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Optimization of micro-grid system using MOPSO

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ABSTRACT

Access to a reliable source of electricity is a basic need for any community as it can improve the living standards characterized via the improvement of healthcare, education, and the local economy at large. There are two key factors to consider when assessing the appropriateness of a micro-grid system, the cost-effectiveness of the system and the quality of service. The tradeoff between cost and reliability of the system is a major compromise in designing hybrid systems. In this way, optimization of a Hybrid Micro-Grid System (HMGS) is investigated. A hybrid wind/PV system with battery storage and diesel generator is used for this purpose. The power management algorithm is applied to the load, and the Multi-Objective Particle Swarm Optimization (MOPSO) method is used to find the best configuration of the system and for sizing the components. A set of recent hourly wind speed data from three meteorological stations in Iran, namely: Nahavand, Rafsanjan, and Khash, are selected and tested for the optimization of HMGS. Despite design complexity of the aforementioned systems, the results show that the MOPSO optimization model produces appropriate sizing of the components for each location. It is also suggested that the use of HMGS can be considered as a good alternative to promote electrification projects and enhance energy access within remote Iranian areas or other developing countries enjoying the same or similar climatic conditions.

1. Introduction

Access to a reliable source of electricity is a basic need for any community; however, according to the United Nations Development Program (UNDP) report, more than a quarter of the people around the globe have no access to electricity, particularly those living in rural areas [1]. Rural areas are normally far from the national grid and located in extreme terrain, such as mountainous areas or thick jungle, where extending the transmission line can be extremely costly or unfeasible. However, there is high potential for renewable resources, such as wind, solar, and hydro power, which are omnipresent, abundant, free, clean, and easily accessible. Renewable energy in the form of a Hybrid Micro-Grid System (HMGS) offers an optimal, reliable, and cost-effective solution for utilizing localized renewable energy resources.

They provide centralized electricity generation at the local level by combining the renewable energy sources with a diesel generator as a back-up system. These systems start from a range of simple 5 kW single phase to provide electricity for a single home up to a large 3-phase network, as a major power supply for the whole community. However, they can easily scaled up and connect to the national grid when the demand grows or the community extends [2].

Wind and solar energy are complementary on a daily, annual, and regional basis; accordingly, the energy provided by wind turbines and PV has become a major renewable energy resource in stand-alone systems [3,4]. However, storage resources and diesel generators are also used to overcome the intermittent nature of wind and solar energy [5–7]. System components are effectively connected together through an AC-network, in which generation components can be placed on any location or property and the system is readily expandable.

Hybrid systems provide an opportunity to use the advantages of renewable resources in combination with conventional ones. Existing studies show a significant development in the design,

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Nomenclature

a	coefficient of fuel consumption ($a = 0.246$ L/kW)
AD	autonomy days
b	coefficient of fuel consumption ($b = 0.08415$ L/kW)
c_1	cognitive parameter
c_2	social parameter
DOD	depth of discharge (DOD = 80%)
EL	load (kWh)
f	objective function
G	solar radiation (W/m^2)
G_{ref}	solar radiation at reference conditions ($G_{ref} = 1000$W/m^2)
i	real interest rate
k	number of objectives
K_t	temperature coefficient of the PV panel ($K_t = -3.7 \times 10^{-3}$ (1/°C))
n	amortization period
$P(t)$	generated power (kW)
P^g	the best global position
P^i	the best individual particle position
P_{Load}(h)	hourly power consumption
$P_{N\text{-}pv}$	rated power under reference conditions
$P_{pv\text{-}out}$	output power of PV
P_r	rated power of diesel generator
P_{rated}	rated power
$q(t)$	fuel consumption (L/h)
r_1	random number between 0 and 1
r_2	random number between 0 and 1
T_{amb}	ambient temperature
T_{ref}	cell temperature at reference conditions ($T_{ref} = 25$ °C)
v	particle velocity
V	wind speed in the current time step
$V_{cut\text{-}in}$	cut in speed
$V_{cut\text{-}out}$	cut out speed
V_{ik}	inertia
V_{rated}	nominal wind speed
w	weight ($0 < w < 1$)
x	particle position, the vector of decision variables
η_b	battery efficiency ($\eta_b = 85\%$)
η_{inv}	inverter efficiency ($\eta_{inv} = 95\%$)
η_{10}	efficiency of the inverter at 10% of its nominal power
η_{100}	efficiency of the inverter at 100% of its nominal power
$\eta_{brake\ thermal}$	brake thermal efficiency of diesel generator
$\eta_{overall}$	overall efficiency of diesel generator

analysis, and implementation of such systems over the last decade. Hybrid systems are divided into two categories of stand-alone and grid-connected systems. In stand-alone systems, energy provided by wind turbines and PV is the major renewable energy resource [3,8]. Moreover, magnetic energy storage (SMES), fuel cell-electrolyzers, gasoline/kerosene systems, grid-connection and storage batteries are used to overcome the intermittent nature of wind and solar energy in these systems [5,6,9].

According to the potential of renewable resources and the purpose of using a hybrid system in the area of study, different configurations of renewable and conventional energy resources and storage systems are presented. For instance, Ref. [10] offered a combination of wind-battery system by using design-space approach. The system includes DC and AC buses to feed the load. Ref. [11] studied the modeling, control and power management of hybrid systems using a wind turbine and microturbine. Power management and the control strategy algorithm for a hybrid wind/photovoltaic/fuel cell power system containing an ultra-capacitor bank as an energy storage system was studied in Ref. [12]. Another study conducted by Caisheng and Nehrir [7] on hybrid wind–photovoltaic–fuel cell–electrolyzer–battery, power management and control strategies of systems under different scenarios was investigated using the real time-series data and load profile in the Pacific Northwest region. Ref. [13] proposed a hybrid wind/photovoltaic/fuel cell generation system containing hydrogen tank to minimize the annual cost of the hybrid system by using the Particle Swarm Optimization algorithm. It was found that the cost of the system directly depends on its reliability.

HMGSs need to be adequately informed and assessed during the initial stages. However, designing a renewable energy system with low adverse socioeconomic and environmental impact is one of the challenges within their development. Thereby, knowledge of all the factors that influence the performance of the system and the accurate sizing of each component are prerequisites for accurate designing of the HMGS model.

At present, many studies focus on the optimization of stand-alone electrification systems without considering micro-grid design [14]. In this sense, software tools are broadly used for simulating, optimizing, and sizing of such systems. The utilized software tools have been named as: HOMER, HYBRID2, HYBRIDS, HOGA, PVSYST, SOMES, RAPSIM, SOLSIM, INSEL, PV-DESIGN PRO [15], RSHAP, ORIENTE. Nevertheless, HOMER (hybrid optimization model for electric renewables) is so far the most common tool for cost, sensitivity analysis, and validation tests of hybrid stand-alone systems. However, these software have their own disadvantages, such as black box utilization [16]. The computational optimization methods using bio-inspired technologies have also been significantly developed in recent years. They can effectively increase the efficiency of hybrid systems by finding the best configuration to optimize the technical and economic criteria.

Genetic algorithm (GA) is an efficient method to optimize the sizing of hybrid systems, especially in complex systems, where a large number of parameters have to be considered. It provides a variety of hybrid systems with different sizes of components to satisfy the load demand in a given location and evaluates them according to the defined fitness function, albeit, the GA is not easy to code, especially for optimization of HMGS [16–18].

Particle swarm optimization (PSO) is another method that can be pointed out as being a simple concept, with easy coding implementation, robustness to control parameters, and computational efficiency by generating high-quality solutions with shorter calculation time and stable convergence characteristics [16,19]. PSO performance is comparable to genetic algorithm, but it is faster and less complicated; it has also successfully been applied to a wide variety of problems. It is simple to implement and is an efficient global optimizer for continuous variable problems [20]. PSO has become one of the favorite optimization methods as it presents high speed of convergence for single-objective optimization [21]; moreover, it can effectively find the Pareto front in multi-objective problems such as optimization of HMGS.

Many studies have been carried out in recent years substantiating the point that PSO yielded satisfactory outcomes [13,22–27]. In Ref. [28], PSO was suggested as one of the most useful and promising methods in designing the hybrid systems due to the use of global optima to find the best solution.

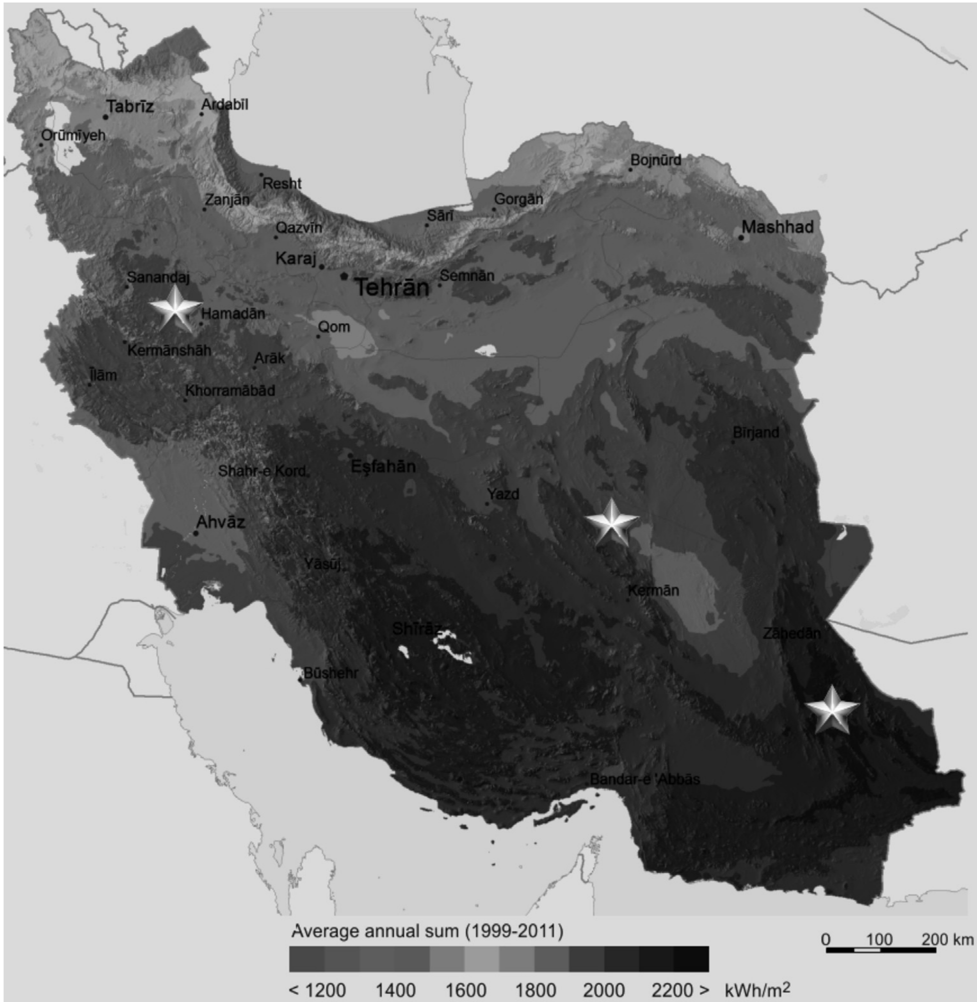

Fig. 1. Global horizontal irradiation in Iran [30].

The objective of this study is to select the HMGS components in order to have a reliable and cost effective system for a number of households. To accomplish this, a multi-objective PSO optimization method is applied to meet certain criteria in order to find the lowest Cost of Electricity (COE) and the lowest Loss of Power Supply Probability (LPSP). Moreover, the renewable factor is introduced to guarantee that the system mainly works based on renewable energy resources. The meteorological data for the three selected stations in Iran are tested as case studies. The paper is organized into five sections. Following Section 1 on "Introduction", Section 2 describes the "Case study" and the "Hybrid power system" is explained in Section 3. The "Optimization" algorithm and "Results" are presented in Sections 4 and 5, respectively.

2. Case study

In Iran, the Ministry of Energy and Renewable Energy Organization of Iran, which is responsible for rural electrification, has electrified 100% of villages with over 20 households, while those with less than 20 households still need to be electrified. Although some of those villages were electrified by 1 kW solar systems, there are still many remote and low populated villages without access to electricity. These remaining off-grid areas are far from the national grid and mostly located in extreme terrain. Therefore, grid based electrification is neither feasible nor economical for these locations. However, the electrification by renewable resources in the form of HMGS can accelerate this process [29].

Iran has high potential for multiple renewable resources. In this study, the meteorological data for three stations in Iran, namely: Nahavand, Rafsanjan, and Khash, are used to design HMGS. Figs. 1 and 2 show the location of these stations in the atlas of wind speed and horizontal solar irradiation of Iran. Nahavand is located in the west of Iran and lies on the geographical coordinates of 34° 18′ 44″ N, 48° 37′ 25″ E. It is considered as one of the coldest areas in Iran. During winter, the temperature may drop below −30 °C and heavy snowfall is also common, which can persist for up to two months. The second station is Rafsanjan, located in the central region of Iran, situated in geographical coordinates of 30° 24′ 24″ N, 55° 59′ 38″ E with a hot summer and relatively cool spring. The third station is selected in Khash, located in the southeastern part of Iran. It is geographically located at latitude of 28° 13′ 11″ North of the Equator and longitude of 61° 13′ 47″ East. During the winter the temperature may drop some degrees below zero; however, the temperature exceeds 40° in the summer, which results in considerable temperature differences among the seasons. The average wind speed at a height of 40 m and also average horizontal solar radiation of the selected locations, are summarized in Table 1. The meteorological data from the Renewable Energy Organization of Iran is applied for optimization of micro-grids in the aforementioned stations.

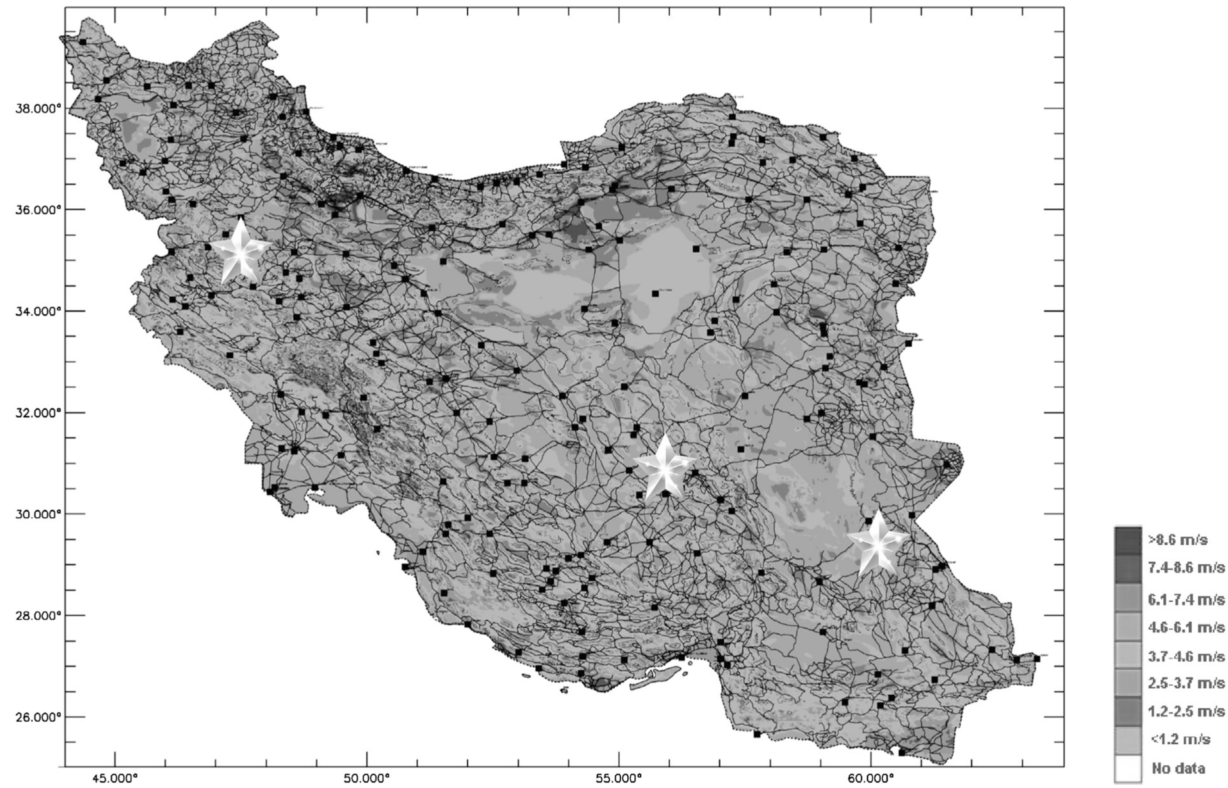

Fig. 2. Mean wind velocity at height of 40 m [31].

3. Hybrid power system

Generally three subsystems joined together to form an HMGS, namely: the production, the distribution, and demand subsystems, which can vary greatly depending on certain parameters, such as the availability of renewable resources, desired services to provide, and demand subsystem [32]. These parameters have a high impact on decision making, and, accordingly, on the cost and reliability of the system. In this section, the design of a wind/solar/diesel/battery is examined as the production subsystem in three selected stations; the load profile, which is the main part of the demand subsystem, is also studied. The configuration of the micro-grid as the distribution subsystem is according to Fig. 3. It is designed as a single phase, low-voltage distribution network to supply 220 V, 50 Hz, AC electricity.

3.1. Components

3.1.1. Wind

Wind can be considered as a free available energy source that can be utilized for electrification. The potential for wind energy is high, especially in the eastern and northwestern regions of Iran. The central and eastern parts of Iran go through seasonally climatic variations although the southern coastal plains have mild winters, and extremely hot and humid summer days. Moreover, in the interior part of southern Iran, the temperature could exceed 48 °C during July [33]. Iran is considered as a medium region of the world regarding wind velocity; however, continuous winds with suitable velocity in some of the regions are capable of generating electricity [34]. In 2006, Iran generated 47 MW of electricity from wind energy which ranked it at number thirty in the world [33,34]. In this study a small wind turbine with 2 kW rated power is considered for the design of HMGS. The detailed characteristics of selected wind turbine can be found in Table 2.

Since the wind speed varies with height, the measured wind speed at anemometer height must be converted to desired hub heights. The power law equation is calculated by the following correlation [35,36]:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{1}$$

In which v_2 is the speed at the hub height (h_2) and v_0 is the speed at the reference height (h_1), and α is the friction coefficient (also known as: Hellmann exponent, wind gradient, or power-law exponent). α is a function of parameters such as wind speed, roughness of terrain, the height above ground, temperature, hour of the day and time of the year [37–39]. The most common way of defining α is based on different types of terrains which can be found in literature [40–42]; however, it is frequently assumed as a value of 1/7.

Power output of wind turbine can be approximated as [43]:

$$\begin{cases} 0 & V < V_{\text{cut-in},} V > V_{\text{cut-out}} \\ V^3\left(\dfrac{P_{\text{r}}}{V_{\text{r}}^3 - V_{\text{cut-in}}^3}\right) - P_r\left(\dfrac{V_{\text{cut-in}}^3}{V_{\text{r}}^3 - V_{\text{cut-in}}^3}\right) & V_{\text{cut-in}} \le V < V_{\text{rated}} \\ P_{\text{r}} & V_{\text{rated}} \le V \le V_{\text{cut-out}} \end{cases} \tag{2}$$

where, P_{rated} is rated power, V is wind speed in the current time step, and $V_{\text{cut-out}}$, V_{rated}, $V_{\text{cut-in}}$ represent cut in wind speed, nominal wind speed and cut out wind speed respectively. Since the $V_{\text{cut-in}}$ is

Table 1
Average wind speed and solar radiation in selected locations.

Location	Average wind speed (m/s)	Average solar radiation (kWh/m^2/d)
Nahavand	5	5.04
Rafsanjan	6	5.45
Khash	5.71	5.39

rather small in small-scale wind turbines, the wind turbines can operate efficiently even when the wind speed is not very high.

3.1.2. PV output

Since Iran is located within the world's Sun Belt, which receives the highest amount of solar radiation throughout the year, it would be desirable to extend the PV system utilization. There are 240–250 days of sunshine per year with an average of 4.5–5.4 kWh/m^2 horizontal daily solar radiation [1,44].

The power supplied by the panels can be calculated as a function of the solar radiation by using the following formula [45]:

$$P_{pv-out} = P_{N-pv} \times \frac{G}{G_{ref}} \times \left[1 + K_t\left((T_{amb} + (0.0256 \times G)) - T_{ref}\right)\right] \tag{3}$$

where, $P_{pv\text{-}out}$ is output power of PV, $P_{N\text{-}pv}$ is rated power under reference conditions, G is solar radiation (W/m^2), G_{ref} is 1000 W/m^2, T_{ref} is 25 °C, K_t is $-3.7*10^{-3}(1/°C)$, and T_{amb} is the ambient temperature.

Fig. 4 illustrates hourly solar radiation data of the three selected stations, which are located in the northwest, central and southeast of Iran.

3.1.3. Diesel generator

By using diesel generators for remote communities and rural industries, the required amount of energy storage will be reduced, which results in a more cost effective and reliable system. Diesel works as a secondary energy source in the case of battery depletion during peak demand. However, avoiding unloaded or even lightly loaded operation of the diesel generator is one of the considerations that should be taken into account [46].

The efficiency and the hourly fuel consumption of the diesel generator should be considered in designing a hybrid system and can be expressed by the following formula [47,48]:

$$q(t) = a.P(t) + b.P_r \tag{4}$$

here, $q(t)$ is fuel consumption (L/h), $P(t)$ is generated power (kW), P_r is rated power, a and b are constant parameters (L/kW), which represent the coefficients of fuel consumption, and can be approximated to 0.246 and 0.08415, respectively [49].

The efficiency of a diesel generator is calculated by: [50].

$$\eta_{overall} = \eta_{brake\ thermal} \times \eta_{generator} \tag{5}$$

where, $\eta_{overall}$ and $\eta_{brake\_thermal}$ represent the overall efficiency and the brake thermal efficiency of diesel generator, respectively.

3.1.4. DC/AC converter (inverter)

Inverters convert the electrical energy from DC into AC with the desired frequency of the load. The efficiency of the inverter can be defined by the following equation:

$$\eta_{inv} = \frac{P}{P + P_0 + kP^2} \tag{6}$$

in which, P, P_0 and k are determined by using the equations given below: [51–54]

$$P_0 = 1 - 99\left(\frac{10}{\eta_{10}} - \frac{1}{\eta_{100}} - 9\right)^2, \; k = \frac{1}{\eta_{100}} - P_0 - 1, \; P = P_{out}/P_n \tag{7}$$

η_{10} and η_{100} are provided by the manufacturers and present the efficiency of the inverter at 10% and 100% of its nominal power respectively.

3.1.5. Design of battery bank

The battery capacity (kW) of the system is designed according to the demand and the days of autonomy using the following equation:

$$C_B = \frac{E_L \cdot AD}{DOD \cdot \eta_{inv} \cdot \eta_b} \tag{8}$$

where E_L is the load, AD is autonomy days (typically 3–5 days), DOD is the depth of discharge (80%), η_{inv} and η_b are the inverter (95%), and battery (85%) efficiencies.

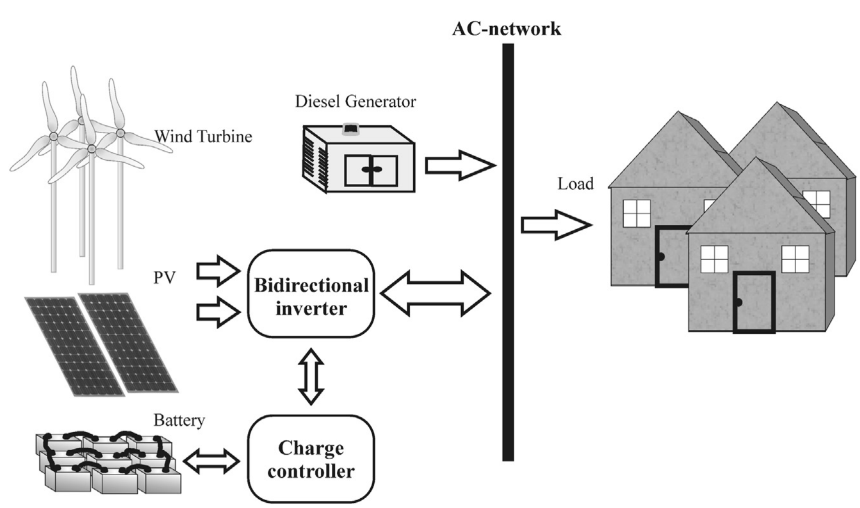

Fig. 3. Schematic of a typical HMGS.

Table 2
Input parameters.

Parameter	Unit	Value
Diesel generator		
Life time	hours	24,000
Initial cost	$/kW	1000
Rated power	kW	4
Inverter		
Efficiency	%	92
Life time	year	24
Initial cost	$	2500
Battery		
Efficiency	%	85
Life time	year	12
Initial cost	$/kWh	280
Rated power	kWh	40
PV		
PV regulator efficiency	%	95
Life time	year	24
Initial cost	$/kW	3400
Rated power	kWh	7.3
PV regulator cost	$	1500
Economic parameters		
Discount rate	%	8
Real interest	%	13
O&M + running cost	%	20
Fuel inflation rate	%	5
Project life time	year	24
Wind		
Model		ZEYU FD-2KW
Wind regulator cost	$	1000
Blades diameter	m	6.4
Swept area	m^2	128.6
Efficiency		0.95
Cut out	m/s	40
Cut in	m/s	2.5
Rated speed	m/s	9.5
Rated power	kW	5
Price	$/kW	2000
Life time	year	24

3.2. Load profile

Studying the load profile of an area is critical in designing a reliable and efficient system for that area. The sizing and modeling of batteries depend on the load profile. Moreover, peak times and the behavior of consumers affect the reliability of the system as well as the sizing of the components and the price of electricity.

The hourly load profile of the typical rural area is shown in Fig. 5. The maximum load is considered as 2 kW, which is sufficient for the basic load of a household. Such a system can power a ranch home's systems and can run lights, fans, TV, refrigerator, computer, etc.

3.3. Power management strategies

The unpredictable nature of renewable resources leads to a very complex power management strategy for HMGS's, especially when it is essential to have a reliable source of energy to match the time distribution of load demand. Since the amount of generated power from renewable resources is limited, the capacity of the generator cannot be immediately increased to match the increase in demand. Moreover, sometimes the amount of electricity generation is more than the demand; in this case, a dump load is required to dissipate excess energy produced and protect the batteries from overcharging. Therefore, having a power management strategy would be one of the main criteria to design such systems. The following cases will be considered in the simulation to apply power management strategies:

Case 1 Sufficient generated energy is provided by renewable sources and the extra energy is used to charge a battery bank.

Case 2 Same as *case* 1 but the surplus energy generated by renewable resources is greater than the need to supply the load and the battery bank. Therefore, in this case the surplus of power is consumed in a dump load.

Case 3 Renewable resources fail to provide sufficient energy to meet the load. The priority in this case, is to use the stored

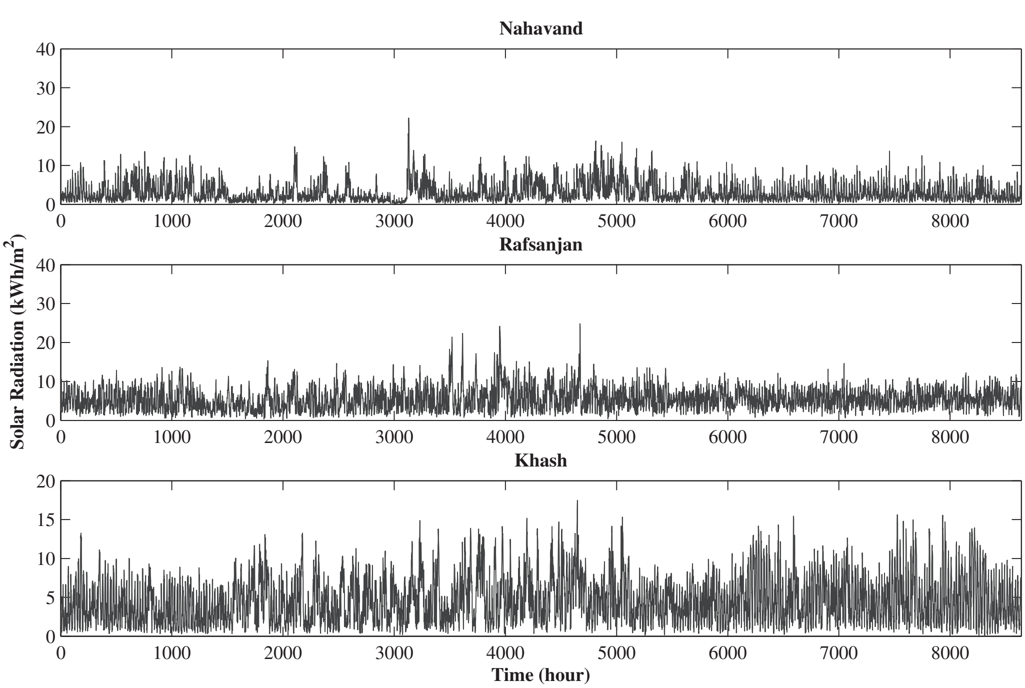

Fig. 4. Solar radiation during a year.

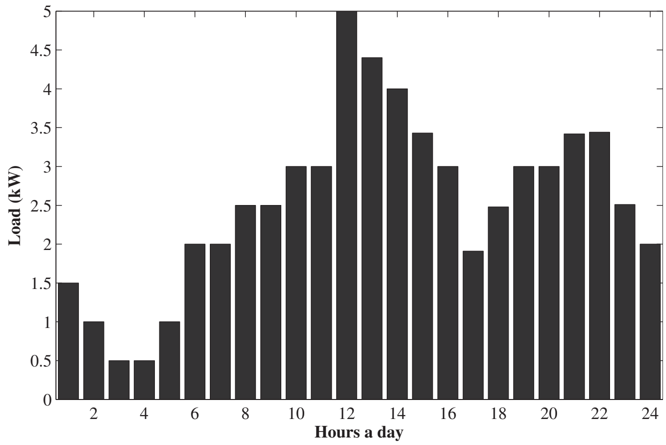

Fig. 5. Hourly typical rural household load profile (kW).

energy in the batteries rather than operating the diesel generator. In this case, the shortage of power generation is supplied from a battery.

Case 4 The generated energy from the renewable sources is not sufficient to meet the demanded load and the battery bank is also depleted. In this case the diesel generator is switched on to supply the load and to charges the batteries.

The main flowchart, for different modes of operation, is shown in Fig. 6. The algorithms for strategy 2, strategy 3, and strategy 4 are given in Figs. 7–9, respectively.

4. Optimization

To design a low cost and highly efficient HMGS, priority should be given to sizing the system components. The combination of generation sources and using high quality components also has a considerable influence on the life time of the system, and can decrease the cost of electricity for end-users in remote areas.

4.1. Cost analysis

Cost of electricity (COE) is one of the most well-known and used indicators of economic profitability of hybrid renewable energy systems [55]. It is defined as the constant price per unit of energy (or cost per unit of electricity). It is calculated using the following expression [19,55,56]

$$\mathrm{COE}\left(\frac{\$}{\mathrm{kWh}}\right) = \frac{\mathrm{Total\ Net\ Present\ cost}(\$)}{\sum_{h=1}^{h=8760} P_{\mathrm{load}}(\mathrm{h})(\mathrm{kWh})} \times \mathrm{CRF} \tag{9}$$

Total net present cost includes all the installed capital costs, i.e. the present cost, operation and maintenance cost, and replacement cost. $P_{\mathrm{load}}(\mathrm{h})$ is the hourly power consumption. CRF is a ratio to calculate the present value of the system components for a given time period taking into consideration the interest rate. It is calculated by:

$$\mathrm{CRF} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{10}$$

where, i is the real interest rate and n is the system life period (or Amortization period), which is usually equal to the life of the PV panel, due to its longer life expectancy as compared to other components [57].

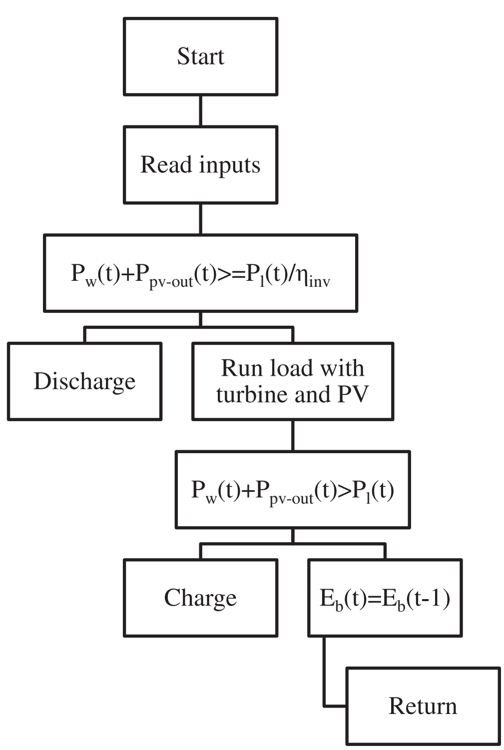

Fig. 6. Main flowchart of the hybrid system.

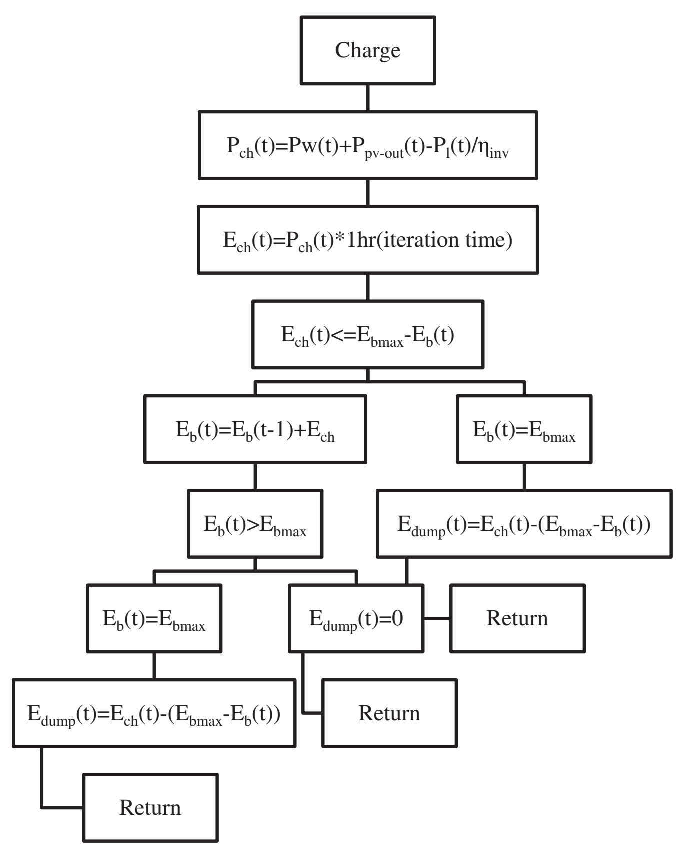

Fig. 7. Flowchart of the charging mode of operation.

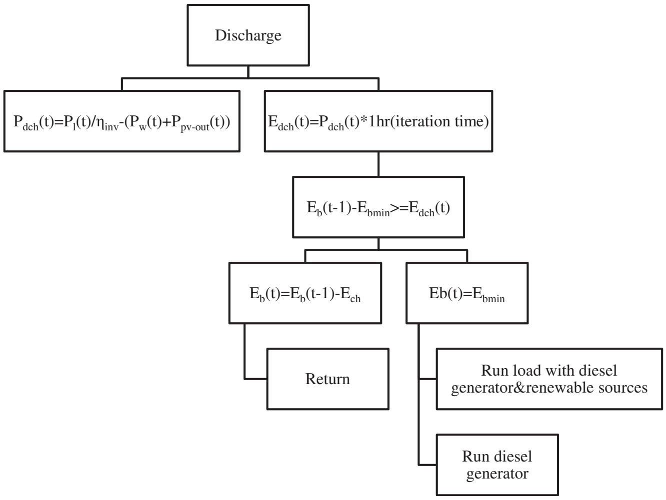

Fig. 8. Flowchart of the discharging mode of operation.

4.2. Reliability analysis

Loss of power supply probability (LPSP) is a statistical parameter, which indicates the probability of power supply failure either due to low renewable resource or technical failure to meet demand. There are two methods of calculating LPSP, i.e. chronological simulation and probabilistic techniques. The former technique uses time-series data in a given period and the latter is based on the energy accumulative effect of the energy storage system, as shown in equation (11) [30]. It can be described by the following equation [19,50,58,59]:

$$\mathrm{LPSP} = \frac{\sum\left(P_{\mathrm{load}} - P_{\mathrm{pv}} - P_{\mathrm{wind}} + P_{\mathrm{soc_{min}}} + P_{\mathrm{diesel}}\right)}{\sum P_{\mathrm{load}}} \tag{11}$$

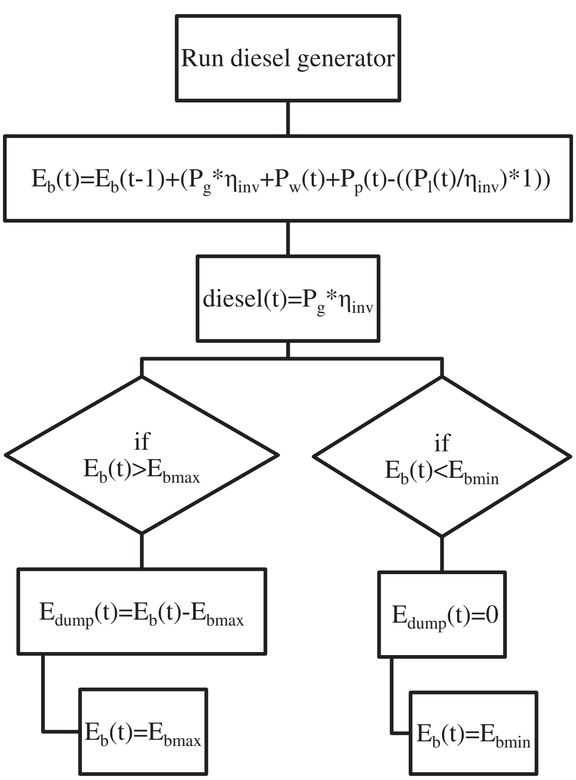

Fig. 9. Flowchart of the diesel mode of operation.

In this study the reliability evaluations are carried out in the worst conditions, when

$$P(t)_{\mathrm{Load}} > P(t)_{\mathrm{generate}}.$$

4.3. Renewable factor

Renewable factor is defined for PSO programing as a boundary to determine the amount of energy coming from a diesel generator as compared to the renewable generator. The renewable factor of 100% shows the ideal system based on renewable resources only. However the renewable factor of zero percent shows that the amount of power coming from a diesel generator is equivalent to the power from renewable resources. Hence:

$$\text{Renewable factor}(\%) = \left(1 - \frac{\sum P_{\mathrm{diesel}}}{\sum P_{\mathrm{pv}} + \sum P_{\mathrm{wind}}}\right) \times 100 \tag{12}$$

4.4. Multi objective optimization

Optimization of HMGS is considered as a multi-objectives problem and there are many methods to solve such an issue. However, among them all, linear scalarization is a popular approach due to its simplicity. In this method a multi-objective problem is converted into a single objective problem in which objectives can either combine in a linear function or treated as constraints. The goal is to optimize the linear function as well as satisfy some inequality constraints to find a single point in Pareto front as the best solution [60,61]. The fitness function computes as:

$$\text{fitness} = \min\left\{\sum_{i=1}^{k} w_i \frac{f_i(x)}{f_i^{\max}}\right\} \text{with } w_i \geq 0 \text{ and } \sum_{i=1}^{k} w_i = 1 \tag{13}$$

and the constraints define as:

$$\min g_i(x) \geq 0 \text{ for } i \in \{1, \ldots, m\} \tag{14}$$

where x is the vector of decision variables, the weights (w_i) indicate the relative importance of each objective, k is the number of objectives, f is the objective function, and $f_i^{\max}$ is the upper bound of ith objective function.

In hybrid generation systems the COE and LPSP are equally important concerns to achieve the optimum system which can guarantee reliable and uninterrupted supply of energy at a competitive cost with the conventional power derived from the fossil fuel and grid extension. In order to balance these two objectives the weights (w_i) are adjusted at 0.5 for both.

4.5. Particle swarm optimization

PSO first described by Kenney and Eberhart in 1995, was inspired by two separate concepts: the idea of swarm intelligence based on the social interaction exhibited by swarm, and the field of evolutionary computation. In PSO algorithm, two best values determine each particle's position. The first one is the best value that the particle achieved so far and has been stored. This value is named as individual best. Another one is obtained by the PSO optimizer among the population so far, which is called global best. Also each particle has a position representing the value of variables and a velocity that directs the particle towards the individual and global bests. The fitness function is a particular type of objective function to find the best solution from among all feasible solutions. In PSO, the constraints can also be included in the fitness function.

The PSO algorithm consists of three main steps, as follows:

- Evaluate the fitness of each particle
- Update individual and global best fitness and position
- Update velocity and position of each particle

Each particle remembers the best fitness value it has achieved during the operation of the algorithm. The particle with the best fitness value compared to other particles is also calculated and updated during iterations. The process is repeated until some stopping criteria, such as the number of iterations or predefined target fitness values are met.

The position of each particle in the swarm is updated using the following equation:

$$x^i_{k+1} = x^i_k + v^i_{k+1} \tag{15}$$

where x is particle position and v is particle velocity in the iteration k. The velocity is calculated as follows [62]:

$$v^i_{k+1} = k \times \left[v^i_k + c_1 r_1 \left(p^i_k - x^i_k\right) + c_2 r_2 \left(p^g_k - x^i_k\right)\right] \tag{16}$$

$$k = \frac{2}{\left|2 - \varnothing - \sqrt{\varnothing^2 - 4\varnothing}\right.} \tag{17}$$

$$\varnothing = c_1 - c_2 \quad \varnothing > 4 \tag{18}$$

where, P^i is the best individual particle position and P^g is the best global position, c_1 and c_2 are the cognitive and social parameters, respectively; r_1 and r_2 are random numbers between 0 and 1. c_1 and c_2 are usually close to 2 and affect the size of particle's step towards the individual best and global best, respectively. In this study, both values are assumed to be 2 in order to attract the particle towards the best points equally.

V^i_k, called inertia, makes the particle move in the same direction and with the same velocity.

$c_1.r_1.(p^i_k - x^i_k)$, is called the cognitive component, and causes the particle to return to a previous position in which it has experienced higher individual fitness.

$c_2.r_2.(p^i_k - x^i_k)$, is called the social component, which causes the particle to tend to return to the best region the swarm has found so far and to follow the best neighbor's direction. If $c_1 >> c_2$ then each particle is more attracted to individual best positions, conversely, if $c_2 >> c_1$, then the particles are more attracted to the global best positions.

In this paper, the fitness function is defined as minimum COE (Cost of Electricity) and LPSP (Loss of power supply probability), and a penalty term is associated with the inequality constraint of a renewable factor. The main program is developed in MATLAB software to design and manage the power and the operation of the system.

4.5.1. PSO optimization procedure

The complete flow of the algorithm applied for techno-economic analysis of HMGS is given below.

Step1) Initialization.

a) Load meteorological data (hourly wind speed, solar radiation, and ambient temperature during one year)
b) Load component's characteristics (according to Table 2)
c) Load economic parameters (according to Table 2)
d) Set the constants:
   Number of houses for a hybrid system (load) = 15
   Personal and global learning coefficients, $c_1 = c_2 = 1$,
   Inertia weight, $w = 0.5$, and
   Inertia weight damping ratio, $W_{damp} = 0.99$
e) Set the constraint:
   Renewable energy factor (equation (12)) greater than the value of 0.01
f) The list of tasks is as follows. The dimension of the PSO algorithm is the number of tasks.
   Upper bound and lower bound of nominal power of PV (kW), [45,15]
   Upper bound and lower bound of autonomy days, [3,0]
   Upper bound and lower bound of the number of wind turbines, [10,0] and
   Upper bound and lower bound of the number of diesel generators, [4,0]
g) The position and velocity of particles are randomly selected in order to generate the initial population and then applied to the objective functions to find the optimum fitness value.
h) If the positions of randomly chosen particles exceed the limitation of renewable factor, return to (d).
   Evaluate each particle in the swarm and find the best fitness value among the whole swarm (minimum COE and LPSP).
i) Set the global best value. The particle with minimum price of electricity and loss of power supply probability is chosen as the global best.

Step2) Update iteration variable.
Step3) Update inertia weight.
Step4) Update velocities.
Step5) Update positions.
Step6) Apply the updated values of the objective function to find COE and LPSP.
Step7) Update individual best position.
Step8) Update global best position.
Step9) Stopping criterion. If the number of iterations exceeds the maximum number of iterations then stop; otherwise go to step 2.

It is noteworthy that the idea in Step 1.f is to define our search space. In each iteration, LPSP and COE of generated particles are calculated and if they meet our constraint (Step 1.e), then they will be accepted as PSO particles in the population.

5. Results

5.1. Simulation results

Three locations in Iran – Nahavand, Rafsanjan, and Khash – are used in this study to investigate the optimization of a Hybrid Micro-

Table 3
PSO result.

Station	Nahavand	Rafsanjan	Khash
Number of iterations	100		
Number of particles	100		
Power of PV panels (kW)	45	45	45
Days of autonomy	3	3	3
Number of wind turbines	10	10	10
Power of diesel generator (kW)	4	1	1
LPSP (%)	8	7	9
COE ($/kWh)	1.87	0.32	0.35
Renewable factor (%)	60	97	95

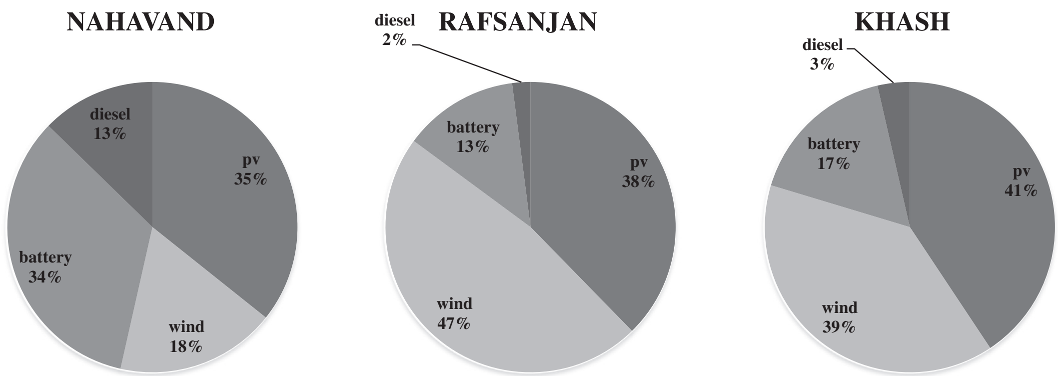

Fig. 10. Percentage of energy provided by PV, wind turbine, diesel generator, and battery through a year.

Grid System (HMGS). For the load profile, a typical rural daily load with a peak of 2 kW is used for each house. Moreover, the community consists of 15 households. The input parameters are tabulated in Table 2.

The power management strategy for a Hybrid Micro-Grid System is performed to maintain a continuous power to the load demand in different modes of operation. The Particle Swarm Optimization (PSO) method is applied in order to obtain the best configuration of system and for sizing the components. The Cost of Electricity (COE) and Loss of Power Supply Probability (LPSP) are defined as objective functions (equation (13)).

The results show that PSO provides optimum wind, solar, and battery ratings. The best founded solution displayed in Table 3. As shown, the PSO optimization model produces appropriate sizing for each location. Nahavand has less renewable resources compared to the other two stations. As a result using diesel generators is compulsory for this location to meet the demand load. The results are also reflected in the higher price of electricity as well as low renewable energy factor. Rafsanjan, which is located in the central part of Iran has high wind speed and moderate solar radiation. The results from PSO optimization show that the highest reliability with lowest cost and high contribution of renewable energy are achieved for this location. The third station is in Khash, which is located in the southeastern part of Iran with high renewable resources. The result is close to Rafsanjan and the potential for using a micro-grid system for this location is also very high. Khash is located in one of the poorest provinces in Iran. Therefore, using renewable energy for this location can enhance the energy access of the poor communities and increase their standard of living. It is also evident that using wind turbine in Iran has a great advantage as it reaches the upper band for the three stations. However, by increasing the number of wind turbines the LPSP of the system is highly increased and therefore the upper limit is remained the same.

The percentage of energy provided by PV, wind turbine, diesel generator, and battery over a year are represented in Fig. 10. As can be seen, Nahavand's HMGS basically works on battery and diesel generator due to the low potential of renewable energy. However, Rafsanjan with a high potential for wind energy and solar energy can be a good location to apply HMGSs. Khash is located in the province of Sistan–Baluchestan, one of the poorest provinces in Iran, which has the lowest human development index in the country. The result of optimization in this location shows that the HMGS can be applied for this location with a high value for renewable factor. Therefore, using renewable energy can be considered as a good alternative to enhance energy access in remote areas in Iran. The utilization of the proposed method can help to overcome some of the technical barriers that still limit the distribution of micro-grid projects.

Swarms motion in 100 iterations is graphed in Fig. 11. It can be seen that 100 particles fly from random initialization toward the particle best and global best so that all the particles converge to one

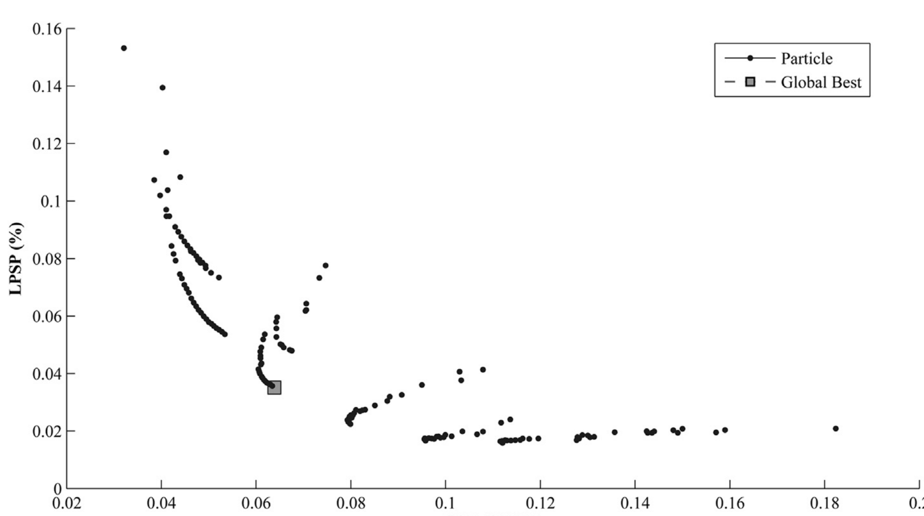

Fig. 11. PSO simulation process.

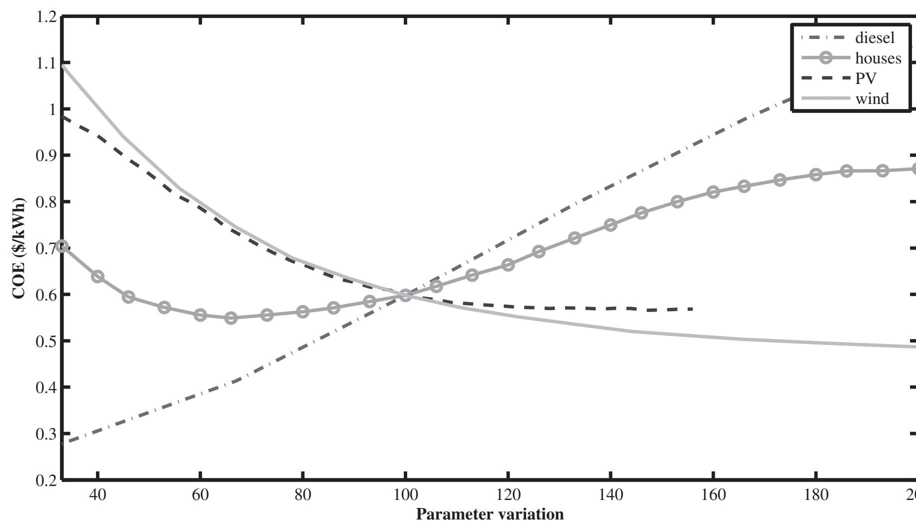

Fig. 12. Sensitivity of COE to variation of different parameters.

point which is called Global best. Since the optimal combinations can be located in some far points from each other with the same fitness value and different configurations in the objective domain, designing such systems is a complex task. Nevertheless, the particles become very close to each other after 100 iterations and the best combination is identified. Moreover, the results for some independent runs almost converge to the same optimal fitness value.

However, as it can be clearly seen from Fig. 11, the linear aggregation function usually cannot find all Pareto front points of interest to solve multi-objective problems [61]; therefore in order to find a better decision, the number of points on Pareto front should be increased either by variation of the w_i through the program or other nonlinear aggregation functions which will be presented in future works.

5.2. Sensitivity analysis

The sensitivity analysis has been extended to qualify and quantify the effect of parametric variation in the cost of electricity for HMGS, which is computed by PSO algorithm. Four input parameters were selected as sensitivity coefficients and the results were computed with respect to the nominal points in Table 3. The effect of COE, as one of the main objectives, was analyzed due to the variation of the number of wind turbines, diesel generator, PV power, and number of households in the community. For sensitivity analysis, parameter variations from 33% to above 160% were considered and the sensitivity curve is shown in Fig. 12. It can be seen from the graph that the COE is more affected by a variation in the number of diesel generators due to their fuel consumptions. The number of households in the community has a nonlinear effect on COE. It can also be observed that the COE values are larger and more sensitive for a lower number of wind turbine and PV panels. However, the cost will be less and more stable by increasing the number of renewable resources. The reason lies in the fact that PV panels and wind turbines have a long life time in comparison to other components of the system.

6. Conclusion

Access to a reliable source of electricity is a basic need for any community; it can improve the standard of living by enhancing healthcare, education and the local economy. Implementation of micro-grids can be considered as the most promising solution for rural electrification by decreasing the installation costs and increasing the supply quality. This paper proposes a control strategy for a Hybrid Micro-Grid System to maintain continuous power to the load demand in different modes of operation. The combination of wind, PV, diesel generator, and battery storage with variable loads is considered for this purpose. The Multi-Objective Particle Swarm Optimization (MOPSO) method is applied in order to obtain the best configuration of the system and sizing of the components. The Cost of Electricity (COE) and Loss of Power Supply Probability (LPSP) are defined as objective functions. Sensitivity analysis is also carried out in order to verify the results. The meteorological data of three stations in Iran – Nahavand, Rafsanjan, and Khash – which are located in the northwest, central and southeast of Iran, are tested for this purpose. Nahavand's HMGS basically works on a battery and diesel generator, due to the low potential of renewable energy. However, Rafsanjan with its high potential for wind energy and solar energy can be a good location to apply HMGSs. Khash, which is located in the province of Sistan–Baluchestan, one of the poorest provinces in Iran, has the lowest human development index in the country; the result of optimization in this location shows that HMGS can be applied for this location with a high renewable factor. Therefore, using renewable energy can be considered as a good alternative to enhance energy access in remote areas in Iran. The utilization of the proposed method can help to overcome some of the technical barriers that still limit the distribution of micro-grid projects. It can be also used as a starting point or a support tool to promote electrification projects and design efficient projects faster.

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