Research Article

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Optimizing energy for the independent electric power system with power-to-gas storage technology

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Abstract: This research shows the operational aspects of an autonomous electrical system that incorporates power-to-gas (PtG) technology. PtG technology plays a crucial role in energy storage by utilizing stored gas to power reserve generators during critical supply-demand situations. The primary focus of this study is to minimize fuel costs for the generators, which serves as an economic indicator, while simultaneously maximizing the system's reliability index, which is a technical indicator. To achieve these objectives, the particle swarm optimization algorithm is employed to determine the optimal levels of the objectives. Finally, various approaches are employed to validate the effectiveness of the proposed model and the utilization of PtG storage technology.

Keywords: power-to-gas technology, Independent electrical system, technical and economic objectives, Particle swarm optimization algorithm

Nomenclature

t, T	Time, Hour
n, N	Index of diesel generator (DGs)
bdg, BDG	Index of backup diesel generator (BDG)
A, B, X	DGs' cost factor, \$/MW
Λ_{su}	Setting up the cost of BDG, \$
A_C	PV area, m^2
I_s	Solar irradiance, kW/m^2
C_p	WT power factor, MW
A	WT rotor area, m^2
V_r	Wind speed, m/s
D_e, D_{UM}	Total demand and unmet demand, MW
P_{PV}, P_{WT}	Power of PV and WT, MW
P_n, P_{BDG}	Power of DGs and BDG, MW
P_{PtG}^{in}	Power to PtG, MW
G_{PtG}^{out}	Gas of PtG, m^3
η_{el}, η_{mta},	The electrolyzer and methanization efficiency, %

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1 Introduction

1.1 Aims and literature review

Recently, high energy consumption is becoming a significant issue in many countries for using different technologies like storage systems, smart grids, and distributed energy resources (DERs) for optimal energy generation (Han and Yu 2023). However, current electrical distribution networks are converting to modern electrical systems with improvement invasion of the mentioned technologies (Mitova et al. 2022). The application of these technologies can vary based on the structure of the energy system (Elhassan 2023). For instance, the off-grid electrical distribution systems (OGEDSs) are one of the opportune networks to operate these technologies. Due to a flaw in primary energy providers like power plants, OGEDSs exhibit reduced reliability in meeting supply demands. Hence, storage systems such as power-to-gas (PtG) technology are utilized as one effective and high-efficiency gas storage system (Gorla et al. 2020). Using PtG technology, the electrical energy is converted to natural gas. Stored gas is injected into generators for energy generation to meet peak demand (Norouzi and Bozorgian 2023). The storage systems are used according to the geographic location of the places, such as the efficiency of the storage configuration, the capacity of the storage systems, the topology of the energy system, and the time of the stored energy (Norouzi and Fani 2022). OGEDSs are the most appropriate energy systems for the PtG storage systems installation with integration into the smart

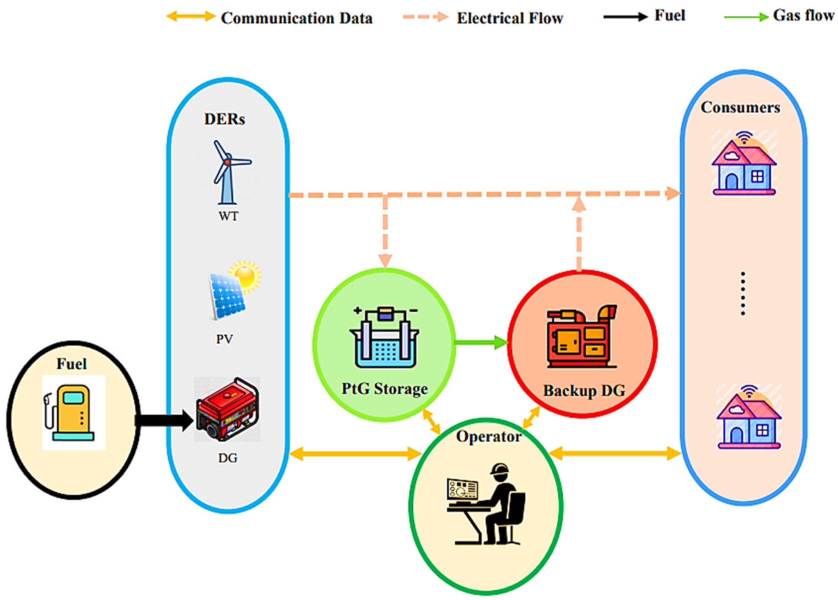

Figure 1: Overview of the proposed OGEDS (this image is drawn by authors).

grid technology (Ajam et al. 2022). In Figure 1, the proposed OGEDS is shown that consists of operators, consumers, DERs, PtG storage system, and backup diesel generator (BDG). The DERs can be classified as photovoltaic (PV) panels, diesel generators (DGs), and wind turbines (WTs).

The operator has a coordinator role between consumers and the energy generation side for implementing optimal energy balance via communications data flow. Figure 2 illustrates the PtG system, which utilizes electrical generation from DERs to power the electrolyzer as the primary energy source. The initial step involves the production of hydrogen (H_2) by combining water (H_2O). The generated hydrogen is then stored in a dedicated tank. During the subsequent mechanization process, the stored H_2 is amalgamated with carbon dioxide (CO_2) (Schiebahn et al. 2015; Sterner and Specht 2021). In conclusion, the production of H_2O and methane gas (CH_4) is achieved. The CH_4, known for its flammability, is utilized in BDG for the purpose of generating electricity during crucial periods. Over the course of many years, nations have shown a keen interest in the harmonious integration of energy systems, leading to the initiation of numerous projects aimed at overcoming obstacles in the realm of synergistic ideal energy carriers.

Many scholars have used and expanded on this paradigm in modelling, optimization, and implementation. These systems confront significant challenges ranging from production to consumption. Concerns over fossil fuel usage and technical indices have grown in recent years. Their usage is not logical because of their low efficiency, shortage of fossil fuels, and environmental impacts (Pourghasem et al. 2019; Ullah H. et al. 2024). As the globe strives to create a clean environment, renewable energy resource utilization has grown dramatically.

Optimum performance is a management problem in energy system operation that can optimally satisfy all energy demand types by integrating renewable energy resources with existing power plants and off-grid modes.

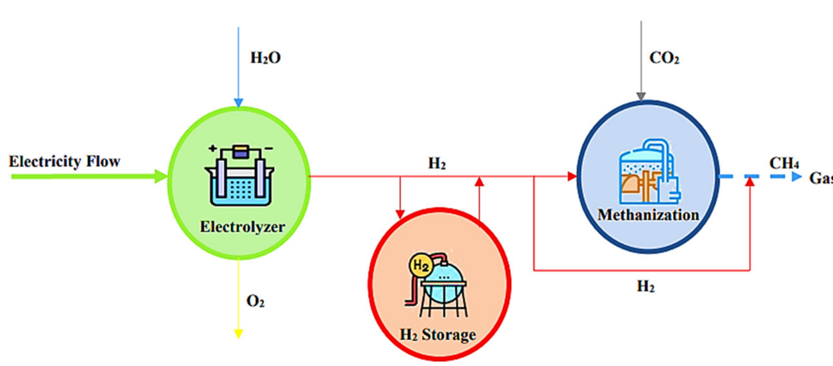

Figure 2: PtG storage system (Schiebahn et al. 2015; Sterner and Specht, 2021).

For example, in the study by Lak Kamari et al. (2020), energy scheduling and planning DERs by optimal sizing and installation in an OGEDS are studied by HOMER software. In this study, cost of energy and emission pollution are minimized. In the study by Das et al. (2017), environmental optimization of the OGEDS is done with capacity's design of the energy resources in off and connected types. The hydrogen storages are installed in the OGEDS for life-cycle modelling based on load demand supplying in peak demand and economic objectives (Mehrjerdi and Hemmati 2019). Vahedipour-Dahraie et al. (2020) proposed energy configuration of the DERs and electric vehicle stations considering various geographical locations for reducing energy generation costs in power plants. The optimal energy planning risk management is proposed by Vahedipour-Dahraie et al. (2019) for the economic generation of battery storage and DERs. The energy dispatch considering PtG technology and economic suitability was presented by Gahleitner (2013) for minimizing the carbon emissions generation of the energy system in the connected mode. Zhang et al. (2015) considered the role of electric vehicles with uncertainties by a robust optimization model for managing risk and energy generation costs. Chaichan et al. (2022) employed a Peer-to-Peer approach with energy generation from the energy market to stimulate OGEDS in demand load scheduling using demand side management programs.

1.2 Novelties and contributions

This study proposes energy optimization based on economic and technical objectives in OGEDS. The modelling optimization is implemented by a multicriteria problem, such as minimizing the fuel's cost of the DGs on the generation side and maximizing the reliability system for supply-demand on the consumers' side. The PtG is used as the energy storage system for supply demand in critical operation times. In this technology, the gas stored in the PtG configuration is injected into the BDG for operation in peak demand and optimal participation in energy generation. The use of a particle swarm optimization algorithm (PSOA) is suggested for the optimization of energy. Also, the weight sum approach is used to determine the optimal solution for multicriteria problems in the frontier solutions of objectives. Therefore, contributions and novelties are summarized as follows:

- Energy optimization of OGEDS with economic and technical objectives is proposed.
- A multicriteria problem for economic and technical objectives is modelled.
- The PtG technology is considered the gas storage system in OGEDS.
- The gas stored in the PtG unit is applied to the BDG unit for energy generation in critical times.
- The proposed energy optimization is solved by PSOA.
- The optimal compromise solution of frontier solutions is achieved by the weight sum approach.

2 Methodology

In this section, mathematical formulation of the OGEDS based on Figure 1 is modelled as follows.

2.1 DERs mathematical formulation

DERs consist of the PV system, WT, and DGs. DERs are modelled as follows.

2.1.1 PV modelling

The power obtained by PV is modelled subject to solar irradiance rate each time (Tazvinga et al. 2014, 2015):

$$P_{\mathrm{PV}}(t) = \eta_{\mathrm{PV}} \times A_{\mathrm{C}} \times I_{\mathrm{s}}(t). \tag{1}$$

2.1.2 WT modelling

Also, the generated power by WT is dependent on the speed of the wind at each time (Tazvinga et al. 2014, 2015):

$$P_{\mathrm{WT}}(t) = \frac{1}{2} \times \eta_t \times C_{\mathrm{p}} \times A \times V_{\mathrm{r}}^3(t). \tag{2}$$

2.1.3 DG modelling

DGs are modelled with attention to supplying fuels to DGs for power generation. The fuels have costs and are modelled as quadratic polynomial function as follows:

$$C_{\mathrm{DG}}(t,N) = \sum_{t=1}^{T}\left\{\sum_{n=1}^{N} AP_n^2(t,N) + BP_n(t,N) + X\right\} \quad \forall t, N. \tag{3}$$

2.2 PtG storage modelling

As mentioned earlier, the gas stored in PtG technology is injected into BDG for power generation in critical times.

The PtG storage system is formulated as follows (Zeng et al. 2019):

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

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

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

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

Equations (4) and (5) define the maximum amount of electrical energy that can be injected and the maximum output gas amount in the PtG unit. These equations incorporate the binary variable uPtG, which indicates that the output gas and injected power cannot be concurrently utilized. Furthermore, equations (6) and (7) represent the injected gas quantity into the BDG unit and the corresponding consumed gas cost, respectively.

2.3 Multicriteria problem modelling

The formulation of multicriteria problems involves the utilization of objective functions, which include 1) the minimization of fuel costs consumed by DGs and BDG and 2) the maximization of system reliability for supply–demand on the consumers' side. The formulation of multicriteria problems can be expressed in the following manner.

2.3.1 First problem

The first problem involves modelling the minimization of fuel costs consumed by DGs and BDG.

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

The DGs and BDG consumed fuels costs are represented by equations (3) and (7), respectively, where C_{DG} and C_{BDG} denote these costs.

2.3.2 Second problem

The maximizing system reliability for supplying demand on the consumer's side is considered the second problem. This problem is modelled based on the unmet demand by the generation side.

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

Lead to:

$$0 \le D_{\mathrm{UM}}(t) \le D_{\mathrm{e}}(t) \times u_{\mathrm{UM}}(t) \quad \forall t, \tag{10}$$

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

The unmet demand limit is modelled by (10), and the unmet demand status is given by (11).

2.4 Limitations modelling of OGEDS

$$\begin{aligned} &\sum_{n}^{N} P_n(t, N) + \sum_{\mathrm{bdg}=1}^{\mathrm{BDG}} P_{\mathrm{BDG}}(t, \mathrm{bdg}) + P_{\mathrm{PV}}(t) \\ &+ P_{\mathrm{WT}}(t) - P_{\mathrm{PtG}}^{\mathrm{in}}(t) = D_{\mathrm{e}}(t) - D_{\mathrm{UM}}(t) \quad \forall t, \end{aligned} \tag{12}$$

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

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

The limitation (12) is a balance between the demand and generation sides. The capacities of DGs and BDG are limited by (13) and (14), respectively.

3 Solution methodology

The PSOA is an optimization method for stochastic search. This algorithm is taken from the social conduct of fish, birds, and bees. In this method, a particle set will be established as groups. For formulation, PSOA, two variables v and x are named particle position and particle velocity, respectively. The most desired particle location is guided by merit in the objective function utilizing p_best, and the particle's best location in the whole group is as g_best. For assurance of PSOA convergence, a coefficient called contraction coefficient is necessary for better adjusting of PSOA parameters. Therefore, the velocity and position of the particle based on the contraction coefficient can be written as follows (Baghaee et al. 2017):

$$\begin{aligned} v_{d+1} = \alpha(&w \times v_d + \varphi_1 \times \mathrm{rand}(p\_\mathrm{best} - x_d) \\ &+ \varphi_2 \times \mathrm{rand}(g\_\mathrm{best} - x_d)), \end{aligned} \tag{15}$$

$$x_{d+1} = x_d + v_{d+1}, \tag{16}$$

where d is the repetition counter, x_d is the particle position in repetition, x_{d+1} is the position of the particle in v_d repetition, and $d + 1$ is particle velocity in d repetition. The w is inertia weight, and ϕ_1 and ϕ_2 are the coefficients of acceleration for every single particle. Rand is a generator that produces random numbers exhibiting a consistent distribution within the [0, 1] range. α shows a function based on ϕ_1 and ϕ_2 for more convergence of the PSOA. The suitable choice of w has caused balance in local and global search space. Generally, w for a better and optimized function of an algorithm will dynamically change:

$$w = w_{\max} - \frac{w_{\max} - w_{\min}}{\text{iter}_{\max}} \times \text{iter}, \tag{17}$$

where iter shows the current iteration. For decreasing the steps of the search, velocity of the particle will be limited by the $v_{\max}$ value:

$$v \in [-v_{\max} v_{\max}]. \tag{18}$$

Here, $v_{\max}$ will improve the local search and the $v_{\max}$ will be justified for each decision variable between 10% and 20% of the variable range.

3.1 Decision-making method

As this study focuses on optimizing multicriteria problems simultaneously, it leads to the identification of cutting-edge solutions. Consequently, the operator, for making decisions, must determine the optimal compromise solution for multicriteria problems within these frontier solutions. By utilizing equation (19) for normalization and equation (20) to determine the ξ^k maximum rate, the optimal middle-ground solution is obtained (Mazzeo et al. 2018) as follows:

$$\xi_i^k = \begin{cases} 1 & f_i^k \le f_i^l \\ \dfrac{f_i^u - f_i^k}{f_i^u - f_i^l} & f_i^l \le f_i^k \le f_i^u, \\ 0 & f_i^k \ge f_i^u \end{cases} \tag{19}$$

$$\zeta^k = \frac{\sum_{i=1}^{I} \omega_i \cdot \zeta_i^k}{\sum_{k=1}^{K} \sum_{i=1}^{I} \omega_i \cdot \zeta_i^k}. \tag{20}$$

Subject to:

$$\sum_{i=1}^{I} \omega_i = 1 \quad \omega_i \ge 0, \tag{21}$$

where f_i^u and f_i^l represent the maximum and minimum values of the ith objective, respectively. In addition, f_i^k, ξ_i^k, and ω_i denote the values of the ith objective in the kth solution, the value of the solution in the ith objective, and the weight value in the ith objective, respectively. In this approach, the operator must choose an optimal compromise solution using the weighted sum method in equation (20), taking into account the priority of objectives.

4 Case mode study

To demonstrate the performance of the suggested optimization approach in OGEDS, we consider two cases for investigation based on numerical modelling on the 21-node test system (Chamandoust et al. 2022), which is shown in Figure 3. The case mode investigations are implemented as follows:

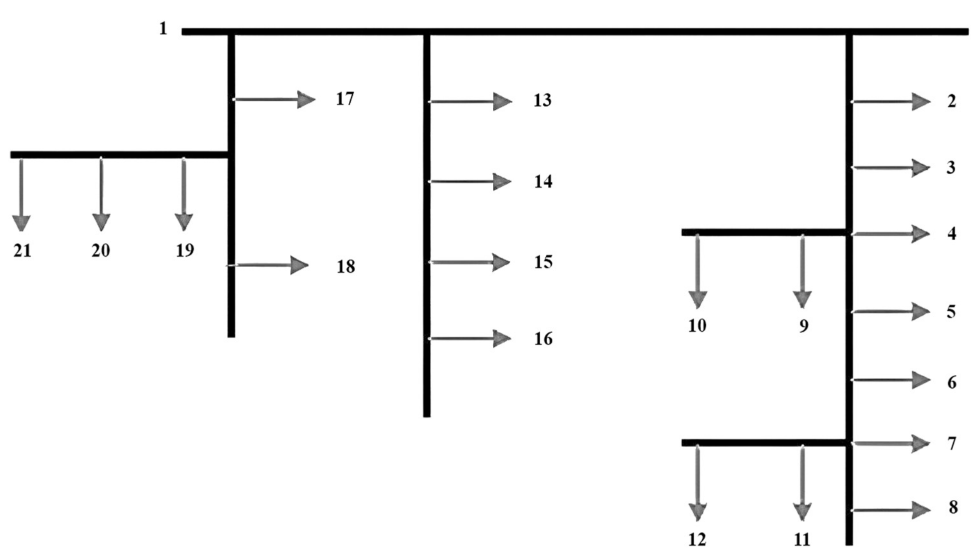

Figure 3: 21-node test system as OGEDS (Chamandoust et al. 2022).

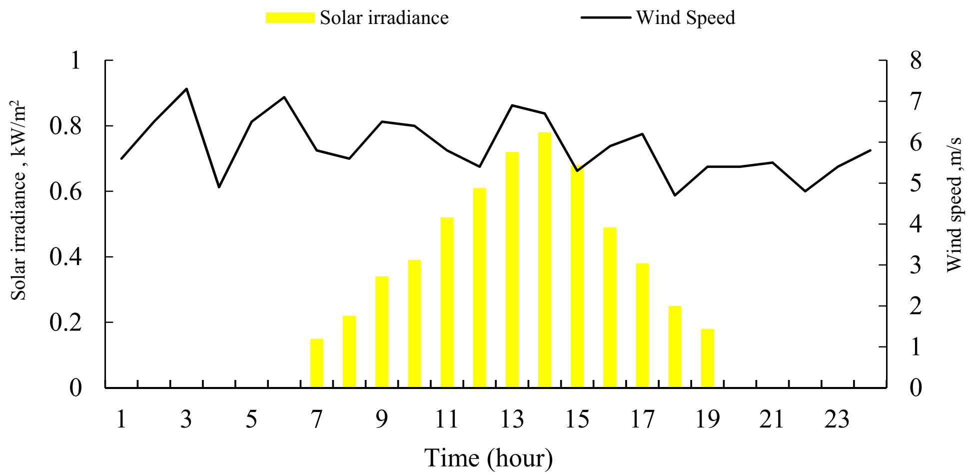

Figure 4: Forecast of the wind speed and solar irradiance (this image is drawn by authors).

First case study: Energy optimization of the OGEDS without considering PtG storage technology.

Second case study: Energy optimization of the OGEDS considering PtG storage technology.

The energy optimization process in OGEDS is conducted with a 24-h forecast, taking into account the predicted wind speed and solar irradiance for power generation through WT and PV systems. Because of the uncertain nature of speed of the wind and solar irradiance, we have employed the Monte Carlo simulation method for generating random variables for these factors. The prediction of solar irradiance and wind speed relies on the utilization of the Beta and Weibull probability density functions, respectively. Consequently, Figure 4 illustrates the representation of wind speed and solar irradiance. Furthermore, references (Tazvinga 2014, 2015) serve as the source for obtaining the date of WT and PV. Figure 5 showcases the load demand of consumers in the OGEDS. The data pertaining to the PtG storage system can be found in Table 1. The efficiency, fuel cost, and maximum capacity of the BDG are considered by %95, 250$/MW, and 0.25 MW, respectively. In Table 2, DG information is given.

4.1 Discussion and results

The results of the first and second case studies are analyzed in this section. Also, a discussion of cases' results shows the PtG storage system's superiority. Optimizing the multicriteria problems by PSOA is done, and the optimal compromise solution in the solutions is determined by the weight sum method. In Figures 6 and 7, frontier solutions and optimal compromise solutions of the

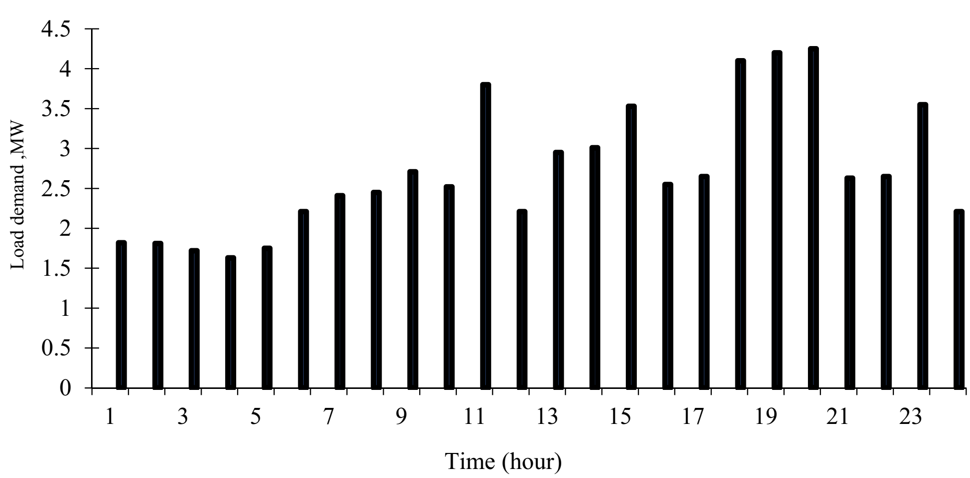

Figure 5: Load demand of consumers (this image is drawn by authors).

Table 1: Data of PtG

Parameters	Value
η^{el}	85%
η^{mta}	80%
$P_{PtG}^{in,max}$	0.35 MW
$G_{PtG}^{out,max}$	300 m^3

Table 2: DG-related data

Parameters	*A* ($/MW^2)	*B* ($/MW)	*X* ($)	P^{max} (MW)
DG 1	98.2	86.2	128.8	0.95
DG 2	93.2	75.6	123.5	0.95
DG 3	90.4	73.3	120.7	1

multicriteria problems for the first and second case studies are obtained, respectively. In these figures, fuel cost is taken into account as the first problem (f_1) and the reliability of OGEDS (f_2) is considered the second problem. The amounts of the first and second problems in the optimum compromise solution related to the first case study in Figure 5 are equal to $96803.4 and 77.4%, respectively. The fuel costs of the DGs 1, 2, and 3 in the first case are obtained by $34523.2, $31547.4, and $30734.8, respectively. On the other side, the values of the fuel costs and reliability for the second case study in Figure 6 are $88347.4 and 81.4%, respectively. In the second case, the outputs reveal that the PtG storage system plays a significant role. It sequels to a decrement of 8.74% in fuel costs and an improvement of 4% in reliability when compared to the initial case study. With the participation of the PtG storage

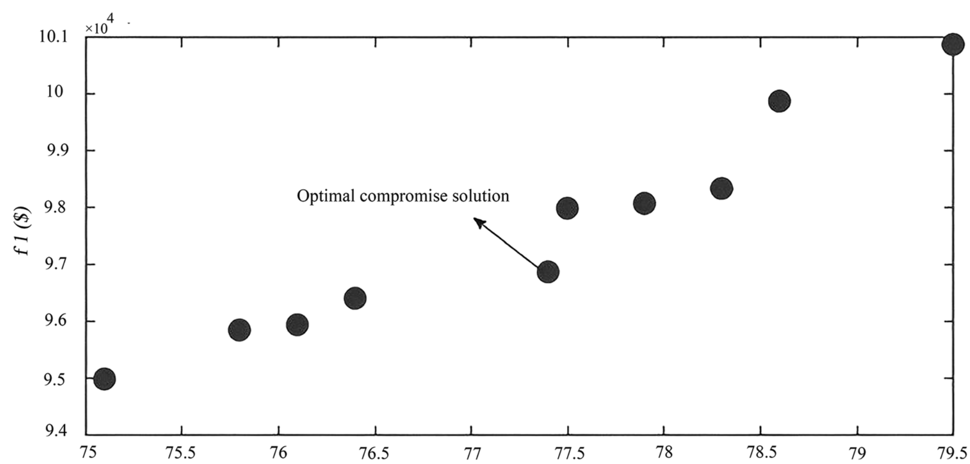

Figure 6: Frontier solutions in the first case (this image is drawn by authors).

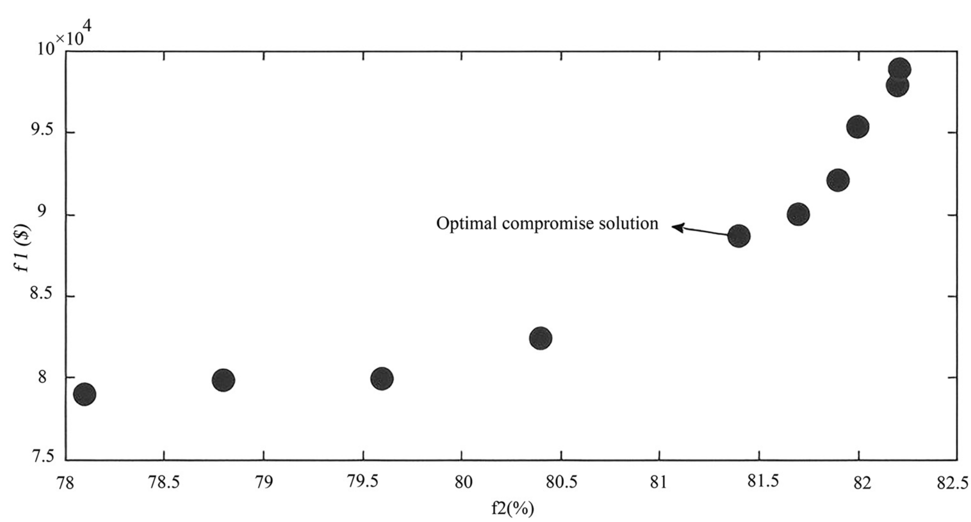

Figure 7: Frontier solutions in the second case (this image is drawn by authors).

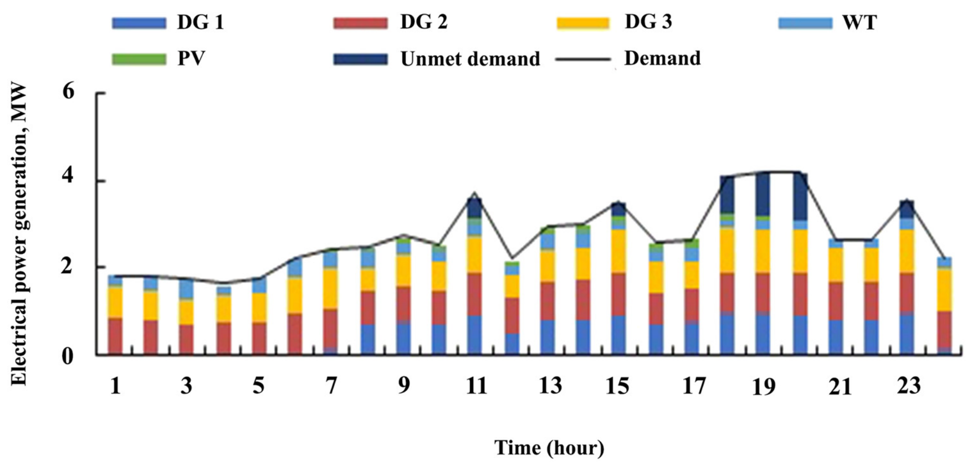

Figure 8: Power generation in the first case (this image is drawn by authors).

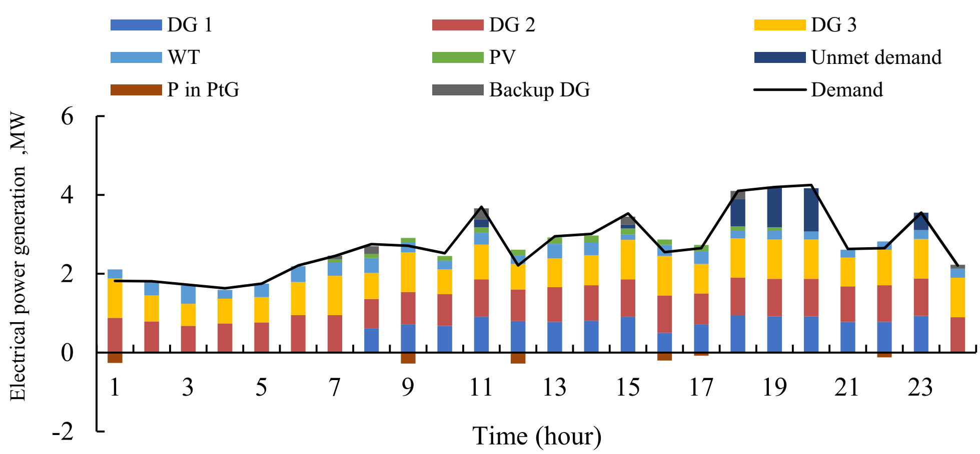

Figure 9: The generation of power in the second case (this image is drawn by authors).

configuration and the low fuel cost of the BDG in the second case, DGs' cost is reduced. Also, the performance of the PtG and BDG sequels to increments in capacity generation of OGEDS to meet demand, whereby reliability is improved.

Figure 8 illustrates the power generated in the initial case study. In this particular scenario, DGs 2 and 3 efficiently meet the supply-demand requirements at all hours with lower fuel costs compared to DG 1. However, due to the limited power generation capacity of DERs, there are instances where the demand cannot be fully met. Specifically, at times of 11, 15, 18, 19, 20, and 23 h of the day, there is no fulfilled demand. In the first case, a total of 4.3 MW of demand remains unfulfilled by DERs, with the highest value of unmet demand reaching 1.14 MW at hour 20. However, the second case study illustrates the power generation achieved by DERs and BDG, as depicted in Figure 9. In this case, the BDG is supplied with energy from the PtG storage system during critical hours to fulfil the demand. The WT and PV systems contribute to the PtG system's power generation at specific hours, namely, 1, 9, 12, 16, 17, and 22. On the other hand, the BDG operates and generates power during hours 7, 8, 11, 15, 18, and 24. The cumulative power generation achieved by the BDG amounts to 1.07 MW, resulting in a 20.8% reduction in unmet demand compared to the first case study. Furthermore, the utilization of the BDG enables a decrease in power generation by DG1, which is associated with high fuel costs.

The factors contribute to minimizing fuel costs and maximizing reliability index with participation of the PtG system are as follows:
1) The reason for minimizing fuel costs in the second case study is lack of the operation cost of the PtG system.
2) The reason for maximizing reliability index in the second case study is an increase in generation capacity in the generation side.

5 Conclusion

The presented article presents the technical and economic optimization of the OGEDS using PtG storage technology. The main focus is on addressing the multicriteria problem, specifically the cost and reliability of fuel, as the primary economic and technical objectives. The proposed approach utilizes PSOA optimization and the weight sum method to obtain an optimal compromise solution. Two case studies are conducted to demonstrate the superiority of this approach. The results indicate that incorporating the PtG storage system for feed BDG leads to an increase in capacity generation with optimal fuel cost in the OGEDS. Furthermore, the proposed approach achieves optimal values for both economic and technical objectives compared to the first case study.

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Data availability statement: Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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