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Optimal sizing of hybrid WT/PV/diesel generator/battery system using MINLP method for a region in Kerman

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Abstract. Renewable resources have drawn attention because of their role in reducing pollution and improving technical issues. It is notable that simultaneous use of several resources in the form of hybrid systems requires studying many different aspects involved. One of the most important issues of hybrid systems is system optimality. Therefore, the most effective approach is to combine components to minimize the cost. Different approaches have been proposed for determining the size of hybrid system components to optimize the proposed system. These methods are classified into three categories: classic, artificial intelligence, and computer program methods. In this paper, the optimal size of components was obtained using Mixed Integer Nonlinear Programming (MINLP) method. Outputs of this algorithm were compared with two other algorithms and the advantage of this method was demonstrated. This paper achieved better responses in a shorter amount of time.

1. Introduction

Rapid development of today's world comes with growing energy consumption every day. Energy is consumed in different areas including transportation, heating, electricity generation, etc. Electricity is mainly generated using fossil fuels. Alarmed by growing fuel costs and emission of greenhouse gases, governments are seeking novel methods to generate electricity. Renewable resources like solar, wind, geothermal, waves, and biomass energies have long been studied in order to investigate possible alternatives to fossil fuels. These resources are free and cause no pollution. Among such resources, solar panels and wind turbines have enjoyed long-standing popularity and their advantages are quite clear [1,2]. Power generation using renewable resources is employed in the distributed form on the consumer load side and in the centralized form on the distribution network and sub-transmission side. Since the presence of renewable resources like sun and wind is variable and their presence is not guaranteed at all times, different other energy generation resources are employed for energy generation. To this end, the concept of hybrid renewable energy resource has been put forward which involves using several resources that generate energy together [3–5]. Since the constant presence of renewable resources cannot be guaranteed, some tools such as a battery, superconductor magnetic energy storage, flywheel, hydroelectric pump, compressed air, and hydrogen generator are employed in these systems to store energy [6,7]. Moreover, in order to maximize reliability and reduce costs, an energy generation resource is used as backup in most hybrid systems. This resource can be a diesel generator or another resource that operates with fuel.

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In all existing systems, economic concerns come to fore. Each energy generation system requires an input energy resource like wind, sun, biomass, biogas, etc. Therefore, using renewable system requires investigating environmental conditions. Following the study of the geography of each region, suitable energy generation systems for that region are selected. After selecting a suitable resource, it should be determined how to combine these resources to obtain cost-effective energy generation [8]. Determining the size of hybrid system components for optimal energy generation has drawn much attention in recent years and many methods have been proposed to obtain an optimal combination of components. Artificial intelligence, multiple-objective design, iteration-based methods, analytic methods, probabilistic methods, etc. are a few examples that have been proposed for determining the size of energy generation system components [9].

In [10], a graphical-numerical method was proposed to determine the optimal size of a hybrid system including photovoltaic, battery, and diesel generator for different regions; then, artificial intelligence was used to obtain optimal values without using different geographical regions. In [11], size of components of a hybrid system including photovoltaic, wind, and battery was optimized using a triple objective function for minimizing cost, emission of pollutant gases, and uncertainty. To this end, Abes et al. [12] also used a triple-objective function for reducing cost and pollutants without providing consumption optimization using the Genetic Algorithm (GA) on a system including wind, photovoltaic, and battery. In [13], an iterative-based method was employed for a system comprising Photo Voltaic (PV), battery, and microturbine as the backup. By using different values for the combination of battery and solar panels and calculating the cost, the best combination was obtained. In [14], optimization was performed for a system comprising PV, battery, and biomass considering access to biomass and weather conditions using Mixed Integer Nonlinear Programming (MINLP) method. In [2], an innovative method was proposed for a system comprising wind turbine, solar panel, battery, and diesel generator as backup. In this paper, a mathematical formula is defined for each component and cost function is obtained. Then, Discrete Harmony Search (DHS) with optimal iteration is obtained. The advantage of this method is that it is not trapped in local optimums and gives the most optimum point because of its different parameters.

Particle Swarm Optimization (PSO) is one of the optimization methods that has been widely used for optimizing renewable hybrid systems [15–18]. This algorithm has good features like feasibility, flexibility, and simplicity; however, it is not efficient for systems with more than three components. Another problem with this algorithm is achieving a local optimum response [19]. Another method used for optimizing hybrid systems is Simulated Annealing (SA) [20–22]. SA is a general probabilistic method that can be properly applied to general optimization, but it cannot outperform other methods in terms of accuracy [18]. Another method widely used to determine the optimal size of renewable hybrid systems is GA [23–26]. The shortcoming of this method is the large number of iterations that increases the time required to obtain a solution [19]. Moreover, since a large number of solutions are investigated at each iteration, calculation time is also increased [27]. Another optimization method is Discrete Harmony Search (DHS) [5]. This method gives an absolute optimal solution, but in complicated problems, calculation time increases and convergence decreases [28]. In [29], differential evolution was used for optimizing hybrid systems. This method only gives a correct response at a high speed rate if a boundary is determined for solutions, and the closer the initial value to the optimal solution is, the better the response will be. Other methods have also been proposed for optimizing renewable hybrid systems that give good solutions for a specific target. In [30], training and learning-based optimization was proposed, which is an important factor in optimizing the oscillating behavior of solar irradiation and wind speed. For complex systems, [31] proposed modified electric system cascade analysis, which would give good responses. In addition to these methods, there is a software product that can determine the optimal size of components. One of these widely used software products is HOMER [32–35] and it is characterized by more accurate responses and, yet, longer computation time than other algorithms like PSO or GA [36]; moreover, it does not eliminate excess energy generated from renewable systems; thus, a method that can provide a more optimal response can be proposed [37]. In [38], some of these methods and some other new methods were presented.

In this study, a hybrid system comprising PV/wind/battery and the diesel generator is used for determining the optimal size of the component. Although using diesel generator causes some pollution, it increases system reliability; moreover, using a battery is more cost effective than diesel generator without battery and it shortens the operation time of diesel generator. Therefore, a hybrid system comprising solar panel/wind turbine/battery/diesel generator as a backup is more cost effective, causes less pollution, and increases reliability [39–41]. In different studies, the methods proposed to determine the optimal size of components give approximate results and do not obtain accurate results. In this study, the optimization problem is performed using GAMS after presenting an accurate mathematical model of each component and formulating economic problems. As its advantage, this method achieves an accurate and certain solution. This method is used for different combinations and results are investigated. Section 2 proposes a mathematical model of renewable resources and mathematical formulation of optimization. Section 3 presents the applicability of GAMS for modeling under different conditions and gives the results. Finally, the paper is concluded.

2. Introducing system components and problem formulation

In this section, the model of all system components is described and then, modeling is presented.

2.1. Modelling components of solar system

Generation of solar cell depends on different factors like solar irradiation, irradiation angle, environment temperature, and cleanliness of solar panels. In this study, it is assumed that solar system has maximum power point tracking and suitable maintenance is considered. Moreover, the effect of temperature on output power of PVs can be ignored, according to [42], because the effect of it is less than 0.5%. Therefore, the output power of each panel can be calculated using the following equation:

$$p_{PV} = A.I.\eta_{PV}. \tag{1}$$

In Eq. (1), A denotes panel area in m^2, I solar irradiation in $\mathrm{kW/m}^2$, and η_{pv} total efficiency including efficiency of solar panel and converter. If it is assumed that the number of solar panels is N_{PV}, the power generated by solar system is $P_{PV} = N_{PV}.p_{PV}$.

2.2. Modelling wind turbine

For a wind turbine, if wind speed is greater than the initial value of generator, turbine starts operating and when wind speed reaches a nominal value, generator's generation becomes constant and when wind speed reaches the threshold value, the turbine stops to preserve the generator. If the power generated by each generator is p_{WT}, the following relations can be used to obtain power.

$$p_{WT} = \begin{cases} 0 & v \leq v_{cut-in}\,,\; v \geq v_{cut-out} \\ P_r \frac{v(t)-v_{cut-in}}{v_r - v_{cut-in}} & v_{cut-in} < v < v_r \\ P_r & v_r \leq v < v_{cut-out} \end{cases} \tag{2}$$

In Eq. (2), v_{cut-in} and $v_{cut-out}$ are starting and ending speed thresholds, V_r is wind turbine nominal speed, and P_r is wind turbine nominal power. If the number of wind turbines is N_{WT}, the total power of the wind system is $P_{WT} = N_{WT}.p_{WT}$.

2.3. Modeling diesel generator

Diesel generator is used as backup; when the generated power is low and stored energy reaches minimum allowed value, diesel starts operating and supplying much demanded energy. Fuel consumption of diesel generator depends on output power of diesel generator, which is determined using the following equation. This equation is a linear equation for diesel generator, which was introduced in [43]:

$$Cons_D = B_D.P_N^D + A_D.P_D. \tag{3}$$

In this equation, $Cons_D$ is diesel fuel consumption; P_N^D and P_D are nominal power and generator output, respectively; B_D and A_D are fuel consumption coefficients calculated using the consumption curve. Therefore, fuel consumption cost is obtained as follows:

$$C_f = P_{Fuel}.Cons_D, \tag{4}$$

where P_{Fuel} is fuel consumption cost.

2.4. Modeling battery

In renewable systems with wind and solar resources, since wind and solar energy resources vary randomly, battery is also used to store excess energy and compensate energy shortage, when necessary.

Battery charging state can be obtained as follows: if the total output power is greater than PV system and wind turbine, excess generated energy is stored in the battery.

$$E_{Batt}(t) = X(t).\Big[E_{Batt}(t-1).(1-\sigma) + \Big[(E_{PV}(t) + E_{WT}(t)) - \frac{E_{Load}(t)}{\eta_{Inv}}\Big].\eta_{Batt}\Big]. \tag{5}$$

In this equation, $E_{Batt}(t)$ and $E_{Batt}(t-1)$ are battery charges at t and $t-1$. σ is battery discharge rate in each hour, E_{Load} is load value, and η_{Batt} and η_{Inv} are efficiency rates of battery and inverter. $X(t)$ is the binary coefficient (0 or 1) for determining the charge condition.

Moreover, if the power generated by PV and wind resource is lower than consumption, energy stored in battery can compensate energy shortage. The following equation shows battery energy at time t in the discharging mode. $Y(t)$ is a binary coefficient (0 or 1) for determining discharge condition.

$$E_{Batt}(t) = Y(t).\Big[E_{Batt}(t-1).(1-\sigma) - \Big[\frac{E_{Load}(t)}{\eta_{Inv}} - (E_{PV}(t) + E_{WT}(t))\Big]/\eta_{Batt}\Big]. \tag{6}$$

In the discharging mode, battery discharging efficiency is considered 1. Moreover, for preventing overlapping between charge and discharge conditions, Eq. (7) is used:

$$X(t) + Y(t) \leq 1. \tag{7}$$

2.5. Modeling cost

Cost function for optimal design is to minimize annual cost (C_T). Annual cost includes annual investment costs (C_{Cpt}), annual maintenance cost (C_{Mtn}), and annual fuel consumption of diesel generator (C_{Fuel}). In order to design an optimal hybrid system, the optimization problem should be solved through optimization techniques using Eq. (8):

$$\text{Minimize} \quad C_T = C_{Cpt} + C_{Mtn} + C_{Fuel}. \tag{8}$$

Maintenance costs develop throughout the year, but investment cost is consumed at the beginning of the project. Therefore, investment cost is converted to annual cost using investment cost correction factor.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}, \tag{9}$$

in this equation, i is the profit rate and n is exploitation period.

In PV/wind/battery system, lifetime is considered to be 5 years. Using current single-payment value, we have:

$$C_{Batt} = P_{Batt}.\left(1 + \frac{1}{(1+i)^5} + \frac{1}{(1+i)^{10}} + \frac{1}{(1+i)^{15}}\right). \tag{10}$$

C_{Batt} is current value of the battery and P_{Batt} is battery price.

In this way, it is assumed that converter lifetime is 10 years and its current value is calculated as follows:

$$C_{Conv/Inv} = P_{Conv/Inv}.\left(1 + \frac{1}{(1+i)^{10}}\right). \tag{11}$$

$C_{Conv/Inv}$ is current value of the converter and $P_{Conv/Inv}$ is converter price. Annual investment cost and maintenance cost are obtained through Eqs. (11) and (12):

$$C_{Cpt} = \frac{i(1+i)^n}{(1+i)^n - 1}[N_{Wind}.C_{Wind} + N_{PV}.C_{PV} + N_{Batt}.C_{Batt} + N_{Conv/Inv}.C_{Conv/Inv} + C_{Diesel}], \tag{12}$$

where N_{Wind}, N_{PV}, N_{Batt}, and $N_{Conv/Inv}$ are the number of wind turbines, solar panels, battery, and converter, respectively; C_{Wind}, C_{PV}, C_{Batt}, and C_{Diesel} are price of wind turbine, solar panel, battery, and diesel generator, respectively:

$$C_{Mtn} = N_{Wind}.C_{Mtn-Wind} + N_{PV}.C_{Mtn-PV} + C_{Mtn-Diesel}. \tag{13}$$

$C_{Mtn-Wind}$ and C_{Mtn-PV} are the annual maintenance costs of each wind unit and $C_{Mtn-Diesel}$ is the hourly maintenance cost of the diesel generator. Maintenance of battery and converter is neglected.

2.6. Problem constraints

For a wind/solar/diesel/battery hybrid system, the following constraints should be satisfied:

$$N_{Wind} = Integer, \qquad 0 \le N_{Wind} \le N_{Wind}^{\text{Max}}, \tag{14}$$

$$N_{PV} = Integer, \qquad 0 \le N_{PV} \le N_{PV}^{\text{Max}}, \tag{15}$$

$$N_{Batt} = Integer, \qquad 0 \le N_{Batt} \le N_{Batt}^{\text{Max}}. \tag{16}$$

In these equations, N_{Wind}^{Max}, N_{PV}^{Max}, and N_{Batt}^{Max} are the maximum number of wind, solar, and battery units.

The minimum value announced by the manufacturer for diesel generator is 30% of its nominal power. Moreover, in the long operation mode, maximum suitable value is 90% of nominal power. Battery should also meet the allowed range ($E_{Batt}^{\min} \le E_{Batt}^{t} \le E_{Batt}^{\max}$)). Maximum charging value of the battery is obtained using its nominal value and minimum charging value is obtained using Depth of Discharge (DOD).

$$E_{Batt}^{\min} = (1 - DOD).S_{Batt}. \tag{17}$$

S_{Batt} is the nominal capacity of the battery.

2.7. Optimization algorithm and problem data

In order to optimize the described system, this paper has employed MINLP method in GAMS. In this method, generation and consumption at each hour are considered. Figure 1 shows wind speed and solar irradiation at each hour during a day in a region in Kerman (Rafsanjan city). Figure 2 shows required load in this region [5]. Table 1 shows parameters of system components that can be used to solve the problem. In order to calculate costs, exploitation lifetime is considered to be 20 years; all costs are modified for 20 years by defining cost correction factor Eq. (9). Using data of Figure 1, the power generated by wind turbines and solar panels are calculated. This data was created from 5 years data [5]. Then, the number of wind turbines, solar panels, and battery are considered

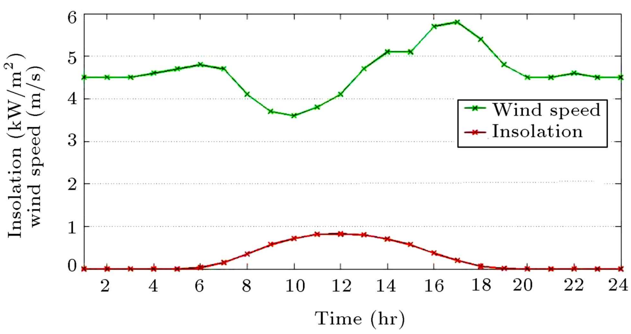

Figure 1. Wind speed (m/s) and solar irradiation (kW/m^2).

Table 1. Parameters of the system components.

Wind turbine	**Value**	**PV panel**	**Value**
P_r	1 kW	P_r	120 W
v_{cut-in}	2.5 m/s	C_{PV}	614$
$v_{cut-out}$	13 m/s	C_{Mnt-pv}	0$
v_r	11 m/s	A	1.07 m^2
C_{Wind}	3200$	Efficiency	12%
$C_{Mtn-Wind}$	100$	Life span	20 years
Life span	20 years		
Diesel generator	**Value**	**Battery**	**Value**
P_N^D	1.9 kW	Voltage	12 V
A_D	0.2461 l/kWh	S_{batt}	1.35 kWh
B_D	0.082 l/kWh	η_{Batt}	85%
C_{Diesel}	1713.15$	C_{batt}	130$
$C_{Mnt-Diesel}$	0.2$	DOD	0.8
Life span	8760 h	σ	0.0002
		Life span	5 years
Power converter	**Value**	**Economic parameter**	**Value**
Rated power	3 kW	i	5%
η_{Inv}	95%	n	20 years
C_{Conv}	2000$		
Life span	10 Years		

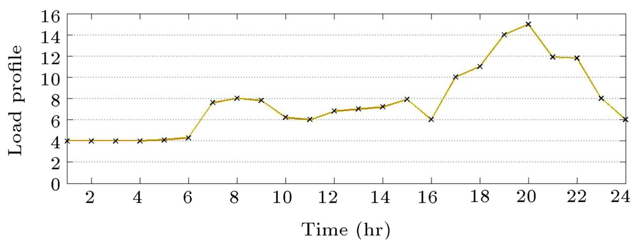

Figure 2. Load profile of the region (kW.h).

Table 2. Optimal values of hybrid system for different algorithms.

	MINLP	**DHS**	**DSA**
N_{WT}	31	37	36
N_{PV}	0	0	0
N_{Batt}	21	26	50
Total cost	13641.157$	15672.94	16036.8

as variables of the problem such that profile resources defined in Figure 2 are satisfied; this combination should be selected such that it would minimize cost.

3. Simulation and results

In this paper, simulations are performed using GAMS and results are compared with DHS (Discrete Harmony Search) and DSA (Discrete Simulated Annealing) methods. In fact, DSA is an optimization method that involves heating and controlled cooling of a material to increase the size of its crystals and reduce their defects; therefore, this method can be used to find an approximation of a global minimum for a function with a large number of variables. Besides, DHS is another optimization method that is inspired by the improvisation process of jazz musicians. It uses a stochastic random search instead of a gradient search so that derivative information is unnecessary. These two methods are recognized as metaheuristic methods. As can be seen in Table 2 which shows simulation results, the most optimal combination is obtained when solar panel does not exist. Outputs are obtained when there are 31 wind turbines, 21 batteries, 6 converters, and 1 diesel generator and annual cost is 13641.127$. According to Table 2, although evaluation of all the three methods has shown that using solar panel in this region is not cost effective, MINLP method gives better responses than the other two methods [5]. In another comparison, if solar panel is used, as can be seen in Table 3, total cost will be 15790.34$, which is more than previous case; other methods have also obtained similar results. In addition, if it is assumed that only diesel generator is used for supplying the load, calculations show that cost is increased to 64055/46$/year and increases pollution. The proposed method responds in 0.09 s and DHS responds in 0.5 s, indicating that the proposed method

Table 3. Optimal values for different algorithms in the presence of solar panel.

	MINLP	DHS	DSA
N_{WT}	29	35	31
N_{PV}	14	11	38
N_{Batt}	23	27	22
Total cost	15677.34$	15790.34$	15843.67$

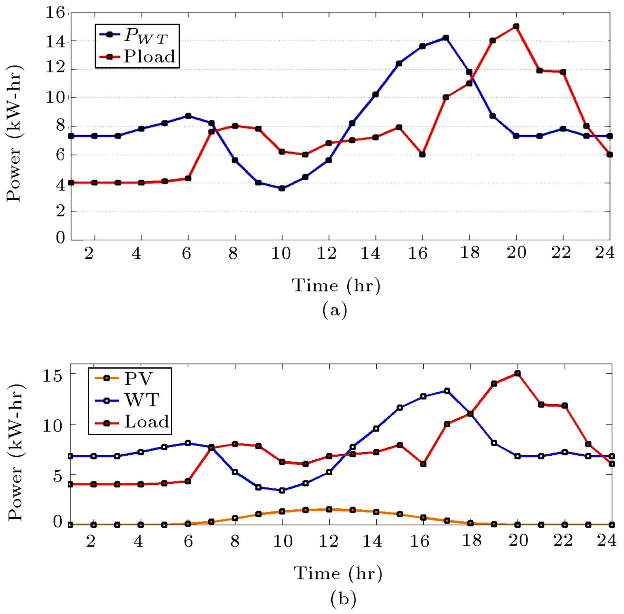

Figure 3. Power generated by resources and consumption load: (a) Wind turbine and (b) wind turbine and solar panel.

calculates the response in a shorter amount of time. Computation error of this method is 0.54%.

Generated power of each component in different cases is plotted in Figure 3. Figure 3(a) shows optimal case in which only wind turbine exists and Figure 3(b) shows the case in which both wind turbine and solar panel are used. In Figure 3, when the total power generated by wind turbine and solar panel is greater than consumption power, excess generation flows into the battery; in addition, when generated power is less than consumption power, power shortage is compensated by battery. Figure 4 shows battery energy for (a) wind-battery and (b) wind-solar-battery. It can be seen in Figure 4 that battery is not completely discharged; therefore, load is supplied continuously. In order to compare cost and share of each component in total cost, cost circular diagram is shown in Figure 5. Figure 5(a) shows the cost share of optimal case and Figure 5(b) shows cost share in the presence of solar panel.

4. Conclusion

In this paper, the optimal size of a hybrid system comprising wind turbine, solar panel, battery, and diesel

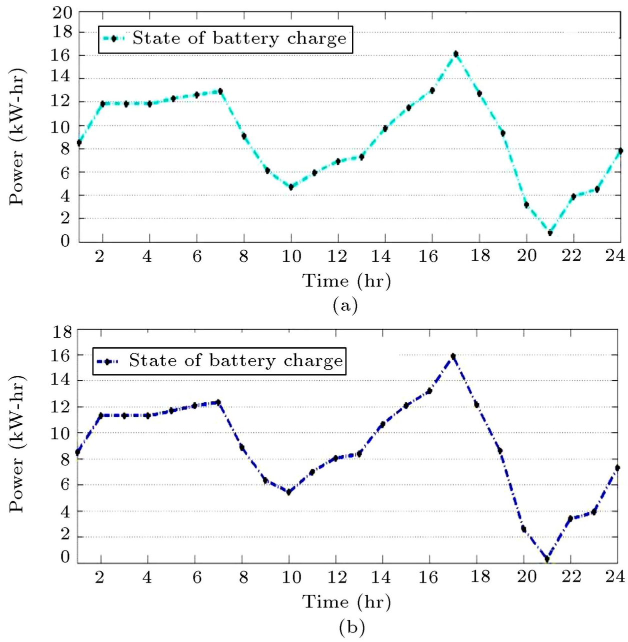

Figure 4. Battery charge level: (a) Wind turbine-battery, and (b) wind turbine-solar panel-battery.

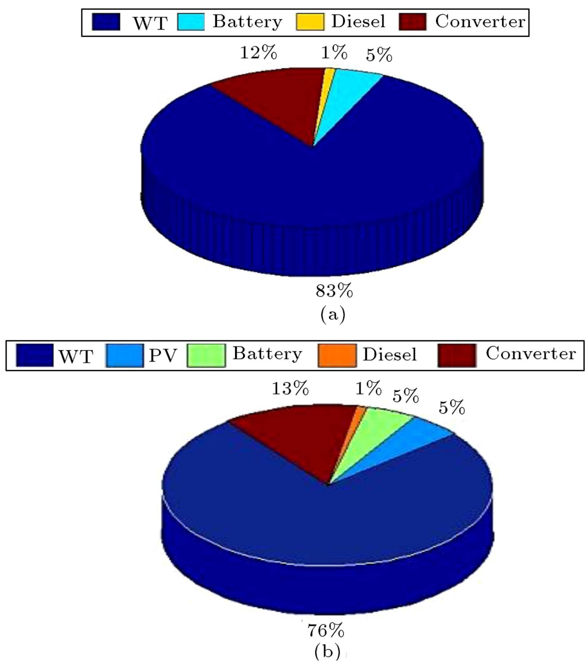

Figure 5. Cost of each component vs. total cost: (a) Wind turbine/battery and (b) wind turbine/solar panel/battery.

generator is determined using GAMS and Mixed Integer Nonlinear Programming (MINLP) method. Results showed that using renewable systems was cost effective and eliminated pollution. Moreover, this method was compared with Discrete Harmony Search (DHS) and Discrete Simulated Annealing (DSA). Results indicated that MINLP would show better and more reliable results than the other two methods. In addition, the results showed that using the solar panel in this region would not be cost effective and the best combination would include the wind turbine, battery, and diesel generator.

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