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Optimal Energy Management in a Smart Micro Grid with Demand Side Participation

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***Abstract* – The energy management in energy systems is the main solution for energy companies in order to provide minimization of the energy generation costs and emission polluting. In this work, a multi-criteria optimization model is implemented for minimizing the generation cost and emission in a smart micro grid (SMG) at day-ahead planning. In this modelling, the demand side participates in optimal energy management through two strategies such as demand shifting and onsite generation by the energy storage system (ESS). The optimal participation of demand side is modelled based on energy price in energy market. Implementation of the proposed approach in GAMS software is done, and weight sum method (WSM) is employed for solving multi-criteria optimization. The desired optimal solution of multi-criteria objectives is found via the max-min fuzzy procedure. Finally, confirmation of the proposed approach is analysed by numerical simulation in two case studies.**

***Keywords* – Energy management; max-min fuzzy procedure; multi-criteria optimization; optimal participation of demand side; weight sum method (WSM)**

Nomenclature		
t, h	Time Indices	h
N, n	Load Indices	–
U, u	Generator unit (GU) Indices	–
ED_{DS}	Electrical demand with shifting strategy	kW
θ	Level of the demand shifting	%
P^{r}_{ESS}	Power rate of ESS	kW
P^{DIS}_{ESS}	Power discharge of ESS	kW
P^{CH}_{ESS}	Power charge of ESS	kW
f_{GC}	Objective functions generation cost	–
f_{EP}	Objective functions emission polluting	–
α, β, χ	Cost factors of electrical generated by GU	$/kW
ω, ξ, ψ	Cost factors of thermal generated by GU	$/kW

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μ, λ, δ	Emission factors of GU	g/kW
σ	Emission factor of electrical market	g/kW
C_{pur}	Costs of purchased power from electrical market	$
P_{pur}	Purchased power from electrical market	kW
C_{op}	Operation costs of ESS	$
η_{dis}	Efficiency of ESS in discharging state	%
η_{ch}	Efficiency of ESS in charging state	%
υ_{ESS}	Binary variable of ESS	–

1. INTRODUCTION

The employment of smart micro grids (SMGs) technologies alongside different generator units (GUs) such as electrical, thermal and storage systems are developing in energy system infrastructures in many countries [1]–[5]. In SMGs communication links have been provided between the generation side and the demand side, in order to achieve the optimal energy consumption via economic signals to demand side. These signals lead to a decrease in energy consumption at high energy price in the energy market [6]–[10]. The participation of the demand side in energy management with the name demand response (DR) programmes is defined [11]–[15]. The DR can be implemented in various types by demand side with attention to energy prices in the day-ahead market [16]–[20]. On the other side, DR programmes are not limited to economic indices, and optimal energy consumption has notable effects on generation emission from the generation side [20]–[25]. Using DR, optimal energy balance based-economic and environmental indices are provided in between generation and demand sides [26]–[30].

The investigations on energy management in different systems are studied in diverse types of modelling and approach. In [31], the economic modelling of the SMG is presented without consideration of the environment index and DR programs. The energy management in the residential section is studied in [32] to minimise the demand side bill. In [33], the optimal installation of the GUs in a SMG is implemented based on load demand uncertainty. The energy-saving in smart buildings with optimal charging and discharging of electric vehicles (EVs) is proposed in [34]. The self-scheduling of the load demand based on the energy output of renewable energy is implemented in [35]. In [36] demand interrupting approach is used for objectives optimization such as economic and technical indices. In [37] minimizing the generation costs and maximizing the reliability indices of the SMG are studied. The demand reduction in [38] is done to increase energy efficiency by optimal scheduling of appliances in the residential section. In [39] energy management of an SMG is proposed, to improve technical and economic issues by reconfiguration approach and installation of the energy storage system (ESS). In [40] and [41] scheduling modelling of the SMG is studied for energy management using peak shaving modelling.

In this article, a multi-criteria optimization problem based-economic and environment model is proposed for optimal energy management in an SMG at the day-ahead. The objectives include minimization of the 1) generation costs and 2) emission pollution on the generation side. As well, load scheduling of DR programs on the demand-side is considered as demand shifting and onsite generation by ESS with attention to electrical price in the energy market. The objective functions are optimized using the weight sum method (WSM), and the desired optimal solution in Pareto frontier solutions of objectives is determined via

the max-min fuzzy method. Accordingly, the novelty and contributions in this article can be listed by the following items:

1. A multi-criteria optimization is proposed to provide minimization of the generation cost and emission;
2. Two strategies are provided to the demand side participation in optimal energy management;
3. The WSM is used to obtain Pareto frontier solutions of multi-criteria optimization;
4. Using max-min fuzzy method, desired optimal solution is found.

The outline of the article is arranged as follows: The topology of the SMG is presented in section 2. In section 3, an optimization method is provided. The simulation is done in section 4. Finally, the conclusion is in section 5.

2. SMG TOPOLOGY

In Fig. 1. the topology of proposed SMG is shown. The SMG comprised of four sections as follows:

1. Demand side. This section has required energies, such as electrical and thermal for consumption. On the other hand, the demand side plays an optimal role in energy consumption, the modelling of which will be analysed in the next subsection;
2. Energy markets. The electrical market is considered as the main energy supplier, which has diverse price in each time [42], [43];
3. GUs. The GUs are diesel generator (DG), boiler and combined heat and power (CHP). These units are feed by fossil fuels to energy generation [44];
4. Energy management operator. In this section, optimal coordination via communication links between demand side and generation side is done based on pre-defined objective functions and existing constraints to optimal energy management at day-ahead.

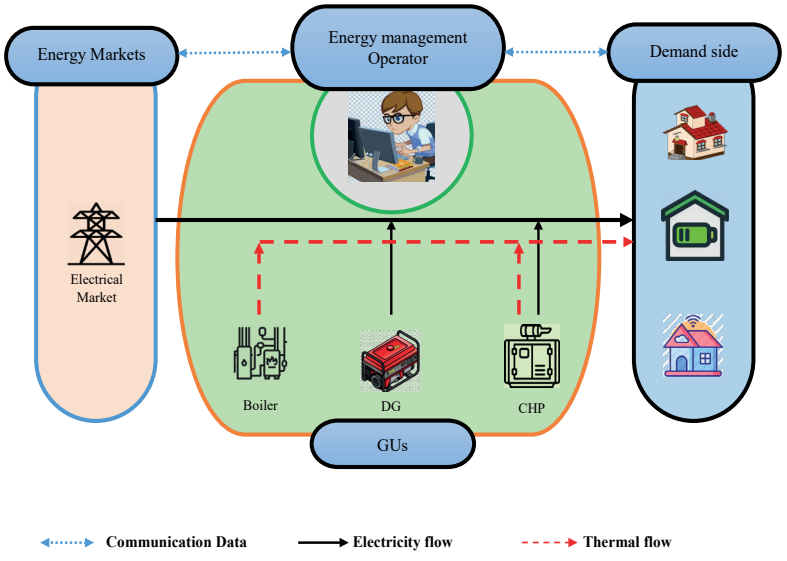


Fig. 1. SMG topology.

2.1. Demand Side Participation Modelling

2.1.1. Modelling Demand Shifting

Using demand shifting strategy, load demand at high price electrical market can be moved to low price. This strategy modelling is as follow [35]:

$$ED_{DS}(t) = \sum_{t'}\sum_{ds=1}^{DS} ED_{DS}(t,t) - \sum_{t'}\sum_{ds=1}^{DS} ED_{DS}(t,t)\sum_{ds=1}^{DS} ED_{DS}(t,t) \quad \forall t\,, \tag{1}$$

$$0 \le \sum_{t'}\sum_{ds=1}^{DS} ED_{DS}(t,t') \le \Theta \times \sum_{ds=1}^{DS} ED_{DS}(t) \qquad \forall t\,, \tag{2}$$

where Eq. (1) and Eq. (2) are demand shifted from t to t', and limit of the demand shifted, respectively.

2.1.2. Modelling Onsite Generation

The onsite generation strategy using ESS is done. The demand side can be charged self-ESS at low electrical price and discharged at high price to meet self-demand. The modelling onsite generation strategy based-ESS is as follow [36]:

$$0 \le P_{\mathrm{ESS}}^{\mathrm{DIS}}(t,\mathrm{ESS}) \le u_{\mathrm{ESS}}(t,\mathrm{ESS}) \cdot P_{\mathrm{ESS}}^{\mathrm{r}} \qquad \forall t,\mathrm{ESS} \tag{3}$$

$$0 \le P_{\mathrm{ESS}}^{\mathrm{CH}}(t,\mathrm{ESS}) \le [1 - u_{\mathrm{ESS}}(t,\mathrm{ESS})] \cdot P_{\mathrm{ESS}}^{\mathrm{r}} \qquad \forall t,\mathrm{ESS} \tag{4}$$

$$\left[\sum_{t\in T} P_{\mathrm{ESS}}^{\mathrm{DIS}}(t,\mathrm{ESS}) \cdot \frac{1}{\eta_{\mathrm{dis}}}\right] - \left[\sum_{t\in T} P_{\mathrm{ESS}}^{\mathrm{CH}}(t,\mathrm{ESS}) \cdot \eta_{\mathrm{ch}}\right] = 0 \qquad \forall t,\mathrm{ESS} \tag{5}$$

The Eq. (3) and Eq. (4) are limit of discharge power and charge power of ESS, respectively. The Eq. (5) is an onsite generation model by ESS.

2.2. Objective Functions Modelling

In this subsection, objective functions including generation cost and emission polluting are modelled by Eq. (6) and Eq. (7), respectively.

$$\begin{aligned} \min f_{GC} = &\sum_{t=1}^{h}\sum_{u=1}^{U}\left\{\alpha P^2(t,u) + \beta P(t,u) + \chi(t,u)\right\} \\ &+ \left\{\omega T^2(t,u) + \xi T(t,u) + \psi(t,u)\right\} + \left\{C_{pur} \cdot P_{pur}(t)\right\} \\ &+ \left\{C_{\mathrm{ESS}} \cdot \left(\frac{P_{\mathrm{ESS}}^{\mathrm{DIS}}(t)}{\eta_{\mathrm{dis}}}\right)\right\} + \left\{C_{\mathrm{ESS}} \cdot (-P_{\mathrm{ESS}}^{\mathrm{CH}}(t) \cdot \eta_{ch})\right\} \end{aligned} \tag{6}$$

$$\begin{aligned} \min f_{EP} = &\sum_{t=1}^{h}\sum_{u=1}^{U}\left\{\mu P^2(t,u) + \lambda \mathrm{P}(t,u) + \delta(t,u)\right. \\ &\left. + \mu T^2(t,u) + \lambda T(t,u) + \delta(t,u)\right\} + \left\{\ \cdot P_{pur}(t)\right\} \end{aligned} \tag{7}$$

The generation costs of GUs are modelled by the first and second terms of Eq. (6), respectively. The third, fourth and fifth terms of the Eq. (6) are respectively generation costs of the electrical market, discharge and charge of ESS. And emission generation by GUs and the electrical market is modelled in the first and second terms of Eq. (7), respectively.

2.3. Constraints

The proposed approach is optimized according to several constraints:

$$\left\{\sum_{u=1}^{U} P(t,u) + P_{pur}(t) + \sum_{\mathrm{ESS}=1}^{\mathrm{ESS}} P_{\mathrm{ESS}}^{\mathrm{DIS}}(\mathrm{ESS},t)\right\} = \left\{ED(t) + \sum_{\mathrm{ESS}=1}^{\mathrm{ESS}} P_{\mathrm{ESS}}^{\mathrm{CH}}(\mathrm{ESS},t)\right\} \tag{8}$$

$$\left\{\sum_{u=1}^{U} T(t,u)\right\} = \left\{TD(t)\right\} \tag{9}$$

$$P^{\min} \le P(t,u) \le P^{\max} \tag{10}$$

$$T^{\min} \le T(t,u) \le T^{\max} \tag{11}$$

The constraints Eqs. (8)–(11) are electrical energy balance, thermal energy balance, electrical and thermal generation bound of GUs, respectively.

3. OPTIMIZATION METHOD

Since, the multi-criteria model including generation cost and emission are optimized, simultaneous. The WSM is employed to optimization of the objective functions. In this method, objectives are turned to one objective and Pareto frontier solutions are obtained by diverse values of weights. The WSM is modelled as follows [38]:

$$Of = \left(w_1 \cdot f_{GC}\right) + \left(w_2 \cdot f_{EP}\right), \tag{12}$$

subject to:

$$w_1 + w_2 = 1. \tag{13}$$

Here, w_2 and w_2 are weights for objective functions such as generation cost and emission, respectively.

3.1. Max-Min Fuzzy Procedure

In this subsection, the max-min fuzzy procedure is used to determine the desired optimal solution in between Pareto frontier solutions. The operator as a decision maker should implement the maximum trade-off for objectives. The process of the max-min fuzzy procedure is modelled as follows [45]–[49]:

$$\theta^{f_n(k)} = \begin{cases} 0 & \text{otherwise} \\ \dfrac{f_n^{\max} - f_n(k)}{f_n^{\max} - f_n^{\min}} & f_n^{\min} \le f_n(k) \le f_n^{\max} \end{cases}, \tag{14}$$

$$\max(\min \theta^{f_n(k)}). \tag{15}$$

Using Eq. (14), all objectives are normalized, and by Eq. (15) maximum trade-off can be calculated. Here f_n^{max}, f_n^{min} and $f_n(k)$ are maximum, minimum value of nth objective and value of the nth objective in kth solution, respectively.

4. NUMERICAL SIMULATION

In this section, two case studies are considered for confirmation of the multi-criteria optimization problem and the proposed approach. The case studies are as follows:

- Case 1) Multi-criteria optimization problem in SMG without demand side participation;
- Case 2) Multi-criteria optimization problem in SMG with demand side participation.

In this study, GUs include two CHPs, two boilers and two DGs. The data of GUs are provided in Table 1 and Table 2 [50]–[52]. The data of ESS is given in Table 3. In Fig. 2 and Fig. 3, electricity prices in day-ahead energy market and energy demand are depicted, respectively [38], [39]. The emission factor of the electrical market is taken by 980 g/kWh. The value of the demand participation in demand shifting is equal to 40 %. The simulation is implemented using *GAMS* software in core i7 PC system with CPU 2.5 GHz by *DICOPT* solver and mixed integer nonlinear program (*MINLP*).

TABLE 1. ECONOMIC AND EMISSION DATA OF GUS

Parameters, Units	**α, $/kW²**	**β, $/kW**	**χ, $**	**ω, $/kW²**	**ξ, $/kW**	**ψ, $**	**μ, g/kW²**	**λ, g/kW**	**δ, g**
DG 1	57.8	190.5	250	–	–	–	5.6	9.3	34
DG 2	58.3	197.3	268	–	–	–	5.3	9.6	77
Boiler 1	55.3	194.5	155	–	–	–	5.3	9.3	47
Boiler 2	62.6	194.5	185	–	–	–	5.3	6.6	76
CHP 1	75.4	194.4	264	26.2	28.5	61.1	5.6	18.2	220
CHP 2	85.3	192.3	286	24.8	25.4	61.2	5.2	50.4	252

TABLE 2. ENERGY GENERATION LIMIT OF GUS

Parameters, Units	P^{min}, **kW**	P^{max}, **kW**	T^{min}, **kW**	T^{max}, **kW**
DG 1	0	120	–	–
DG 2	0	150	–	–
Boiler 1	–	–	0	150
Boiler 2	–	–	0	150
CHP 1	0	115	0	155
CHP 2	0	130	0	155

TABLE 3. ESS PARAMETERS

Parameters	Value
η^{ch}	85 %
η^{dis}	90 %
P^{r}_{ESS}	50 kW
C_{ESS}	15 $
Number	1

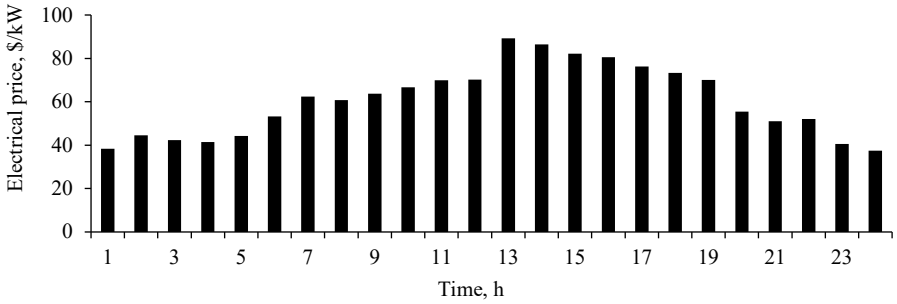


Fig. 2. Electrical price in day-ahead [38], [39].

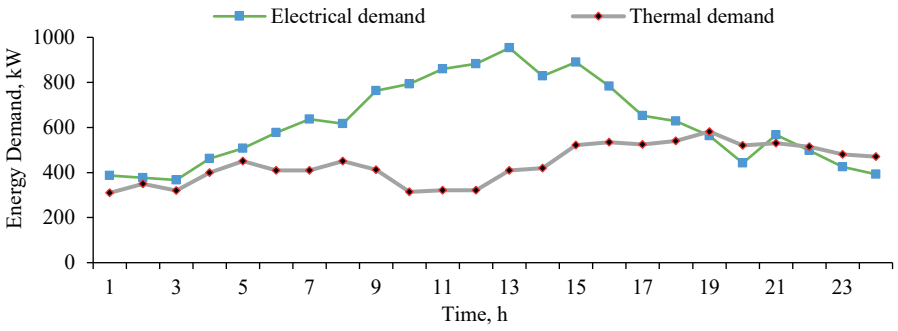


Fig. 3. Electrical and thermal demand.

4.1. Results Evaluation

As mentioned before, two case studies are considered to validation of the proposed approach subject to demand side participation in SMG. In this subsection, obtained results of the simulation are analysed as a comparative study.

In Table 4. Pareto frontier solutions of objectives in case studies are listed with attention to different values of weights by WSM. The weights are changed with a value of 0.2 for each objective. As well in this table, the desired solution of each case with maximum trade-off is bolded using the max-min fuzzy procedure. The maximum trade-off of objective functions for Cases 1 and 2 in, the desired solution is equal to 0.761 and 0.763, respectively. In Case 1, the third solution is selected as the desired solution. The generation cost and emission in Case 1, have values of $ 426 132.2 and 5330.1 kg, respectively. However, with the participation of the demand side in Case 2, emission and generation costs are minimized by 10.43 % and 21.32 % than Case 1, respectively. In Case 1, generation cost and emission of the electrical market are equal to $ 281 802.3 and 3573.51 kg, respectively. This while, emission and generation costs of the electrical market in Case 2 are decreased by 25.4 % and 20.3 % according to Case 1, respectively. The optimal reshaping of electrical demand by demand shifting and utilization of the ESS with low cost leads to more participation of GUs and a reduction of the energy market participation in meeting demand.

In Fig. 4, the electrical demand with consideration of the demand shifting strategy is shown. It is visible that the demand for the high electrical price is shifted to low prices. This strategy

leads to reduce generation costs and emissions of the electrical market, due to high electrical prices at peak demand and high emission factors of the electrical market.

In Tables 5 and 6, electrical and thermal generation in Cases 1 and 2 are listed, respectively. In Table 5, electrical purchased from the electrical market is done at hours 5–19 in high electrical price and peak demand, due to low electrical generation by GUs. On the other hand, in Table 6, with the participation of the demand side in optimal energy consumption and onsite generation by ESS, electrical generation from the electrical market is reduced by 32.3 % than Case 1.

TABLE 4. PARETO FRONTIER SOLUTIONS OF CASE STUDIES

Solutions	**Weights**		**Case 1**		**Case 2**	
#	w_1	w_2	**Generation cost, $**	**Emission polluting, kg**	**Generation cost, $**	**Emission polluting, kg**
1	1	0	483 324.3	0	396 571.3	0
2	0.8	0.2	453 574.3	4587.8	376 542.3	4054.7
3	0.6	0.4	**426 132.2**	**5330.1**	359 876.3	4565.6
4	0.4	0.6	398 765.3	6544.3	**335 250.2**	**4763.3**
5	0.2	0.8	355 474.2	7254.2	302 476.3	5132.3
6	0	1	0	7565.4	0	5563.5

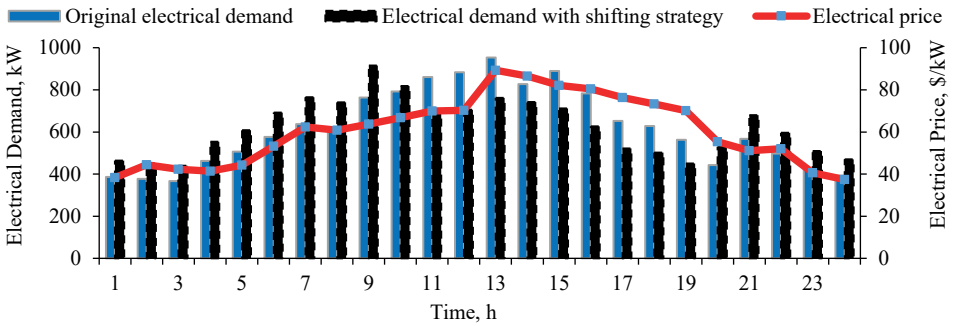


Fig. 4. Electrical demand with demand shifting strategy.

TABLE 5. OPTIMAL ENERGY GENERATION IN CASE 1

Hour	**Electrical energy generation, kW**					**Thermal energy generation, kW**			
	DG 1	DG 2	CHP 1	CHP 2	Electrical market	Boiler 1	Boiler 2	CHP 1	CHP 2
1	88	113	102.2	83.7	0	100	110	40.3	60.4
2	78	105	115	79	0	100	110	100	97.3
3	90	120	115	42	0	100	110	97.1	79.3
4	102	135	115	109.2	0	100	110	98.7	110.4
5	114	150	115	110.2	18	100	110	100	115
6	120	150	115	109.5	82	100	110	99.5	110.4
7	120	150	115	108.1	142	100	110	100	115
8	120	150	113	111.2	122	100	110	101.2	116.2
9	120	150	115	112	265	100	110	100	102
10	120	150	108	130.5	278.1	100	110	100	5.6

11	120	150	115	127.3	347.3	100	110	103.2	10.2
12	120	150	109.5	128.3	370.4	100	110	100	11.5
13	120	150	114.5	111.2	455.2	100	110	100	100
14	120	150	113.3	110.8	432.1	100	110	100	110
15	120	150	115	110	394.4	100	110	100	112
16	120	150	113	110	288	100	110	98.3	117.6
17	120	150	113.4	111.2	158	100	110	102.3	109.2
18	120	150	114.3	113.1	133	100	110	101.3	108.8
19	120	150	115	110.2	68	100	110	113.4	110.2
20	110	142	114.3	75.3	0	100	110	100	95
21	120	150	112.5	113.8	0	100	110	100	109
22	110	142	115	110.2	0	100	110	100	105
23	100	134	115	76	0	100	110	100	95.6
24	90	126	113.8	66.2	0	100	110	100	87.3

TABLE 6. OPTIMAL ENERGY GENERATION IN CASE 2

Hour	**Electrical energy generation, kW**						**Thermal energy generation, kW**			
	DG 1	DG 2	CHP 1	CHP 2	Electrical market	ESS	Boiler 1	Boiler 2	CHP 1	CHP 2
1	120	150	97.6	110	0	–13.2	100	110	40.3	60.4
2	120	150	115	110	0	–42.6	100	110	100	97.3
3	120	145	115	110	0	–50	100	110	97.1	79.3
4	120	150	115	110	59.4	0	100	110	98.7	110.4
5	120	150	115	110	113.4	0	100	110	100	115
6	120	150	115	110	197.4	0	100	110	99.5	110.4
7	120	150	115	110	269	0	100	110	100	115
8	120	150	115	110	245.4	0	100	110	101.2	116.2
9	120	150	115	123	404.5	0.4	100	110	100	102
10	120	150	115	121.1	311.6	0	100	110	100	5.6
11	120	150	115	119.5	183.4	0	100	110	103.2	10.2
12	120	150	115	121	200	0	100	110	100	11.5
13	120	150	115	110	217.3	50	100	110	100	100
14	120	150	115	121.8	200	35.1	100	110	100	110
15	120	150	115	121.5	205.4	0	100	110	100	112
16	120	150	115	110	131.4	0	100	110	98.3	117.6
17	120	150	115	110	27.4	0	100	110	102.3	109.2
18	120	150	115	110	7.4	0	100	110	101.3	108.8
19	120	150	115	110	0	–44.6	100	110	113.4	110.2
20	120	150	115	110	0	35.4	100	110	100	95
21	120	150	115	110	185.4	0	100	110	100	109
22	120	150	115	110	100.7	0.61	100	110	100	105
23	120	150	115	110	15	0	100	110	100	95.6
24	110	142	115	103.4	0	–6.6	100	110	100	87.3

In Table 6, the power charge of ESS is scheduled at hours 1–3, 19 and 24. The ESS at mentioned hours is fed by DGs and CHPs with low cost and emission; and discharged at a high electrical price in the market. This strategy has an optimal effect on electrical purchases from the energy market and leads to decrease costs and emissions. The amount of the generation cost and emission production by GUs to meet thermal demand in both cases is similar.

5. CONCLUSION

In this article, the optimal energy management of the SMG is analysed with consideration of the demand side participation in the day-ahead electrical market. The demand side has two strategies of the DR onsite generation by ESS and shifting their demand. The multi-criteria problem such as generation cost and emissions are minimized subject to demand side participation and constraints. Hence, the main conclusions of the results can be expressed as follows:

1. The optimal shifting of the electrical demand leads to modification of the consumption pattern with attention to electrical price in the energy market. The demand shifting and ESS are provided reshape of the peak electrical demand at operation time to optimal energy dispatch of generation side in meet demand with minimum cost and emission;
2. The participation of the demand side leads to a decrease in electrical generation by the electrical market with a high emission factor. The charging of ESS is done by GUs and low electrical price, and feed demand by ESS occurs at a high price.

It can be concluded that the demand side participation in energy management has been provided with the optimal level of the energy balance among the generation side and demand side to enhance the efficiency of the proposed SMG, and improve environmental and economic indices.

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