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Operation of the Multiple Energy System with Optimal Coordination of the Consumers in Energy Market

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Abstract **– In this paper, optimal coordination of the demand side under uncertainty of the energy price in energy market is studied. The consumers by demand response programs (DRPs) have optimal role in minimization of the energy generation costs in multiple energy system. The consumers can participate via local generation strategy (LGS) and demand curtailment strategy (DCS). The optimal coordination is considered as two stage optimization, in which minimization of the consumers' bills is done in first stage. In following, the minimization of the generation costs is performed in second stage optimization. The LGS is taken into accounted through optimal discharging of plug electric vehicles (PEVs). Finally, numerical simulation is implemented to show superiority of the proposed approach to minimization of the energy generation costs.**

Keywords **– Demand curtailment strategy (DCS); demand response programs (DRPs); multiple energy system; onsite generation strategy (LGS); optimal coordination.**

Nomenclature		
t, T	Time index	hour
s, S	Scenario index	–
n, NC	Consumer index	–
EC, NGC	Electrical company (EC) and natural gas company (NGC)	–
D_E^n	Total electrical demand at n^{th}	kWh
D^n_{NCL}, D^n_{CL}	Non-curtailable demand, curtailable demand, respectively	kWh
P_{PEV}^{ch}, P_{PEV}^{dch}	Power charge and discharge of the PEV, respectively	kWh
P^r_{PEV}	Power rate of the PEV	kWh
P_{EC}, P_{CHP}	Power generated by EC and power of CHP, respectively	kWh

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P_{GAS}	Gas generated by NGC	m^3
H_{CHP}, H_{BO}	Heat generated by CHP and boiler, respectively	kWh
C_{EP}, C_{GP}	Electrical price and gas price, respectively	$
C_{EC}, C_{NGC}	Generation costs of the EC and NGC	$
η^{ch}, η^{dch}	PEV efficiency in charge and discharge modes, respectively	%
u_{PEV}	Binary variable of PEV (1 = discharge mode and 0 = otherwise)	–

1. INTRODUCTION

Integration of the smart grids technology in energy systems have provided new revolution in energy systems' infrastructures [1]–[5]. In these infrastructures, demand side have relevance with generation side at any times [6]–[10]. As well, energy companies using these infrastructures can be managed self-grids to decrease energy losses and costs [11]. On the other side, developing urbanization in many countries and consumption of the fossil fuels to energy generation are increasing in the power plants [12]–[14]. Hence, participation of the demand side in optimal energy consumption has direct effects on economic and technical indices. This participation can do by energy price signals and demand response programs (DRPs) in the energy markets [15]–[22]. The utilization of these strategies are various subject to energy system topology [23]–[25]. For instance, multiple energies like natural gas and electrical energy in smart grid technology with energy storage systems (ESSs) technology are effective strategies to optimal energy consumption [26]–[28]. In such energy systems, consumers can meet self-demand using multi-parallel energy resources [29]–[33]. Also, consumers by self-energy resource can have optimal role to the meet self-demand in high energy price [34]–[38]. The proposed topology of the smart multiple energy system in this paper is shown in Fig. 1. The proposed energy system including pparticipants as follows:

1) Energy companies: The energy companies are electrical company (EC) and natural gas company (NGC). These companies have various prices at each hours in energy markets [39]–[41],
2) Distributed generators (DGs): The DGs are combined heat and power (CHP) units and boiler units. The DGs are fed by natural gas to energy generation [42]–[45],
3) Operator: This participant is main coordinator between generation side and demand side. The operator can provide optimal status of the system via informing energy prices to consumers at operation time [46], [47].

The operation of the various energy systems is studied by many researchers. Authors in [48] optimal power management of the electrical system considering uncertainty of the renewable energy systems is studied. In [49], the demand management by load shifting strategy in smart buildings to reducing the energy costs is proposed. The energy planning in the hybrid energy system based on optimal sitting and sizing of the DGs is studied in [50]. The scheduling of the energy hub system in smart buildings without consideration of the DRPs is proposed in [51]. In [52], multi-objectives optimization of the multiple energy system is analyzed with stochastic modeling of the electrical price in energy market. In [53], the economic and environmental modelling of the electrical energy systems under risk assessment for electrical price is proposed. The assessment of the reliability index in electrical grids with attention to consumers' satisfaction level and minimization of the blackouts is studied in [54]. The co-optimization modelling is presented in [55] to energy-saving in electrical microgrids via demand shifting strategy. In [56], optimal load control is implemented in multiple energy systems via uncoordinated and coordinated modelling of the DGs.

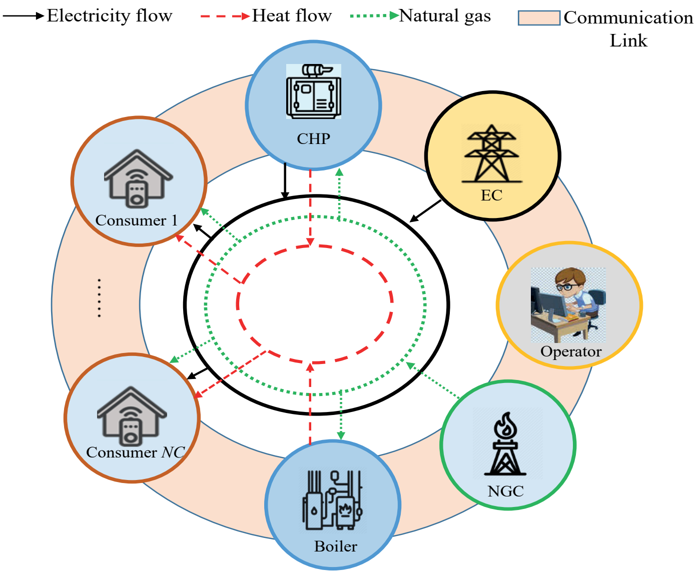


Fig. 1. Smart multiple energy system topology.

This paper presents two-stage energy optimization of the smart multiple energy system with DRPs and uncertainty of the electricity price (EP) and gas price (GP) in the energy market. The consumption costs of the consumers at first stage are optimized via demand curtailment strategy (DCS). As well, local generation strategy (LGS) is implemented by plug electric vehicles (PEVs) in second stage. The optimized load demand at first stage is considered in second stage alongside LGS to minimizing the generation costs. Thus, contributions and novelties of this work can be summarized as follow:

1. A modelling two-stage energy optimization is proposed in smart multiple energy system.
2. The DCS and LGS of the DRPs are considered in first and second stages to minimizing generation costs.
3. The PEVs are proposed to meet demand in peak time via LGS and optimal participation in second stage.
4. The energy prices including EP and GP are modelled under uncertainty approach.

2. UNCERTAINTY MODELLING

The uncertainty of the energy prices including EP and GP in energy market is modelled by lognormal probability density function Eq. (1) as follow [49]:

$$f(p)=\frac{1}{p\sigma\sqrt{2\pi}}e^{\left(-\frac{(\mathrm{Ln}(p)-\mu)^2}{2\sigma^2}\right)}, \tag{1}$$

where *p,* μ and σ are distribution function parameter, mean value and standard deviation, respectively.

By Monte Carlo technique, scenarios or random variables for distribution function parameter (*p*) are generated at day-ahead. In this modelling, EP and GP are distribution function parameters (*p*). On the other side, probability in each scenario can be modelled by Eq. (2) [56]:

$$\pi_s = \pi_s^{\mathrm{EP}} \times \pi_s^{\mathrm{GP}} , \tag{2}$$

where π_s, π_s^{EP} and π_s^{GP} are probability of scenario *s*, probability of EP and GP at scenario *s*, respectively.

3. PEV MODELLING

The PEVs can be used by consumers as energy resource to feed self-demand. The PEV is taken into account as LGS in second stage optimization. The LGS modelling by PEVs is as follow [50]:

$$0 \le P_{\mathrm{PEV}}^{\mathrm{ch}}(s,t) \le \left[1 - u_{\mathrm{PEV}}(s,t)\right] \times P_{\mathrm{PEV}}^{r} \qquad \forall s,t , \tag{3}$$

$$0 \le P_{\mathrm{PEV}}^{\mathrm{dch}}(s,t) \le u_{\mathrm{PEV}}(s,t) \times P_{\mathrm{PEV}}^{r} \qquad \forall s,t , \tag{4}$$

$$\left[\sum_{t\in T} P_{\mathrm{PEV}}^{\mathrm{dch}}(s,t,\mathrm{lg}) \times \frac{1}{\eta^{\mathrm{dch}}}\right] - \left[\sum_{t\in T} P_{\mathrm{PEV}}^{\mathrm{ch}}(s,t) \times \eta^{\mathrm{ch}}\right] = 0 \qquad \forall s,t , \tag{5}$$

where charging power and discharging power of the PEV are modelled by Eq. (3) and Eq. (4), respectively. LGS by PEV are modelled by Eq. (5).

4. OPTIMIZATION APPROACH MODELLING

The two-stage optimization problem of the proposed approach is modelled in this section. The mathematical modeling for proposed approach is as follow.

4.1. First stage

The DCS in first stage optimization is modelled. In this strategy, consumers' bill subject to EP is minimized. Hence, electrical demand using DCS can be optimized. The objective function of the DCS is modelled by Eq. (6):

$$\min f_{fs} = \sum_{s=1}^{S} \pi_s \sum_{t=1}^{T} \sum_{n=1}^{NC} \left\{ C_{\mathrm{EP}}(s,t) \times D_n^{\mathrm{E}}(t) \right\} \qquad \forall s,t,n , \tag{6}$$

subject to:

$$P_{\mathrm{EC}}(s,t) = D_n^{\mathrm{E}}(s,t) \qquad \forall s,t,n , \tag{7}$$

$$D_n^{\mathrm{E}}(s,t) = D_{\mathrm{NCL}}^{\mathrm{E}}(s,t) - D_{\mathrm{CL}}^{\mathrm{E}}(s,t) \qquad \forall s,t,n , \tag{8}$$

$$0 \le D_{\mathrm{CL}}^{\mathrm{E}}(s,t) \le D_{\mathrm{CL}}^{\mathrm{E,max}} \qquad \forall s,t,n , \tag{9}$$

where Eqs. (7)–(9) are power balance, electrical demand modelling and bound of the curtailable demand in DCS, respectively.

4.2. Second stage

The minimization of the generation costs as objective function in second stage optimization is considered. The modelling generation costs is formulated by Eq. (10) [2]:

$$\min f_{ss} = \sum_{s=1}^{S} \pi_s \sum_{t=1}^{T} \left\{ C_{\mathrm{EC}}(s,t) + C_{\mathrm{GAS}}(s,t) + \sum_{chp=1}^{CHP} C_{\mathrm{CHP}}(s,t,CHP) + \sum_{bo=1}^{BO} C_{\mathrm{BO}}(s,t,BO) \right\}, \tag{10}$$

where:

$$C_{\mathrm{EC}}(t) = C_{\mathrm{EP}}(s,t) \times P_{\mathrm{EC}}(s,t) \qquad \forall s,t, \tag{11}$$

$$C_{\mathrm{NGC}}(s,t) = C_{\mathrm{GP}}(s,t) \times P_{\mathrm{GAS}}(s,t) \qquad \forall s,t, \tag{12}$$

$$C_{\mathrm{CHP}}(s,t,CHP) = \left\{ C_{GP}(s,t) \times (H_{CHP}(s,t,CHP) + P_{\mathrm{CHP}}(s,t,CHP)) \right\} \qquad \forall s,t,CHP, \tag{13}$$

$$C_{\mathrm{BO}}(s,t,BO) = \left\{ C_{\mathrm{GP}}(s,t) \times (H_{\mathrm{BO}}(s,t,BO) \right\} \qquad \forall s,t,BO. \tag{14}$$

Here, Eqs. (11)–(14) are generation costs of the EC, NGC, CHP units and boilers units, respectively [2]. It should be mentioned, we assumed that efficiency of DGs are equal to 100 %.

4.2.1. Constraints

In second stage optimization, implementation of some constraints is necessary. These constraints are modelled as follow.

$$\begin{aligned} &P_{\mathrm{GAS}}(s,t) - \sum_{chp=1}^{CHP} P_{\mathrm{CHP}}(s,t,CHP) - \\ &\sum_{chp=1}^{CHP} H_{\mathrm{CHP}}(s,t,CHP) - \sum_{bo=1}^{BO} H_{\mathrm{BO}}(s,t,BO) = D_n^{\mathrm{GAS}}(s,t) \qquad \forall s,t \end{aligned} \tag{15}$$

$$\sum_{chp=1}^{CHP} H_{CHP}(s,t,CHP) + \sum_{bo=1}^{BO} H_{\mathrm{BO}}(s,t,BO) = D_n^{\mathrm{H}}(s,t) \qquad \forall s,t \tag{16}$$

$$P_{\mathrm{EC}}(s,t) + \sum_{chp=1}^{CHP} P_{\mathrm{CHP}}(s,t,CHP) + \sum_{pev=1}^{PEV} P_{\mathrm{PEV}}^{\mathrm{dch}}(s,t) = \sum_{pev=1}^{PEV} P_{\mathrm{PEV}}^{\mathrm{ch}}(s,t) + D_n^{\mathrm{E}}(s,t) \qquad \forall s,t \tag{17}$$

$$P_{\mathrm{CHP}}^{\min} \le P_{\mathrm{CHP}}(s,t,CHP) \le P_{\mathrm{CHP}}^{\max} \qquad \forall s,t,CHP \tag{18}$$

$$H_{\mathrm{CHP}}^{\min} \le H_{\mathrm{CHP}}(s,t,CHP) \le H_{\mathrm{CHP}}^{\max} \qquad \forall s,t,CHP \tag{19}$$

$$H_{\mathrm{BO}}^{\min} \le H_{\mathrm{BO}}(s,t,BO) \le H_{\mathrm{BO}}^{\max} \qquad \forall s,t,BO \tag{20}$$

The gas energy balance, heat energy balance and electrical energy balance are constrained by Eqs. (15)–(17), respectively. Constraints (18)–(20) are electrical and heat generation by DGs.

5. NUMERICAL SIMULATION AND CASE STUDIES

To validation and confirmation of the proposed approach, numerical simulation based on two case studies are done. The case studies are as follows: 1) Optimization of the proposed approach without DCS and LGS; 2) Optimization of the proposed approach with DCS and LGS.

The 15-node test system as proposed energy grid is depicted in Fig. 2. In Fig. 3, flowchart of the optimization approach is shown. In Fig. 4, the gas price and electrical price at 5 scenarios are simulated by Monte Carlo technique. In order to reduction of the computations time and computational burden; the optimization approach is solved at fourth scenario. The DGs data are given in Table 1 [48]–[51]. It should be mentioned that all DGs are feed by natural gas. The PEV data is provided in Table 2 [52]–[55]. As well, energy demand of the consumers is shown in Fig. 5. The maximum curtailable demand for implementation of the DCS at each node is 25 kWh [5], [56]–[69]. The GAMS software is employed to solving numerical simulation.

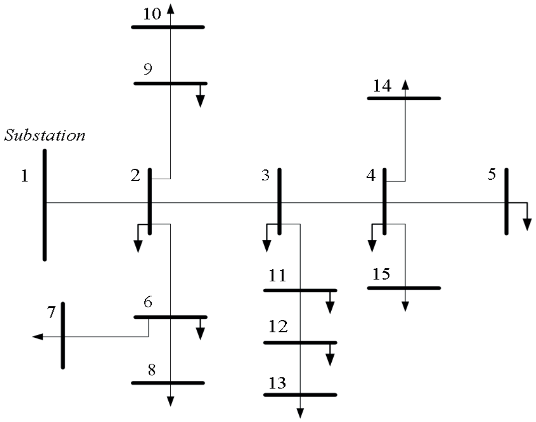


Fig. 2. 15-node test system.

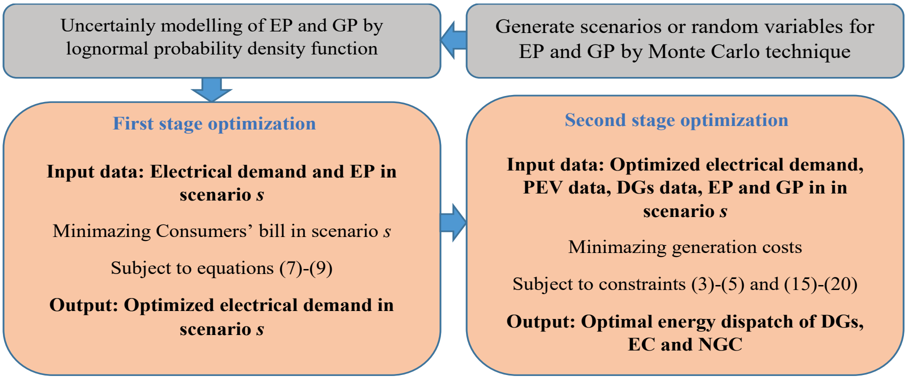
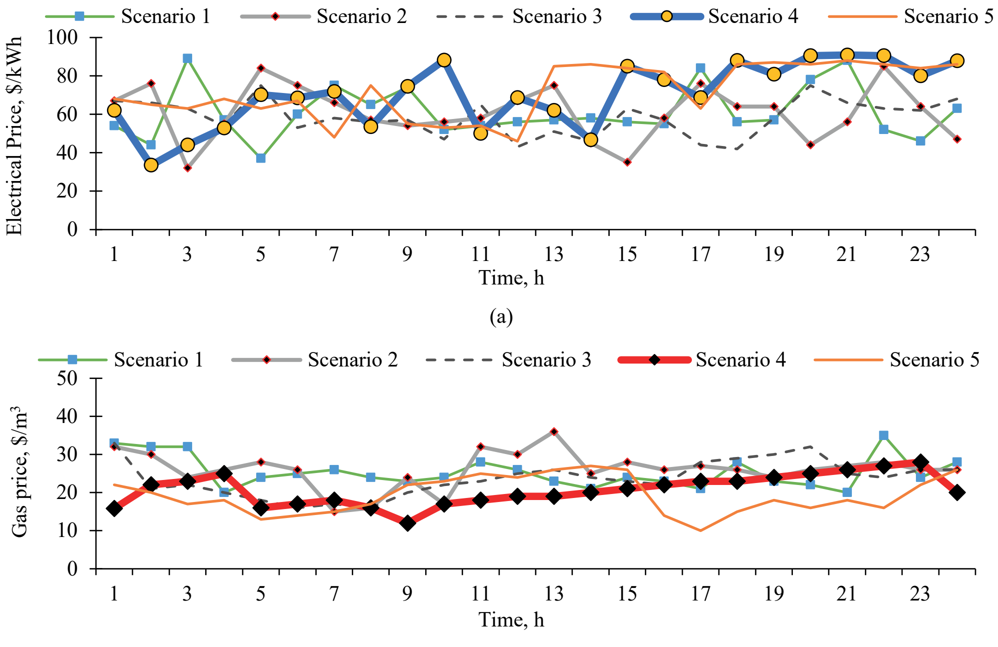


Fig. 3. Flowchart of the proposed approach.



(a)

(b)

Fig. 4. Energy price in energy market: (a) Electrical price, and (b) Gas price.

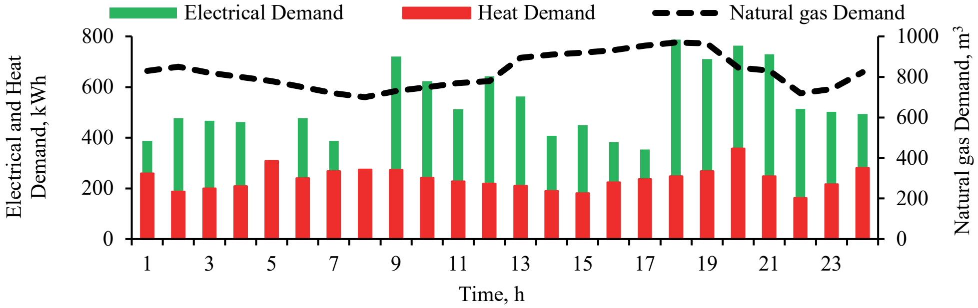


Fig. 5. Energy demand.

TABLE 1. DGs DATA

Parameters **Units**	P^{min} **kWh**	P^{max} **kWh**	H^{min} **kWh**	H^{max} **kWh**	**Location, Node**
Boiler 1	–	–	0	100	3
Boiler 2	–	–	0	120	8
CHP 1	0	125	0	100	10
CHP 2	0	120	0	110	12

TABLE 2. PEV DATA

Parameters	**Value**
η^{ch}	90 %
η^{dis}	95 %
P^{r}_{PEV}	50 kWh
Location (node)	6

5.1. Discussion and results analysis

The results analysis of the mentioned case studies are discussed in this subsection. As well, results are compared than each other for showing superiority of the DCS and LGS. As mentioned before, optimization is done in fourth scenario and results are analysed in this scenario.

In Fig. 6, electrical demand in first stage is optimized by DCS. In this figure, optimized electrical demand is curtailed at high EP. The total consumers' bill without DCS and with DCS is equal to $ 894 182.6 and $ 790 441.2, respectively. Also, total demand curtailment is 710 kWh. In Fig. 7, electrical generation in Case 1 are depicted.

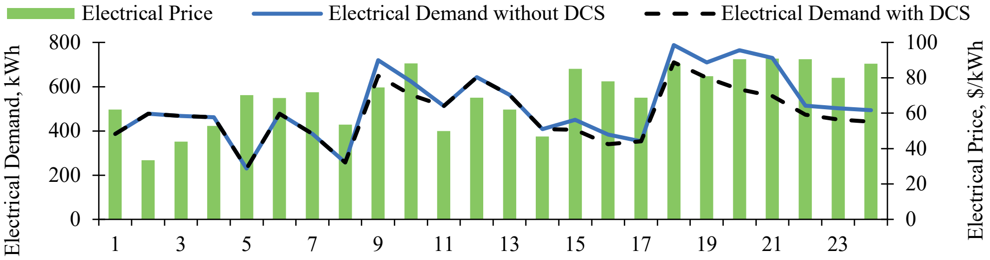


Fig. 6. Electrical demand with DCS and without DCS.

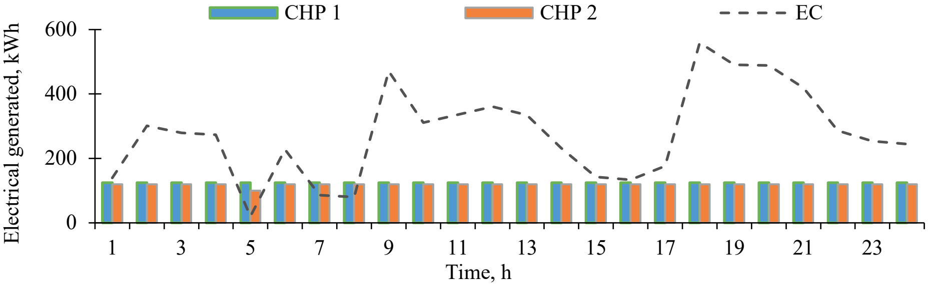
In Fig. 7(a), electrical energy generation without DCS and LGS is shown. As shown, EC has more participation in meet demand at than DGs. The generation cost of the NGC, EC and DGs in Case 1 are equal to $ 357 795.6, $ 467 163.4 and $ 147 220.1, respectively. It's visible, EC in Case 1 has most generation cost in comparison with NGC and DGs. The maximum electrical generation by EC in Case 1 at high EP and peak demand is done. In Fig. 7(b), power generation in Case 2 with implementing LGS and DCS is shown. In Case 2, cost of the EC is reduced by 12.3 % in comparison to Case 1. The power generation of the EC in Fig. 7(b) at peak demand is less than Fig. 7(a). Also, electrical demand is meet at hours 10 and 18 with high EP by PEV. The PEV is feed at low EP, and power of the PEV is used to meet demand at peak. The total discharging power and total charging power of PEV are equal to 98 kWh and 100 kWh in total operation time, respectively.

In Fig. 8, heat generation by CHPs and boilers in Cases 1 and 2 are operated. The heat generation by DGs at all times is done and generation cost to heat generation in both case are almost same.

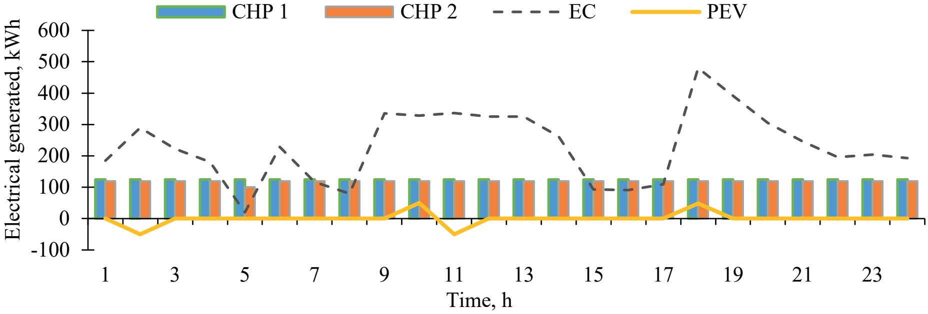
The results obtained in case studies are listed in Table 3. As shown, generation cost in Cases 1 and 2 are equal to $ 967 465.2 and $ 879 323.4, respectively. In Case 2, minimum generation cost in energy system are provided, due to implementing DCS and LGS. The reduction value of the generation cost in Case 2 than Case 1 is equal to $ 88 141.8.

TABLE 3. RESULTS OF THE CASE STUDIES

Case study	Case 1	Case 2
Generation cost, $	972 179.1	879 323.4

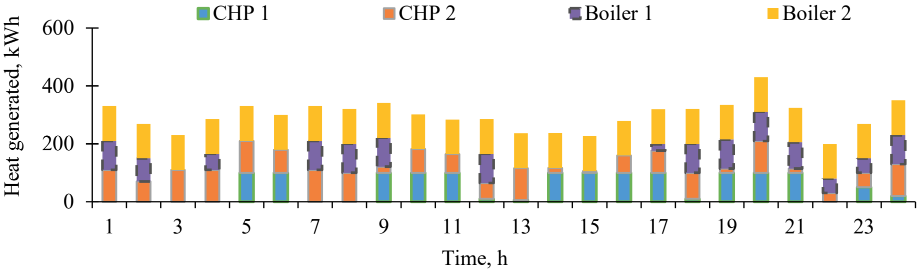


(a)

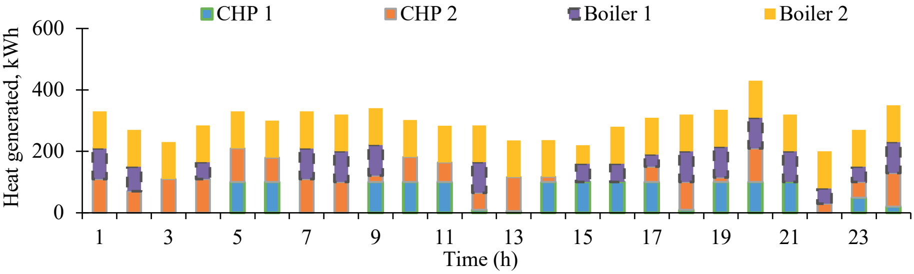


(b)

Fig. 7. Electrical generated: (a) Case 1, and (b) Case 2.



(a)



(b)

Fig. 8. Heat generated: (a) Case 1, and (b) Case 2.

6. CONCLUSION

In this paper, optimal operation of the multiple energy system is studied based on uncertainty of the EP and GP in energy market. The LGS and DCS are utilized as optimal solution to consumers' participation in energy market. The optimization is modelled as two stage problem in proposed approach. The consumes' bill is minimized in first stage by DCS, whereby energy demand is optimized. Thus, optimized energy demand is taken into accounted in second stage to minimizing generation cost. The obtained results of the numerical simulation in two case studies are expressed as follow:

Case 1) In this case, LGS and DCS are not taken into account. The generation cost is equal to $ 972 179.1.

Case 2) The DCS and LGS are implemented in Case 2. The reduction rate of the generation cost in this case than Case 1 is equal to 9.55 %.

With attention to obtained results, participation of the consumers in energy market leads to decrease generation cost, and economic status of the system is provided.

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