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Optimum Design of a Hybrid Renewable Energy System

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1. Introduction

In Iran, 100% of the region populated with more than 20 families is electrified. For the other regions the electrification will be done. These regions almost are rural and remote areas. For utility company it is important that electrification be done with the least cost.

Many alternative solutions could be used for this goal (decreasing the cost). Using renewable energy system is one of the possible solutions. A growing interest in renewable energy resources has been observed for several years, due to their pollution free energy, availability, and continuity. In practice, use of hybrid energy systems can be a viable way to achieve trade-off solutions in terms of costs. Photovoltaic (PV) and wind generation (WG) units are the most promising technologies for supplying load in remote and rural regions [Wang et al., 2007]. Therefore, in order to satisfy the load demand, hybrid energy systems are implemented to combine solar and wind energy units and to mitigate or even cancel out the power fluctuations. Energy storage technologies, such as storage batteries (SBs) can be employed. The proper size of storage system is site specific and depends on the amount of renewable energy generation and the load.

Many papers are discussed on design of hybrid systems with the different components. Also, various optimization techniques are used by researchers to design hybrid energy system in the most cost effective way.

Rahman and Chedid give the concept of the optimal design of a hybrid wind-solar power system with battery storage and diesel sets. They developed linear programming model to minimize the average production cost of electricity while meeting the load requirements in a reliable manner, and takes environmental factors into consideration both in the design and operation phases [Chedid et al., 1997]. In [Kellogg et al, 1996], authors proposed an iterative technique to find the optimal unit sizing of a stand-alone and connected system. In 2006 is presented a methodology for optimal sizing of stand-alone PV/WG systems using genetic algorithms. They applied design approach of a power generation system, which supplies a residential household [Koutroulis et al, 2006]. In [Ekren, 2008], authors used the response surface methodology (RSM) in size optimization of an autonomous PV/wind integrated hybrid energy system with battery storage. In [Shahirinia, 2005], an optimized design of stand-alone multi sources power system includes sources like, wind farm, photovoltaic array, diesel generator, and battery bank based on a genetic algorithm is presented. Also, authors in [Koutroulis et al, 2006, Tina, 2006] used multi-objective genetic algorithm, in

order to calculate reliability/cost implications of hybrid PV/wind energy system in small isolated power systems. Yang developed a novel optimization sizing model for hybrid solar-wind power generation system [Yang et al., 2007]. In [Terra, 2006] an automatic multi-objective optimization procedure based on fuzzy logic for grid connected HSWPS design is described. In some later works, PSO is successfully implemented for optimal sizing of hybrid stand-alone power systems, assuming continuous and reliable supply of the load [Lopez, 2008, Belfkira, 2008]. Karki and Billinton presented a Monte-Carlo simulation approach to calculate the reliability index [Karki et al., 2001] and Kashefi presented a method for assessment of reliability based on binomial distribution function for hybrid PV/wind/fuel cell energy system that is used in this study [Wang et al., 2007].

As previous studies shown, renewable energies are going to be a main substitute for fossil fuels in the coming years for their clean and renewable nature [Sarhaddi et al., 2010]. Photovoltaic solar and wind energy conversion systems have been widely used for electricity supply in isolated locations that are far from the distribution network.

The future of power grids is expected to involve an increasing level of intelligence and integration of new information and communication technologies in every aspect of the electricity system, from demand-side devices to wide-scale distributed generation to a variety of energy markets.

In the smart grid, energy from diverse sources is combined to serve customer needs while minimizing the impact on the environment and maximizing sustainability. In addition to nuclear, coal, hydroelectric, oil, and gas-based generation, energy will come from solar, wind, biomass, tidal, and other renewable sources. The smart grid will support not only centralized, large-scale power plants and energy farms but residential-scale dispersed distributed energy sources [Santacana et al., 2010].

Being able to accommodate distributed generation is an important characteristic of the smart grid. Because of mandated renewable portfolio standards, net metering requirements and a desire by some consumers to be green, there is an increasing need to be prepared to be able to interconnect generation to distribution systems, especially renewable generation such as photovoltaic, small wind and land fill gas powered generation [Saint, 2009].

The future electric grid will invariably feature rapid integration of alternative forms for energy generation. As a national priority, renewable energy resources applications to offset the dependence on fossil fuels provide green power options for atmospheric emissions curtailment and provision of peak load shaving are being put in policy [Santacana et al., 2010]. Fortunately, Iran is a country with the adequate average of solar radiation and wind speed for setting up a hybrid power generation e.g. the average of wind speed and perpendicular solar radiation were recorded for Ardebil province is 5.5945 m/s and 203.1629 W/m² respectively in a year.

In this study, an optimal hybrid energy generation system including of wind, photovoltaic and battery is designed. The aim of design is to minimize the cost of the stand-alone system over its 20 years of operation. The optimization problem is subject to economic and technical constraints. Figure 1 shows the framework of activities in this study.

The generated power by wind turbine and PV arrays are depended on many parameters that the most effectual of them are wind speed, the height of WT's hub (that affects the wind speed), solar radiations and orientation of PV panels. In certain region, the optimization variables are considered as the number of WTs, number of PV arrays, installation angle of PV arrays, number of storage batteries, height of the hub and sizes of DC/AC converter. The

goal of this study is optimal design of hybrid system for the North West of Iran (Ardebil province). The data of hourly wind speed, hourly vertical and horizontal solar radiation and load during a year are measured in the region. This region is located in north-west of Iran and there are some villages far from the national grid. The optimization is carried out by Particle Swarm Optimization (PSO) algorithm. The objective function is cost with considered economical and technical constraints. Three different scenarios are considered and finally economical system is selected.

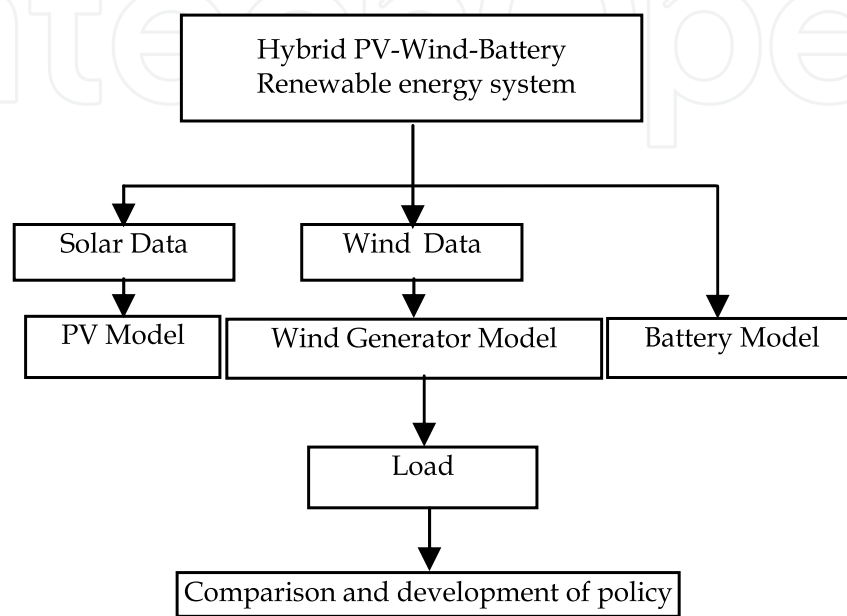


Fig. 1. The framework of activities

This study is organized as follows: section 2 describes the modeling of system components. The reliability assessment is discussed in section 3. Problem formulation and operation strategy are explained in section 4 and 5, respectively. In the next section, is dedicated to particle swarm optimization. Simulation and results are summarized in section 7. Finally, section 8 is devoted to conclusion.

2. Description of the hybrid system

The increasing energy demand and environmental concerns aroused considerable interest in hybrid renewable energy systems and its subsequent development.

The generation of both wind power and solar power is very dependent on the weather conditions. Thus, no single source of energy is capable of supplying cost-effective and reliable power. The combined use of multiple power resources can be a viable way to achieve trade-off solutions. With combine of the renewable systems, it is possible that power fluctuations will be incurred. To mitigate or even cancel out the fluctuations, energy storage technologies, such as storage batteries (SBs) can be employed [Wang et al., 2009].

The proper size of storage system is site specific and depends on the amount of renewable generation and the load. The needed storage capacity can be reduced to a minimum when a proper combination of wind and solar generation is used for a given site [Kellogg, 1996]. The hybrid system is shown in Fig. 2. In the following sections, the model of components is discussed.

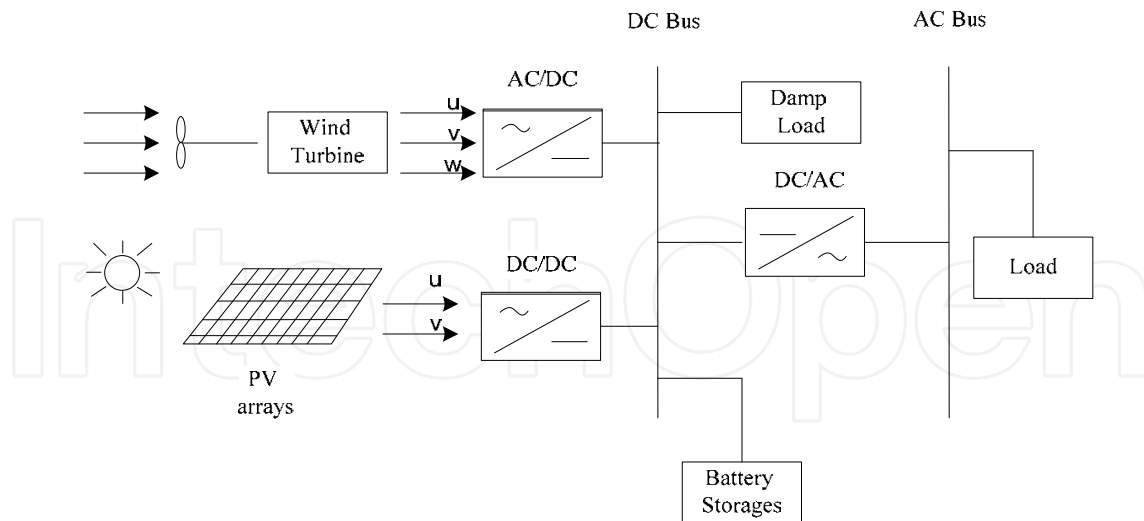


Fig. 2. Block diagram of a hybrid wind/photovoltaic generation unit

2.1 The wind turbine

Choosing a suitable model is very important for wind turbine power output simulations. The most simplified model to simulate the power output of a wind turbine could be calculated from its power-speed curve. This curve is given by manufacturer and usually describes the real power transferred from WG to DC bus.

The model of WG is considered BWC Excel-R/48 (see Fig. 3) [Hakimi et al., 2009]. It has a rated capacity of 7.5 kW and provides 48 V dc as output. The power of wind turbine is described in terms of the wind speed according to Eq. 1.

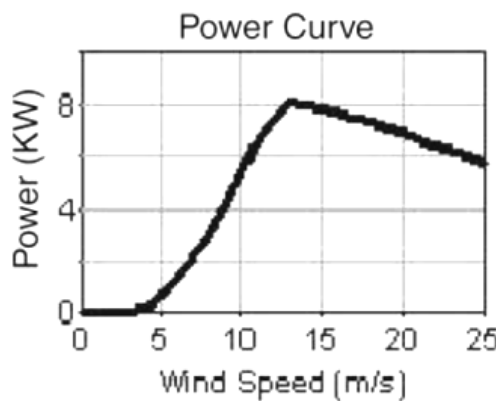


Fig. 3. Power output characteristic of BWC Excel R/48 versus wind speed [Hakimi, 2009].

$$P_W = \begin{cases} 0 & v_W \leq v_{ci}, v_W \geq v_{co} \\ P_{W_{max}} \times \left(\frac{v_W - v_{ci}}{v_r - v_{ci}} \right)^m & v_{ci} \leq v_W \leq v_r \\ P_{W_{max}} + \frac{P_f - P_{W_{max}}}{v_{co} - v_r} \times (v_W - v_r) & v_r \leq v_W \leq v_f \end{cases} \quad (1)$$

where $P_{WG_{max}}$, P_f are WG output power at rated and cut-out speeds, respectively. Also, v_r , v_{ci} , v_{co} are rated, cut-in and cut-out wind speeds, respectively. In this study, the exponent m is considered 3. In the above equation, v_W refers to wind speed at the height of WG's hub. Since, v_W almost is measured at any height (here, 40 m), not in height of WGs hub, is used Eq. (2) to convert wind speed to installation height through power law [Borowy et al., 1996]:

$$v_W = v_W^{measure} \times \left(\frac{h_{hub}}{h_{measure}} \right)^\alpha \quad (2)$$

where α is the exponent law coefficient. α varies with such parameters as elevation, time of day, season, nature of terrain, wind speed, temperature, and various thermal and mechanical mixing parameters. The determination of α becomes very important. The value of 0.14 is usually taken when there is no specific site data (as here) [Yang et al., 2007].

2.2 The photovoltaic arrays (PVs)

Solar energy is one of the most significant renewable energy sources that world needs. The major applications of solar energy can be classified into two categories: solar thermal system, which converts solar energy to thermal energy, and photovoltaic (PV) system, which converts solar energy to electrical energy. In the following, the modeling of PV arrays is described.

For calculating the output electric power of PVs, perpendicular radiation is needed. When the hourly horizontal and vertical solar radiation is available (as this study), perpendicular radiation can be calculated by Eq. (3):

$$G(t, \theta_{PV}) = G_V(t) \times \cos(\theta_{PV}) + G_H(t) \times \sin(\theta_{PV}) \quad (3)$$

where, $G_V(t)$ and $G_H(t)$ are the rate of vertical and horizontal radiations in the t^{th} step-time (W/m^2), respectively. The radiated solar power on the surface of each PV array can be calculated by Eq. (4):

$$P_{pv} = \frac{G}{1000} \times P_{pv, rated} \times \eta_{MPPT} \quad (4)$$

where, G is perpendicular radiation at the arrays' surface (W/m^2). $P_{pv, rated}$ is rated power of each PV array at $G = 1000(W/m^2)$ and η_{MPPT} is the efficiency of PV's DC/DC converter and Maximum Power Point Tracking (MPPT).

2.3 The storage batteries

Since both wind and PVs are intermediate sources of power, it is highly desirable to incorporate energy storage into such hybrid power systems. Energy storage can smooth out the fluctuation of wind and solar power and improve the load availability [Borowy et al., 1996].

When the power generated by WGs and PVs are greater than the load demand, the surplus power will be stored in the storage batteries for future use. On the contrary, when there is any deficiency in the power generation of renewable sources, the stored power will be used to supply the load. This will enhance the system reliability.

In the state of charge, amount of energy that will be stored in batteries at time step of t is calculated:

$$E_B(t) = E_B(t-1) + \left((P_w + P_{pv})(t) - P_{Load}(t) / \eta_{inv.} \right) \eta_{Bat} \quad (5)$$

In addition, Eq. 6 will calculate the state of battery discharge at time step of t :

$$E_B(t) = E_B(t-1) + \left(P_{Load}(t) / \eta_{inv.} - (P_w + P_{pv})(t) \right) \eta_{Bat} \quad (6)$$

where, $E_B(t)$, $E_B(t-1)$ are the stored energy of battery in time step of t and $(t-1)$. P_w , P_{pv} are the generated power by wind turbines and PV arrays, $P_{Load}(t)$ is the load demand at time step of t and η_{Bat} is the efficiency of storage batteries.

2.4 The power inverter

The power electronic circuit (inverter) used to convert DC into AC form at the desired frequency of the load. The DC input to the inverter can be from any of the following sources:

1. DC output of the variable speed wind power system
2. DC output of the PV power system

In this study, supposed the inverter's efficiency is constant for whole working range of inverter (here 0.9).

3. The reliability assessment

A widely accepted definition of reliability is as follows [Billinton, 1992]: "Reliability is the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered". In the following sections, reliability indices and reliability model that is used in this study is described.

3.1 Reliability indices

Several reliability indices are introduced in literature [Billinton, 1994, XU et al., 2005]. Some of the most common used indices in the reliability evaluation of generating systems are Loss of Load Expected (LOLE), Loss of Energy Expected (LOEE) or Expected Energy not Supplied (EENS), Loss of Power Supply Probability (LPSP) and Equivalent Loss Factor (ELF).

In this study, ELF is chosen as the main reliability index. On the other word, the ELF index is chosen as a constraint that must be satisfied but it could be possible to calculate the other indexes as is done in this study (such as EENS, LOLE and LOEE indexes).

ELF is ratio of effective load outage hours to the total number of hours. It contains information about both the number and magnitude of outages. In the rural areas and stand-alone applications (as this study), $ELF < 0.01$ is acceptable. Electricity supplier aim at 0.0001 in developed countries [Garcia et al., 2006]:

$$ELF = \frac{1}{H} \sum_{h=1}^H \frac{E(Q(h))}{D(h)} \quad (7)$$

where, $Q(h)$ and $D(h)$ are the amount of load that is not satisfied and demand power in h^{th} step, respectively and H is the number of time steps (here $H=8760$).

In this study, the reliability index is calculated from component's failure, that is concluding of wind turbine, PV array, and inverter failure.

3.2 System's reliability model

As mentioned, outages of PV arrays, wind turbine generators, and DC/AC converter are taken into consideration. Forced outage rate (FOR) of PVs and WGs is assumed to be 4% [Karki et al., 2001]. So, these components will be available with a probability of 96%. Probability of encountering each state is calculated by binomial distribution function [Nomura 2005].

For example, given n_{WG} fail out of total N_{WG} installed WGs, and n_{PV} fail out of total N_{PV} installed PV arrays are failed, the probability of encountering this state is calculated as follows:

$$f_{ren}(n_{WG}^{fail}, n_{PV}^{fail}) = \left[\binom{n_{WG}^{fail}}{N_{WG}} \times A_{WG}^{N_{WG}-n_{WG}^{fail}} \times (1 - A_{WG})^{n_{WG}^{fail}} \right] \times \left[\binom{n_{PV}^{fail}}{N_{PV}} \times A_{PV}^{N_{PV}-n_{PV}^{fail}} \times (1 - A_{PV})^{n_{PV}^{fail}} \right] \quad (8)$$

The outage probability of other components is negligible. But, because, DC/AC converter is the only single cut-set of the system reliability diagram, the outage probability of it is taken consideration (it's FOR is considered 0.0011 [Kashefi et al., 2009]).

In [Kashefi et al., 2009] an approximate method is used that proposed all the possible states for outages of WGs and PV arrays to be modeled with an equivalent state. This idea is modeled by Eq. 7.

$$E[P_{ren}] = N_{WG} \times P_{WG} \times A_{WG} + N_{PV} \times P_{PV} \times A_{PV} \quad (9)$$

4. Problem formulation

The economical viability of a proposed plant is influence by several factors that contribute to the expected profitability. In the economical analysis, the system costs are involved as:

- Capital cost of each component
- Replacement cost of each component
- Operation and maintenance cost of each component
- Cost costumer's dissatisfaction

It is desirable that the system meets the electrical demand, the costs are minimized and the components have optimal sizes. Optimization variables are number of WGs, number of PV arrays, installation angle of PV arrays, number of storage batteries, and sizes of DC/AC converter. For calculation of system cost, the Net Present Cost (NPC) is chosen.

For optimal design of a hybrid system, total costs are defined as follow:

$$NPC_i = N_i \times (CC_i + RC_i \times K_i + O \& MC_i \times 1 / CRF(ir, R)) \quad (10)$$

where N may be number (unit) or capacity (kW), CC is capital cost (US\$/unit), $O\&MC$ is annual operation and maintenance cost (US\$/unit-yr) of the component. R is Life span of project, ir is the real interest rate (6%). CRF and K are capital recovery factor and single payment present worth, respectively.

$$ir = \frac{(ir_{nominal} - f)}{(1 + f)} \quad (11)$$

$$CRF(ir, R) = \frac{ir(1 + ir)^R}{(1 + ir)^R - 1} \quad (12)$$

$$K_i = \sum_{n=1}^{y_i} \frac{1}{(1 + ir)^{n \times L_i}} \quad (13)$$

4.1 The cost of loss of load

In this study, cost of electricity interruptions is considered. The values found for this parameter are in the range of 5-40 US\$/kWh for industrial users and 2-12 US\$/kWh for domestic users [Garcia et al., 2006]. In this study, the cost of customer's dissatisfaction, caused by loss of load, is assumed to be 5.6 US\$/kWh [Garcia et al., 2006].

Annual cost of loss of load is calculated by:

$$NPC_{loss} = LOEE \times C_{loss} \times PWA \quad (14)$$

where, C_{loss} is cost of customer's dissatisfaction (in this study, US\$5.6/kWh). Now, the objective function with aim to minimize total cost of system is described:

$$Cost = \sum_i NPC_i + NPC_{loss} \quad (15)$$

where i indicates type of the source, wind, PV, or battery. To solve the optimization problem, all the below constraints have to be considered:

$$\begin{aligned} 0 &\leq N_i < N_{max} \\ 10 &\leq H_{hub} \leq 20 \\ 0 &\leq \theta_{PV\&PVT} \leq \pi/2 \\ E_{bat_{min}} &\leq E_{bat} \leq E_{bat_{max}} \\ E[ELF] &\leq ELF_{max} \end{aligned} \quad (16)$$

The last constraint is the reliability constraint. Equivalent Loss Factor is ratio of effective load outage hours to the total number of hours. In the rural areas and stand-alone applications (as this study), $ELF < 0.01$ is acceptable [Tina, 2006]. For solving the optimization problem, particle swarm algorithm has been exploited.

5. Operation strategy

The system is simulated for each hour in period of one year. In each step time, one of the below states can occur:

- If the total power generated by PV arrays and WGs are greater than demanded load, the energy surplus is stored in the batteries until the full energy is stored. The remainder of the available power is consumed in the dump load.

- If the total power generated by PV arrays and WGs are less than demanded load, shortage power would be provided from batteries. If batteries could not provide total energy that loads demanded, the load will be cut.
- If the total power generated by PV arrays and WGs are equal to the demanded load, the storage capacity remains unchanged and all of the generated power will be consumed at the load.

By consideration these states and all the constraints, the optimal hybrid system is calculated.

6. Optimization method

For size optimization of components PSO algorithm is used. Direct search method (traditional optimization method) heavily depends on good starting points, and may fall into local optima. On the other hand, as a global method for solving both constrained and unconstrained optimization problems based on natural evolution, the PSO can be applied to solve a variety of optimization problems that are not well suited for standard optimization algorithms. Moreover, the GA can also be employed to solve a variety of optimization problems. Compared to GA, the advantages of PSO are that PSO is easy to implement and there are few parameters to adjust. PSO has been successfully applied in many areas.

6.1 The PSO algorithm

Particle swarm optimization was introduced in 1995 by Kennedy and Eberhart. The following is a brief introduction to the operation of the PSO algorithm. The particle swarm optimization (PSO) algorithm is a member of the wide category of swarm intelligence methods for solving global optimization problems. PSO is an evolutionary algorithm technique through individual improvement plus population cooperation and competition which is based on the simulation of simplified social models, such as bird flocking, fish schooling and the swarm theory [Jahanbani et al., 2008].

Each individual in PSO, referred as a particle, represents a potential solution. In analogy with evolutionary computation paradigms, a swarm is similar to population, while a particle is similar to an individual.

In simple terms, each particle is flown through a multidimensional search space, where the position of each particle is adjusted according to its own experience and that of its neighbors.

Assume x and v denote a particle position and its speed in the search space. Therefore, the i^{th} particle can be represented as $x_i = [x_{i_1}, x_{i_2}, \dots, x_{i_d}, \dots, x_{i_N}]$ in the N -dimensional space. Each particle continuously records the best solution it has achieved thus far during its flight. This fitness value of the solution is called $pbest$. The best previous position of the i^{th} particle is memorized and represented as:

$$pbest_i = [pbest_{i_1}, pbest_{i_2}, \dots, pbest_{i_d}, \dots, pbest_{i_N}] \quad (17)$$

The global best $gbest$ is also tracked by the optimizer, which is the best value achieved so far by any particle in the swarm. The best particle of all the particles in the swarm is denoted by $gbest_d$. The velocity for particle i is represented as $v_i = [v_{i_1}, v_{i_2}, \dots, v_{i_d}, \dots, v_{i_N}]$.

The velocity and position of each particle can be continuously adjusted based on the current velocity and the distance from $pbest_{i_d}$ to $gbest_d$:

$$v_i(t+1) = \omega(t)v_i(t) + c_1r_1(P_i(t) - X_i(t)) + c_2r_2(G(t) - X(t)) \quad (18)$$

$$X_i(t+1) = X_i(t) + \chi v_i(t+1) \quad (19)$$

where c_1 and c_2 are acceleration constants and r_1 and r_2 are random real numbers drawn from $[0,1]$. Thus the particle flies through potential solutions toward $P_i(t)$ and $G(t)$ in a navigated way while still exploring new areas by the stochastic mechanism to escape from local optima.

Since there was no actual mechanism for controlling the velocity of a particle, it was necessary to impose a maximum value V_{max} , which controls the maximum travel distance in each iteration to avoid this particle flying past good solutions. Also after updating the positions, it must be checked that no particle violates the boundaries of search space. If a particle has violated the boundaries, it will be set at boundary of search space [Jahanbani et al., 2008].

In Eq. (20), $\omega(t)$ is employed to control the impact of the previous history of velocities on the current one and is extremely important to ensure convergent behavior. It is exposed completely in the following section. $\omega(t)$ is the constriction coefficient, which is used to restrain velocity. χ is constriction factor which is used to limit velocity, here $\chi = 0.7$.

7. Simulation results

The first goal of each planning in electrical network is that the system meets the demand. For satisfying this goal, the cost of customer's dissatisfaction is considered as well as the other costs. Flowchart of the proposed optimization methodology is shown in Fig. 4. The hourly data of wind speed, vertical and horizontal solar radiation and residential load during a year is plotted in Fig. 5, Fig. 6 and Fig. 7, respectively. The data that used in this study is the data of Ardebil convince that is located in the North West of Iran (latitude: $38^{\circ}17'$, longitude: $48^{\circ}15'$, altitude: 1345 m). The peak load is considered as 50 kW. In table 1, data that used in the simulation are listed.

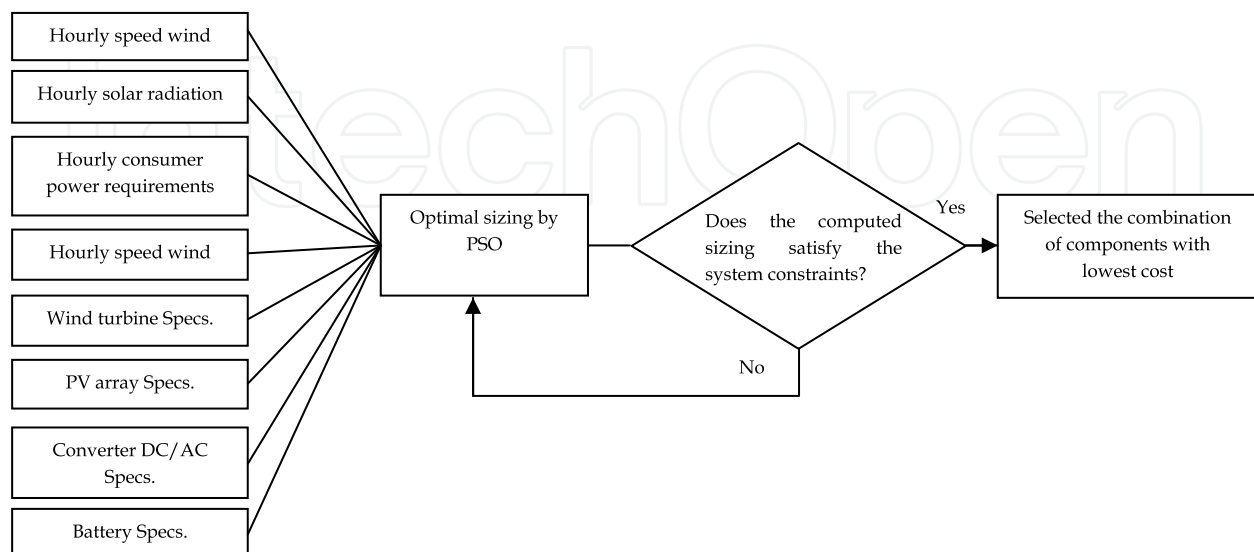


Fig. 4. Flowchart of the proposed optimization methodology.

System parameters	values	System parameters	values
Efficiency of SB	85%	Replacement price of PV array	6000 US\$/unit
Efficiency of inverter	90%	Replacement price of SB	700 US\$/unit
Life span of project	20	Replacement price of inverter	750 US\$/unit
Life span of WTG and PV	20	OM costs of inverter	8 US\$/unit-yr
Life span of SB	10	Cut-in wind speed	3 m/s
Life span of inverter	15	Rated wind speed	13 m/s
PV array price	7000 US\$/unit	Cut-out wind speed	25 m/s
WTG price	19400 US\$/unit	Rated WTG power	7.5 kW
Inverter price	800 US\$/unit	Minimum storage level of battery	3 kWh
Replacement price of WTG	15000 US\$/unit	Maximum total SB capacity	40 kWh

Table 1. Data used for simulation program [Tina et al., 2006, Khan et al., 2005]

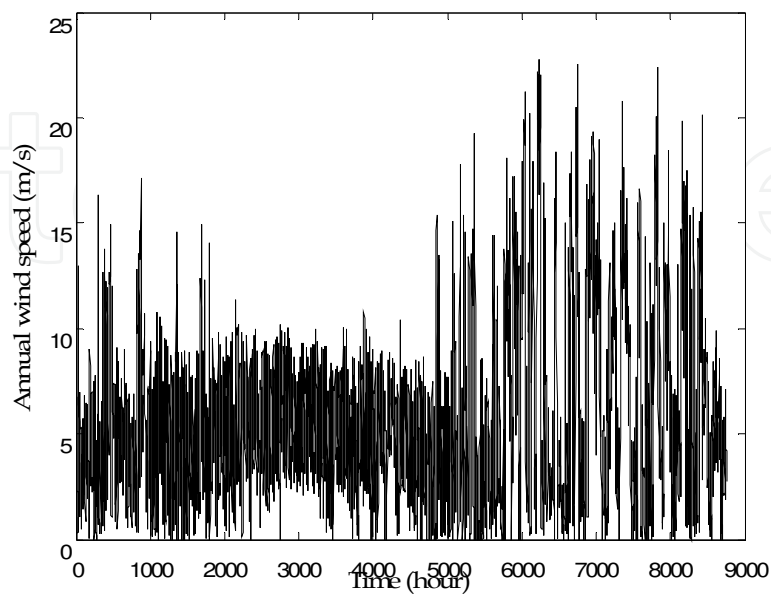


Fig. 5. Hourly wind speed during a year.

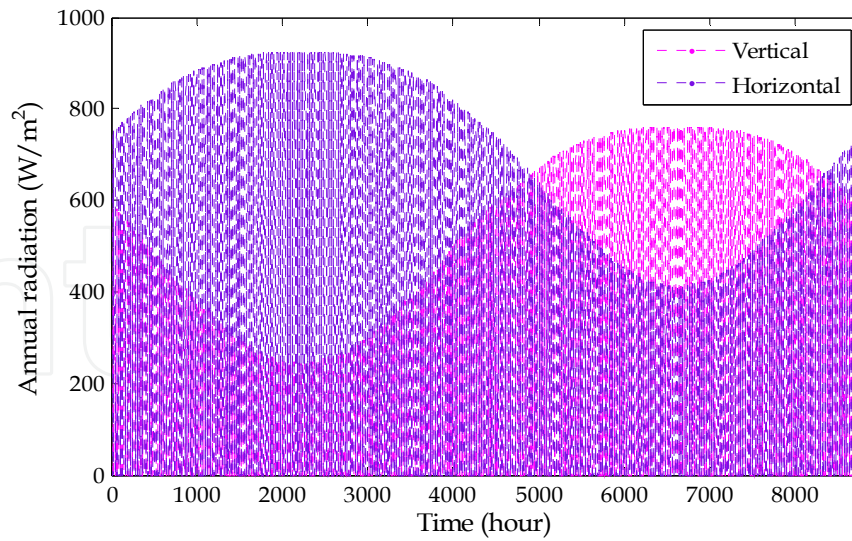


Fig. 6. Hourly vertical and horizontal solar radiation during a year.

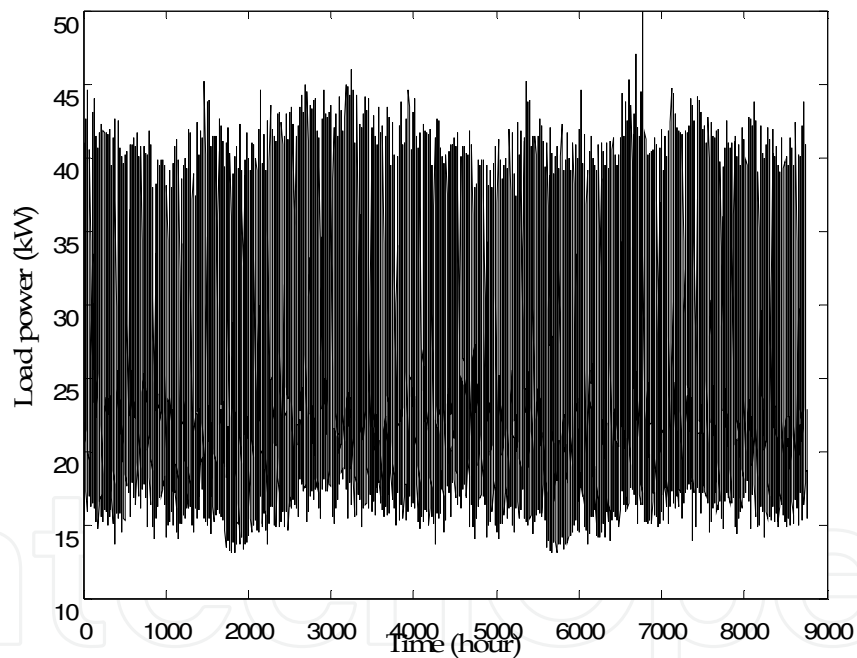


Fig. 7. Hourly residential load during a year.

It is noticeable that the technical constraint, related to system reliability, is expressed by the equivalent loss factor. The reliability index is calculated from component's failure, that includes wind turbine, PV array, battery and inverter failure. The power generated by each wind turbine and PV array can be derived by Eq. (1) and Eq. (3), respectively. The total power that can be generated with N_{WG} wind turbines and N_{PV} PV arrays that n_{WG} and n_{PV} of all wind turbines and PV arrays are out of work, respectively, will be calculated as follows:

$$P_{ren} = (N_{WG} - n_{WG}) \times A_{WG} \times P_{WG} + (N_{PV} - n_{PV}) \times A_{PV} \times P_{PV} \quad (20)$$

As previously mentioned, the reliability constraint is considered as the penalty factor in the objective function. To consider the constraint of reliability in Eq. (16), the excess amount of inequality constraint is multiplied by 1010 and then, this additional cost is added to the objective function in Eq. (15). With this method, the NPC of the system that couldn't satisfy the reliability constraint will increase, and then this system would not be chosen as the best economic system.

One of the best methods in the planning area is using scenario method. To choose the best plan (the minimum cost) different scenarios is implemented. In this study, the optimal size of components for hybrid system is calculated in three scenarios based on proposed approach. These systems are PV/battery system, wind/battery system and PV/wind/battery system. For each system the minimum cost and reliability indices is calculated. The results are shown in the following.

As mentioned before, in this study particle swarm optimization algorithm is used for optimal sizing of system's components. Each particle has 6 variables that are defined as below:

Number of wind turbine	Number of PV array	Angle of PV	Battery capacity	Height of hub	Inverter capacity
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Fig. 8. A typical vector for a particle

Each population consists of 30 particles that are calculated for 120 iterations. The fitness function is defined in Eq. (15). It must be considered that if the costs of loss of load are more expensive than the cost of bigger system, the bigger system will be chosen because it is economically reasonable.

7.1 Scenario I: Wind/PV/battery hybrid system

In this case, a stand-alone hybrid system is considered that is including of wind and PV energy sources and storage batteries. Convergence curves of the PSO algorithm, for five independent runs, are shown in Fig. 9. It is observed that the algorithm converges almost to the same optimal value.

Hourly generated power of PV arrays, WGs is shown in Fig. 10 that could be comparing with load. The hourly expected amount of stored energy in the battery is shown in Fig. 10, too. It is significant that reliable supply of the load at each time step, strongly, depends on the amount of the stored energy. When stored energy in battery reaches its minimum allowable limit, if renewable system cannot satisfy the load, the load will not be supplied. On the other hand, if renewable system can satisfy the load, the extra generated energy will be saved in the battery (and battery is in the state of charge). It is worth pointing out that when the battery has the maximum charge its energy will not increase anymore.

In Fig. 11, the hourly reliability indices in the year are plotted. The amount of hourly demand and load pattern is another important factor in reliability assessment of the system. The size of each component is also calculated and is shown in table 2.

As shown in the above figures, each time step could be analyzed. For example, at around of 6500th time step, the power that is generated by PV arrays and wind turbines is decreased (Fig. 10) and it is not enough to satisfy the load. Also, the energy that saved in the batteries in this step is around the minimum allowable level. So, some of the demand is lost and ELF index is equal to 0.5 (Fig. 11).

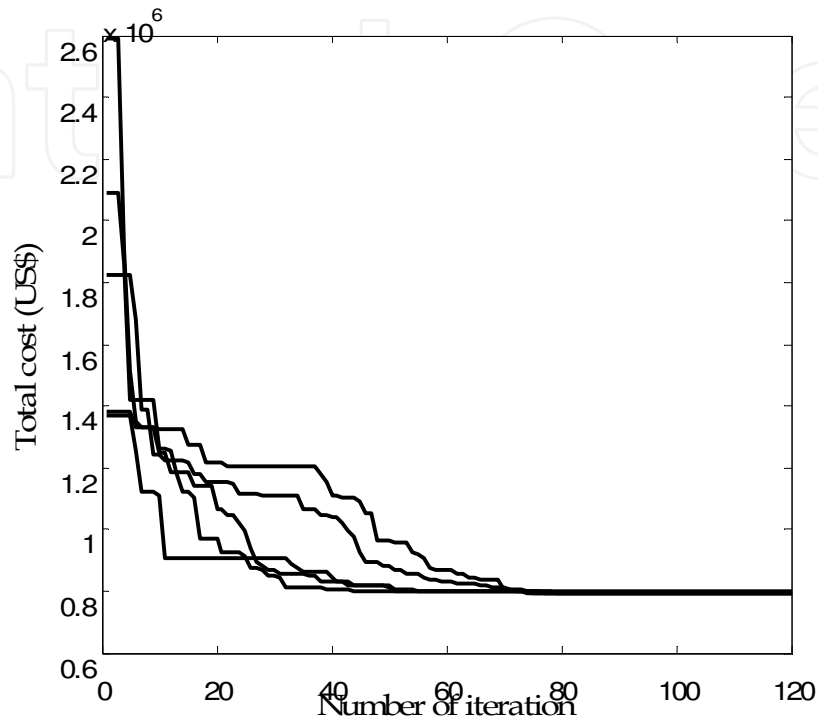


Fig. 9. Convergence of the optimization algorithm

N_{WG}	N_{PV}	N_{Bat}	$P_{inv} (kW)$	θ_{PV}	$H_{hub}(m)$
1	89	12	44	52.61	15.85

Table 2. Optimal combination for hybrid system

ELF	$LOEE (kWh/yr)$	$EENS$	$LOLE(h/yr)$
0.0036	759.49	0.0034	64.57

Table 3. Reliability indices of PV-wind-battery system

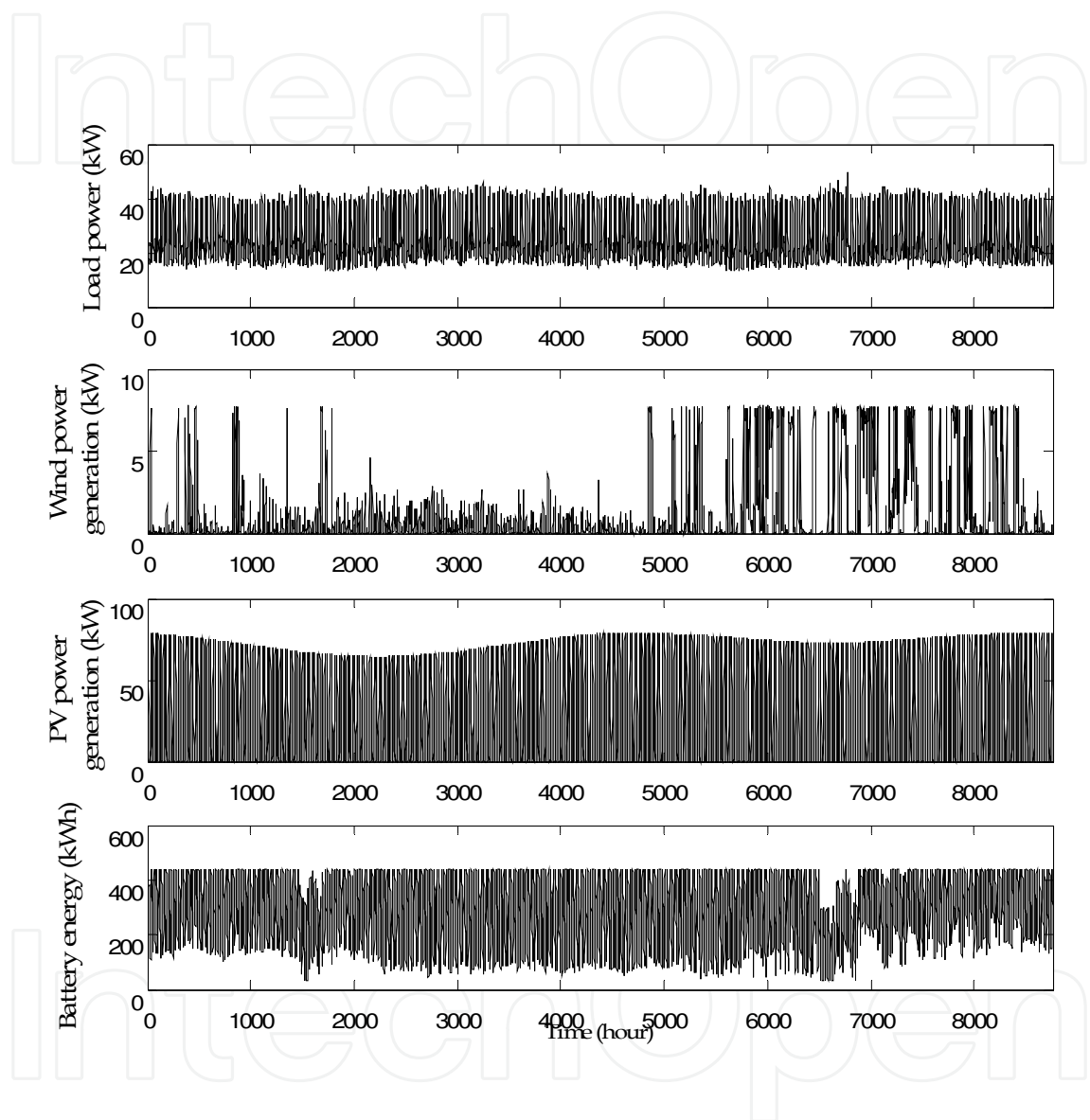


Fig. 10. Hourly generated power of PV arrays, WGs and hourly expected amount of stored energy in the battery during a year.

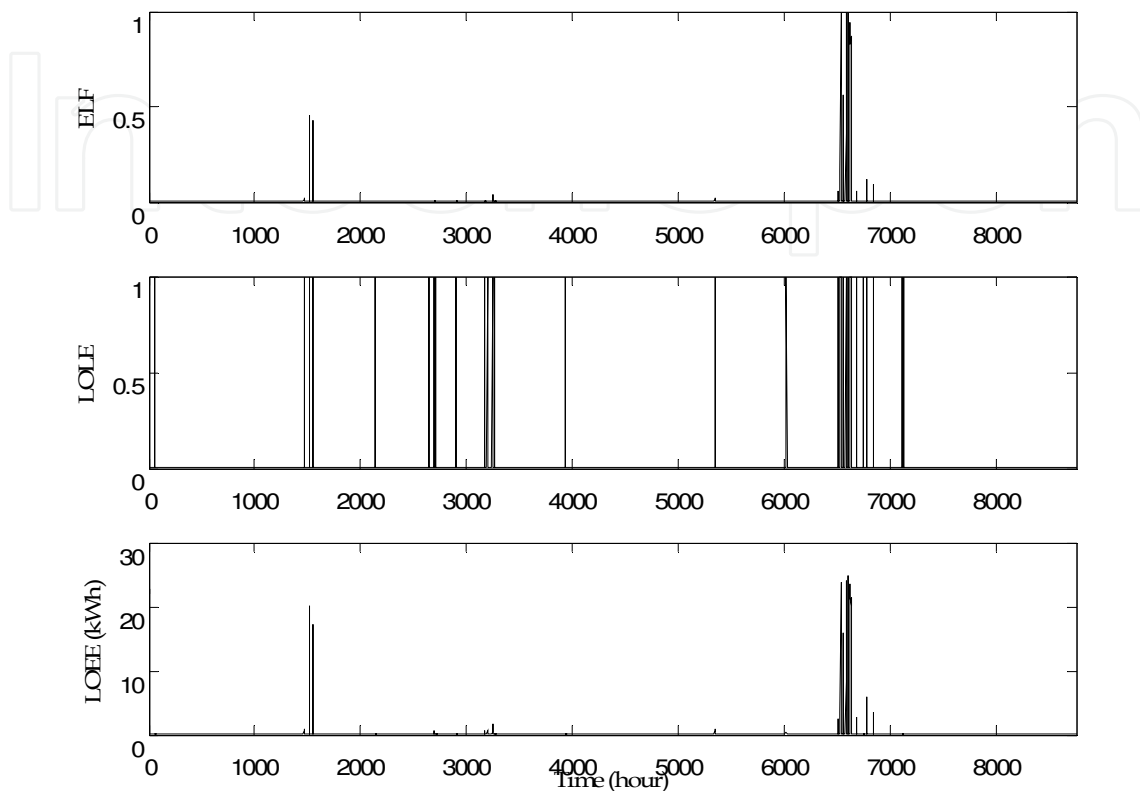


Fig. 11. Hourly reliability indices during a year

In this scenario, the mean of ELF index in the year is 0.002 which is less than the maximum ELF tconstraint (0.01). So, this system would not pay for penalty cost. The NPC, which is calculated for this case, would be equal to 1.29769 MUSD that 31272.02 USD of this cost would be for customer's dissatisfaction.

7.2 Scenario II: Wind/battery system

This system is including of wind source energy and storage batteries. The optimal size of system components is presented in table 4. In this case, the reliability constraint is activated, so it is fixed on maximum allowable value. Because of this, the NPC of system is increased and is reached up to 2.25009 MUS\$. The generated power by wind turbines and amount of energy in storage system is shown in Fig. 12.

As mentioned, in this system, the ELF index is reached to 0.0063 which satisfy the inequality constraint of reliability constraint. Thus, it must not pay the penalty cost and the customer's dissatisfaction cost would be 0.032424 MUS\$.

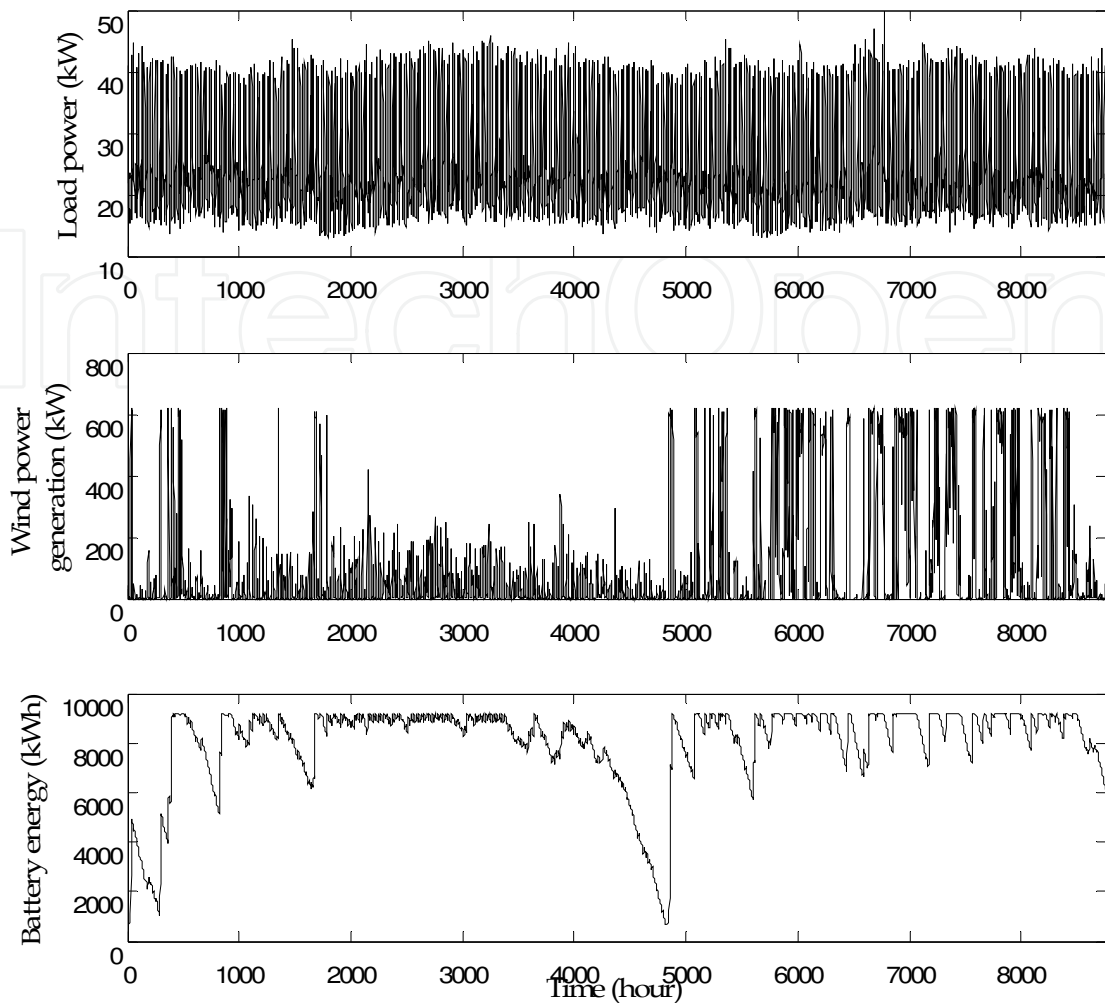


Fig. 12. Hourly generated power of WGs and hourly expected amount of stored energy in the battery during a year.

N_{WG}	N_{PV}	N_{Bat}	$P_{inv} (kW)$	θ_{PV}	$H_{hub}(m)$
80	-	230	44.5	-	19

Table 4. Optimal combination in wind-Battery system

ELF	$LOEE (kWh/yr)$	$EENS$	$LOLE(h/yr)$
0.0063	1315.6	0.0063	77.56

Table 5. Reliability indices of wind-battery system

7.3 Scenario III: PV/Battery systems

The last scenario is a system including of PV source energy and storage batteries. The size of system components is shown in table 6. Total cost and ELF index corresponding to this case are 0.803237 MUS\$ and 0.0022 respectively that, 0.032423 MUS\$ would be paid as customer’s dissatisfaction cost. The output power of PV arrays and battery energy is shown in Fig. 13.

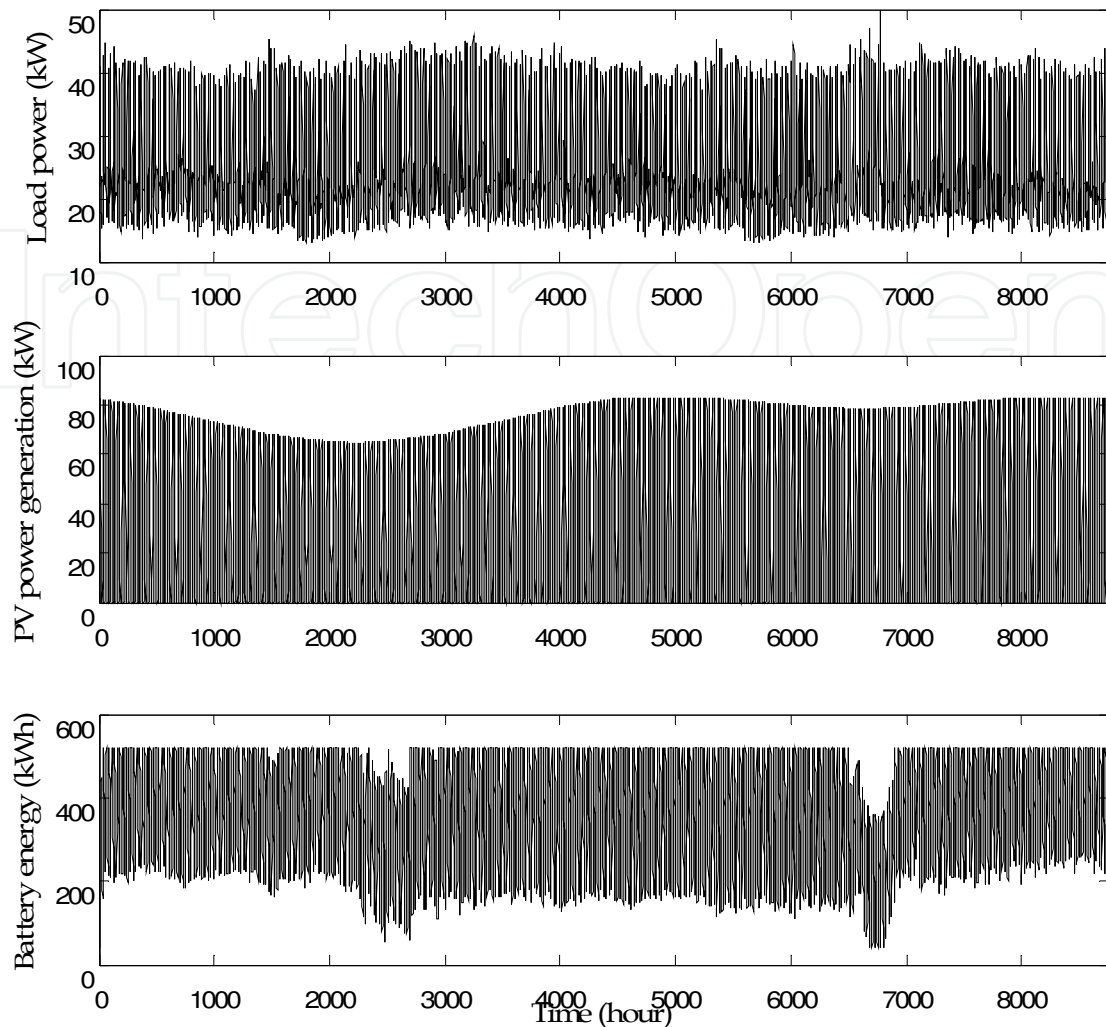


Fig. 13. Hourly generated power of PV arrays and hourly expected amount of stored energy in the battery during a year.

N_{WG}	N_{PV}	N_{Bat}	P_{inv} (kW)	θ_{PV}	$H_{hub}(m)$
-	96	13	44.3	56.74	11

Table 6. Optimal combination in PV-battery system

ELF	$LOEE$ (kWh/yr)	$EENS$	$LOLE$ (h/yr)
0.0022	504.79	0.0024	49.59

Table 7. Reliability indices of PV-battery system

With compare of these scenarios together, it could be seen, the number of batteries in wind-battery system is more than the hybrid system and PV-battery system. That's reasonable because in this region (and almost all of regions) fluctuations of wind are more than the fluctuations in radiation, so, when the wind turbine is used, we needed to add more storage system to be sure that the load would be met in all steps. Also, in this region, the peak load is nearer to the peak of PV generation compared with the peak of wind generation. On the

other hand, Because of this, the reliability index in the system with wind turbine is less than the system with PV array and subsequently, because of increase in costumer's dissatisfaction cost, the cost of the system with wind turbine is more than the system with PV array.

In any of the scenarios, the reliability constraint is not activated and each scenario will be able to satisfy the inequality constraints without penalty cost. As mentioned before, it is possible to analyze each point of the results to investigate the relation between changes of wind, solar radiation and load with ELF index and charging and discharging states of batteries.

8. Conclusions

In this paper, a hybrid generation system is designed for a 20-year period of operation for the North west of Iran. The major components are PV arrays and wind turbines. The major advantage of these components is that when used together, the reliability of the system is enhanced. Additionally, the size of storage systems can be reduced as there is less reliance on one method of power production. Often, when there is no sun, there is plenty of wind and vice versa.

The number of components is directly dependent on the load pattern. The region has a cold climate thus electricity demand in summer is not significantly more than the demand in winter. This is an advantage because the needed battery will decrease and the design system will be more economical.

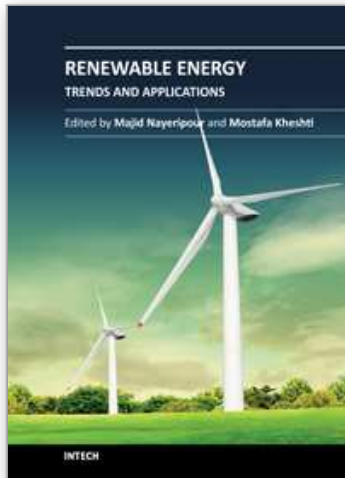
In this study, the batteries are employed as the energy storage system. Optimal combination of components is achieved by particle swarm optimization. The optimization problem is subject to economical and technical constraints. Best configuration with considered reliability constraint is achieved and the system is simulated.

In the future work of this study, uncertainty factors such as generator failures and renewable power availability will also be taken into account in calculating system reliability indexes.

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