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Microgrid energy scheduling with demand response

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Abstract. Distributed energy resources (DERs) are essential for coping with growing multiple energy demands. A microgrid (MG) is a small-scale version of the power system which makes possible the integration of DERs as well as achieving maximum demand-side management utilization. Hence, this study focuses on the analysis of optimal power dispatch considering economic aspects in a multi-carrier microgrid (MCMG) with price-responsive loads. This paper proposes a novel time-based demand-side management in order to reshape the load curve, as well as preventing the excessive use of energy in peak hours. In conventional studies, energy consumption is optimized from the perspective of each infrastructure user without considering the interactions. Here, the interaction of energy system infrastructures is considered in the presence of energy storage systems (ESSs), small-scale energy resources (SSERs), and responsive loads. Simulations are performed using GAMS (General Algebraic modeling system) to model MCMG, which are connected to the electricity, natural gas, and district heat networks for supplying multiple energy demands. Results show that the simultaneous operation of various energy carriers, as well as utilization of price-responsive loads, lead to better MCMG performance and decrease operating costs for smart distribution grids. This model is examined on a typical MCMG, and the effectiveness of the proposed model is proven.

Keywords: demand response; operation; microgrid; distributed energy resources

1. Introduction

Over the past decades, there has been an increase in energy consumption corresponding to technology development while the conventional units encountered fossil fuel restrictions, network losses, and high investment costs. In order to transcend the problem, the penetration of renewable energy resources (RERs) such as PV (photovoltaic panel), WT (wind turbine), and SSER has resulted in optimal operation, low network losses, and improved reliability. On the other hand, the higher penetration of SSERs can cause technical/non-technical problems for future networks such as power quality, reliability, energy management, efficiencies, etc. (Saito *et al.* 2009).

A savior solution that not only solves the old distribution network problems but also deals with multiple energy infrastructure integrations is named microgrid (Joseph and Shahidehpour 2006). MGs as an alternate generating system instead of conventional large-scale power plants are trusted

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to provide both grid operators and consumers with higher efficiency of energy use, improvement in power quality and local reliability, less power losses, and greener energy (Lotfi and Khodaei 2016). The MG idea was proposed in order to surmount the current power system network problems and obtain better system performance. It is expected that the control and operation of power systems improve under consideration of these networks. The MG has to be able to reform itself and return to the optimal state in a condition of incurred fault in power systems (Bourbour 2016). Microgrids (MGs) include several energy carriers that are known as small-scale energy zones or multi-carrier microgrids (MCMGs) (Nikmehr and Najafi Ravadanegh 2015).

The main challenge in the operation of MCMGs is the optimal utilization of different energy resources and components. In previous studies, operation in the presence of various energy infrastructures such as electricity, natural gas, heat, etc. was separately studied, which caused a restriction in optimum operation. However, higher penetration of SSERs with gas consumption has increased the enthusiasm for utilization of network services among energy carriers (Krause *et al.* 2011). For this purpose, the concept of energy hub (EH) system was introduced to define multi-carrier energy systems and the examination of a different form of energy impact on others as well (Geidl and Andersson 2007). The discussions mainly pay attention to different operational issues in multi-carrier energy systems, such as economic dispatch (Saldarriaga *et al.* 2013), optimal gas and power flow (Shilaja and Ravi 2016, Zheng *et al.* 2010), unit commitment (Sreejith *et al.* 2016, Zheng *et al.* 2015), and the optimal coupling of energy carriers (Adamek *et al.* 2014). The MCMG, as a sample structure of the EH to integrate various energies, has been studied in a few papers (Manshadi and Khodayar 2015).

Currently, the optimal operation of various energy carriers is performed autonomously, while most of the existing energy infrastructures experience degeneration. On the other hand, congestion in transmission lines and demand growth has encouraged researchers to pursue solutions for future energy management systems. One way of ensuring the practical usage of available infrastructures through MCMGs is to consider it as an energy hub system. It means that instead of inspecting different carriers in energy systems separately, various energy infrastructures should be investigated and operated simultaneously (Cai *et al.* 2012).

The uncertainty of renewable sources, e.g., wind speed and solar irradiance, was investigated in (Motevasel and Seifi 2014). Furthermore, in (Nikmehr and Najafi Ravadanegh 2015), load uncertainty was modeled and studied. A new technique, based on the Beta probability distribution, for the generation of the aggregate demand patterns through the modeling of the energy consumption behavior of a group of residential consumers is presented (Sajjad *et al.* 2015). A novel robust optimization approach is developed to model a multi-objective microgrid investment costs (Uy *et al.* 2018). A model for optimal operations of a microgrid, including generator scheduling decisions, line connectivity decisions, power trade between main and MG, solar energy integration, and ESS, is developed (Ruiz Duarte and Fan 2019). A two stage robust optimization framework is used to manage the uncertainty of the solar power generation. Then, a reformulation was made for the min-max problem in order to apply the Column-and-Constraint-Generation algorithm. Reference (Urooj and Ahmad 2017) analyze the present and future electricity demand of a household at both rural and urban domestic in Province of Balochistan in Pakistan in 3 years. The results confirm that the demand will be supplied by renewable energy sources due to the greater potential for solar and wind.

A Bellmans dynamic programming method for optimal energy management of a standalone MG is proposed (Heymann *et al.* 2018). The objective function includes the operational cost of generators and load shedding costs. The Pontryagin maximum principle is used by determining five extreme optimal points in order to burden the computational time of the dynamic programming model. Reference (Surender Reddy *et al.* 2016) proposes the optimal generation dispatch of an MG considering the generators, wind turbines, solar PV systems, electrical storages, and plug-in electric vehicles. The proposed optimization problem is solved using hybrid differential evolution and harmony search algorithm. The results indicate that microgrids are more stable along with electrical storage and plug-in electric vehicles. Several techniques such as scenario-based (Zhang *et al.* 2012, Zhang *et al.* 2012) and/or sensitivity analysis (Zhang *et al.* 2012) are employed to address uncertainties.

The goal of (Zakariazadeh *et al.* 2014) is the economic dispatch problem in the form of a multi-objective operation problem that not only operation cost is considered, but also emission in the presence of plug-in electric vehicles is regarded as well. Likewise, Zah *et al.* have optimized a multi-objective problem, in which the lifetime of battery cycles in the designed model has been regarded in the objective function (Zhao *et al.* 2013). Optimum management of existing sources to satisfy demands is one of the main problems in the operation of MGs (Koutsopoulos & Tassiulas, 2011). To achieve this aim, smart grid infrastructure in order to distribute energy among small resources with the lowest price is regarded in (Chen *et al.* 2011). A smart residential energy management system is proposed for residential consumers to reduce the total electricity bill by properly time scheduling of the household appliances (Arun and Selvan 2019). Moreover, the demand response technique is applied to mitigate the peak.

The pattern of energy consumption by customers from their normal consumption in response to changes in the price of electricity over time can change by demand response (DR) programs. The DR programs are designed to induce lower electricity use at times of high wholesale market prices or system reliability jeopardy (Jin *et al.* 2017). Owing to the penetration of different sources in future smart grids, the concept of DR will encompass a wide range of loads. DR programs can be classified into two main categories: incentive-based programs and price-based programs (Albadi and El-Saadany 2008). A hub central control unit in an energy hub system is implemented to control EESs and demand shifting service (Pazouki and Haghifam 2016). Reference (Fisher *et al.* 2018) focus on DR programs to avoid carbon emissions as well as participate in spinning reserve markets.

This paper proposes a novel price-responsive load in an MCMG in order to reshape the load curve, as well as preventing the excessive use of energy in peak load hours. The model correlates the final energy price of responsive loads for multiple carriers with energy market tariffs, energy purchases, and on-site generations. The MCMG is equipped by combine heat and power (CHP), PV, convertors, and electrical and thermal storage systems in a grid-connected mode. The operational optimization of MCMG is carried out to calculate the optimal strategy using the mixed-integer nonlinear programming (MINLP) algorithm via the GAMS software. Briefly, the main novation of this paper is as follows:

1. The integration of multiple energy infrastructure under the concept of MCMG.
2. Proposing a novel price-responsive load which correlates the final energy price of responsive loads for multiple carriers with energy market price, energy purchase, and on-site generations.

The rest of this paper is organized as follows. In Section 2, the structure of a typical MCMG and the mathematical model are provided. The simulation results are presented and analyzed in Section 3, while the paper is concluded in Section 4.

2. System model

An MCMG is formed of a low- or medium-voltage electrical network together with networks of other energy carriers, including natural gas and heat. In other words, energy conversion is possible through some equipment, such as transformers, heat exchangers, co- and tri-generation, and other energy converters. Besides the convertors, DERs like ESSs and RERs, can supply a share of demand and effect a significant reduction in energy cost concerning the time-of-use (TOU) carrier's prices. A DR program can provide more flexibility to the network for meeting the demand in the given period. In this paper, a single bus MCMG with coordination among its equipment to fulfill multiple energy demands, for 24 hours is modeled, as depicted in Fig. 1. The MCMG network is connected to the electric and gas main grid while the energy conversion and store are considered feasible.

2.1 MCMG system modeling

In this paper, the proposed MCMG inspires the energy-hub system model, depicted in Fig. 1. The proposed MCMG, as it has been introduced, is connected to the electric and natural gas main grid. The CHP, boilers, and ESSs exclusively to store or supply demands are used. Here, RERs are embedded too, and they enable MCMGs to interchange electricity and heat. The price-responsive loads are also considered to flat the load curves by shifting a share of the load to off-peak hours. The matrix's model of energy balancing in the input and the output hub ports are described in Eqs. (1)-(3) based on (Geidl and Andersson 2007).

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

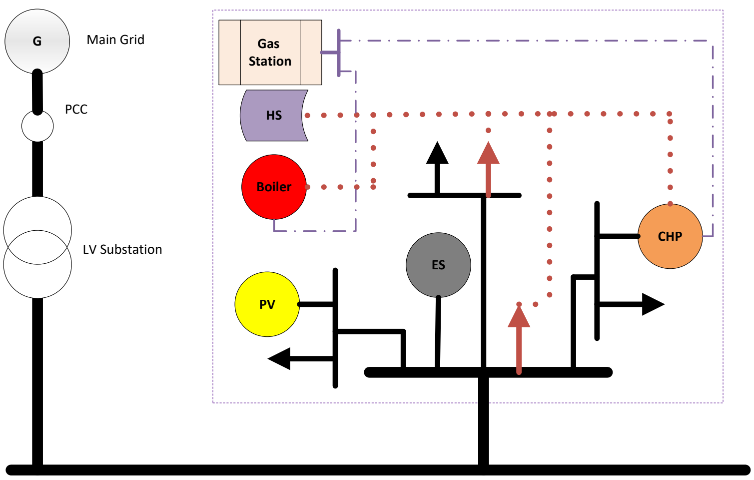


Fig. 1 The proposed MCMG structure

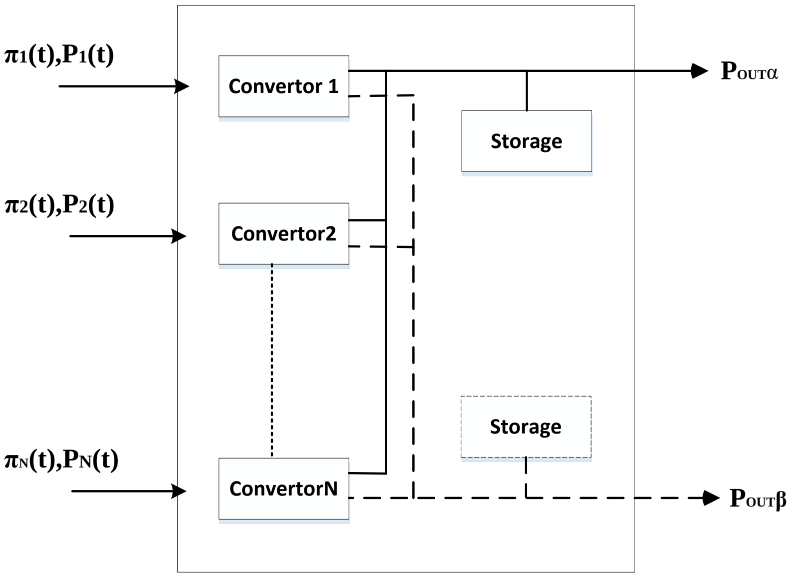


Fig. 2 Correlation between input and output port and energy prices

which $Sc(t)$ and $Sd(t)$ are formulated as below

$$Sc(t) = \frac{1}{\eta_e^{char}} I_e^{char}(t) + \eta_e^{dischar}(1 - I_e^{char}(t)) \tag{2}$$

$$Sd(t) = \frac{1}{\eta_h^{char}} I_h^{char}(t) + \eta_h^{dischar}(1 - I_h^{char}(t)) \tag{3}$$

The ESSs enhance the performance of the MCMG by preventing the wastage of energies. In (Bahramirad *et al.* 2012), the benefits of energy storage elements are studied exclusively. The matrix's model of energy storage is formulated as follows:

$$\begin{bmatrix} Sc(t) & 0 \\ 0 & Sd(t) \end{bmatrix} \times \begin{bmatrix} E_e(t+1) - E_e(t) - E_{e,stb} \\ E_h(t+1) - E_h(t) - E_{h,stb} \end{bmatrix} = \begin{bmatrix} M_e(t) \\ M_h(t) \end{bmatrix} \tag{4}$$

In order to obtain sustainable storage utilization, the storage energies at the end of the last period of the studied time interval are equal to the initial energies:

$$E_e(1) = E_e(24) \tag{5}$$

$$E_h(1) = E_h(24) \tag{6}$$

2.2 Demand response model

In future networks, customers will tend to participate in energy supply because of the high-cost energy market price and online spot market. In other words, the program that enables loads to be cut or shifted to other hours is defined as DR (Sheikhi *et al.* 2015). DR programs are classified into two policies: based on price or encouragement and penalty. In the former, demand patterns changes based on energy prices hourly. This policy is applied in the presented paper. Since the energy prices in the input port of MCMG are specified by the energy price market, the final energy prices (FEPs) of electrical and thermal responsive loads in output port are determined based on received energy, equipment efficiency, and operation strategies. These final prices are modeled in Eqs. (7) and (8), based on Fig. 2.

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

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

Considering the FEP for responsive loads, the elasticity matrix is formulated in (9) and (10). The diagonal elements of the matrix are positive, and the rest are negative.

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

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

Regarding elasticity matrix definition, multi-period time-based demand response is modeled as below

$$D_\alpha(t) = D_{0\alpha}(t)\cdot\left[1+e_\alpha(t,t)\cdot\frac{\rho_{\alpha0}(t)-\rho_{\alpha0}(t')}{\rho_{\alpha0}(t')}\right] + D_{0\alpha}(t)\cdot\left[1+\sum_{\substack{t'=1\\ t\neq t'}}^{24} e_\alpha(t,t')\cdot\frac{\rho_{\alpha0}(t)-\rho_{\alpha0}(t')}{\rho_{\alpha0}(t')}\right] \tag{11}$$

2.3 Objective function (OF) and constraints

The total operational and maintenance (O&M) costs are selected as the two evaluating criteria that are used as the optimal objective to be minimized in Eq. (12). Regarding the presented problem definition in previous parts about MCMG, the objective function for the operation of proposed MCMG is described precisely as below:

$$MIN : OF = \sum_{t=1}^{24}\sum_{i\in\{e,g\}} P_i(t)\cdot\pi_i(t) - \sum_{j\in\{e,h\}} T_j(t)\cdot\psi_j(t) + \mathrm{Cost}_{\mathrm{maintenance}} \tag{12}$$

The objective function is composed of purchased and sold energies and O&M costs. The OF equation details are given precisely as follows:

$$\mathrm{Cost}_{\mathrm{maintenance}}(t)=\mathrm{Cost}^{pv}_{\mathrm{maintenance}}(t)+\mathrm{Cost}^{CHP}_{\mathrm{maintenance}}(t)+C\,\mathrm{ost}^{bo}_{\mathrm{maintenance}}(t) \tag{13}$$

$$\mathrm{Cost}^{pv}_{\mathrm{maintenance}}(t)=Po^{pv}(t)\times K^{pv}_{\mathrm{maintenance}} \tag{14}$$

$$\mathrm{Cost}^{CHP}_{\mathrm{maintenance}}(t)=Po^{chp}(t)\times K^{CHP}_{\mathrm{maintenance}} \tag{15}$$

$$\mathrm{Cost}^{boiler}_{\mathrm{maintenance}}(t)=Po^{boiler}(t)\times K^{boiler}_{\mathrm{maintenance}} \tag{16}$$

$$\mathrm{Cost}^{trans}_{\mathrm{maintenance}}(t)=Po^{trans}(t)\times K^{trans}_{\mathrm{maintenance}} \tag{17}$$

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

$$0\le P_i(t)\le P_{i,\max} \qquad i\in\{e,g\} \tag{18}$$

$$0\le T_j(t)\le T_{j,\max} \qquad j\in\{e,h\} \tag{19}$$

$$0\le Po^{chp}(t)\le Po^{chp}_{\max} \tag{20}$$

$$0\le Po^{boiler}(t)\le P^{boiler}_{\max} \tag{21}$$

$$0\le Po^{trans}(t)\le P^{trans}_{\max} \tag{22}$$

$$0\le Po^{pv}(t)\le Po^{pv}_{\max} \tag{23}$$

$$M_{j,\min}\le M_j(t)\le M_{j,\max} \qquad j\in\{e,h\} \tag{24}$$

$$0\le E_j(t)\le E_{j,\max} \qquad j\in\{e,h\} \tag{25}$$

$$0\le \upsilon(t)\le 1 \tag{26}$$

3. Simulation results and discussion

The model presented in this paper is applied to an industrial zone as an MCMG to illustrate the performance of the proposed method. The proposed MCMG is connected to the electricity, natural gas, and district heat network, as depicted in Fig. 1. The proposed method determines the best operating point of the MCMG’s elements: the transformer, the CHP, the boiler, the PV, and energy storage elements. The characteristics of MCMG’s elements are stated in Table 1.

Electrical and thermal load profiles and RER generation in a 24-hour interval are presented in Figs. 3 and 4, respectively. The electricity purchase and sale prices are considered to be equal in three periods, and the natural gas purchase prices are considered permanently fixed. The details are

Table 1 Technical specification of MCMG's elements

Elements		value	$K_{O\&M}$
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 ESS	Capacity (KW)	1-90	-
Heat ESS	Capacity (KW)	90	-
Inverter	Capacity (KW)	30	0.003
	Efficiency	0.95	

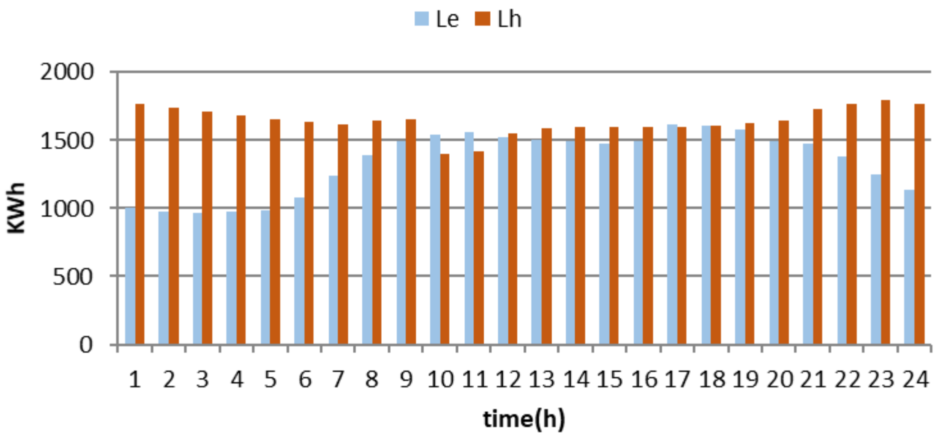


Fig. 3 Correlation between input and output port and energy prices

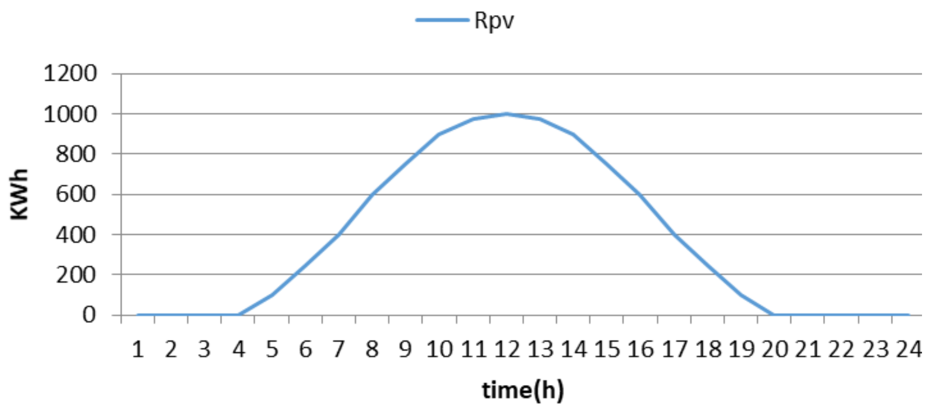


Fig. 4 Correlation between input and output port and energy prices

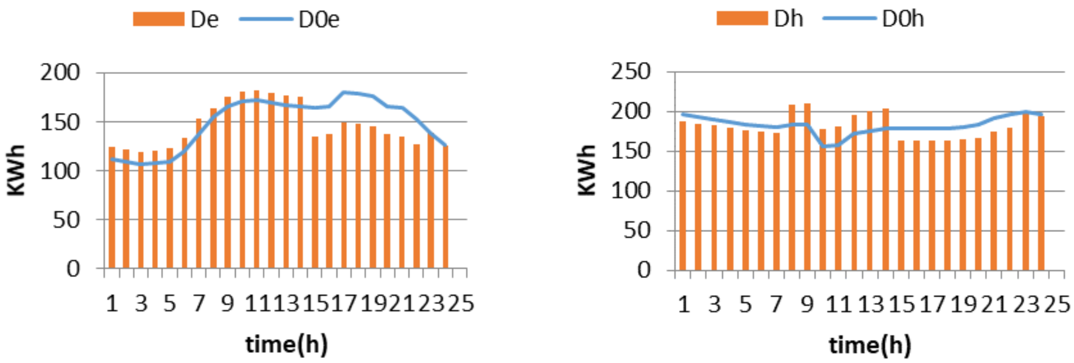
depicted in Table 2. It is significant to be noted that, in order to simplify and lower the

Table 2 Electricity, natural gas, and heat sales' market

	Off-peak	Mid-peak	Peak	Off-peak
π_e, ψ_e (\$/KWh)	0.1014	0.117	0.13	0.1014
π_g (\$/KWh)	0.07	0.07	0.07	0.07
ψ_h (\$/KWh)	0.07	0.08	0.09	0.08

Table 3 Self and cross elasticities of carriers

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



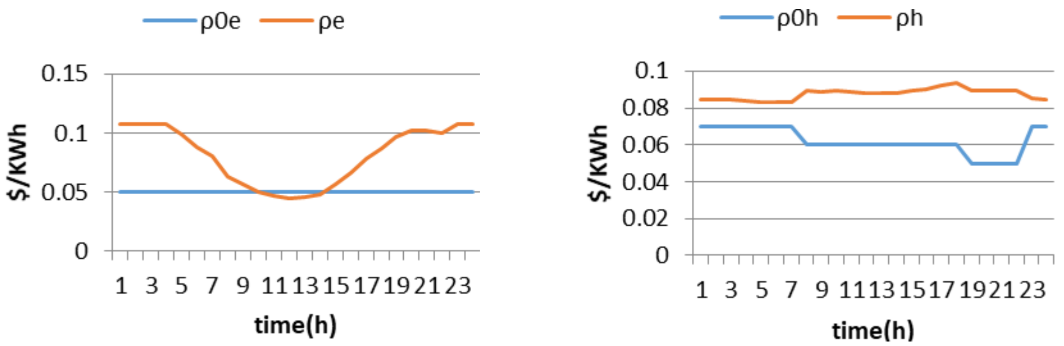
(a) Electrical (b) Thermal

Fig. 5 Responsive load profile under TOU pricing

computational burden of the problem, the uncertainty of loads and PV generation is not considered.

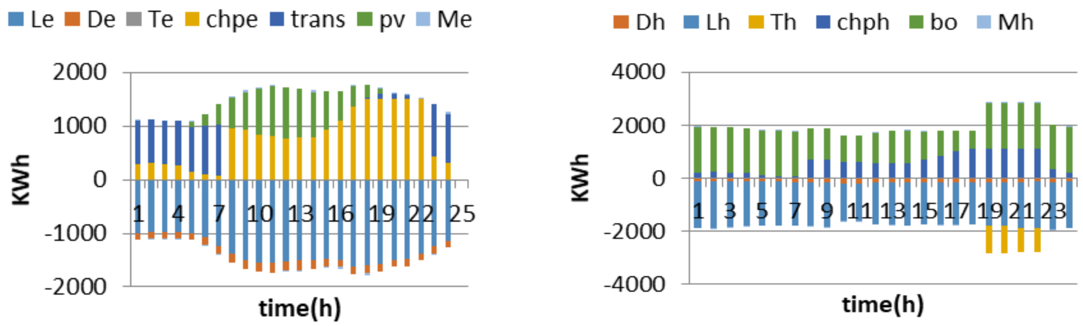
Electrical and thermal responsive loads form 10% of the total loads in this model, as can be observed in Fig. 5(a) and 5(b), respectively. These responsive loads are encouraged to shift their demand from peak intervals to off-peak intervals. As shown in Fig. 5(a) and 5(b), electrical and thermal responsive customers shift their demand to mid- and off-peak hours due to high market price at peaks. The price elasticity described in the model enables customers to help the system operator mitigate peaks. The price elasticity of demand for each period is shown in Table 3.

The base and FEP of electrical and thermal responsive loads are presented in Fig. 6(a) and 6(b), respectively. It can be observed that the FEP of electrical responsive load at some intervals, rather than its base prices are reduced contrary because of PV generation, which has led to less power purchasing from the main grid. This circumstance results in the increase of electricity purchase at these intervals. On the other hand, FEPs of the thermal responsive load is increased for all



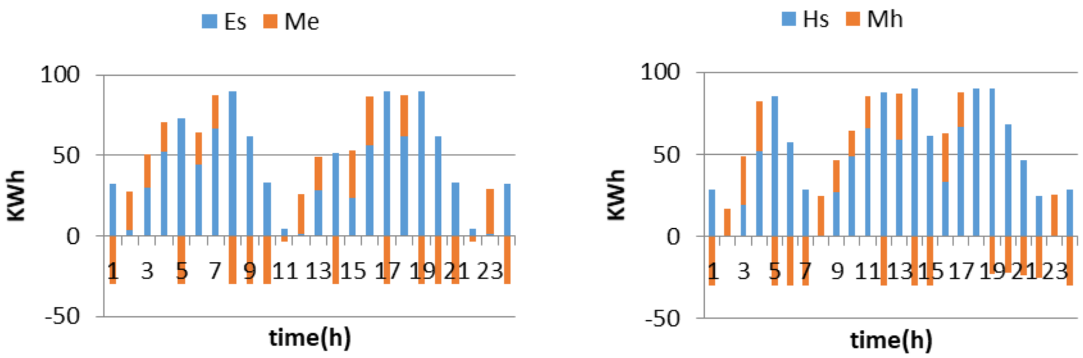
(a) Electrical (b) Thermal

Fig. 6 FEP of responsive load



(a) Electric (b) Heat

Fig. 7 The energy portion of the MCMG network



(a) Electrical (b) Thermal

Fig. 8 Charge and discharge ramp rate and SOC

intervals due to the lack of renewable sources.

The electric and heat balance of the proposed MCMG are depicted in Fig. 7(a) and 7(b), respectively. The gas consumption is increased for supplying CHP to fulfill multiple energy demands, concurrently. According to Fig. 7(a), electricity purchasing in almost all intervals are reduced due to PV generation. Besides, extra electricity is stored in these intervals, and the change

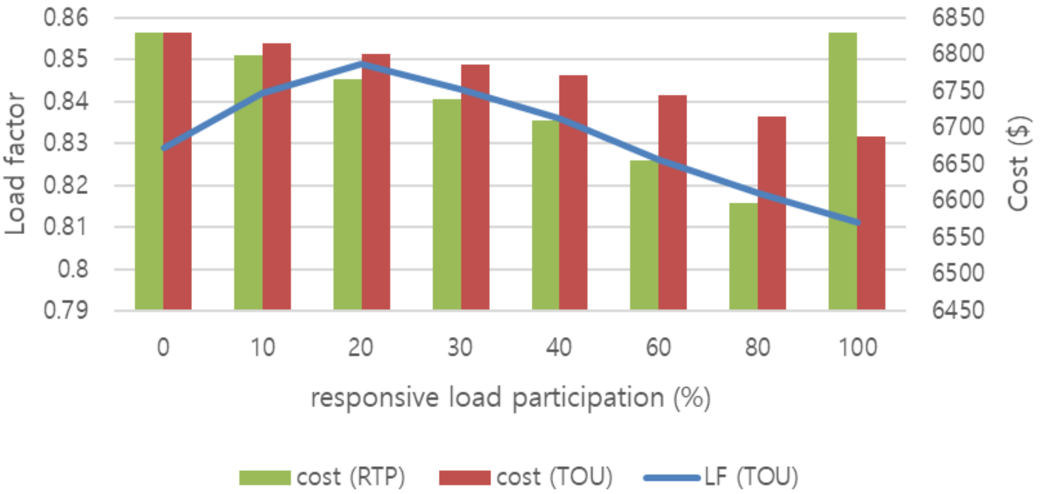


Fig. 9 Responsive load participation impact on MCMG cost and LF

of pattern in the DR program is occurred.

The flexibility of the network is increased by electrical and thermal storage in the designed MCMG to prevent the wastage of energies in such a way that the surplus energies resulting from distributed generations are stored at low prices and injected back into the grid while the price is high. Moreover, the storages provide economic benefits and improve the reliability indices for the MG. The equivalent storage power flows, and the state of charge of the electric and the heat storages are illustrated in Fig. 8(a) and 8(b), respectively. The Es/Hs declares the state of charge in the storages while Me/Mh shows the amount of energy charge/discharge instantaneously in the storages.

The total operating cost is optimized and decreased as an MINLP model, which is calculated 6814.5 $. The price-responsive load participation as 0% to 100% of the total load is analyzed, and load factor (LF) and MCMG cost are compared in Fig. 9. Besides, TOU and real-time pricing (RTP) programs present outstanding results in the optimization process so that the programs are more likely to be beneficial for MCMG's owner. The total cost of the network is lower in the case of higher participation of responsive load. In contrast, the adequate participation of responsive load could improve the LF of the MCMG and vice versa. According to the figure, the total reduction for operation cost using the TOU program is higher than RTP, but it is more realistic.

From the analyses of the above results, it can be concluded that the participation of price-responsive loads and the integration of multiple energy infrastructure in an MCMG are essential to achieve minimum operation costs.

4. Conclusions

In order to find the solutions of optimally DER operations of a grid-tied MCMG industrial zone (represented as energy hub system) comprising CHPs, photovoltaic arrays, electrical and thermal energy storage, and multiple energy demands, a mixed-integer nonlinear programming (MINLP) model has been developed in this paper. The modeling goals were to integrate multiple energy infrastructure and minimize MCMG operation and maintenance costs. The inclusion of price-response loads in energy management leads to lower operating costs at future distribution grids. It gives a realistic perspective of the future smart grid, where customers play a vital role in the smart grid environment. Hence, a novel price-responsive load model characterized by shifting techniques based on the final energy price has also been applied in this study. The proposed DR model correlates the final energy price of price-responsive loads for electrical and thermal loads with energy market tariff, energy purchase, and on-site generations. The common disadvantage of conventional MG structure with one form of energy is resolved by the proposed network with multiple energy carriers as compared to the current electric energy management strategies. Results show that the simultaneous operation of various energy carriers, as well as utilization of price-responsive loads, lead to a beneficial MCMG performance and decrease operating costs for smart distribution grids. This model can be used in different areas, such as industrial and commercial zones, individual facilities, hospitals, and universities. Overall, more economical, effective, and reliable operation is derived from the proposed model.

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References

Adamek, F., Arnold, M. and Andersson, G. (2014), “On decisive storage parameters for minimizing energy supply costs in multi-carrier energy systems”, *IEEE T. Sustain. Energy*, **5**(1), 102-109. https://doi.org/10.1109/TSTE.2013.2267235.

Albadi, M.H. and El-Saadany, E.F. (2008), “A summary of demand response in electricity markets”, *Electric Power Syst. Res.*, **78**(11), 1989-1996. https://doi.org/10.1016/j.epsr.2008.04.002.

Arun, S.L. and Selvan, M.P. (2019), “Smart residential energy management system for demand response in buildings with energy storage devices”, *Front. Energy*, **13**(4), 715-730. https://doi.org/10.1007/s11708-018-0538-2.

Bahramirad, S., Reder, W. and Khodaei, A. (2012), “Reliability-constrained optimal sizing of energy storage system in a microgrid”, *IEEE T. Smart Grid*, **3**(4), 2056-2062. https://doi.org/10.1109/TSG.2012.2217991.

Bourbour, S. (2016), “Development of a Self-Healing strategy for future smart microgrids”, Master Thesis, Murdoch University, Murdoch, Australia.

Cai, N., Nga, N.T.T. and Mitra, J. (2012), “Economic dispatch in microgrids using multi-agent system”, *Proceedings of the 2012 North American Power Symposium*, Champaign, Illinois, U.S.A., September.

Chen, C., Duan, S., Cai, T., Liu, B. and Hu, G. (2011), “Smart energy management system for optimal microgrid economic operation”, *IET Renew. Power Gen.*, **5**(3), 258-267. https://doi.org/10.1049/iet-rpg.2010.0052

Fisher, M., Apt, J. and Sowell, F. (2018), “The economics of commercial demand response for spinning reserve”, *Energy Syst.*, **9**(1), 3-23. https://doi.org/10.1007/s12667-017-0236-x.

Geidl, M. and Andersson, G. (2007), “Optimal power flow of multiple energy carriers”, *IEEE T. Power Syst.*, **22**(1), 145-155. https://doi.org/10.1109/TPWRS.2006.888988.

Heymann, B., Bonnans, J.F., Martinon, P., Silva, F.J., Lanas, F. and Jiménez-Estévez, G. (2018), “Continuous optimal control approaches to microgrid energy management”, *Energy Syst.*, **9**(1), 59-77. https://doi.org/10.1007/s12667-016-0228-2.

Jin, M., Feng, W., Liu, P., Marnay, C. and Spanos, C. (2017), "MOD-DR: Microgrid optimal dispatch with demand response", *Appl. Energy*, **187**, 758-776. https://doi.org/10.1016/j.apenergy.2016.11.093.
Joseph, A. and Shahidehpour, M. (2006), "Battery storage systems in electric power systems", *Proceedings of the 2006 IEEE Power Engineering Society General Meeting*, Montreal, Canada, June.
Koutsopoulos, I. and Tassiulas, L. (2011), "Challenges in demand load control for the smart grid", *IEEE Network*, **25**(5), 16-21. https://doi.org/10.1109/MNET.2011.6033031.
Krause, T., Andersson, G., Fröhlich, K. and Vaccaro, A. (2011), "Multiple-energy carriers: Modeling of production, delivery, and consumption", *Proc. IEEE*, **99**(1), 15-27. https://doi.org/10.1109/JPROC.2010.2083610.
Lotfi, H. and Khodaei, A. (2016), "An efficient preprocessing approach for uncertainty consideration in microgrids", *Proceedings of the IEEE Power Engineering Society Transmission and Distribution Conference*, Dallas, Texas, U.S.A., May.
Manshadi, S.D. and Khodayar, M.E. (2015), "Resilient operation of multiple energy carrier microgrids", *IEEE T. Smart Grid*, **6**(5), 2283-2292. https://doi.org/10.1109/TSG.2015.2397318.
Motevasel, M. and Seifi, A.R. (2014), "Expert energy management of a micro-grid considering wind energy uncertainty", *Energy Conversion Manage*., **83**, 58-72. https://doi.org/10.1016/j.enconman.2014.03.022.
Nikmehr, N. and Najafi Ravadanegh, S. (2015), "Optimal power dispatch of multi-microgrids at future smart distribution grids", *IEEE T. Smart Grid*, **6**(4), 1648-1657. https://doi.org/10.1109/TSG.2015.2396992.
Pazouki, S. and Haghifam, M.R. (2016), "Optimal planning and scheduling of energy hub in presence of wind, storage and demand response under uncertainty", *Int. J. Electrical Power Energy Syst*., **80**, 219-239. https://doi.org/10.1016/j.ijepes.2016.01.044.
Reddy, S.S., Park, J.Y. and Jung, C.M. (2016), "Optimal operation of microgrid using hybrid differential evolution and harmony search algorithm", *Front. Energy*, **10**(3), 355-362. https://doi.org/10.1007/s11708-016-0414-x.
Ruiz Duarte, J.L. and Fan, N. (2019), "Operations of a microgrid with renewable energy integration and line switching", *Energy Syst*., **10**(2), 247-272. https://doi.org/10.1007/s12667-018-0286-8.
Saito, N., Niimura, T., Koyanagi, K. and Yokoyama, R. (2009), "Trade-off analysis of autonomous microgrid sizing with PV, diesel, and battery storage", *Proceedings of the 2009 IEEE Power and Energy Society General Meeting*, Calgary, Alberta, Canada, July.
Sajjad, I.A., Chicco, G. and Napoli, R. (2015), "Probabilistic generation of time-coupled aggregate residential demand patterns", *IET Gen. Transmiss. Distribution*, **9**(9), 789-797. https://doi.org/10.1049/iet-gtd.2014.0750.
Saldarriaga, C.A., Hincapié, R.A. and Salazar, H. (2013), "A holistic approach for planning natural gas and electricity distribution networks", *IEEE T. Power Syst*., **28**(4), 4052-4063. https://doi.org/10.1109/TPWRS.2013.2268859.
Sheikhi, A., Rayati, M., Bahrami, S. and Ranjbar, A.M. (2015), "Integrated demand side management game in smart energy hubs", *IEEE T. Smart Grid*, **6**(2), 675-683. https://doi.org/10.1109/TSG.2014.2377020.
Shilaja, C. and Ravi, K. (2016), "Optimal power flow considering intermittent wind power using particle swarm optimization", *Int. J. Renew. Energy Res*., **6**(2), 504-509.
Sreejith, S., Indragandhi, V.I., Samiappan, D. and Muruganandam, M. (2016), "Security constraint unit commitment on combined solar thermal generating units using ABC algorithm", *Int. J. Renew. Energy Res*., **6**(4), 1361-1372. https://doi.org/10.1234/ijrer.v6i4.4559.g6925.
Urooj, R. and Ahmad, S.S. (2017), "Assessment of electricity demand at domestic level in Balochistan, Pakistan", *Adv. Energy Res*., **5**(1), 57-64. https://doi.org/10.12989/eri.2017.5.1.057.
Uy, L., Uy, P., Siy, J., Chiu, A.S.F. and Sy, C. (2018), "Target-oriented robust optimization of a microgrid system investment model", *Front. Energy*, **12**(3), 440-455. https://doi.org/10.1007/s11708-018-0563-1.
Zakariazadeh, A., Jadid, S. and Siano, P. (2014), "Multi-objective scheduling of electric vehicles in smart distribution system", *Energy Conversion Manage*., **79**, 43-53. https://doi.org/10.1016/j.enconman.2013.11.042.
Zhang, D., Liu, P., Ma, L., Li, Z. and Ni, W. (2012), "A multi-period modelling and optimization approach to the planning of China's power sector with consideration of carbon dioxide mitigation", *Comput. Chem.*

Eng., **37**, 227-247. https://doi.org/10.1016/j.compchemeng.2011.09.001.
Zhang, D., Ma, L., Liu, P., Zhang, L. and Li, Z. (2012), “A multi-period superstructure optimisation model for the optimal planning of China’s power sector considering carbon dioxide mitigation. Discussion on China’s carbon mitigation policy based on the model”, *Energy Policy*, **41**, 173-183. https://doi.org/10.1016/j.enpol.2011.10.031.
Zhang, Q., Mclellan, B.C., Tezuka, T. and Ishihara, K.N. (2012), “Economic and environmental analysis of power generation expansion in Japan considering Fukushima nuclear accident using a multi-objective optimization model”, *Energy*, **44**(1), 986-995. https://doi.org/10.1016/j.energy.2012.04.051.
Zhao, B., Zhang, X., Chen, J., Wang, C. and Guo, L. (2013), “Operation optimization of standalone microgrids considering lifetime characteristics of battery energy storage system”, *IEEE T. Sustain. Energy*, **4**(4), 934-943. https://doi.org/10.1109/TSTE.2013.2248400.
Zheng, Q.P., Rebennack, S., Iliadis, N.A. and Pardalos, P.M. (2010), *Optimization Models in the Natural Gas Industry*, in *Handbook of Power Systems I*, Springer, Berlin, Heidelberg, Germany, 121-148.
Zheng, Q.P., Wang, J. and Liu, A.L. (2015), “Stochastic optimization for unit commitment - A review”, *IEEE T. Power Syst*., **30**(4), 1913-1924. https://doi.org/10.1109/TPWRS.2014.2355204.

CC

Nomenclature

Variables & parameters

Po	generated energy (KWh)
$\mathrm{Cos}t$	cost ($)
P	input energy (KWh)
T	output energy (KWh)
η	efficiency
E	state of charge for energy storages (KWh)
L	non-responsive load (KWh)
D	responsive load (KWh)
D_0	primary responsive load (KWh)
M	storage charge and discharge ramp rate (KWh)
I	binary variable
t	time (hour)
R	renewable generation (KWh)

El	elasticity
ee	elasticity element
K	coefficient

Greek signs

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

Superscripts

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

Footnotes

e	electricity
g	natural gas
h	heat
maintenance	maintenance cost
tot	total
p	input carrier
l	output carrier
α, β	carriers type
0	initial value

stb	standby energy losses
inv	invertor