Journal of Operation and Automation in Power Engineering

Vol. 7, No. 1, May 2019, Pages: 119-128

http://joape.uma.ac.ir

Operation of Multi-Carrier Microgrid (MCMG) Considering Demand Response

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Abstract- *In this paper, the operation of a future distribution network is discussed under the assumption of a multi-carrier microgrid (MCMG) concept. The new model considers a modern energy management technique in electricity and natural gas networks based on a novel demand side management (DSM) which the energy tariff for responsive loads are correlated to the energy input of the network and changes instantly. The economic operation of MCMG is formulated as an optimization problem. 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 MCMG which consists of micro combined heat and power (CHP), photovoltaic (PV) arrays, energy storage systems (ESSs), and electrical and heat loads in grid-connected mode. Results show that the simultaneous operation of various energy carriers leads to a better MCMG performance. Moreover, it has been indicated that energy sales by multi sources to main grids can undoubtedly reduce the total operation cost of future networks.*

Keyword: Demand response, Economic dispatch, microgrid, small-scale energy resource.

NOMENCLATURE

Indices

j	Index for carriers (e, h).
i	Index for carriers (e, g).
e	Index for electricity carrier.
g	Index for natural gas carrier.
h	Index for heat carrier.
lo	Index for loads.
chp	Index for combined heat and power
$boiler$	Index for boiler.
pv	Index for photovoltaic.
inv	Index for inverter.
0	Index for initial value.
$char$	Charge rate Index for storage interface.
$dischar$	Discharge rate Index for storage interface.
stb	Index for standby energy losses for storage [KWh]
$main$	Index for maintenance.

Parameters

L	Total load power [KWh]
π	Energy purchase price [$/KWh]
ψ	Energy sales price [$/KWh]
η	Energy efficiency
ρ_α	Final energy tariff of responsive load [$/KWh]
K	Maintenance coefficient
EL_α	Elasticity matrix
ee_α	Elasticity element

Variables

D	Responsive load [KWh]
T	Transferred energy [KWh]
P	Purchased electricity [KWh]
Po	Energy generation by each units [KWh]
R	Renewable generation [kWh]
M	Storage charge and discharge ramp rate [KWh]
E	State of charge [KWh]
Sc	Storage coupling factors in charging mode

Received: 06 Jan. 2017
Revised: 18 Oct. 2017 and 04 Sep. 2018
Accepted: 10 Oct. 2018
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Digital object identifier: 10.22098/joape.2019.3205.1262
Research Paper

Sd	Storage coupling factors in discharging mode
$\dot{E}$	Storage energy derivatives
I	Binary variable for energy charging or discharging mode.
υ	Dispatch factor
OF	Objective function
Cost	Cost

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, WT (wind turbine) and SSER can result in optimal operation, low network losses and improvement in 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 in Ref. [1].

Future energy network that satisfies communication infrastructure between equipment is named smart grid (SG) [2,3]. However, a small district of energy network along with SSERs including renewable and non-renewable energy resources like PV, WT, storages and responsive and non- responsive loads is named microgrid (MG) in Ref. [4]. 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 in Ref. [5]. Indeed, MG includes electrical and communicational networks, software and hardware devices for monitoring and management of generation, control state, state of charge (SOC) and energy consumption, which causes a remarkable reduction in energy consumption, cost and reliability improvement in the network in Ref. [6].

MGs include several energy carriers that are known as multi-carrier microgrids (MCMGs). The main challenge in the operation of these MGs is the optimal utilization of different energy resources and equipment. In previous studies, the operation and planning of different energy carrier infrastructures, such as electricity, natural gas, and heat, were studied autonomously, which has caused a restriction in their optimal operation. However, a higher penetration of SSERs with gas consumption (especially co- and trigeneration) has increased enthusiasm for the use of network services among energy carriers in Ref. [7]. For this purpose, integrated multi-carrier energy (MCE) systems have been discussed in scientific literature [8, 9]. The concept of the energy hub (EH) system was introduced to define multi-carrier systems [10]. The EH system comprises a variety of energy carriers, convertors, and storage to meet demands [11]. This model has been investigated with respect to operation [12, 13] and planning [14] problems.

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 have encouraged researchers to pursue solutions for future energy management systems. One way of ensuring the effective 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 [15]. Energy optimization has been improved after revealing the energy hub concept [16]. The optimal operation of energy carriers and existing components is the main task of MG central controller (MGCC) which is solved by optimization methods. A decentralized multi agent method to apply economic dispatch (ED) is presented by Cai et al. [17], which this method has been studied in [18,19] as well.

The optimal operation of multi microgrid is studied by Nikmehr et al. in Ref. [20] while the uncertainties of distributed energy resources (DERs) are considered. The economic dispatch problem of MGs has been studied from different point of views, so this problem has shown a vast difference in a piece of paper [21]. The MG optimal dispatch considering demand response (DR) mechanism and flexible loads utility in grid-connected mode is studied [22]. From the source utilization cost reduction viewpoint in [23], an ED method is presented according to marginal cost whereas the optimal operation along with instant energy optimization method in stand-alone mode is studied in Ref. [24]. The goal of Ref. [25] is the ED problem in form of a multi objective operation problem that not only operation cost is considered, but also emission in the presence of electric vehicles is regarded as well. likewise, Zah et al. have optimized a multi objective problem, which the lifetime of battery cycles in the designed model has been regarded in objective function [26].

The economic dispatch optimization problem in literature has been categorized into different models as well as solvers [27,28], e.g. in [20] and [27] used the particle swarm optimization (PSO) algorithm, Tabu search (TS), genetic algorithm (GA) [11,29], ant colony [30] and game theory are methods that used in optimal dispatching problem. Optimum management of existing sources to satisfy demands is one of the main problem in operation of MGs [31]. To achieve this aim, smart grid infrastructure in order to distribute energy among small resources with the lowest price is regarded in [32] and power balances between generation and loads via existing infrastructure and responsive equipment are performed in [33-34].

Loads can be divided into two categories: 1) responsive and 2) non- responsive. Non- responsive loads can be curtailed or shifted to other hours. Owing to the penetration of different sources in future smart grids, the concept of demand side management (DSM) will encompass a wide range of loads [22]. The DSM program only implies load that can be controlled directly (curtailable) or shift their demands to off-peak hours. Direct-responsive and shiftable loads have been discussed in earlier studies [23,24] and [30,35]. Washing machines and dryers, dishwasher, vacuum cleaner etc. are examples of shiftable loads [10].

In [36], a meta-heuristic method to solve the economic dispatch of CHP is proposed. The easily implementation, better convergence, capability of handling several constraints in non-convex and complex search spaces of the algorithm indicate the superiority of the proposed method compared to the recently developed methods. Energy scheduling problem of CHP-based MGs considering uncertainties in load, wind speed, and energy market is carried out [37]. In this paper, the responsive loads in the stochastic programming problem has been implemented in order to have more successful participation of CHP-based MGs in the power market, but the final energy tariff for responsive loads has not been modeled. A more complicated model of the previous paper considering epsilon-constraint method along with fuel cell unit in addition to hydrogen tank is utilized [38]. The MCMG task is to fulfill the demand optimally by its sources and convertors. In other words, the operation cost of MCMG has to be minimized while the load requirements are supplied by SSERs, convertors and energy storage systems in a grid-connected mode. In addition, the operation cost is decreased by energy trading with the main grid. To achieve this goal, a mixed-integer nonlinear programming (MINLP) technique is used and simulated by the GAMS software to solve the operational problem with a novel demand response modeling.

Briefly, the main contribution of this paper is as follows:

- Electric and heat responsive loads modeling in a novel manner that the final energy tariff of responsive loads (ETRL) for carriers are proportionate to input energy prices.
- Simultaneous operation of various carriers in an MCMG and assessment of one energy form's impact on the others.
- The energy hub concept is used to model the proposed MCMG.

The rest of this paper is organized as follows. In Section 2 the structure of a typical MCMG is described. In Section 3, the mathematical model is provided. The simulation results are presented and analyzed in Section 4 while the paper is concluded in Section 5.

2. MCMG STRUCTURE

An MCMG is formed of a low- or medium-voltage electrical network together with networks of other energy carriers, including natural gas and heat. However, energy conversion is possible through some equipment, such as transformers, heat exchangers, co- and tri-generation, and other energy convertors. Besides the convertors, DERs like ESS and RERs, can satisfy demand and effect a significant reduction in energy cost with regard to the time-of-use (TOU) carrier's prices. A DSM program can provide more flexibility to the network for meeting the demand in the given period. A typical MCMG structure is depicted in Fig. 1. It can connect to the main grid, such as to electricity, district heat, and natural gas stations.

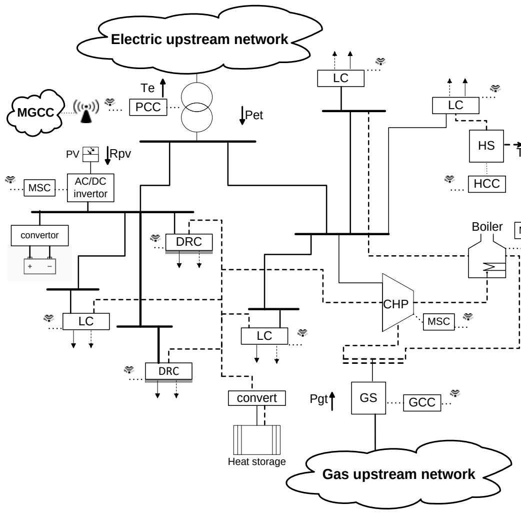

Fig. 1. Typical MCMG structure

3. SYSTEM MODEL

In this paper, the energy scheduling in a single-bus network is carried out as illustrated in Fig. 2. The MCE system to model MCMGs is used along with the various energy carriers considered and different equipment for each MCMG which the energy conversion and store are considered feasible [11]. Fig. 2 illustrates the proposed MCMG in Fig. 1 as an integrated energy system. The depicted network is connected to electric and natural gas main grid while the energy conversion and store are considered feasible.

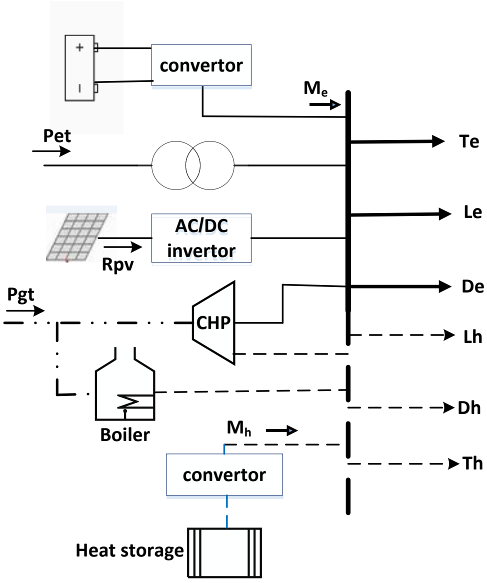

Fig. 2. The proposed single-bus MCMG structure

Equation (1) and (2) show amount of non-responsive and responsive loads regarding single-bus model that are actually the summation of the whole available loads of MCMG.

$$L_j(t) = \sum_{lo=1}^{nl_{lo}} L_{j,lo}(t) \qquad j \in \{e,h\} \qquad (1)$$

$$D_j(t) = \sum_{lo=1}^{nd_{lo}} D_{j,lo}(t) \qquad j \in \{e,h\} \qquad (2)$$

Where $L_j(t)$ and $D_j(t)$ are the summation of all non-responsive/responsive loads in each MCMG $L_{j,lo}(t,)/D_{j,lo}(t,)$ for electrical and thermal consumption at each hour (t), respectively.

3.1. Energy hub system modeling

The general structure of energy hub system is depicted in Fig. 3. The matrix's model of power balancing in input and output port of MCMG based on its equipment efficiencies at given intervals is described as

$$L(t)+T(t) = C \times \begin{bmatrix} P(t) \\ RP(t) \end{bmatrix} - S \times \dot{E}(t) \qquad (3)$$

$$\dot{E}(t) = E(t+1) - E(t) - E_{stb} \qquad (4)$$

In this paper, $T(t)$, Co, $P(t)$, $RP(t)$, S and $\dot{E}(t)$ describe transferred energy, converter coupling matrix, renewable generation, storage coupling factor and the differential of state of charge in storages, respectively. describes the amount of standby energy losses in energy storages. E_{stb}

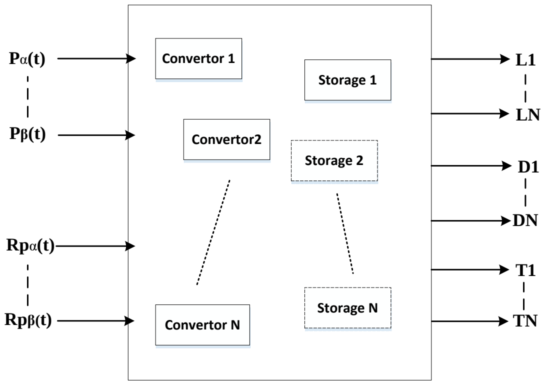

Fig. 3. Integrated energy system with multiple input and output ports

The proposed MCMG that has been introduced, is connected to the electric and natural gas upstream network. Combined heat and power, boilers, electric and heat storages, and PV modules to supply demands are used in the proposed MCMG. RERs are embedded and enabled MCMG to trade electricity to the main grid. In addition to non-responsive loads, responsive loads are considered whereas the consumption can be changed by its instantaneous purchasing price. The energy balance in the network is modeled in (5).

$$\begin{bmatrix} L_e(t) \\ L_h(t) \end{bmatrix} + \begin{bmatrix} D_e(t) \\ D_h(t) \end{bmatrix} + \begin{bmatrix} T_e(t) \\ T_h(t) \end{bmatrix} = \begin{bmatrix} \eta^{trans} & \eta_e^{chp} \times \upsilon(t) & \eta^{inv} \\ 0 & \eta_h^{chp} \times \upsilon(t) + \eta_h^{boiler} \times (1-\upsilon(t)) & 0 \end{bmatrix} \times \begin{bmatrix} P_e(t) \\ P_g(t) \\ R_{pv}(t) \end{bmatrix} - \begin{bmatrix} Sc(t) & 0 \\ 0 & Sd(t) \end{bmatrix} \times \begin{bmatrix} \dot{E}_e(t) \\ \dot{E}_h(t) \end{bmatrix} \qquad (5)$$

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

$$Sc(t) = \frac{1}{\eta_e^{char}} I_e(t) + \eta_e^{dischar}(1 - I_e(t)) \qquad (6)$$

$$Sd(t) = \frac{1}{\eta_h^{char}} I_h(t) + \eta_h^{dischar}(1 - I_h(t)) \qquad (7)$$

where $I_e(t,m)$ and $I_h(t,m)$ are binary variable for energy charging or discharging mode in electrical and thermal energy storages, respectively. η_e^{char} , $\eta_e^{dischar}$, η_h^{char} and $\eta_h^{dischar}$ are the parameters of charge or discharge efficiency in electrical and thermal storage system, respectively. The injected energies to storages in MCMG are formulated in (8) which $\dot{E}(t)$ is the energy derivative that are charging or discharging in storages. Equation (9) defines the relation between state of charge (SOC) and equivalent storage power flows.

$$\begin{bmatrix} Sc(t) & 0 \\ 0 & Sd(t) \end{bmatrix} \times \begin{bmatrix} \dot{E}_e(t) \\ \dot{E}_h(t) \end{bmatrix} = \begin{bmatrix} M_e(t) \\ M_h(t) \end{bmatrix} \quad (8)$$

$$\begin{bmatrix} \dot{E}_e(t) \\ \dot{E}_h(t) \end{bmatrix} = \begin{bmatrix} E_e(t+1) - E_e(t) - E_{e,stb} \\ E_h(t+1) - E_h(t) - E_{h,stb} \end{bmatrix} \quad (9)$$

3.2. Demand side management (DSM) model

In MGs, loads have a tendency to participate in energy supply. In other words, the program that enables loads to be cut or shifted to the other hours is defined as DSM [39]. DSM programs are classified into two policies: based on price or on encouragement and penalty. In the former, the demand changes based on energy tariff in each interval. This method is considered in the presented paper. Since, the energy tariffs in input port of MCMG are specified, thus it is required to model the energy tariff of responsive load (ETRL) in output port of the system. In this case, ETRL for different carriers in system output are determined based on input energy, equipment efficiency and operation. ETRL for electrical and thermal carriers are modeled in (10) and (11) based on Fig. 4. Briefly, the energy tariff for responsive loads have been modeled in market power environment in which it changes owing to the amount of energy purchase costs as well as energy generation.

$$\rho_\alpha(t) = \frac{\sum_{i=1}^{N} P_i(t) \cdot \pi_i(t) \cdot \dfrac{\eta_{i,\alpha}}{\eta_{i,\alpha} + \eta_{i,\beta}}}{Po_\alpha(t) + M_\alpha(t)} \quad (10)$$

$$\rho_\beta(t) = \frac{\sum_{i=1}^{N} P_i(t) \cdot \pi_i(t) \cdot \dfrac{\eta_{i,\beta}}{\eta_{i,\alpha} + \eta_{i,\beta}}}{Po_\beta(t) + M_\beta(t)} \quad (11)$$

$\rho_\alpha(t)$ and $\rho_\beta(t)$ are the final energy price of electrical and thermal responsive loads, respectively. $P_i(t)$ and $\pi_i(t)$ describe the amount of purchased or received energy (i : energy material) at hour t and energy purchase price at hour t . $L_\alpha(t)$, $L_\beta(t)$, $D_\alpha(t)$, and $D_\beta(t)$ are non-responsive and responsive loads for carrier α and β at hour t , respectively. $Po_\alpha(t)$, $Po_\beta(t)$, $M_\alpha(t)$ and $M_\beta(t)$ are the transferred energy and equivalent storage power flows for carrier α and β at hour t , respectively.

Considering ETRL, elasticity matrix that indicates the load change percentage in proportion to price change percentage, are described in (12) and (13). The diagonal elements of mentioned matrix are positive and the rest are negatives, i.e. by energy tariff increasing in an hour, responsive load is decreased at this moment and shift a share of load to other hours.

$$EL_\alpha(t,t') = \begin{pmatrix} ee_\alpha(1,1) & \cdots & ee_\alpha(1,24) \\ \vdots & \ddots & \vdots \\ ee_\alpha(24,1) & \cdots & ee_\alpha(24,24) \end{pmatrix} \quad (12)$$

$$ee_\alpha(t,t') = \begin{cases} t = t' & ee_\alpha(t,t') < 0 \\ t \neq t' & ee_\alpha(t,t') \geq 0 \end{cases} \quad (13)$$

where $EL_\alpha(t,t')$ is the elasticity matrix of responsive loads for carrier α . Regarding to elasticity matrix definition, responsive load is modeled as below

$$D_\alpha(t) = D_{0,\alpha}(t) \cdot \left[1 + \sum_{t'=1}^{24} EL_\alpha(t,t') \cdot \frac{\rho_\alpha(t) - \rho_{0\alpha}(t')}{\rho_{0,\alpha}(t')} \right] \quad (14)$$

In (14), $D_{0\alpha}$ is the base consumption of carrier α which is changing in proportion to primary energy tariff of carrier α at interval t'. Owing to energy changes in output port of MCMG, the new modified consumption of these responsive loads are calculated.

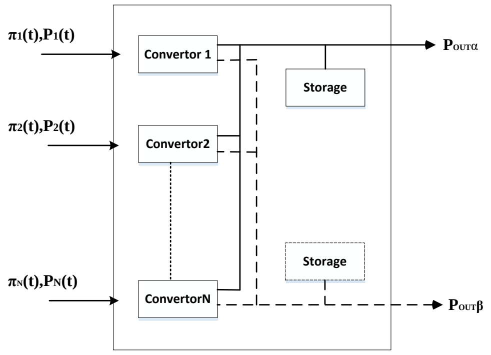

Fig. 4. Correlation between input and output port of carriers and energy tariffs

3.3. Objective function (OF) and Constraints

With regard to the presented problem definition in previous sections, the OF and constraints for the proposed MCMG at the given intervals are modeled as an optimization problem.

The economic dispatch problem of proposed MCMG within 24 hours is a nonlinear problem that the OF includes the purchased and sold power of various carriers in addition to the maintenance cost as below

$$OF = \sum_{t=1}^{24} \sum_{i \in \{e,g\}} P_i(t) \cdot \pi_i(t) - \sum_{j \in \{e,h\}} T_j(t) \cdot \psi_j(t) + \mathrm{Cost}_{\mathrm{main}}(t) \qquad (15)$$

The maintenance cost is obtained as follow

$$\mathrm{Cost}_{\mathrm{main}}(t) = \mathrm{Cost}^{pv}_{\mathrm{main}}(t) + \mathrm{Cost}^{CHP}_{\mathrm{main}}(t) + C\ \mathrm{ost}^{bo}_{\mathrm{main}}(t) + \mathrm{Cost}^{Tr}_{\mathrm{main}}(t) \qquad (16)$$

$$\mathrm{Cost}^{pv}_{\mathrm{main}}(t) = R_{pv}(t) \times \eta^{inv} \times K^{pv}_{\mathrm{main}} \qquad (17)$$

$$\mathrm{Cost}^{CHP}_{\mathrm{main}}(t) = P_g(t) \times \eta^{CHP} \times \upsilon(t) \times K^{CHP}_{\mathrm{main}} \qquad (18)$$

$$\mathrm{Cost}^{boiler}_{\mathrm{main}}(t) = P_g(t) \times \eta^{boiler} \times (1-\upsilon(t)) \times K^{boiler}_{\mathrm{main}} \qquad (19)$$

$$\mathrm{Cost}^{trans}_{\mathrm{main}}(t) = Po_e(t) \times \eta^{trans} \times K^{trans}_{\mathrm{main}} \qquad (20)$$

The electrical and heat balances in MCMG is modeled in (21) under assumption of EH system.

$$\begin{bmatrix} L_e(t) \\ L_h(t) \end{bmatrix} + \begin{bmatrix} D_e(t) \\ D_h(t) \end{bmatrix} + \begin{bmatrix} T_e(t) \\ T_h(t) \end{bmatrix} = \begin{bmatrix} \eta^{trans} & \eta_e^{chp} \times \upsilon(t) & \eta^{inv} \\ 0 & \eta_h^{chp} \times \upsilon(t) + \eta_h^{boiler} \times (1-\upsilon(t)) & 0 \end{bmatrix} \times \begin{bmatrix} P_e(t) \\ P_g(t) \\ R_{pv}(t) \end{bmatrix} - \begin{bmatrix} M_e(t) \\ M_h(t) \end{bmatrix} \qquad (21)$$

In addition, the equality and non-equality constraints due to capacity of equipment and multi-carrier network in single-bus mode, are subjected as follows

$$0 \le P_i(t) \le P_{i,\max} \qquad i \in \{e,g\} \qquad (22)$$

$$0 \le T_j(t) \le T_{j,\max} \qquad j \in \{e,h\} \qquad (23)$$

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

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

$$E_j(0) = E_j(24) \qquad j \in \{e,h\} \qquad (26)$$

$$Po_{CHP,\min} \le Po_{CHP}(t) \le Po_{CHP,\max} \qquad (27)$$

$$0 \le Po_{boiler}(t) \le Po_{boiler,\max} \qquad (28)$$

$$0 \le R_{pv}(t) \le R_{pv,\max} \qquad (29)$$

$$0 \le \upsilon(t) \le 1 \qquad (30)$$

$Po_{CHP}(t)$, $Po_{boiler}(t)$, and $R_{pv}(t)$ are the generated energy of CHPs, boilers and renewable generations. $Po_e(t)$ and K_{main} stand for imported electricity from the main grid and maintenance coefficient for elements, respectively.

4. SIMULATION RESULTS AND DISCUSSION

All the equations have been modeled for the proposed MCMG, which inspired from energy hub system. The primary input information and assumed values of typical MCMG elements in this paper are presented in Table 1. Electrical and thermal load profiles, and RER generation in a 24-hour interval are presented in Fig. 5 and Fig. 6, respectively. It is remarkable that the electricity purchase and sale prices are considered to be equal in three periods and the natural gas purchase prices are permanently fixed. The details are depicted in Table 2.

Table 1. Values of MCMG's elements

Elements		value	$K_{O\&M}$ ($/KWh)
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	0.85	
ES	Capacity(KWh)	1-90	-
HS	Capacity(KWh)	90	-
Inverter	Capacity(KW)	30	0.003

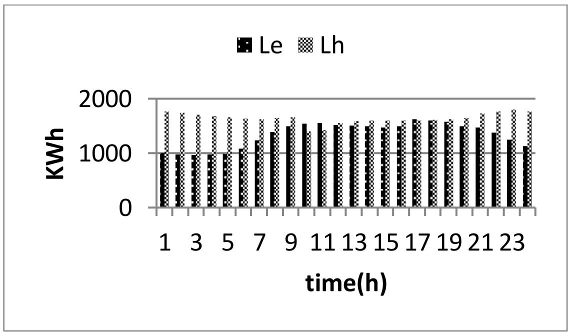

Fig. 5. Electrical and Thermal load profiles of MCMG

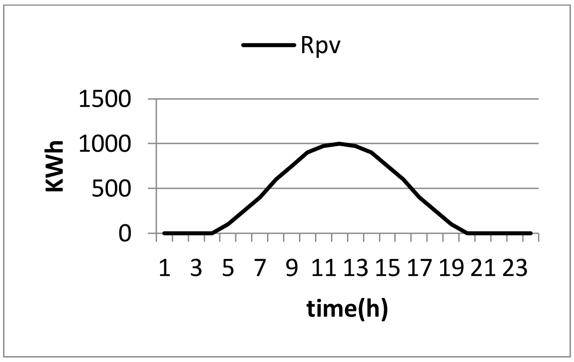

Fig. 6. Hourly generation of PV

Table 2. Electricity, natural gas and heat tariffs

	Time (h)			
	t1*t7	t8*t18	t19*t22	t23*t24
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

Electrical and thermal responsive load form 10% of total loads as it can be observed in Fig. 7 and Fig. 8, respectively. These responsive loads are encouraged or forced to shift their demand from peak intervals to off-peak intervals. The peak period for electrical load is considered from interval 15 to interval 22, whereas heat demand occurs in intervals 1–8 and 15–24. It can be observed that the consumption of responsive loads is shifted from peak to off-peak periods in proportion to energy tariff changes.

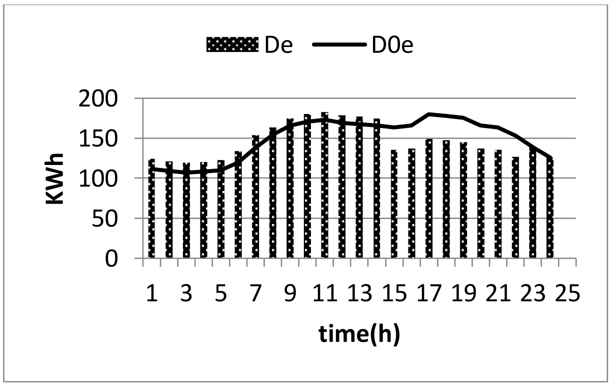

Fig. 7. Electrical responsive load profile under TOU pricing

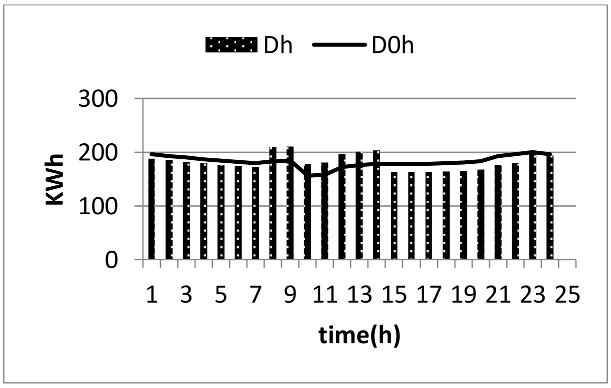

Fig. 8. Thermal responsive load profile under TOU pricing

The elasticity matrix that shows the shifting percentage of loads at period t to period t' is supposed in Table 3.

Table 3. Elasticity matrix

Elasticity	Time (h)	t1*t7	t8*t14	t15*t22	t23*t24
Electrical	t1*t7	0	0.01	0.02	0
	t8*t14	0	-0.01	0.01	0
	t15*t22	0	0	-0.03	0
	t23*t24	0	0	0	0
Heat	t1*t7	0.03	0	0	0
	t8*t14	0.02	0	0.02	0.02
	t15*t22	0.01	0	-0.02	0.01
	t23*t24	0	0	0	-0.03

The base and final ETRL for electrical and thermal carriers are presented in Fig. 9 and Fig. 10, respectively. It can be observed that, the final output carrier prices 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. On the other hand, final output carrier price of thermal responsive load is increased for all intervals due to lack of free heat generations.

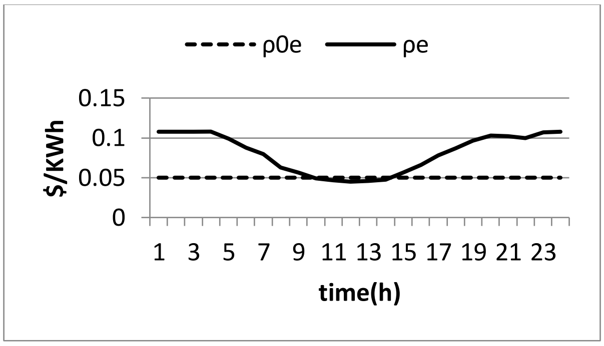

Fig. 9. Energy purchase tariff for electrical responsive load

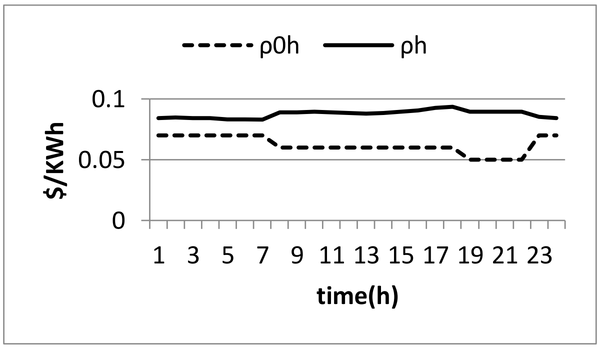

Fig. 10. Energy purchase tariff for thermal responsive load

The electric and heat balance of proposed MCMG are depicted in Fig. 11 and Fig. 12, respectively. It is obvious that the gas consumption is increased for supplying CHP to fulfill multiple energy demands, concurrently. According to Figure 11, electricity purchasing in almost all intervals are reduced due to PV generation. In addition, extra electricity is stored in these intervals and the change of pattern in DSM program is occurred despite the fact that the costumers were encouraged to have less demands at peak and to shifts their demands to off-peak intervals. The heat generation by boiler is increased in interval 19 to 22 due to high price sales of this carrier as it is observable in Fig. 12. This surplus heat is sold to the main grid.

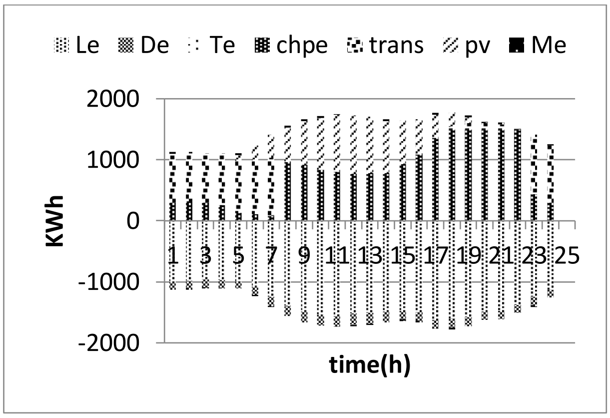

Fig. 11. Electric portion of the MCMG network

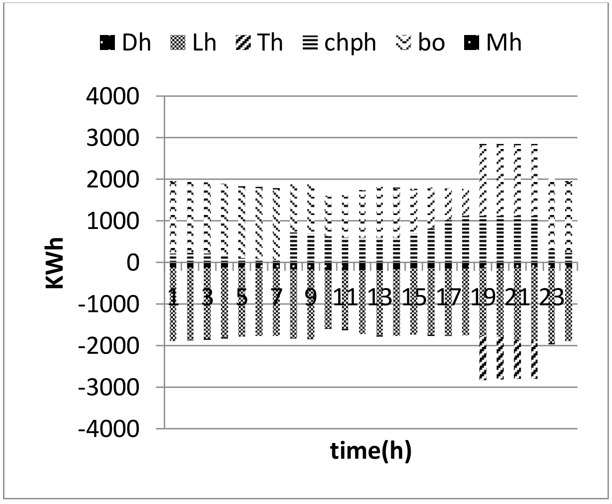

Fig. 12. Heat portion of the MCMG network

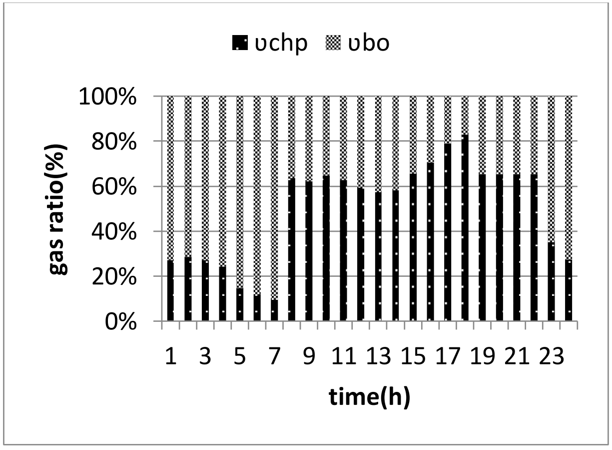

Fig. 13. Natural gas input ratio for gas consumers

Flexibility of the network has been increased by embedding storages in proposed MCMG to prevent wastage of energies in a way that, surplus generated energies by distributed generations (DGs) are stored in low prices and injected to the grid while the price is high. The equivalent storage power flows and state of charge (SOC) of electric and heat storages are shown in Fig. 14 and Fig. 15, respectively.

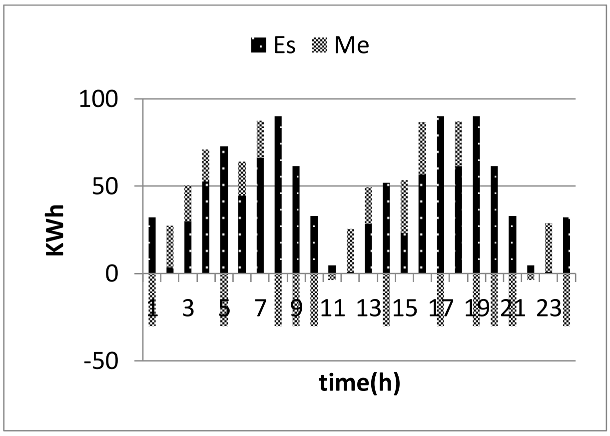

Fig. 14. Electrical charge and discharge ramp rate and SOC.

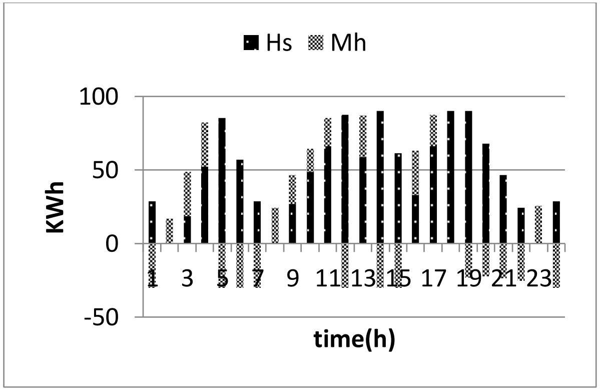

Fig. 15. Heat charge and discharge ramp rate and SOC.

Comparison of simultaneous and individual operation of multiple carriers on the total cost of MCMG is simulated as a scenario and advantage of simultaneous operation of multiple carriers is proved in in Table 4. It is clear that the proposed model has been effective in improving the operational performance of MCMG and reduced the total cost of MCMG. It is necessary to note that, the natural gas tariff is considered permanent equal to 0.05 $/hour and all the loads are supposed non-responsive.

Table 4 Simultaneous and individual operation assessment on the total cost of MCMG

	Thermal supply	Electrical supply	Simultaneous operation
Cost ($)	3387.638	2584.086	5007.057
Total cost ($)	5971		

Responsive load participation as none to 100-percentage of the total load is studied and its impact on the load factor (LF) and total cost of MCMG is demonstrated in Fig. 16. It is observable that, the total cost of the network is reduced by higher participation of responsive loads as an active load in the network whereas LF of the MCMG gets worse. Moreover, it indicates that, 20% participation of responsive loads have the highest value of LF in the system. The total operation cost is optimized and decreased as an MINLP model which is calculated 6814.5 $.

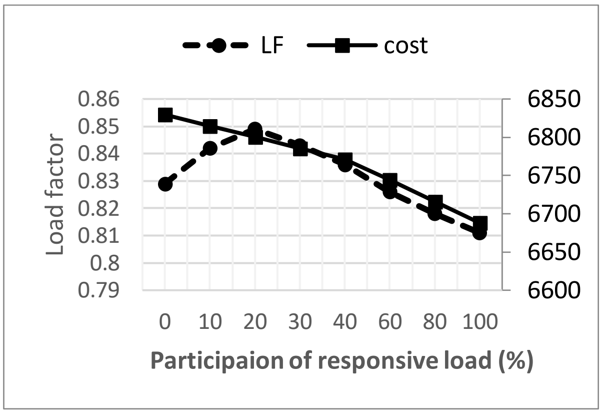

Fig. 16. Impact of responsive load participation on LF and total cost of MCMG

5. CONCLUSIONS

In this paper, the optimal economic dispatch in a typical MCMG (represented as energy hub system) comprising CHPs, photovoltaic arrays, electrical and thermal energy storages, and multiple energy demands is carried out along with responsive demands. The modelling goals were to integrate multiple energy infrastructure and minimize MCMG operation and maintenance cost. The proposed demand response 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 prevalent disadvantage of conventional MG structure with one form of energy is resolved by the proposed network with multiple energy carriers as compared to the prevailing electric energy management strategies. Moreover, energy interactions are considered within MCMG. The results show that the simultaneous operation of multiple energy infrastructures is more beneficial than the operation of a single one. Moreover, the demand response program has resulted in a realistic perspective for a future distribution network, which leads to a beneficial operation and to a consequent reduction in the total cost within the MCMG.

REFERENCES

[1] N. Saito, T. Niimura, K. Koyanagi, and R. Yokoyama, "Trade-off analysis of autonomous microgrid sizing with PV, diesel, and battery storage," *IEEE Power Energy Soc.* Gen. Meeting, Calgary, AB, Canada, pp. 1–6, Jul. 2009.

[2] A. Ipakchi and F. Albuyeh, "Grid of the future," *IEEE Power Energy Mag.*, vol. 7, no. 2, pp. 52–62, Mar. 2009.

[3] U.S. Department of Energy, "The Smart Grid: An Introduction," *Commun*, vol. 99, p. 48, 2010.

[4] H. Jiayi, J. Chuanwen, and X. Rong, "A review on distributed energy resources and microgrid," *Renew. Sustain. Energy Rev.*, vol. 12, no. 9, pp. 2472–2483, Dec. 2008.

[5] S. Bourbour, "Development of a Self-Healing strategy for future smart microgrids," Bourbour, Soheil <http//researchrepository.murdoch.edu.au/view/author/Bourbour, Soheil.html> Dev. a Self-Healing Strateg. Futur. smart microgrids. Masters by Res. thesis, Murdoch Univ., 2016.

[6] S. Conti and S. A. Rizzo, "Probability of adequacy evaluation considering power output correlation of renewable generators in Smart Grids," *Int. J. Electr. Power Energy Syst.*, vol. 61, pp. 145–151, 2014.

[7] T. Krause, G. Andersson, K. Frohlich, and A. Vaccaro, "Multiple-energy carriers: modeling of production, delivery, and consumption, "*Pros. IEEE*, vol. 99, no. 1, pp. 15–27, Jan. 2011.

[8] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klockl, G. Andersson, and K. Frohlich, "Energy hubs for the future," *IEEE Power. Energy Mag*, vol. 5, pp. 24–30., Jan.-Feb. 2007.

[9] C. Liu, M. Shahidehpour, and J. Wang, "Coordinated scheduling of electricity and natural gas infrastructures with a transient model for natural gas flow," *Chaos J.*, vol. 21, Jun. 2011.

[10] M. Geidl and G. Andersson, "Optimal power flow of multiple energy carriers," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 145–155, 2007.

[11] A. Sheikhi, A. M. Ranjbar, and H. Oraee, "Financial analysis and optimal size and operation for a multicarrier energy system," *Energy Build.*, vol. 48, pp. 71–78, May 2012.

[12] M. Moeini-Aghtaie, A. Abbaspour, M. Fotuhi-Firuzabad, and E. Hajipour, "A decomposed solution to multiple-energy carriers optimal power flow*," IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 707–716, 2014.

[13] M. Geidl, "Integrated Modeling and Optimization of Multi-Carrier Energy Systems", *Ph.D. dissertation*, ETH Diss. 17141, 2007

[14] M. Geidl and G. Andersson, "Optimal coupling of energy infrastructures," *IEEE Lausanne POWERTECH, Proc*, 2007, pp. 1398–1403.

[15] G.G. Florea, R.Dobrescu, and O.I. Rohat, "From Bridge to Control Hub – The Power Smart Grid Evolution", *2nd Int. Conf Syst. Comput. Sci (ICSCS).*, Villeneuve d'Ascq, France ,August 26-27, 2013

[16] M.Shahidehpour, "Our aging power systems Infrastructure and life extension issues", *IEEE Power Energy Mag.*, pp 43-22. 2011

[17] N. Cai, N. T. T. Nga, and J. Mitra, "Economic dispatch in microgrids using multi-agent system," North Amer. Power Symp. (NAPS), Champaign, IL, USA, pp. 1–5, Sep. 2012.

[18] Y. Xu and W. Liu, "Stable multi-agent-based load shedding algorithm for power systems," *IEEE Trans. Power Syst.*, vol. 26, no. 4, pp. 2006–2014, Nov. 2011.

[19] M. A. Abido, "Multi objective evolutionary algorithm for electric power dispatch problem," *IEEE Trans. Evol. Comput.*, vol. 10, no. 3, pp. 315–329, Jun. 2006.

[20] N.Nikmehr, S.N.Ravadanegh "Optimal Power Dispatch of Multi-Microgrids at Future Smart Distribution Grids" *IEEE Trans on Smart Grid*, vol. 5, no. 1, pp. 1949-3053,Jan. 2015.

[21] C. A. Hernandez-Aramburo, T. C. Green, and N. Mugniot, "Fuel consumption minimization of a microgrid," *IEEE*

Trans. Ind. Appl., vol. 41, no. 3, pp. 673–681, May/Jun. 2005.

[22] M. Jin, W. Feng, P. Liu, C. Marnay, and C. Spanos, “MOD-DR: Microgrid optimal dispatch with demand response,” *Appl. Energy*, vol. 187, pp. 758–776, 2017.

[23] K. De Brabandere, K. Vanthournout, J. Driesen, G.Deconinck, and R. Belmans, “Control of microgrids,” *IEEE Power Eng. Soc. Gen. Meeting*, Tampa, FL, USA, pp. 1–7, Jun. 2007

[24] S. Qingjun, G. Guangchao, and J. Quanyuan, “Real-time energy dispatchof standalone microgrid,” *Proc. Chin. Soc. Elect*. Eng, (CSEE), pp. 26–35. 2012.

[25] A. Zakariazadeh, S. Jadid, and P. Siano, “Multi-objective scheduling of electric vehicles in smart distribution system,” *Energy Convers. Manage.*,vol. 79, pp. 43–53, Mar. 2014.

[26] B. Zhao, X. Zhang, J. Chen, C. Wang, and L. Guo, “Operation optimization of standalone microgrids considering lifetime characteristics of battery energy storage system,” *IEEE Trans. Sustain. Energy*, vol. 4, no. 4, pp. 934–943, Oct. 2013.

[27] M. Yuyang, L. Jinling, and Z. Guodong, “Improved multi-objective particle optimization algorithm based scheduling optimization of gridconnected microgrid,” *Elect. Power Sci. Eng.*, vol. 28, no. 7, pp. 15–20, 2012.

[28] D. Deng and G. Li, “Research on economic operation of grid-connected DC microgrid,” *Int. Conf. Renew. Power Gener*. (RPG 2015), p. 6 .-6 ., 2015.

[29] Y. Kinjyo et al., “Optimal operation of smart grid with fuel cell in isolated islands,” *J. Int. Council Elect. Eng.*, vol. 2, no. 4, pp. 423–429, 2012.

[30] A. Xin, C. Minyong, and L. Zhili, “Based on chaos ant colony algorithm for the micro-grid environmental and economy operation,” *J. Univ. North China Elect. Power J.*, vol. 36, no. 5, pp. 2–6, 2009.

[31] I. Koutsopoulos and L. Tassiulas, “Challenges in demand load control for the smart grid,” *IEEE Netw.*, vol. 25, no. 5, pp. 16–21, Sep./Oct. 2011.

[32] C. Chen, S. Duan, T. Cai, B. Liu, and G. Hu, “Smart energy management system for optimal micro grid economic operation,” *IET Renew. Power Gener.*, vol. 5, no. 3, pp. 258–267, 2011.

[33] J. Guerrero, M. Chandorkar, T. Lee, and P. Loh, “Advanced control architectures for intelligent microgrids—Part I: ecentralized and hierarchical control,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1254–1262, Apr. 2013.

[34] J. M. Guerrero, P. C. Loh, T.-L. Lee, and M. Chandorkar, “Advanced control architectures for intelligent microgrids—Part II: Power quality, energy storage, and AC/DC microgrids,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1263–1270, Apr. 2013.

[35] M. Varadarajan and K. S. Swarup, “Solving multi-objective optimal power flow using differential evolution,” *IET Gen. Transm. Distrib.*, vol. 2, no. 5, pp. 720–730, Sep. 2008.

[36] A. Haghrah, M. Nazari-Heris, and B. Mohammadi-Ivatloo, “Solving combined heat and power economic dispatch problem using real coded genetic algorithm with improved Mühlenbein mutation,” *Appl. Therm. Eng.*, vol. 99, pp. 465–475, 2016.

[37] M. Alipour, B. Mohammadi-Ivatloo, and K. Zare, “Stochastic Scheduling of Renewable and CHP-Based Microgrids,” *IEEE Trans. Ind. Inf.*, vol. 11, no. 5, pp. 1049–1058, 2015.

[38] M. Nazari-Heris, S. Abapour, and B. Mohammadi-Ivatloo, “Optimal economic dispatch of FC-CHP based heat and power micro-grids,” *Appl. Therm. Eng.*, vol. 114, pp. 756–769, 2017.

[39] A.Sheikhi, M.Rayati, S.Bahrami, and A.M.Ranjbar “Integrated Demand Side Management Game in Smart Energy Hubs”, ” *IEEE Trans. Smart Grid*, vol. 5, no. 1 Jan. 2015.