in thermal and electrical loads, solar generations, and the electricity market.
Reference [33]	- Investigation of the hybrid method for rescheduling demand-side management and generation utilizing different DRPs in congestion management. - The paper scrutinizes the effect of DRP and RER's uncertain output on different parameters of the power system.
Reference [31]	- A smart EMS is presented for residential demands to reduce electricity bills by suitable time-scheduling in the household devices
Reference [36]	- A central control system in an energy hub system is used for control steps and peak shaving service.
Reference [28]	- Introducing of a multi-objective optimization in which the battery life cycles have been considered in the extracted model in the cost function
Reference [37]	- Focusing on DRPs to prevent carbon emissions and load participation in spinning reserve markets
Reference [41]	- Focus on combined cooling, heating, and power microgrid to alleviate these issues. - A multi-carrier energy storage system composed of thermal storage system, ice storage system, and hydrogen storage system are integrated into the proposed system to benefit from their techno-economic advantages.
Reference [42]	- Focus on the concept of hydrogen-based smart micro energy hub (SMEH) considering integrated demand response (IDR) and fuel cell-based hydrogen storage system (HSS). - IDR is introduced to control consumers' electrical and heat demand patterns. - HSS not only can convert power from renewable energy sources (RESs) to hydrogen (P2H) in a low electricity price period and vice versa (H2P) in a high electricity price period but also can supply the hydrogen-based industry
Reference [43]	- Introducing an Information Gap Decision Theory (IGDT)-based model for EH management, taking into account the demand response (DR). The proposed model is applied to a semi-realistic case study with large consumers within a day ahead of the scheduling time horizon.

$$\begin{bmatrix} L_e(t) \\ L_h(t) \end{bmatrix} + \begin{bmatrix} D_e(t) \\ D_h(t) \end{bmatrix} + \begin{bmatrix} T_e(t) \\ T_h(t) \end{bmatrix} = \begin{bmatrix} \eta^{\text{trons}} & \eta_e^{chp} \times v(t) & \eta^{inv} \\ 0 & \eta_h^{chp} \times v(t) + \eta_h^{bo} \times (1 - v(t)) & 0 \end{bmatrix} \times \begin{bmatrix} P_e(t) \\ P_g(t) \\ P_g(t) \end{bmatrix} - \begin{bmatrix} Sc(t) & 0 \\ 0 & Sd(t) \end{bmatrix} \times \begin{bmatrix} \dot{E}_e(t) \\ \dot{E}_h(t) \end{bmatrix} \quad (1)$$

which $Sd(t)$ and $Sc(t)$ are as bellow:

$$Sc(t) = \frac{1}{\eta_e^{\text{char}}} I_e^{chr}(t) + \eta_e^{\text{discha}} \left(1 - I_e^{chr}(t)\right) \quad (2)$$

$$Sd(t) = \frac{1}{\eta_h{}^{\text{char}}} I_h^{\text{char}}(t) + \eta_h^{dschar} \left(1 - I_h^{\text{char}}(t)\right) \quad (3)$$

The storage enhances the performance of the MCMG by preventing the wastage of energy. In [44], the advantages of energy storage elements are exclusively investigated. The matrix's model of energy storage is written as follows:

$$\begin{bmatrix} Sc(t) & 0 \\ 0 & Sd(t) \end{bmatrix} \times \begin{bmatrix} E_e(t+1) - E_e(t) - E_e^{stb} \\ E_h(t+1) - E_h(t) - E_h^{stb} \end{bmatrix} = \begin{bmatrix} M_e(t) \\ M_h(t) \end{bmatrix} \quad (4)$$

To achieve sustainable storage utilization, it is necessary to consider the initial energy levels and the stored energy at the end of the last period within the investigation time interval:

$$E_e(1) = E_e(24) \quad (5)$$

$$E_h(1) = E_h(24) \quad (6)$$

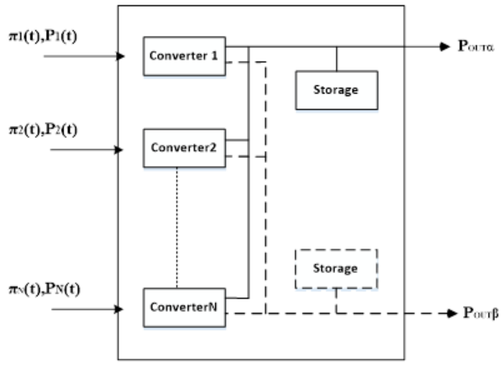


Fig. 2. Correlation between energy prices and output and input port

2.2. Demand response model

Due to the high costs in the energy market, users will seek to engage in energy supply within future networks. To avoid this problem, software allowing load reduction or transferring to other times may be used [45]. DRPs may be applied as a solution, categorized into two strategies: punishment and price or incentive. Demand patterns fluctuate hourly, depending on energy costs. This policy is implemented in this article. As the energy market price defines the prices of energy at the input port of the MCMG, the final prices of energy (FPE) for thermal and electrical responsive loads at the output port depend on received energy, operating strategies, and efficiencies of devices. These final costs are modeled in Eqs. (7) and (8) according to Fig. 2.

$$\rho_\alpha(t) = \frac{\sum_{i=1}^{N} P_i(t)\cdot\pi_i(t)\cdot\frac{\eta_{i,\alpha}}{\eta_{i,\alpha}+\eta_{i,\beta}}}{L_\alpha(t)+D_\alpha(t)+M_\beta(t)} \tag{7}$$

$$\rho_\beta(t) = \frac{\sum_{i=1}^{N} P_i(t)\cdot\pi_i(t)\cdot\frac{\eta_{i,\beta}}{\eta_{i,\alpha}+\eta_{i,\beta}}}{L_\beta(t)+D_\beta(t)++M_\beta(t)} \tag{8}$$

This paper utilizes two different methods of DRPs to verify the effectiveness of the FEP as follows:

2.2.1. *DRP based on elasticity matrix concept (the first model of DRP)*

Assuming the FEP for responsive loads, an elasticity matrix is formulated in Eqs. (9) and (10). The non-diagonal elements are negative, and the diagonal elements are positive.

$$EL_i(t) = \begin{pmatrix} ee_i(1,1) & \cdots & ee_i(1,24) \\ \vdots & \ddots & \vdots \\ ee_i(24,1) & \cdots & ee_i(24,24) \end{pmatrix} \quad i\in\{\alpha,\beta\} \tag{9}$$

$$e_i\left(t,t'\right) = \begin{cases} t=t' & e_i\left(t,t'\right)<0 \\ t\neq t' & e_i\left(t,t'\right)\geq 0 \end{cases} \quad i\in\{\alpha,\beta\} \tag{10}$$

Regarding the elasticity matrix definition, the multi-period time-based demand response is modelled below:

$$D_\alpha(t) = D_{0\alpha}(t)\cdot\left[1+e_\alpha(t,t)\cdot\frac{\rho_{\alpha 0}(t)-\rho_{\alpha 0}\left(t'\right)}{\rho_{\alpha 0}\left(t'\right)}\right] + D_{0\alpha}(t)\cdot\left[1+\sum_{\substack{t'=1\\ t=t'}}^{24} e_\alpha\left(t,t'\right)\cdot\frac{\rho_{\alpha 0}(t)-\rho_{\alpha 0}\left(t'\right)}{\rho_{\alpha 0}\left(t'\right)}\right] \tag{11}$$

It is noted that Eq. (12) calculates the initial energy price for responsive loads.

$$\rho_{\alpha 0}(t) = \frac{\sum_t D_{\alpha 0}(t)\cdot\pi_e(t)}{\sum_t D_{\alpha 0}(t)} \tag{12}$$

2.2.2. *DRP based on shifting technique (the second model of DRP)*

The DR framework of reference [36] is also used in this study, which is outlined in Eqs. (13) to (17). Demand fluctuations must be balanced regularly Eq. (14). Equations Eqs. (15) and (16) represent the effect of registered consumers engaging in DRPs on the demand share. In other words, it determines the maximum hourly number of movable demands of different users. To avoid simultaneous upward and downward movement, Eq. (17) is necessary.

$$D_\alpha(t) = D_{0\alpha}(t) + D_\alpha^{\text{shup}}(t) + D_\alpha^{\text{shdo}}(t) \tag{13}$$

$$\sum_t D_\alpha^{shpp}(t) = \sum_t D_\alpha^{\text{shdo}}(t) \tag{14}$$

$$0 \leq D_\alpha^{\text{shn}\,p}(t) \leq D_{0\alpha}(t)\cdot IS_\alpha^{\text{shup}}(t) \tag{15}$$

$$0 \leq D_\alpha^{\text{shdo}}(t) \leq D_{0\alpha}(t)\cdot IS_\alpha^{\text{shdo}}(t) \tag{16}$$

$$0 \leq IS_\alpha^{\text{shup}}(t) + IS_\alpha^{\text{shdo}}(t) \leq 1 \tag{17}$$

2.3. Constraints and Objective function

The total operating and maintenance (O&M) expenses are picked as two evaluation criteria employed as the ideal goal to be reduced, as described in Eq. (18). Considering the problem specification stated in previous sections, the goal function for the operation of the suggested MCMG is precisely specified exactly as follows:

$$
\begin{aligned}
MIN : OF = & \sum_{t=1}^{24} \sum_{i\in\{e,g\}} P_i(t) \cdot \pi_i(t) \\
& - \sum_{j\in\{e,h\}} T_j(t) \cdot \psi_j(t) + \mathrm{Cos}\, t^{\mathrm{main}} \\
& + \sum_{t=1}^{24} \sum_{i\in\{e,h\}} \left[D_l^{\mathrm{shup}}(t) - D_l^{\mathrm{shdo}}(t) \right] \cdot \rho_l(t)
\end{aligned} \tag{18}
$$

In this study, Eqs. (7), (8) and (18), which represent the final costs, establish the MINLP nature of the proposed approach. The first and second terms indicate the costs associated with energy import and export, while the third term specifies the cost of unit maintenance. The last term is the MCMG customers' advantages in changing their demand from peak periods to off-peak periods, which is only used for the second DRP model. The goal function comprises acquired and sold energies, O&M expenses, and energy demand shifting costs. The objective equation specifics are presented exactly as follows:

$$
\begin{aligned}
\mathrm{Cos}\, t^{\mathrm{main}}(t) = & \,\mathrm{Cos}\, t^{pv,\,\mathrm{main}}(t) \\
& + \mathrm{Cos}\, t^{CHP,\,\mathrm{main}}(t) + C\,\mathrm{os}\, t^{bo,\,\mathrm{main}}(t)
\end{aligned} \tag{19}
$$

$$\mathrm{Cos}\, t^{pv,\,\mathrm{main}}(t) = Po^{pv}(t) \times K^{pv,\,\mathrm{main}} \tag{20}$$

$$\mathrm{Cos}\, t^{CHP,\,\mathrm{main}}(t) = Po^{chp}(t) \times K^{CHP,\,\mathrm{main}} \tag{21}$$

$$\mathrm{Cos}\, t^{\mathrm{boiler,main}}(t) = Po^{\mathrm{boiler}}(t) \times K^{\mathrm{boiler,main}} \tag{22}$$

$$\mathrm{Cos}\, t^{\mathrm{trons,\,main}}(t) = Po^{\mathrm{tricns}}(t) \times K^{\mathrm{trcons,\,main}} \tag{23}$$

Amounts of purchased electricity, gas, selling electricity and heat power to the network and capacities of elements are respectively constrained as follows:

$$0 \le P_i(t) \le P_i^{\max} \quad i \in \{e, g\} \tag{24}$$

$$0 \le T_j(t) \le T_k^{\max} \quad j \in \{e, h\} \tag{25}$$

$$0 \le PO^{chp}(t) \le PO^{chp,\max} \tag{26}$$

$$0 \le \mathrm{Po}^{\mathrm{boiler}}(t) \le P^{\mathrm{boiler},\max} \tag{27}$$

$$0 \le PO^{\mathrm{trons}}(t) \le P^{\mathrm{trrons,\,max}} \tag{28}$$

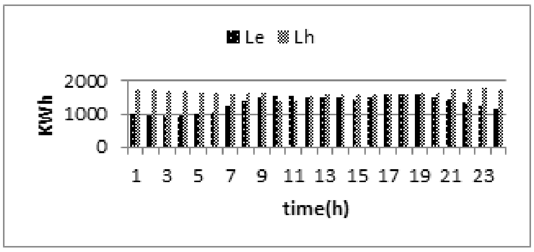


Fig. 3. profiles of the thermal/electrical loads in MCMG

$$0 \le Po^{pv}(t) \le Po^{pv,\max} \tag{29}$$

$$M_j^{\min} \le M_j(t) \le M_j^{\max} \quad j \in \{e, h\} \tag{30}$$

$$0 \le E_j(t) \le E_j^{\max} \quad j \in \{e, h\} \tag{31}$$

3. The results of the simulation and discussion

The introduced model in this article is exerted to an industrial zone as a multi-carrier MG to evaluate the efficiency of the suggested method. The suggested multi-carrier MG is connected to the grid, natural gas, and district heat network, as shown in Fig. 1. The suggested method specifies the best operating point of the MCMG's elements, including the boiler, CHP, transformer, PV, and energy storage elements. The specifications of MCMG's elements are mentioned in Table 2. The model is optimally scheduled in two reported cases at 24 hours. In case 1, the energy scheduling of the proposed model considering DRPs is scrutinized. The second case analyzes the impact of uncertainties on the system. The uncertainties corresponding with the thermal and electrical load forecast errors, photovoltaic generation, and electricity price are assumed in the operation management of the proposed MCMG.

Case 1. MCMG operation with DRPs Thermal and load profiles of PV for the 24-hour are shown in Figs. 3 and 4, respectively. The power purchase and prices are assumed to have the same values in three periods (time-of-use (TOU) policy), and the prices of natural gas are fixed, as depicted in Table 3. It is noteworthy to mention that the uncertainty of loads and solar generation is not assumed to simplify and lower the computational burden of the problem.

According to Figure 5(a)-(b), electrical and thermal responsive loads each account for 10% of this model's total loads. The responsive demand loads are encouraged to

Table 2. Comparison of time performance and performance with different superpixel methods

Elements		value	Ko&m
Interconnector	Trans Efficiency	0.92	0.002
CHP	Capacity (kW)	1500	0.00587
	Electrical Efficiency	0.4	
	Heat Efficiency	0.3	
Boiler	Capacity (kW)	1700	0.001
	Heat Efficiency (kW)	0.85	
Electrical storage	Capacity (kW)	1 − 90	-
Heat storage	Capacity (kW)	90	-
Inverter	Capacity (kW)	30	0.003
	Efficiency	0.95	

Table 3. Electricity, Natural gas, and heat sales' market price

($/kWh)	Time (hour)			
	1 − 7	8 − 18	19 − 22	23 − 24
π_e, ψ_e	0.1014	0.117	0.13	0.1014
π_g	0.07	0.07	0.07	0.07
ψ_h	0.07	0.08	0.09	0.08

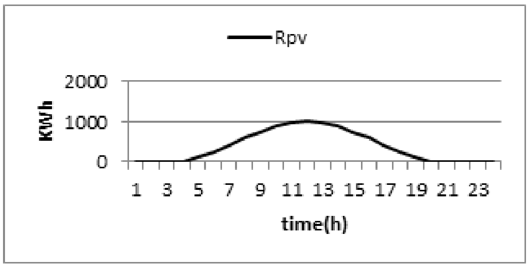
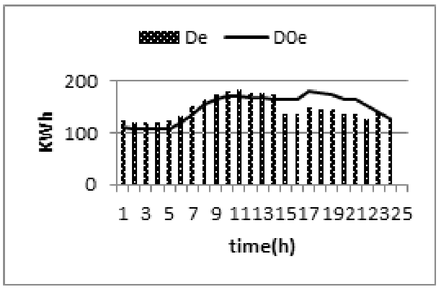
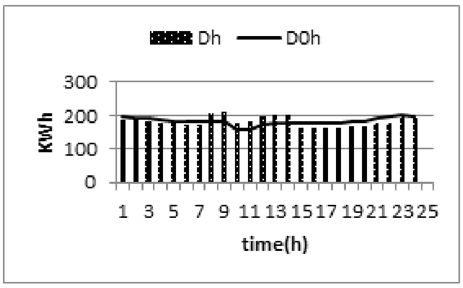


Fig. 4. Hourly generation of the photovoltaic system



(a) Electrical



(b) thermal

Fig. 5. Responsive load profile under FEP in case 1

move from peak to off-peak periods. As shown in Fig. 5 (a) and (b), electrical/thermal sensitive loads are shifted to demand during off-peak times, with customers participating as active loads. Table 4 displays the price elasticity of demand each time.

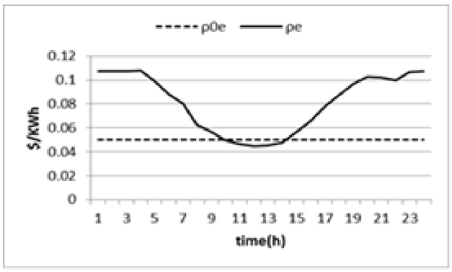
The thermal and electrical responsive loads' FEP and basis are shown in Fig. 6 (a)-(b), respectively. Due to solar production, the FEP of the electric responsive load is decreased at certain periods compared to its base price, resulting in less energy purchased from the main grid. These factors increase power purchases during these periods. In contrast, the FEPs of the thermally responsive load rise at every interval.

Fig. 7(a)-(b) depicts the electric and heat balances of the proposed MCMG. CHP increases gas consumption to meet numerous energies needs simultaneously. According to Fig. 7(a), solar power reduces electricity imports at almost all intervals. In addition, more power is stored during these periods, and the DRP has resulted in a shift in the pattern.

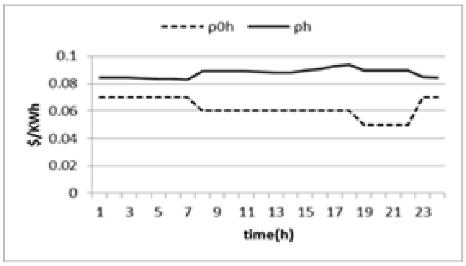
Fig. 8 (a)-(b) depicts, respectively, the equivalent storage

Table 4. Self and cross elasticities of carriers

		Peak	Off-peak	valley
Electricity	Peak	-0.03	0.01	0.02
	Off-peak	0.01	-0.01	0.01
	valley	0.02	0.01	0
Heat	Peak	-0.03	0	0
	Off-peak	0.01	-0.02	0.02
	valley	0.02	0.01	0

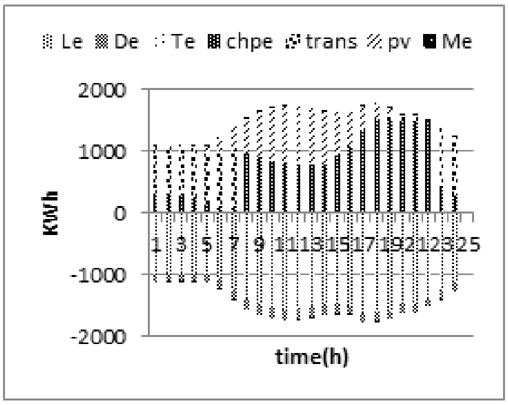


(a) Electrical

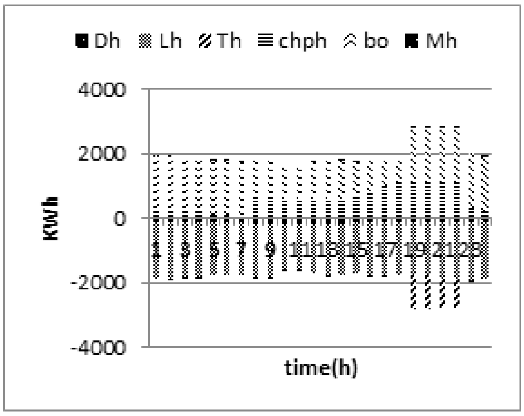


(b) thermal

Fig. 6. FEP of responsive load in case 1



(a) Electrical



(b) thermal

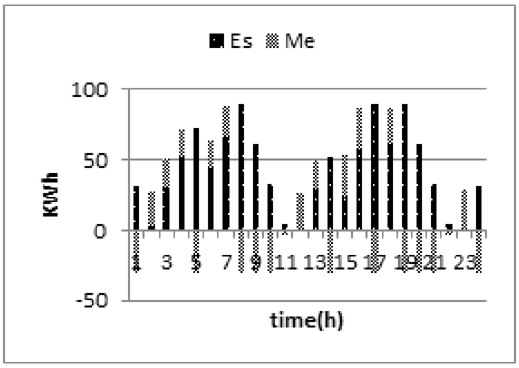
Fig. 7. The energy portion of the MCMG network – the first model of DRP in case 1

power flows and the state of charge (SOC) of the electric and heat storages.

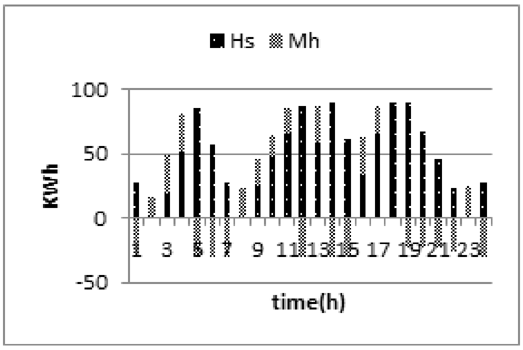
As an MINLP model, the overall operating cost is optimized and lowered. The price-responsive load participation from 0% to 100% of the total load is investigated, and the load factor (LF) and MCMG cost for two suggested DRP models are compared in Fig. 9. In addition, the FEP and TOU programs achieve exceptional outcomes in the optimization process, increasing the likelihood that these programs will be advantageous for the MCMG's owner. Both of the suggested DRP outcomes support the effectiveness of the FEP strategy.

The findings indicate that the engagement of 20% of consumers yields the greatest LF in both models. The presented results indicate that the total cost of MCMG under the FEP policy is proportional to customer participation in DRPs compared to the TOU policy. In both models, the overall cost of the network is lower when responsive load participation is greater. In contrast, the inclusion of responsive load would either increase or degrade the LF of each model's MCMG.

According to the analyses of the preceding findings, the involvement of price-responsive loads and the integration

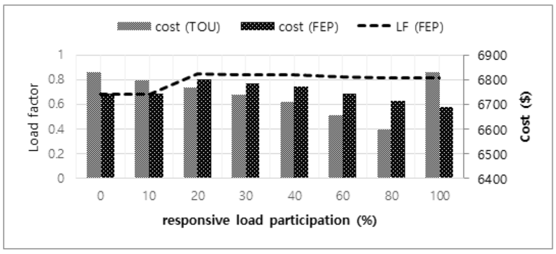


(a) Electrical

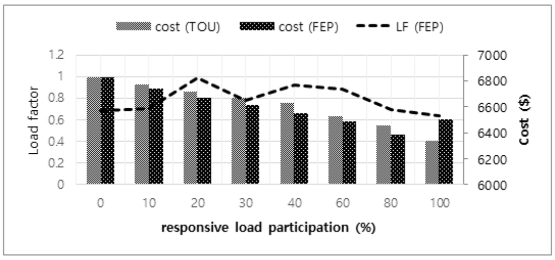


(b) thermal

Fig. 8. The rate of charge/discharge and SOC – the first model of DRP in case 1



(a) Electrical



(b) thermal

Fig. 9. The impact of participation of responsive load on MCMG cost and LF for different DR models in case 1

of diverse energy infrastructure in MCMGs are essential for reaching optimum operating costs.

Case 2. MCMG operation with DRPs under uncertainties Case 2 examines energy scheduling studies pertaining to uncertainties related to demands, power costs, and photovoltaic output. The data are only presented in probability and cumulative distribution function (PDF and CDF) versions for a certain hour (noon). Fig. 10 depicts the probabilistic form of power flows of a storage system and the SoC of electricity and heat storage. Under unpredictable conditions, it is evident that the performance of the electrical storage would be highly difficult. As seen in Fig. 11 , electrical/ thermal loads, which are responsive, are shifted to off-peak times, i.e., consumers are active loads.

Fig. 12 depicts the probability density function (PDF) of FEP for electrically and thermally sensitive loads at a certain hour. The FEP might vary significantly depending on the unpredictability of system parameters. In an unpredictable environment, the load factor of the MCMG would likewise fluctuate between 72% and 87%. (See Fig. 13.

Lastly, the PDF and CDF of the overall case 2 cost are shown in Fig. 14. Comparing case 1's deterministic model to case 2's uncertain model reveals that the overall cost of the system in instance 2 is much higher. In conclusion, the probabilistic analysis of the system significantly makes the optimization algorithm more complex, but it provides the dispatcher with a better understanding of the risk of change in the total system cost, and the obtained results are more reliable from the perspective of energy operation management.

4. Conclusions

In order to find the optimal operation solution of a grid-tied MCMG, a nonlinear mixed-integer programming model was extracted in this study, the model's goals were integrating multiple energy facilities and minimizing the multi-carrier microgrid and costs of maintenance and operation under uncertainties. This paper proposed a novel price-responsive load that integrates the final price of energy of demanded loads for multiple carriers with energy market price, site generations, and energy purchase. Also, the proposed method has been analyzed on two different DRP models to verify the model's effectiveness. The proposed multi-carrier microgrid was investigated considering the uncertainties in thermal and electrical loads, solar generations, and the electricity market.

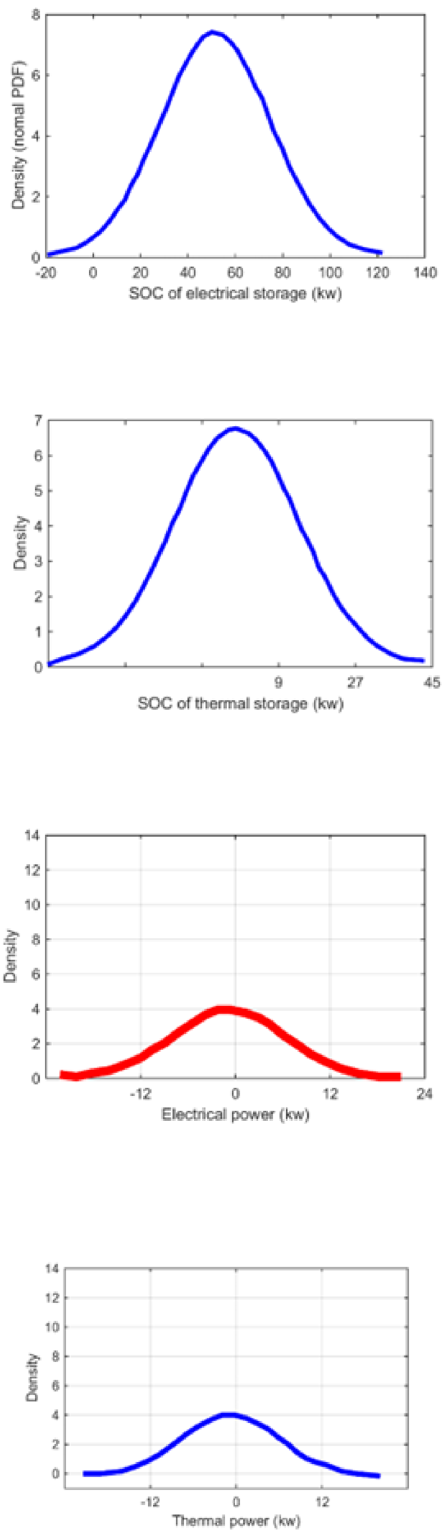


Fig. 10. PDF of storage energy flows and state of charges in case 2

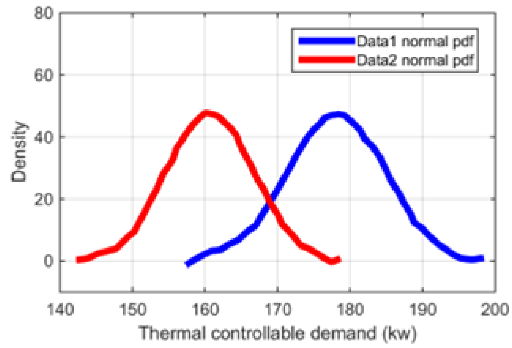


Fig. 11. The probability density function of thermal /electrical load profile under final energy price policy in case 2

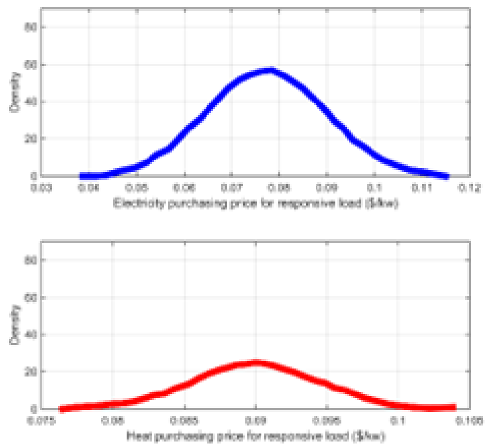


Fig. 12. PDF of FEPs for responsive loads in case 2

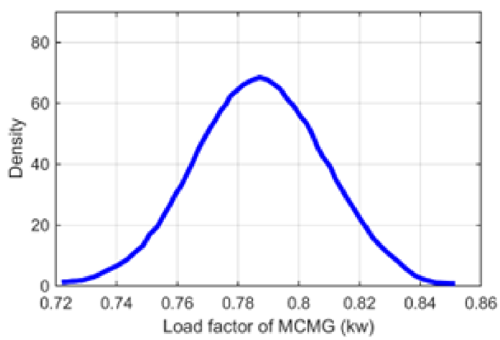


Fig. 13. PDF of load factor in case 2

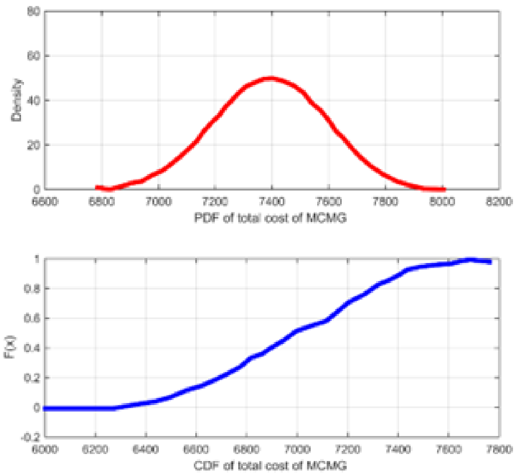


Fig. 14. The overall cost of the MCMG in case 2

Including price-response loads in energy management would result in lower operating costs at future distribution grids. It also would give a realistic perspective of the smart grids in future while allowing customers' participation in the smart grid environment. Thus, a new price-responsive load model, which is characterized by shifting techniques based on the final price of energy, was also applied in this study. The proposed DR program model integrates the final price of energy for price-responsive loads for the thermal and electrical energy consumers with energy purchase, on-site generations, and energy market impost. The superiority of the proposed price-responsive method by two different demand response models is affirmed. The usual drawback of the conventional microgrid structure with a single form of energy was solved by the presented network with multiple energy carriers compared to the overall electric EM strategies. Results show that the simultaneous operation of different energy carriers and utilization of price-responsive loads resulted in lower operating costs for smart distribution grids. Finally, the impact of uncertain parameters was assessed in the system, enhancing the optimal solution's trustworthiness. The proposed model can be utilized in several fields, including industrial and commercial zones.

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nomenclature

Footnotes

0 initial value
α, β carriers type
e electriccity
g natural gas
h heat
p, l Input/output carrier
stb standby energy losses

Greek Symbols

ψ energy sales price ($/kWh)
ρ final energy price of responsive load
π energy purchase price ($/kWh)
v dispatch factor (%)

Subscripts

chp combined heat and power
bo boiler
char charging power of the storage interface
dischar discharging power of the storage interface
main maintenace
trans transformer
pv photovoltaic

Variables & Parameters

η efficiency
$Cost$ cost($)
D responsive load (kWh)
$D^{\text{shup/shdo}}$ shifted up/down energy demand (kWh)
D_0 primary responsive load (kWh)
E state of charge for energy storage (kWh)
ee elasticity element
El elasticity
I binary variable
$IS^{\text{sh}\,p/shdo}$ shifting up/down the state of the demand {0/1}
K coefficient
L non-responsive load (kWh)
M The ramp rate of the charge and discharge in storage (kWh)
P input energy (kWh)
Po generated energy (kWh)
R renewable generation (kWh)
T output energy (kWh)
t time (hour)

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