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TECHNO-ECONOMIC ANALYSIS AND OPTIMAL DESIGN OF AN OFF-GRID HYBRID PV/WIND/DIESEL SYSTEM WITH BATTERY STORAGE

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Abstract

Diesel power technology has been utilized worldwide, especially in remote regions, because of its low initial capital cost. But it has negative effects on the surrounding environment and causes global warming. Also the power supply of off-grid remote area and applications at minimal cost and with low emissions is an important issue when discussing future energy concepts. In Iran, the cost of fuel is highly subsidized. If Iran removes the fuel subsidy, the cost of diesel fuel would increase and the renewable energy systems would become more attractive.

This paper presents techno-economic analysis, modeling and optimization of a photovoltaic (PV)/wind/diesel/battery-based hybrid system for electrification to an off-grid remote area located in Rafsanjan, Iran, for different diesel generator fuel price scenarios. For this location, different hybrid (PV/wind/diesel/battery) systems are studied and compared in terms of cost and pollution for two scenarios. For cost analysis, a mathematical model is introduced for each system's component and then, in order to satisfy the load demand in the most cost-effective way, two discrete versions of particle swarm optimization algorithm are developed to optimally size the systems components. As an efficient search method, PSO has simple concept, is easy to implement, can escape local optima, by use of probabilistic mechanisms, and only needs one initial solution to start its search. Simulation results indicate that only under a subsidized diesel fuel price scenario, the diesel-only system has the minimum cost, but by the elimination of diesel fuel price subsidies and reduce the costs of photovoltaic panels and wind turbines, the role of the diesel generator decreases in hybrid (PV/wind/diesel/battery) energy systems.

Keywords: Hybrid PV-wind-diesel-battery system, Optimum sizing, Fuel prices, Economic evaluation.

1. Introduction

For remote systems, the hybrid energy systems have been considered as preferable. Such systems are usually equipped with diesel generators to meet the peak load demand during short periods, when there is a deficit of available energy. However, using diesel fuel is so expensive and increases the amount of carbon dioxide (CO_2) emitted. On the other hand, hybrid energy systems are best suited to reduce dependence on fossil fuel and without causing greenhouse gases using available wind speed and solar radiations. So, they can significantly contribute in decreasing the electricity generation cost in stand-alone systems which produce power independently of the utility grid. Combination of renewable energy sources and diesel generators makes a system with high reliability and low pollution.

For a PV/wind/diesel hybrid system, it is necessary to provide an energy storage device. The storage system meets the remaining demand when the renewable sources have low energy. Conventionally, deep-cycle lead acid batteries are used for energy storage. Using PV/wind/diesel/battery energy source leads to a reliable energy source and reduces the total maintenance cost. Such systems are usually installed in locations where fuel supplies are expensive and unreliable, or where strong incentives for the use of renewable energy exist [1].

In recent years, investigation of off-grid hybrid systems based on renewable sources and diesel generators have attracted significant attention [1-18]. One of the most important aspects of the hybrid systems which leads to having a cost-effective system is optimal sizing. Finding the optimum size means to determine the number of wind turbines, PV panels, diesel generators and batteries with the load demand so as to minimizing the total annual cost of the system. Although various aspects of diesel-based hybrid systems have been considered in the literature, an informative model and efficient optimization tool for optimal sizing and techno-economic analysis and environmental pollution are seldom found. To efficiently and economically use the energy sources integrated in the hybrid system, an appropriate sizing methodology is crucial. If the hybrid systems are optimally designed, they can be cost-effective and reliable. This paper presents the modelling and optimization of an off-grid hybrid energy system with the effect fuel prices for electrification to a remote area located at Rafsanjan, Iran for different strategy. For each scenario a comparison has been made between the highly reliable PV/diesel/battery, WT/diesel/battery, diesel-only and hybrid (PV/WT/diesel/battery) systems. The system consists of photovoltaic panels and wind turbines as renewable power sources, a diesel generator for backup power and batteries to store excess energy and improve the system reliability. The parameter considered in this paper to measure the pollutant emission is the (kg of CO_2, SO_2, and NO_2). It represents the large percentage of the emission of fuel combustion. Further, CO_2 represents the main cause of the greenhouse effect. So we evaluate the amount of the CO_2 produced by the use of diesel generator in the PV/WT/diesel/battery system during one year of the operation of the system.

Optimal sizing of hybrid systems is a very difficult task which needs the development of mathematical models for the components and using optimization techniques. In this paper, for cost analysis, a mathematical model is introduced for each system's component and then, two discrete versions of particle swarm optimization (PSO) are introduced and used to optimally size the system components to satisfy the load in the most cost-effective way. PSO is a popular generic probabilistic solo-algorithm which is used for global optimization. As an efficient search method, PSO has simple concept, is easy to implement, can escape local optima, and then, a discrete particle swarm optimization algorithm with constriction factor (DPSO-CF)-based optimization technique is proposed to optimally size the system components.

2. Unit sizing

The schematic drawing of a typical stand-alone (photovoltaic-wind-battery-diesel) hybrid system is shown in Fig.1. The system consists of PV panels and WTs as renewable power sources, a diesel generator for backup power and batteries to store excess energy and improve the system reliability. As can be seen, an inverter is used before the load, since most of electric appliances are supplied with AC power. In such system, when the power produced by the renewable sources (P_{re}) at time t is not enough to supply the load power (P_l), the storage system (battery bank) is used. If the load demand is high and the storage system energy is not enough to meet the total energy, the diesel generator works to satisfy the remaining load. This strategy can be explained by the following steps.

Step 1. If $P_{re}(t) < P_l(t)$, go to Step 3, otherwise go to Step 2.

Step 2. Charge the battery bank, set $t = t + 1$, and go to step 1.

Step 3. Discharge the battery bank. If *SOC* (state of the charge) < SOC_{min}, start diesel, otherwise, set $t = t + 1$, and go to Step 1.

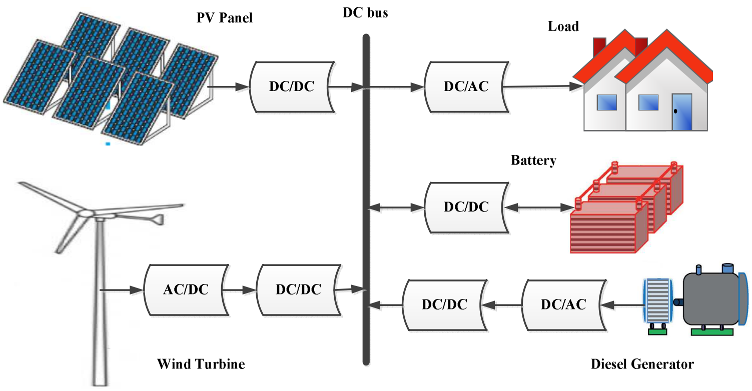

Figure 1: Schematic of the PV/WT/diesel/battery-based hybrid system.

2. 1. Resource and load data

The hourly wind speed data and solar insolation data during a one-year period, which was collected in a remote area in the Iran's Southern (Rafsanjan, Kerman province), regions, are shown in Fig. 2 and Fig. 3, respectively. The hourly load profile during a year of ten typical residential building located in Iran is shown in Fig.4. These sets of data are used in the calculations of the present study.

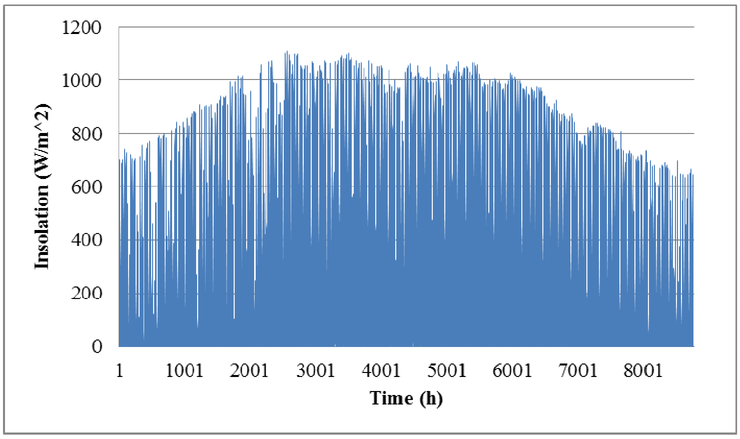

Figure 2: Hourly profile of insolation during a year.

2. 2. Wind Turbine (WT)

For a WT, if the wind speed exceeds the cut-in value, the wind turbine generator starts generating. If the wind speed exceeds the rated speed of the WT, it generates constant output power, and if the wind speed exceeds the cut-out value, the wind turbine generator stops running to protect the generator. The power of the WT is described in terms of the wind speed by Eq. (1) [19, 20]. The specifications of a typical WT used in the present work are shown in table 1

$$P_{Wind-Each}(t)=\begin{cases} 0 & if \quad v \le V_i \ \ or \ \ v \ge V_o \\ P_r \dfrac{v-V_i}{V_r-V_i} & if \quad V_i < v < V \\ P_r & if \quad V_r \le v < V_o \end{cases} \tag{1}$$

where $P_{Wind-Each}(t)$ is the power generated by each WT; v is the wind speed; V_i, V_o, V_r, are cut-in, cut-out, rated, or nominal speed of the WT, respectively; and P_r is the WT rated power.

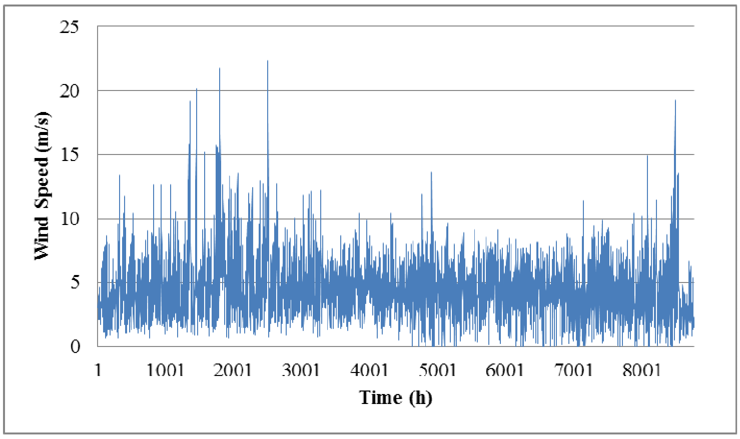

Figure 3: Hourly wind speed during a year (at height of 10 m).

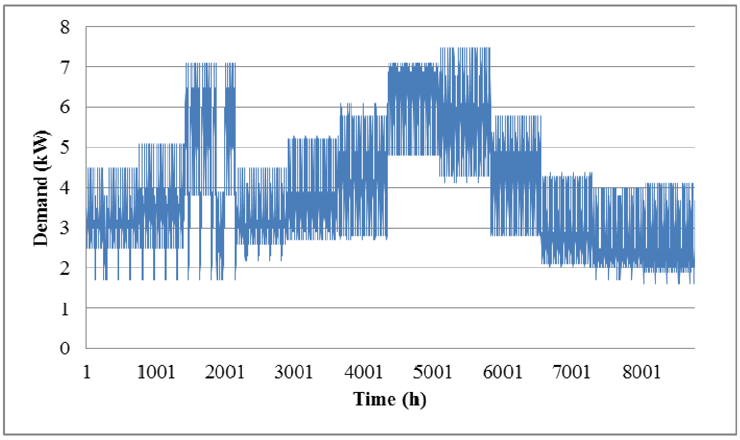

Figure 4: Hourly load demand during a year.

2. 3. Photovoltaic cells

The output power of each photovoltaic panel, with respect to the solar radiation power, can be calculated by Eq. (2) [20, 21]. The characteristics of PV panels used in the present study are presented in Table 2

$$P_{PV-Each}(t)=\begin{cases} P_R\left(\dfrac{r^2}{R_{SRS}R_{CR}}\right) & if \quad 0\le r<R_{CR} \\ P_R\dfrac{r}{R_{SRS}} & if \quad R_{CR}\le r<R_{SRS} \\ P_R & if \quad R_{SRS}\le r \end{cases} \tag{2}$$

where $P_{PV-Each}(t)$ is the power generated by each PV panel, P_R is the PV rated power, r is the solar radiation factor, R_{CR} is a certain radiation point set usually as 150 (W/m^2), and R_{SRS} is the solar radiation in the standard environment set usually as 1,000 (W/m^2).

Table 1.Wind turbine parameters.

P_r	1 kW
V_i	3 m/s
V_o	20 m/s
V_r	9 m/s
T_p	1443 $
T_{if}	0.25 × T_p
N_{Wind}^{max}	200
C_{Man}^{Wind}	100 $/year
Life Span	20 years

Table 2. PV panel parameters.

P_{rs}	260 W
P_p	312 $
P_{if}	0.5 × P_p
C_{Man}^{PV}	20 $/ year
Life Span	20 years
N_{PV}^{max}	200

2. 4. Diesel generator

As a backup power system, diesel generator begins to work when the produced power is not enough and the storage system energy is at the lowest level. In this case, diesel begins to work and satisfies the deficit power. The parameter considered in this paper to measure the pollutant emission is the kg of CO_2, SO_2 and NO_x. CO_2 represents the main cause of the greenhouse effect and the large percentage of the emission of fuel combustion. So we evaluate the amount of the emission produced by the use of diesel generator in the hybrid PV/wind/ diesel system with battery storage during one year of operation. The fuel consumption of the diesel generator, $Cons_D$ (l/h), depends on the output power and is defined by the following equation:

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

where P_N^D is the rated power, P_D is the output power of the diesel generator, and B_D = 0.0845 (*l*/kWh) and A_D = 0.246 (*l*/kWh) are the coefficients of the consumption curve. The factor considered, in this paper, to assess the emission of CO_2 was 3.15 $kgCO_2/l$, SO_2 was 0.04 kgSO2/*l*, and NO_x was 0.06 $kgNO_x/l$ [2, 22].

The hourly cost of the fuel consumption can be obtained by Eq. (4).

$$C_f = P_{fuel} \times Cons_D \tag{4}$$

where P_{fuel} is the fuel price. The characteristics of diesel generators used in the present study are presented in Table 3

2. 5. Battery

Battery discharging or charging of the input power can be negative or positive. State of charge (*SOC*) battery, according to the calculations of productivity and time consumption, is obtained thus:

If $P_{PV}(t)+P_{Wind}(t)=P_{Dmd}(t)$, then the battery capacity will not change. When the total output power of the WTs and PV panels is more than the load power, $P_{PV}(t)+P_{Wind}(t)>P_{Dmd}(t)$, the battery bank is in charging state, and the charged amount of the battery at time (*t*) is expressed by Eq.(5) [9, 23-25].

$$E_{Batt}(t)=E_{Batt}(t-1).(1-\sigma)+\left[\left(P_{Wind}(t)\times\eta_{Inv}^2+P_{PV}(t)\times\eta_{Inv}\right)-\frac{P_L(t)}{\eta_{Inv}}\right]\times\frac{\eta_{BC}}{\eta_{Inv}} \tag{5}$$

In this equation, $E_{Batt}(t-1)$ and $E_{Batt}(t)$ are the charge quantities of battery bank at time *t*-1, and *t*, $P_L(t)$ is the energy demand for the particular hour. $P_{Wind}(t)$ is the power generated by the WTs, $P_{PV}(t)$ is the power generated by the PV panels, η_{Inv} is the efficiency of the inverter, η_{BC} is the charge efficiency of battery bank, and σ is the hourly self-discharge rate.

When $P_{PV}(t)+P_{Wind}(t)<P_{Dmd}(t)$, the total output powers of the WTs and PV panels are less than the load power, the battery is in the state of discharge, and the charged quantity of the battery at time (*t*) is expressed by Eq. (6). The battery bank with the nominal capacity is only allowed to be discharged to a limited extent [9, 23-26]..

$$E_{Batt}(t)=E_{Batt}(t-1).(1-\sigma)-\left[\frac{P_L(t)}{\eta_{Inv}}-\left(P_{Wind}(t)\times\eta_{Inv}^2+P_{PV}(t)\times\eta_{Inv}\right)\right]/\eta_{BF}\times\eta_{Inv} \tag{6}$$

where η_{BF} is the discharging efficiency of battery bank. The profile battery banks used are shown in Table 3.

3. Formulation of the optimum design problem

3.1. Objective function

In this section, the objective function of the optimum design problem is the minimization of the total annual cost (C_{Tot}). The total annual cost consists of the annual capital cost (C_{Cap}), the annual maintenance cost (C_{Man}), and the total annual cost of fuel consumption of the diesel generator (C_{Fuel}). To optimally design the hybrid generation system, the optimization problem defined by Eq. (7), should be solved using an optimization method,

$$Minimize \quad C_{Tot} = C_{Cap} + C_{Man} + C_{Fuel} \tag{7}$$

Capital cost occurs at the beginning of a project while maintenance cost occurs during the project life.

In order to convert the initial capital cost (P) to the annual capital cost (A), capital recovery factor (CRF), defined by Eq. (8), is used.

$$CRF = \frac{A}{P} = \frac{j\,(1+j)^n}{(1+j)^n - 1} \tag{8}$$

In this equation, n denotes the life span and j is the interest rate of the system.

Some components of PV/WT/diesel/battery system need to be replaced several times over the project's lifetime. In this paper, the lifetime of PV/WT/diesel/battery is assumed to be 5 years. By using the single payment present worth factor, we have

$$C_{Batt} = P_{Batt} \times \left(1 + \frac{1}{(1+i)^5} + \frac{1}{(1+i)^{10}} + \frac{1}{(1+i)^{15}} \right) \tag{9}$$

where C_{Batt} is the present worth of battery, and P_{Batt} is the battery price.

In the same way, the lifetime of converter/inverter is assumed to be 10 years. By using the single payment present worth factor, we have

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

where $C_{Conv/Inv}$ is the present worth of converter/inverter components, and $P_{Conv/Inv}$ is the converter/inverter price.

By breaking up the capital cost into the annual costs of the WT, PV panels, converter/inverter, battery, and diesel generator, Eq. (11) is obtained.

$$C_{Cap} = CRF \times \left[N_{Wind} \times C_{Wind} + N_{PV} \times C_{PV} + N_{Batt} \times C_{Batt} + N_{Conv/Inv} \times C_{Conv/Inv} + N_{Diesel} \times C_{Diesel} \right] \tag{11}$$

In this equation, N_{Wind} is the number of WTs; C_{Wind} is the unit cost of WT, which is defined as the sum of turbine price (T_{pr}) and turbine installation fee (T_{inf}); N_{PV} is the number of PV panels; C_{PV} is the unit cost of PV panels, which is defined as the sum of panel price (P_{pr}) and panel installation fee (P_{inf}); N_{Batt} is the number of batteries; $N_{Conv/Inv}$ is the number of converter/inverter systems; N_{Diesel} is the number of diesel generator; and C_{Diesel} is unit cost of the diesel generator.

For the annual maintenance cost, Eq. (12) is obtained.

$$C_{Man} = N_{Wind} \times C_{Man}^{Wind} + N_{PV} \times C_{Man}^{PV} + C_{Mat}^{Diesel} \quad (12)$$

In this equation, C_{Man}^{Wind} is the annual maintenance cost of wind turbine, C_{Man}^{PV} is the annual maintenance cost of PV panel, and C_{Man}^{Diesel} is the hourly maintenance cost of the diesel generator. The maintenance costs of inverter and battery bank are ignored.

For the total annual cost of fuel consumption of the diesel generator, Eq. (13) is obtained.

$$C_{Fuel} = \sum_{f=1}^{8760} C_f \quad (13)$$

In this equation, C_f is the hourly cost of the fuel consumption.

Table 3: Component parameters.

j	6 %
n	20 years
Battery	
S_{Batt}	2.1 kWh
η_{BC}	95 %
η_{BF}	100 %
C_{Batt}	170 $
Life Span	5 years
DOD	0.8
σ	0.0002
N_{Batt}^{max}	200
Voltage	12 V
Diesel generator	
P_N^D	9.875 kW
Continous Output	8.750 kW
C_{Diesel}	6975 $
C_{Man}^{Diesel}	0.33 $/h
Life Span	8760 h
C_{fuel} (the first scenario)	0.3 $/L
C_{fuel} (the second scenario)	1.2 $/L
Inverter	
Rated power	2 kW
η_{Inv}	80 %
Voltage	24 V
C_{Inv}	751.24 $
Life Span	10 years

3.2. Constraints

At any time, the charge quantity of battery bank should satisfy the constraint of $E_{Batt}(t_{\min}) \le E_{Batt}(t) \le E_{Batt}(t_{\max})$, minimum charge quantity of the battery bank, defined by Eq. (14), is used.

$$E_{Batt}(t_{\min}) = (1 - DOD) \times S_{Batt} \tag{14}$$

where $E_{Batt}(t_{\max})$ is the maximum charge quantity of battery bank, *DOD* is the obtained by maximum depth of discharge battery bank, and S_{Batt} is the value of nominal capacity of battery bank. For the diesel generator, the minimum output power recommended by the manufacturer is 30% of the rated power. Moreover, during the continuous output power, the maximum output power recommended by the manufacturer is 90% of the rated power for the diesel generator.

4. Methodology

4.1. Discrete particle swarm optimization algorithm (DPSO)

Particle swarm optimization originally invented by Kennedy and Eberhart in 1995, PSO is a population-based metaheuristic algorithm attempting to discover the global solution of an optimization problem by simulating the animals' social behavior such as fish schooling, bird flocking, etc. In PSO algorithm, each feasible solution of the problem is called a particle which is specified by a vector containing the problem variables. Particles have memory and thus retain part of their previous state. There is no restriction for particles to share the same point in belief space, but anyway, their individuality is protected. Each particle's movement is the composition of two randomly weighted influences and an initial random velocity: sociality, the tendency to move towards the neighbourhood's best previous position and individuality, the tendency to return to the particle's best previous location.

The standard PSO algorithm utilize a real-valued multidimensional space as belief space, and evolves. The particles fly through the n dimensional domain space of the function to be optimized (in this paper, minimization is assumed). The state of each particle is represented by its position $X_i = (X_{i1}, X_{i2}, \ldots, X_{in})$ and velocity $V_i = (V_{i1}, V_{i2}, \ldots, V_{in})$. The states of the particles are updated. The three key parameters to particle swarm optimization algorithm are in the velocity update equation. First is the momentum component, which is the cognitive component. Here the acceleration constant c_1 controls how much the particle heads toward its personal best position. The second component is the inertial constant *w*, which controls how much the particle remembers its previous velocity [27]. The third component, referred to as the social component, draws the particle toward swarm’s best ever position; the acceleration constant c_2 controls this tendency. At the beginning of the algorithm, a group of particles is randomly initialized in the search space. Each particle makes use of its memory and flies through the search space for obtaining a better position than its current one. In its memory a particle memorizes the best experience found by itself (p_{best}) as well as the group’s best experience (g_{best}). The position of each particle in that space is achieved using the following equations:

$$v_i^{k+1} = w^k . v_i^k + c_1 . r_1 . \left(p_{best}^k - x_i^k\right) + c_2 . r_2 . \left(g_{best}^k - x_i^k\right) \tag{15}$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{16}$$

where v_i^k is the component in dimension *d* of the i^{th} particle velocity in iteration *k*, x_i^k is the component in dimension *d* of the i^{th} particle position in iteration *k*, c_1 and c_2 are constant weight factors, p_{best} is the best position achieved so far by particle i, g_{best} is the best position found by the neighbours of particle i, r_1 and r_2 are random factors in the between 0 and 1 interval, and w is inertia weight which is started from a positive initial value (w_0) and is decreased during the iterations by $w\,(iter+1) = \beta \times w\,(iter)$.

The procedure of standard DPSO is described in steps 1-9:

1. A population is randomly generated in the search space.
2. The initial velocity of each particle is randomly generated.
3. Objective function value for each particle is calculated.
4. The initial position of each particle is selected as its p_{best} and the best particle among the population is chosen as g_{best}.
5. Particles move to new positions based on Eqs. (15) and (16).
6. If a particle exceeds the allowed range it is replaced by its previous position.
7. Objective function value for each particle is calculated.
8. p_{best} and g_{best} are updated.
9. The stopping criterion is checked. If it is satisfied the algorithm is terminated and g_{best} is selected as the optimal solution. Otherwise, Steps 5 to 8 are repeated.

4.2. Discrete particle swarm optimization algorithm with constriction factor (DPSO-CF)

In this part, the speed clamping effect has been introduced to avoid the phenomenon of "swarm explosion." With no limit on the maximum velocity of the particles, a simple one-dimensional analysis of the swarm dynamic concludes that the particle velocity can grow unlimited while the particle oscillates around an optimum point increases its distance to the optimum on each iteration. Additional studies proved that this mechanism was not sufficient to properly control the particle's velocities. When compared to EC techniques [28, 29], the DPSO quickly identified the region where the optimum was located but had trouble adjusting the velocity to lower values in order to perform a fine-grained search of the area. In this version of the DPSO algorithm, the following modified velocity equation is used:

$$v_i^{k+1} = W.v_i^k + C_1.r_1.\left(p_{best}^k - x_i^k\right) + C_2.r_2.\left(g_{best}^k - x_i^k\right) \tag{17}$$

For the initial version of the DPSO, the values for C_1 and C_2 have to be selected. This selection has an effect on the convergence speed and the capability of the algorithm to find the optimum, but different values may be good for different problems. Ample work has been done to choice a combination of values that works well in a diversified amount of problems. Addition to this, the DPSO method sometimes suffers from the problem of premature convergence. To prevent this problem, the constriction factor (CF) was included. This factor helps to control velocity dynamism with respect to fast change in position. Therefore, a steady and stable convergence was achieved. In this paper, discrete particle swarm optimization algorithm with constriction factor the constriction (DPSO-CF) is applied to solve the optimal sizing problem. For the constricted version of DPSO, the following restrictions are proposed:

$$CF = \frac{2}{\left|ph_i - 2 + sqrt\left(ph_i^2 - 4\times ph_i\right)\right|} \qquad W = w \times CF \tag{18}$$

$$ph_i = ph_{i1} + ph_{i2} \qquad (19)$$
$$ph_{i1} + ph_{i2} \geq 4$$

$$C_1 = CF \times ph_{i1} \qquad (20)$$
$$C_2 = CF \times ph_{i2}$$

where CF is the constriction factor, C_1 is the cognitive parameter, and C_2 is the social parameter. ph_i is the coefficient of contraction, and ph_{i1} and ph_{i2} are positive numbers.

5. Results and cost analysis

The experimental data used here for wind speed and solar insolation is obtained from Rafsanjan, Iran (latitude: 30.40 º). Figs. 2 and 3 show the hourly insolation and wind speed (at height of 10 m) profiles of during a year. Table 1 and Table 2 list the WT and PV panel parameters, respectively. The parameters related to the other components have been given in Table 3; also this table shows the diesel fuel price under two different scenarios. Fig. 4 shows the hourly load profile during a year.

MATLAB environment is used to implement the proposed methodology. Parameter setting of the algorithms is as follows:

DPSO: N_p = 10; c_1 = 2; c_2 = 2, β = 0.99; w_0 =1; $iter_{max}$ = 100.

DPSO-CF: N_p = 10; ph_{i1}= 2.05; ph_{i2}=2.05; $iter_{max}$ = 100.

DPSO-CF and DPSO try to find the optimum number of each component. The minimum and maximum bounds of the decision variables are set to 0 and 200, respectively. At initial moment, it is assumed that the charge of each battery is 30 % of its nominal capacity.

In Iran, the cost of fuel is highly subsidized. According to the radiation data and wind speed if Iran removes the fuel subsidy, the cost of diesel fuel would increase and the PV panels, WTs or hybrid PV/WT/diesel/battery systems would become more attractive. Hybrid PV/WT/diesel/battery systems which use PV and WT energy, combined with diesel generation power and battery bank storage are an excellent solution to decrease diesel generator costs, pollution, and electrification of remote rural areas.

Tables (4) to (5) summarize in detail the results of optimum sizing for different hybrid systems: PV/WT/diesel/battery, PV/diesel/battery, WT/diesel/battery, and diesel generator alone, for first scenario and second scenario respectively. The first scenario (subsidize fuel price, Table 4) the optimum number of PV panels, WTs and batteries in the PV/WT/diesel/battery, PV/diesel/battery, and WT/diesel/battery, are equal to zero, it is clear that economically the diesel generators system is a better choice for providing power.

Table 5 shows the optimum number and cost of each component as well as the total annual cost for second scenario (removes the fuel subsidy, the cost of diesel fuel would increase to 1.2 $). This table shows the best performance of DPSO-CF and DPSO during 30 runs. It is clear that economically the PV/diesel/battery-based hybrid system is a better choice for providing power. The total annual costs for PV/WT/diesel/battery, PV/diesel/battery, WT/diesel/battery, and diesel generator alone systems are found 24008.6 $, 24008.6 $, 28820.8 $, and 31036.5$, respectively. For the PV/diesel/battery system, it is found that the optimum number of PV panels, batteries and diesel generator are 91, 37, and 1, respectively. Also by the complete removal of diesel fuel price subsidies, the role of the diesel generator further decreases in hybrid energy systems. Also economically the PV/diesel/battery, PV/WT/diesel/battery and WT/diesel/battery-based hybrid systems are a better choice of a diesel generator alone. Also number of WTs, PV panels, and batteries by the complete removal of diesel fuel price subsidies, for the PV/diesel/battery and WT/diesel/battery are increased. Moreover, with the increase in fuel prices diesel generators and with improvement in the efficiency of all three PV, WT and battery storage system can be economically better. Also this table shows that an emissions for PV/diesel/battery-based hybrid system is a better choice for providing less pollution emissions. The total annual pollution emissions, CO_2 for PV/WT/diesel/battery, PV/diesel/battery, WT/diesel/battery, and diesel generators alone systems are found 21807.6 Kg, 21807.6 Kg, 29933.9 Kg, and 54239.4 Kg respectively, which are WT/diesel/battery-based hybrid system pollution emissions greater than of the other hybrid systems. The pollution emissions, SO_2, NO_x, and total fuel in a year for WT/diesel/battery-based hybrid system are found 380.1 Kg, 570.2 Kg, and 9502.8 L, respectively, which are the pollution emissions less than first scenario. It is seen that the best performances of DPSO-CF and DPSO algorithms during 30 runs is same.

Table 4. Summary of the results for the hybrid systems obtained by DPSO-CF algorithm for the first scenario.

hybrid systems	PV/WT/diesel/battery	PV/diesel/ battery	WT/diesel/ battery	Diesel alone
N_{PV}	0	0	N/A	N/A
N_{Wind}	0	N/A	0	N/A
N_{Batt}	0	0	0	N/A
N_{Diesel}	1	1	1	1
Total annual cost ($)	15539.5	15539.5	15539.5	15539.5
Total fuel in a year (L)	17218.9	17218.9	17218.9	17218.9
CO_2 (Kg)	54239.4	54239.4	54239.4	54239.4
SO_2 (Kg)	688.8	688.8	688.8	688.8
NO_x (Kg)	1033.1	1033.1	1033.1	1033.1

Table 6 summarizes the mean (Mean), standard deviation (Std.), best (Best) and worst (Worst) values obtained by DPSO and DPSO-CF over 30 runs. Based on the Mean index, DPSO-CF finds better results than DPSO for all the hybrid systems. Based on the Mean index DPSO-CF outperforms DPSO algorithm while based on the Best index the performance of DPSO-CF and DPSO is same

Table 5. Summary of the results for the hybrid systems obtained by DPSO and DPSO-CF algorithm for the second scenario.

hybrid systems	PV/WT/diesel/battery		PV/diesel/battery		WT/diesel/battery		Diesel alone	
algorithm	DPSO	DPSO-CF	DPSO	DPSO-CF	DPSO	DPSO-CF	DPSO	DPSO-CF
N_{PV}	91	91	91	91	N/A	N/A	N/A	N/A
N_{Wind}	0	0	N/A	N/A	10	10	N/A	N/A
N_{Batt}	37	37	37	37	143	143	N/A	N/A
N_{Diesel}	1	1	1	1	1	1	1	1
PVcost ($)	5533	5533	5533	5533	-	-	N/A	N/A
WT cost ($)	0	0	N/A	N/A	2572.6	2572.6	N/A	N/A

Diesel cost (*$*)	8164.3	8164.3	8164.3	8164.3	8461.3	8461.3	9863.5	9863.5
Battery cost (*$*)	1493.2	1493.2	1493.2	1493.2	5771.1	5771.1	N/A	N/A
Converter/Inverter cost (*$*)	510.4	510.4	510.4	510.4	612.4	612.4	510.4	510.4
Fuel cost (*$*)	8307.7	8307.7	8307.7	8307.7	11403.4	11403.4	20662.4	20662.4
Total annual cost (*$*)	24008.6	24008.6	24008.6	24008.6	28820.8	28820.8	31036.5	31036.5
Total fuel in a year (*L*)	6923.1	6923.1	6923.1	6923.1	9502.8	9502.8	17218.9	17218.9
CO_2 (*Kg*)	21807.6	21807.6	21807.6	21807.6	29933.9	29933.9	54239.4	54239.4
SO_2 (*Kg*)	276.9	276.9	276.9	276.9	380.1	380.1	688.8	688.8
NO_x (*Kg*)	415.38	415.38	415.38	415.38	570.2	570.2	1033.1	1033.1

Fig. 5 illustrates the load curve and the produced power of the PVs, diesel generator and the storage level of the battery bank for the optimized hybrid (PV/diesel/battery) systems for the second scenario, it is seen that the diesel generator more works in the during peak hours load and is lower the storage level of the battery bank for the peak hours. Fig. 6 shows the convergence process of the DPSO-CF and DPSO algorithm for finding the optimal size of the systems for the second scenario. In this figure, the minimum of total annual cost (corresponding to the best performance) during the iterations has been shown. As the figure shows, during the iterations, the total cost of the system decreases. This means that the optimization technique decreases the total cost by moving toward the optimum size. For such systems, there is no information about the optimum size, so any reduction of the cost function is significant, because it leads to having more knowledge about the optimal sizing.

Table 6. The mean, standard deviation, best, worst performances of the algorithms over the hybrid systems.

Hybrid system	Index	Algorithm	
		DPSO	DPSO-CF
PV/Wind/battery	*Mean*	24531.69	24440.26
	Std.	274.04	255.11
	Best	24212.71	24212.71
	Worst	25357.05	24979.6
	Rank	2	1
PV/battery	*Mean*	24243.35	24106.68
	Std.	1261.45	387.70
	Best	24008.57	24008.57
	Worst	31036.47	26163.81
	Rank	2	1
Wind/battery	*Mean*	29606.36	29462.92
	Std.	519.97	618.37
	Best	28820.82	28820.82
	Worst	31138.54	31138.54
	Rank	2	1
Average rank		2	1
Final rank		2	1

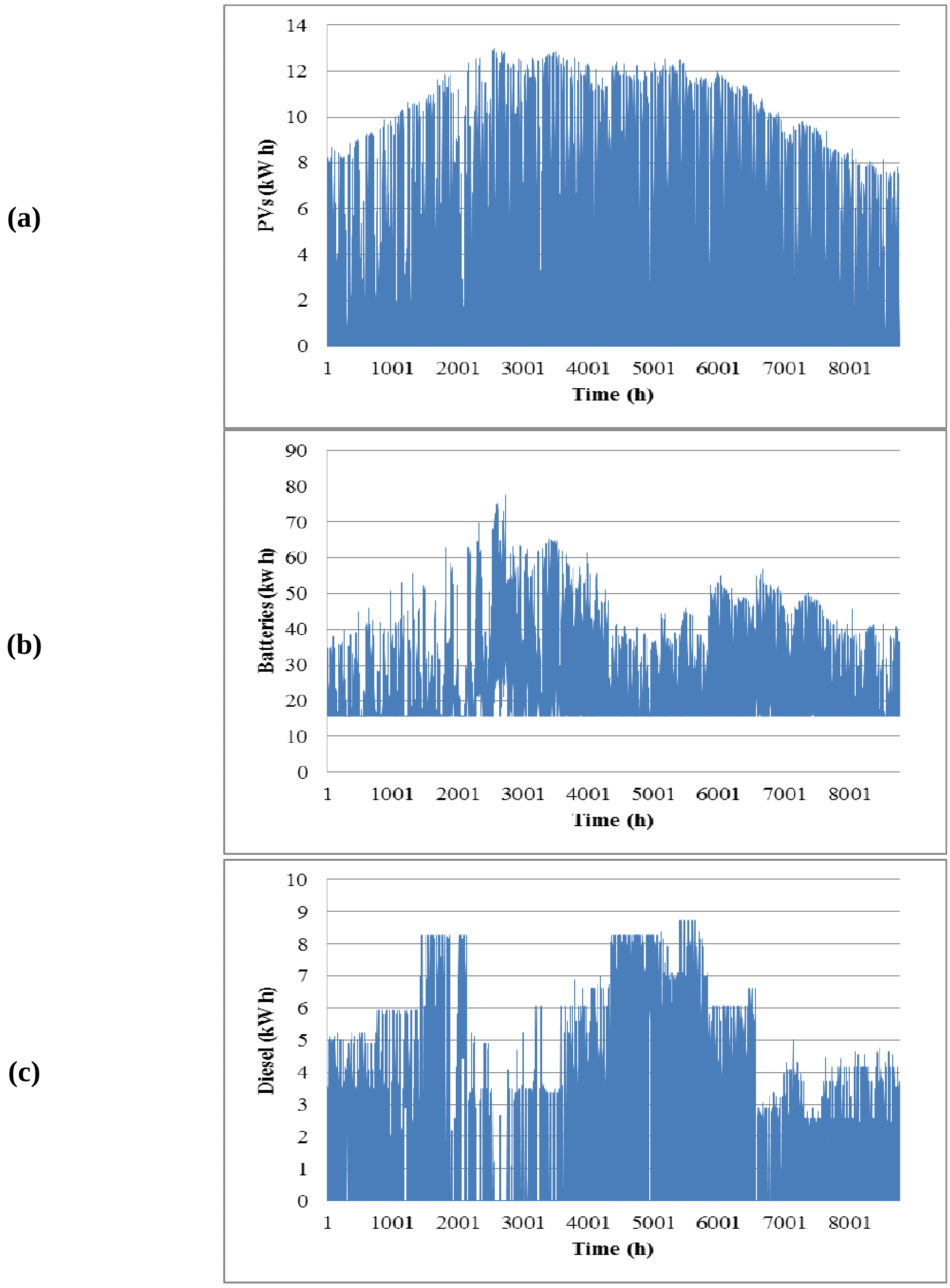

Figure 5: The change of power during a year for PV/diesel/battery system for the second scenario. (a) PVs produced power; (b) Storage level of the batteries; (c) Diesel generators produced power.

(a)

(b)

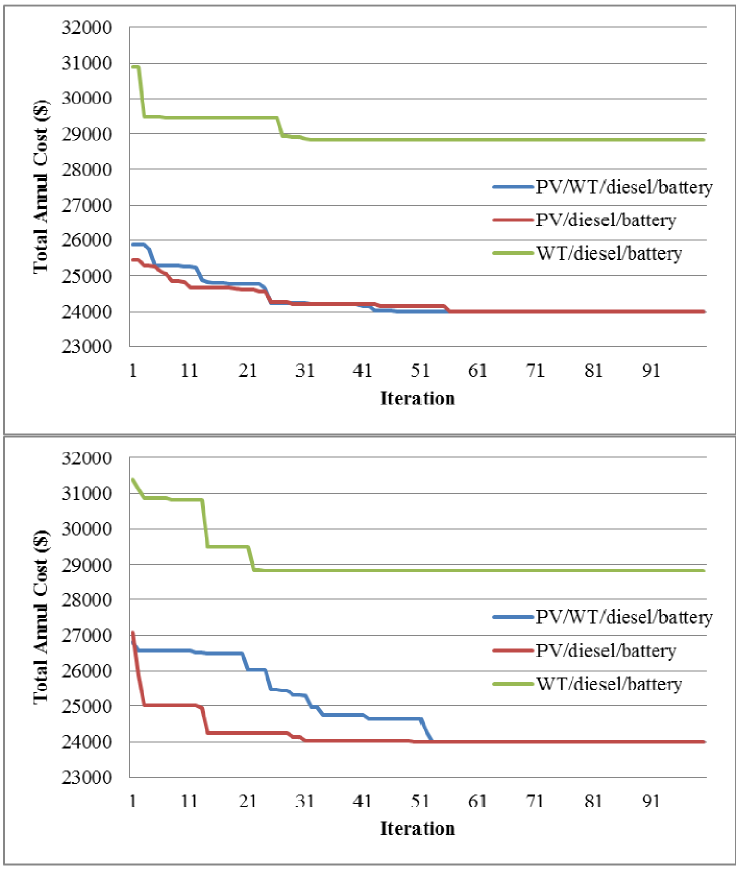

Figure 6: Convergence process of the algorithms for finding the optimum size of the hybrid systems for the second scenario (a) DPSO; (b) DPSO-CF.

6. Conclusion

This paper presents techno-economic analysis, modeling and optimization of a PV/WT/diesel -based hybrid system with battery storage for electrification to an off-grid remote area located in Rafsanjan, Iran, for different diesel generator fuel price scenarios. The optimal sizing of the system is found by two particle swarm optimization algorithm (inspired by social behavior of animals). For this location, different generation systems (PV/WT/diesel/battery, PV/diesel/battery, WT/diesel/battery, and diesel alone) are studied and compared in terms of cost and pollution for two scenarios.

Simulation results indicate that only under a subsidized diesel fuel price scenario (the first scenario), the diesel alone system is the best option to supply the load requirements of the present study. The elimination of the present diesel fuel price subsidies by Iran decreases the role of the diesel generator in hybrid PV/WT/diesel/battery systems (The second scenario, the cost of diesel fuel would increase to 1.2 $). Nevertheless, with the increase in fuel prices diesel generators and using PV/WT/diesel/battery energy source, in the near future PV/diesel/battery systems will be a more desirable economical alternative and leads to a less-polluting reliable energy source to electrification of the remote regions in Rafsanjan, Iran. Moreover, using DPSO-CF outperforms DPSO in terms of the accuracy because DPSO-CF leads to finding the minimal objective function. DPSO-CF is a heuristic technique that uses stochastic techniques instead of differential relations to find the global solution.

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