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Techno-Economic Energy Optimization of the Off-Grid Electrical System with Power to Gas Storage Technology

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Abstract: Renewable energy sources (RESs) have undeniable advantages over the recent years not only to supply electrical demand but also electrical demand. However, maximum use of the RES's power has always been challenging as high penetration of the RESs as well as their intermittent nature might compromise the distribution networks power flow constraints. This paper proposes optimal energy operation of the off-grid distribution network (DN) with participation of the power-to-gas (PtG) storage system. In this regard, PtG system is considered as an energy supplier in the DN. The natural gas generated by using PtG is applied to backup diesel generators for meeting demand at peak times. The objective functions in the system are modeled based on technical and economic modeling including minimize the operation cost and maximize the system reliability. The optimal energy operation in the two case studies is assumed considering non-participation and participation of the PtG system. To solving of the energy optimization, particle swarm optimization algorithm is proposed. Finally, proposed case studies under numerical simulation are implemented for validation of the participation of the PtG system.

Keywords: Renewable Energy Sources (RESs), distribution networks, Power-to-Gas (PtG) technology, reserve generators

Nomenclature		
t,T	Hour	-
n,N	Diesel generators (DGs) units index	-
bdg, BDG	Backup diesel generator (BDG) units index	-
A,B,X	Fuel cost factor of DGs	\$/MW
Λ	cost of BDG	\$/MW
A_C	Area of PV panel	m^2
I_s	Solar irradiance	kW/m^2
C_p	Power generation factor of WT	MW
A	Area of the WT rotor	m^2
V_r	Wind speed	m/s
C_{DG},C_{BDG}	Cost of DGs and BDGs	\$
D_e,D_{UM}	Total demand and unmet demand	MW
P_{PV}, P_{WT}	Power generated by photovoltaic (PV) panels and wind turbine (WT)	MW
P_n, P_{BDG}	Power generated by DGs and BDG	MW
P^{in}_{PtG}	Power injected to Power-to-gas (PtG) storage system	MW
G^{out}_{PtG}	Output Gas by PtG storage system	m^3
η_t,η_{PV}	Efficiency of WT and PV	%
$\eta_{el},\eta_{mta},\eta_{BDG}$	Efficiency of electrolyzer, methanization and BDG	%

1. Introduction

1.1 Motivations

Recently, humans and modern societies are dependent on synergy in energy systems, and different ideas have addressed problems in synergistic energy. The energy optimization is critical in tackling such problems. These systems face major problems ranging from generation to consumption [1]. The conventional fossil fuel deficiency all over the world and global consensus to have a cleaner environment have dramatically changed operational strategies of the distribution network (DN) by integration of renewable energy sources (RESs). Despite the economic and environmental privileges of RESs penetration into the DN, limited capacity and contravention of the DN constraint result in the spilling of energy, which declines network efficiency. In order to accommodate RESs to the DN, many studies have been proposed to manage different issues, such as improvement of the DN operation [2], risk assessment for enhancing RESs integration, and also decreasing operational cost besides improving reliability and security of the DN [2]. However, the uncertain feature of RESs causes the incorporation of energy storage systems (ESSs) in the DN. In spite of the high cost and short life of electrical storages, ESSs can contribute to decrease RESs' drawbacks and offer flexible solutions for RESs operation. The ordinary electrical DN are changing to modern DN with enhancement penetration of RES and ESS [2][3]. The use of these resources can be varied subject to topology of DN [3]. For example, the off-grid DNs are one of the appropriate systems to usage of these resources. The off-grid DNs because of the non-energy supplied with high reliability such as power plants have unreliable generation in meeting demand. Thus, employing ESSs like power-to-gas (PtG) system can increase generation capacity for optimal operation of the off-grid DNs [4]. In Fig.1. overview of the proposed off-grid DNs is demonstrated. The off-grid DNs including consists of photovoltaic (PV) panels, diesel generators (DGs), wind turbine (WT), backup diesel generator (BDG), PtG system, operator and consumers. In Fig.2. PtG storage system is demonstrated. In this figure, electrical generation of the other resources is injected to electrolyzer. In first step, hydrogen (H_2) with combining water (H_2O) is obtined. The hydrogen generated is stored in hydrogen tank. In methanization process, stored H_2 is combined with carbon dioxide (CO_2) [5]. Finally, H_2O and methane gas (CH_4) are obtained as gas output. The CH_4 as flammable gas is applied to BDG for electrical generation at peak hours.

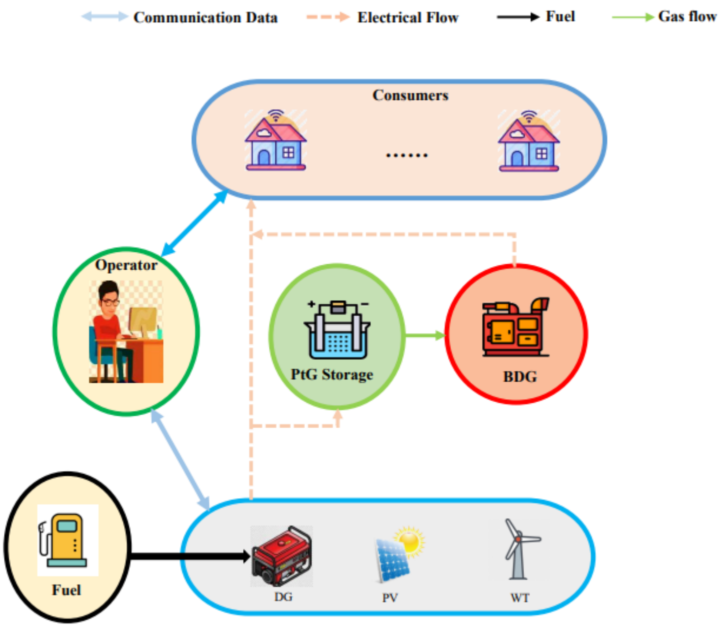

Fig.1 - Overview of the Off-grid DN

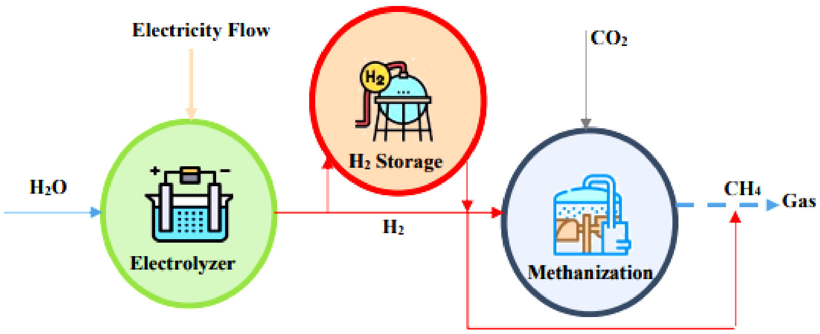

Fig. 2 - PtG system

1.2 Literature Review

The operation of the energy system has been studied in diverse approaches. For example, authors in [6] has established a cooperative game-based platform for peer-to-peer energy trading among microgrids, in which ESSs, demand response programs, and vehicle-to-grid technology of electric vehicles (EVs) have been used as flexible technologies. According to [7], a transactive energy solution has been proposed to co-optimize gas and power grid, in which ESSs have been considered to play a supportive role in the intermittent power of the RESs and the stochastic conditional value at risk technique has been developed to cope with the RESs uncertainty feature. The impact of BESSs' capacity on the DN operation and relieving congestion have been quantified in [8]. For instance, load shifting and providing a regulated voltage profile have been investigated in [9] by energy management systems using ESSs. Study [10] has proposed a framework for reducing congestion in line with the spatiotemporal location optimization of the ESSs. Reference [11] has introduced a model to determine the optimal position and charging/discharging scheduling of the ESS to participate in day-ahead marketing. Moreover, transporting excess energy from solar parks to demand centers has been proposed in [12] by the means of the ESS, while relieving line congestion. Furthermore, a cost-minimizing scheduling method of EVs charging in the DN has been presented in [13] in an uncertainty arising from EVs behavior. Reference [14] has done a techno-economic assessment in order to optimize performance of RESs using hydrogen storages to mitigate the variability of renewable sources. Optimal scheduling of microgrids has been investigated in [15], in which microgrids have been equipped with ESSs. Moreover, the uncertainty of RESs, electrical and hydrogen demands, and electricity prices have been tackled by robust optimization. Study [16] has been proposed to assess the EV potential in vehicle-to-grid operation as ESSs to supply residential consumers. In Table 1. a summary of the mentioned papers in the literature is compared with this paper.

1.3 Contributions

In this work operation of the off-grid DN with consideration of the PtG system is studied. The optimization of the objective functions is modeled by bi-criteria problem considering technical and economic indices. The technical index is proposed for maximize reliability and economic index is considered for minimize the operation cost. On the other side, PtG technology is modelled as ESS for meeting energy demand in peak times. The operation of the PtG technology is implemented via injecting gas stored to BDG for meeting energy demand at peak hours. By using particle swarm optimization algorithm and weight sum approach, bi-criteria problem is optimized, simultaneously. Thus, contributions are listed as follow:

1) An operation of the off-grid DN with PtG storage system is presented.
2) The economic and technical modelling is presented as bi-criteria problem.
3) The particle swarm optimization algorithm and weight sum approach are used as solving method.

Table 1 - Survey of mentioned studies with this work

Ref	Type of ESS	Objective functions		Optimization method	Network
	PtG	Operation cost	Reliability	Particle swarm optimization	Off-grid
[5]	-	-	-	-	-
[6]	-	-	-	-	-
[7]	-	-	-	-	-
[8]	-	✓	-	-	-
[9]	-	-	-	-	-
[10]	-	✓	-	-	-
[11]	-	-	-	-	-
[12]	-	✓	-	-	-
[13]	-	-	-	-	-
[14]	-	✓	-	-	✓
[15]	-	-	-	-	-
[16]	-	-	-	-	-
[17]	-	✓	-	-	-
This paper	✓	✓	✓	✓	✓

1.4 System Modelling

The modelling system is proposed in this section:

1.5 PV Modelling

The PV modelling is as follow [17] [18]:

$$P_{PV}(t) = \eta_{PV} \times A_C \times I_s(t) \tag{1}$$

1.6 WT Modelling

The WT modelling is as follow [17] [18]:

$$P_{WT}(t) = \frac{1}{2} \times \eta_t \times C_p \times A \times V_r^{\,3}(t) \tag{2}$$

1.7 DG Modelling

The DG modelling is as follow:

$$C_{DG}(t,N)=\sum_{t=1}^{T}\left\{\sum_{n=1}^{N}\mathrm{A}P_n^2(t,N)+\mathrm{B}P_n(t,N)+\mathrm{X}\right\} \qquad \forall t,N \tag{3}$$

1.8 PtG System Modelling

The gas generated by PtG system is applied to BDG. The PtG system is modelled as follow [19]:

$$0\le P_{PtG}^{in}(t)\times\eta_{el}\le u_{PtG}(t)\times P_{PtG}^{in,\max} \qquad \forall t \tag{4}$$

$$0\le G_{PtG}^{out}(t)\times\eta_{mta}\le[1-u_{PtG}(t)]\times G_{PtG}^{out,\max} \qquad \forall t \tag{5}$$

$$G_{PtG}^{out}(t)=\eta_{BDG}\times P_{BDG}(t) \qquad \forall t,bdg \tag{6}$$

$$C_{BDG}=\Lambda_{su}\times P_{BDG}(t) \qquad \forall t,bdg \tag{7}$$

The limit of the injected electrical energy and limit of the output gas in PtG technology are formulated by equations (4) and (5), respectively. In these equations, u_{PtG} is binary variable and represents that injected power and output gas are not operated at same times. In the following, equations (6) and (7) are value of gas injected into BDG and the cost of the consumed gas by BDG, respectively.

2. Bi-Criteria Problem

The modelling of bi-criteria problems are objective functions such as 1) minimizing the operation cost and 2) maximizing the reliability system. The bi-criteria problems is modelled as follow:

2.1 Frist Objective

The minimizing the costs of the consumed fuels by DGs and BDG is modelled as the first problem:

$$\min f_1=\sum_{t=1}^{T}\left\{\sum_{n=1}^{N}C_{DG}(t,N)+\sum_{bdg=1}^{BDG}C_{BDG}(t,BDG)\right\} \tag{8}$$

Where C_{DG} and C_{BDG} are respectively costs of the consumed fuels by DGs and BDG, which they are modelled by equations (3) and (7), respectively.

2.2 Second Objective

The reliability of the system in meeting demand is considered as second objective:

$$\max f_2=\sum_{t=1}^{T}\left[1-\frac{D_{UM}(t)}{D_e(t)}\right]\times 100 \tag{9}$$

Subject to:

$$0\le D_{UM}(t)\le D_e(t)\times u_{UM}(t) \qquad \forall t \tag{10}$$

$$u_{UM}(t)=\begin{cases}1 & D_e(t)>P_n(t,N)+P_{WT}(t)+P_{PV}(t)+P_{BDG}(t,bdg)-P_{PtG}^{in}(t)\\ 0 & Otherwise\end{cases} \qquad \forall t \tag{11}$$

The unmet demand is proposed by (10), and status of the unmet demand is given by (11). Where u_{UM} is binary variable, that represents status of unmet demand by generation side. In this equation, if u_{UM}=1 unmet demand is done.

3. Limitations of DN

The DN modelling is done subject to limitations such as energy balance limit, limit of DG and BDG power generation.

$$\sum_{n}^{N} P_n(t,N) + \sum_{bdg=1}^{BDG} P_{BDG}(t,bdg) + P_{PV}(t) + P_{WT}(t) - P_{PtG}^{in}(t) = D_e(t) - D_{UM}(t) \qquad \forall t \tag{12}$$

$$0 \le P_n(t,N) \le P_n^{\max} \qquad \forall t, N \tag{13}$$

$$0 \le P_{BDG}(t,bdg) \le P_{BDG}^{\max} \qquad \forall t, bdg \tag{14}$$

4. Particle Swarm Optimization Algorithm

First, Kennedy and Eberhart created the particle swarm optimization algorithm in 1995. It is based on the predatory bird population in the two-dimensional space of simulation. It was created with simulating a streamlined social system, and it has proven to be effective in finding solution of continuous nonlinear optimization problems. Scholars were widely concerned in optimization and the progress of computing because of its notion of simplicity, ease of implementation, and computing efficiency. Additionally, the energy system's algorithm's direction has been gradually taken into consideration. In N-dimensional space, any particle was seen as a point by the particle swarm optimization algorithm: $X_i=(X_{i1},X_{i2}, \ldots, X_{in})$. Individual particles were best known for the initial iteration's i-particle position, which is the best fitness, recorded as $pBest_i$, Global best refers to the best particle fitness across all particles in the current iteration, recorded as $gBest_i$, changes the location of the particles' speed in mind for V_i, $V_i=(V_{i1}, V_{i2}, \ldots, V_{in})$. Finally, it is possible to determine each particle's updated position and velocity using the following formulas [20]:

$$V_{id}^{k+1} = \omega \times V_{id}^{k} + C_1 \times rand() \times \left(pBest_{ig}^{k} - X_{id}^{k}\right) + C_2 \times rand() \times \left(gBest_{id}^{k} - X_{id}^{k}\right) \tag{15}$$

$$X_{id}^{k+1} = X_{id}^{k} + V_{id}^{k+1} \tag{16}$$

In the iteration k and next iteration k+1, X_{id}^{k} and X_{id}^{k+1} are the position of the d-dimensional portion of the particle i. V_{id}^{k} and V_{id}^{k+1} are the speed location of the i-d-dimensional particle's portion. C_1 , C_2, who are each believed to be two plus confining indices, demonstrate the adjustment of the largest step that affects the $gBest_i$ and the $pBest_i$ particle flight directions, respectively. *rand()* generates a random value in the interval [0,1].

4.1 Decision Making Method

The bi-criteria problems are optimized in this study, simultaneously. The frontier solutions of the problems are obtained. Hence, operator must be determined optimal compromise solution for multi-criteria problem in the frontier solutions as decision maker. Using (17), all problems are normalized and by (18) maximum rate of ξ^k is considered as optimal compromise solution [21]- [25].

$$\xi_i^k = \begin{cases} 1 & f_i^k \le f_i^l \\ \dfrac{f_i^u - f_i^k}{f_i^u - f_i^l} & f_i^l \le f_i^k \le f_i^u \\ 0 & f_i^k \ge f_i^u \end{cases} \tag{17}$$

$$\zeta^k = \frac{\sum_{i=1}^{I} \omega_i . \zeta_i^k}{\sum_{k=1}^{K} \sum_{i=1}^{I} \omega_i . \zeta_i^k} \tag{18}$$

Subject to:

$$\sum_{i=1}^{I} \omega_i = 1 \qquad \omega_i \geq 0 \tag{19}$$

Where f_i^u and f_i^l are maximum and minimum value of *ith* objective, respectively. And f_i^k, ξ_i^k and ω_i are values of *ith* objective in *kth* solution, value of solution in *ith* objective and *kth* solution and weight value in *ith* objective, respectively.

5. Case Studies

To show the efficiency of optimization model in off-grid DN; The two case studies considering numerical simulation on 21-bus test system in Fig.3 is done. The cases are as follow:

Case I) Operation of the off-grid DN without PtG system.

Case II) Operation of the off-grid DN with PtG system.

The operation of the off-grid DN is done at day-ahead with the forecast of the solar irradiance, load demand and wind speed. The solar irradiance, load demand and wind speed are provided in Table.1. The date of WT and PV are taken from References [26]. The data of the DGs, BDG and PtG storage system are listed in Table.2. It should be mentioned, we used three DGs with same data.

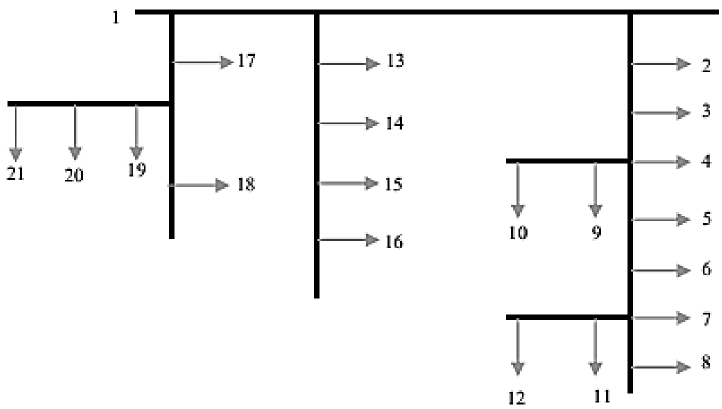

Fig. 3 - 21-bus test system

Table 2 - Value of the solar irradiance, load demand and wind speed

Hour	Solar irradiance (kW/m^2)	Wind speed (m/s)	Load Demand (MW)
1	0	5.6	1.82
2	0	6.5	1.81
3	0	7.3	1.72
4	0	4.9	1.63
5	0	6.5	1.75
6	0	7.1	2.21
7	0.15	5.8	2.41
8	0.22	5.6	2.45
9	0.34	6.5	2.71
10	0.39	6.4	2.52
11	0.52	5.8	3.8

12	0.61	5.4	2.21
13	0.72	6.9	2.95
14	0.78	6.7	3.01
15	0.68	5.3	3.53
16	0.49	5.9	2.55
17	0.38	6.2	2.65
18	0.25	4.7	4.1
19	0.18	5.4	4.2
20	0	5.4	4.25
21	0	5.5	2.63
22	0	4.8	2.65
23	0	5.4	3.55
24	0	5.8	2.21

Table 3 - Data of DGs, BDG and PtG system

Parameters	Value	Unit
DG data		
A	86.3	$\$/MW^2$
B	90.6	$/MW
X	102.2	$
P^{max}	0.95	MW
BDG data		
η_{BDG}	90	%
Λ	240	$/MW
$P^{max}{}_{BDG}$	0.25	MW
PtG data		
η^{el}	88	%
η^{mta}	85	%
$P_{PtG}{}^{in,max}$	0.34	MW
$G_{PtG}{}^{out,max}$	310	m^3

5.1 Results

The results of the numerical simulation in cases I and II are explained in this section. The case studies are proposed considering PtG participation in the off-grid DN. The bi-criteria problem by using particle swarm optimization is solved. Also, wight sum method is used for finding optimal solution. In Figs.4 and 5, solutions of the bi-criteria problem and optimal solution for the case studies I and II are depicted, respectively. As mentioned before, operation cost is modelled as first objective (f_1) and reliability is formulated as second objective (f_2). The level of the reliability and operation cost in the optimal solution in the case I in Fig.4. is 77.39% and $96826.3, respectively. However, level of the reliability and operation cost in case II in Fig.5 is 81.4% and $88418.3, respectively. Regarding results in the cases II and participation of the PtG system in this case, 8.8% of operation costs are reduced and reliability is increased by 4% than case I. These results represent that, utilization of the BDG and PtG have provided optimal level of the capacity generation in the DN for meeting demand with low operation cost.

In Fig.6 power operated in case I is indicated. Due to low power generation by resources at hours 11,15,18, 19, 20 and 23; the unmet demand is accomplished in these hours at peak demand. The total unmet demand in case I is 4.4MW, and maximum level is 1.13MW at hour 20.

The energy generation by resources and BDG in case II is shown by Fig.7. The PtG system is employed to feed BDG for meet demand. The power production by WT and PV system is applied to PtG system in low demand and at hours 1, 9, 12, 16, 17 and 22. Whereas, BDG is operated in peak demand at hours 7, 8, 11, 15, 18 and 24. The operation of the BDG leads to increase generation power in the DN with value 1.08 MW. Also, unmet demand is reduced by 20.9% than first case study.

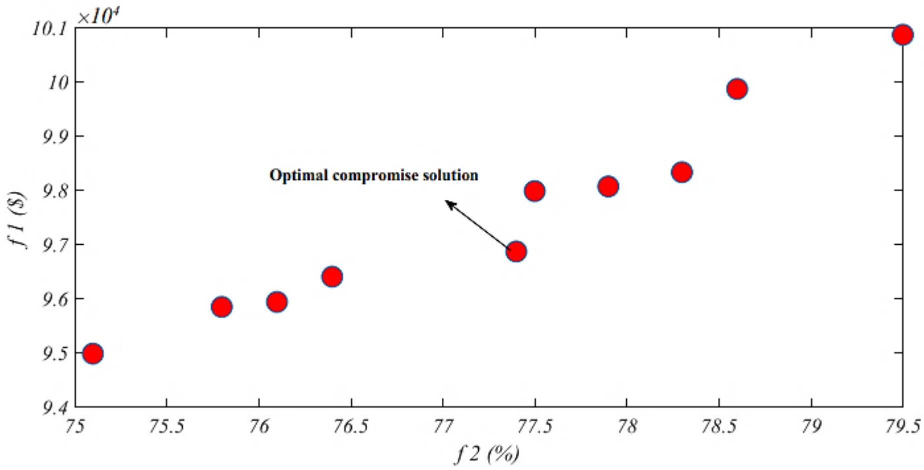

Fig. 4 - Solutions in case I

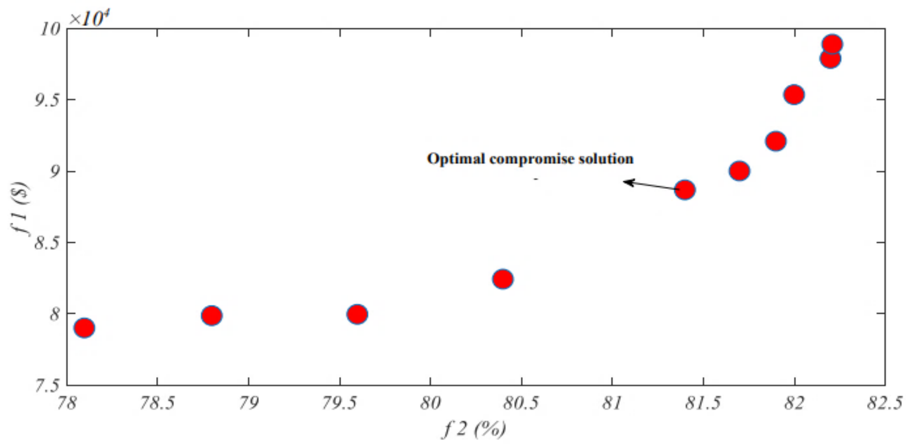

Fig. 5 - solutions in second case II

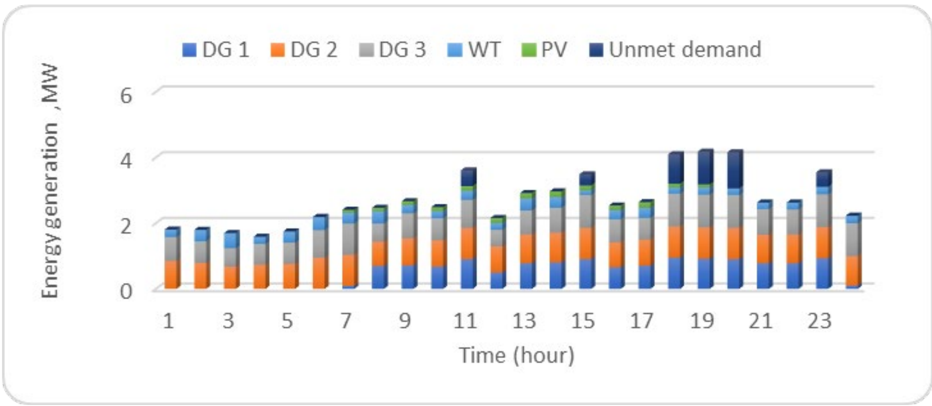

Fig. 6 - Power generation in first case

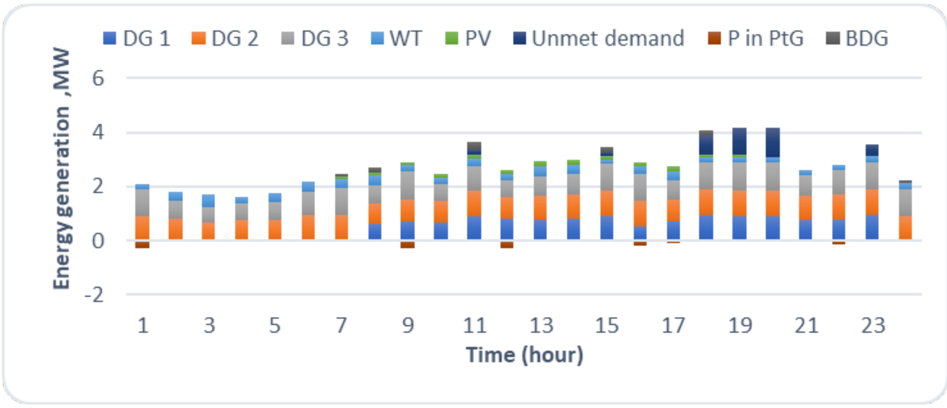

Fig. 7 - Power generation in second case

6. Conclusion

This paper proposes optimal energy operation of the off-grid DN with participation of the PtG storage system. The PtG system is considered as an energy supplier in the DN. The natural gas generated by using PtG is applied to BDG for meeting demand at peak times. The objective functions in the system modeled based on technical and economic modeling including minimize the operation cost and maximize the system reliability. The optimal energy operation in the two case studies is assumed considering non-participation and participation of the PtG system. To solving of the energy optimization, particle swarm optimization algorithm is proposed. The results of the simulation show, the employing PtG has increased capacity of DN for improve reliability and operation costs.

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