Optimal Sizing and Management of Hybrid Renewable Energy System for Highways Lighting

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Abstract- The energy consumption for the purpose of lighting has comprised about 30% of energy consumption and around 45% to 50% of peak load in Iran. Based on the statistics of the road maintenance and transportation organization of Iran (RMTO), the quantity of installed lighting equipment had significant growth in recent years. An appropriate combination of renewable energy resources leads to reliable, green and economic generation system. Using hybrid solar-wind systems to supply street lightings' required energy with low-power lamps is an impressive method to decrease energy consumption. In this paper, a comprehensive study is carried out to achieve an optimal design for a hybrid solar-wind system that supplies electricity to the roads and highways lights in Iran. In the proposed approach, to achieve an optimum design for the hybrid system, suitable options for each part of the system is selected according to its technical specifications, and then the capacity and the number of components is determined in order to minimize an objective function comprised of a cost function, loss of power supply probability (LPSP) and subject to satisfy prevailing technical constraints. Bat algorithm (BA) is employed to solve the proposed optimization problem. Simulation results show the effectiveness of the proposed method in various situations of operation for the case study of Tabriz city regard to pertaining load profile and weather data. The case study is categorized into three scenarios in which the hybrid system has different schemes, and the results show that the proposed hybrid system is notably practical and cost-effective to supply electrical energy of highway and street lightings.

Keywords: Hybrid Energy System, Bat Algorithm, Renewable Energy, Optimization, Street Lightings, Energy Cost.

1. Introduction

Energy consumption is experiencing an irregular and immethodical raise in both developing (%5) and developed countries (%1) [1-2]. Based on statistics and information issued by the international energy agency (IEA), in the next few years, incremental demand will be remarkable in developing countries. It is notable that the economic growth in China and other developing countries have a slowing trend. However, USA's demand will continue to have incremental demand [3]. Tensions and conflicts in the Middle East have increased concerns about the production and consumption of crude oil and gas [4]. According to performed studies, the amount of annual global consumption has estimated in the range of 16.9 TW in average, and it is expected to get duplicated in the next 40 years [5-6]. Fossil fuels and petroleum are the main resources of supplying this enormous amount of energy [7-8]. Combustion of these substances will release a huge amount of gas emission and will cause drastic air pollution [9]. Such pollutant gases and emissions not only have a destructive effect on atmosphere and environment but also cause serious harms on human health [10-12].

Regard to the mentioned topics, it is needed to enhance renewable energy sources (RES) as an appropriate alternative for fossil fuels in the energy part of leading countries to achieve sustainable development [13-16]. Another advantage of renewable energy sources, in contrast with fossil sources, is its appropriate contribution all over the world so that it is enough to cover all global energy demand [17-20]. According to the conducted researches, the global potential of wind sources has been estimated about 72 TW, so that this capacity is more than five times of the world's energy needs and more than 40 times of electricity consumption in 2011

[21-22]. Similarly, the received solar energy on the earth's surface is equal to 0.9 billion TWh of electricity, so that this potential capacity of energy exploitation is 6000 times more than current annual consumption of the world [23-24].

In recent years Iran is affected by technology developments, family modernization, and electronic devices usage expansion. Also, the country has experienced a significant increment in its energy consumption (particularly fossil fuels) due to energy resources abundance. These two factors and lack of environment-friendly technology caused many environmental problems. Therefore, the study of integration of renewable energy sources in Iran in order to decrease air pollution and increase economic growth is very important [25].

In recent years based on managers and energy experts' attitude about renewable energies usage, numerous researches have been conducted in Iran in clean energies field [26-30]. In addition to the efforts which are taken to expand renewable and sustainable generation, some other actions are done in the field of use of new lamps and lighting devices which have lower consumption and pollution. As mentioned before, in Iran a relatively large part of consumed energy is used to supply needed electricity for lighting [31]. Around 4% of total consumed energy and around 6% of peak loads is used for highway and another urban street lights [32-33].

Base on road maintenance and transportation organization of Iran statistics, the total length of light-equipped suburban roads is increased from 1921 Km in 2006 to 4156 Km in 2014. Accordingly, the length of the light-equipped freeways and length of light-equipped highway is increased from 279 and 966 Km in 2006 to 538 and 2267 Km in 2014 respectively. Furthermore, the amount of installed light equipment has had 116 % growth, during 10 recent years in Iran. The high penetration of wind and solar energy potential in Iran necessitates the utilization of hybrid solar-wind systems in order to supply electrical energy for highways and street's lighting with low-power energy-efficient lamps [34].

Various types of method are presented to design optimum hybrid wind and solar system [35-49]. As it is mentioned in [35], the authors employed a network-independent pattern to design a hybrid (PV/wind/Batt) system with high reliability and minimum overall cost. The results of a study in [35] show that PSO-CF algorithm gives more reasonable results. But in this study, the researcher has not represented a specific strategy in order to optimize system reliability modeling. The authors in [36] have used a new meta-heuristic algorithm called Cuckoo Search (CS) for hybrid energy system design. The focus of authors in [36] is only on reliability indices of the system such as loss of load expected (LOLE) and expected energy not supplied (EENS) without any discussion about economic relations. In addition, in [37], an effective method using Hybrid Big Bang–Big Crunch (HBB–BC) algorithm for optimal sizing of a stand-alone hybrid power system containing photovoltaic panel, wind turbine, and battery bank is presented. In [37], the authors have used expected energy not supplied (EENS) for reliability modeling which is not appropriate to analyze of highly sensitive electrical loads, which incur an extraordinary and irrecoverable cost by load shedding. This matter necessitates the employment of other reliability indices types beside EENS. Moreover, as it is discussed in [38], the genetic algorithm (GA) is employed to investigate a tri-objective design of a grid independent PV/Wind/Split-diesel/Battery hybrid energy system for a typical residential building with the objective of minimizing the Life Cycle Cost (LCC), CO_2 emissions and dump energy. In [38], the system reliability mode is not presented. In addition, the proposed approach is not compared with other available methods. The author in [39] has used a mine blast algorithm (MBA) to solve the optimal sizing of a hybrid system consisting of photovoltaic modules, wind turbines and fuel cells (PV/WT/FC) to meet a certain load of a remote area in Egypt. The main objective of the optimal sizing process is to achieve the minimum annual cost of the system with load coverage. The researcher is only pursuing annual costs minimization and has not carried out any system reliability modeling. In [40], a wind–solar standalone hybrid energy system (HES) for an un-electrified village in the central part of India – Madhya Pradesh is represented. To implement this standalone HES sizing, ant colony optimization technique has been used. In this study reliability and economic modeling is well described, however, the simulation period is very short and ACO algorithm results have not compared with results of other similar algorithms.

As expressed in [41], a hybrid renewable energy system (PV/WT/battery) optimization model based on particle swarm optimization in Kerman, Iran, is performed. They used different PSO variants to find the optimal design variable amounts which are minimizing the life cycle cost. In [42], the researchers have designed a multi-objective hybrid renewable energy system using a preference-inspired co-evolutionary algorithm and applied it to the case study system consisting of PV panels, wind turbines, batteries, and diesel generators. The algorithm is improved using enhanced fitness assignment method and goal vectors. As well, as it is investigated in [43], the authors have developed an optimization model based on meta-model based algorithm called A-STRONG to find the optimal size of PV, wind and diesel power generator and energy storage system. The study investigates power generation allocation and transmission within the hybrid renewable energy system to find minimum expected total cost under uncertain circumstances. In [44], a hybrid renewable system including biomass gasification and photovoltaic panels with battery is proposed and is practically tested in order to supply electrical demand of ISTA-DRC laboratory complex in the Republic of Congo is designed. The authors of [45] have used a simulation-based optimization approach for optimal sizing of a hybrid renewable energy system and minimizing total net present cost, CO_2 emission and maximizing renewable energy ratio simultaneously. In addition, the authors in [46] have conducted a techno-economic feasibility study of an off-grid hybrid renewable energy based power systems to satisfy the electrical needs of a rural community in Sri Lanka. In [47], the researchers have performed the optimal sizing of a stand-alone hybrid photovoltaic/wind/hydrogen system supplying a desalination unit which responds local demands of fresh water. The methodology aims in order to find the optimal technical–economic structure among a set of systems components. In [48], an ant colony optimization (ACO) using continuous domains based integer programming for optimal sizing of hybrid photovoltaic–wind energy system in order to minimize the total design cost is employed. Ultimately, in [49], the optimal sizing and optimizing of a hybrid photovoltaic/battery/diesel generator for remote locations of India, using artificial intelligence techniques (AIT) without any metrological data is performed.

In general, various approaches are employed to optimize the size of the hybrid system all over the world. The hybrid street lighting systems are broadly applicable, but the economic optimization for determining the optimal size of such systems was out of scope of researches. In many countries, the street lighting systems are based on available typical manufactured sizes. It is an inappropriate strategy because the selected hybrid system may be insufficient or non-economic for a specific region. Therefore, the hybrid system experts and operators must optimize the street lighting based on the specific climate condition of the considered site.

In this paper, the feasibility of different cases (three scenarios) of a hybrid system to supply electricity of highways and street lighting using low-power lamps for Tabriz city in Iran is presented. The main objective of this study is to minimize the costs of this system during the lifetime considering demand satisfaction constraints as well as technical restrictions. The objective function of this hybrid system (solar, wind and battery energy storage) is to minimize the cost function and to achieve maximum possible reliability. The loss of power supply probability index (*LPSP*) is used as the reliability index in the proposed approach. Moreover, in order to assess the long-term viability of the model in term of economic conditions over the lifetime of generating asset the levelized energy cost (*LEC*) index is employed. The bat meta-heuristic algorithm is applied to solve the optimization problem. The effectiveness of the proposed method is compared with *GA* and *PSO* algorithm. The simulation of the proposed hybrid system is conducted through three scenarios, in which the hybrid system has various schemes. Simulation results show the perfect performance of the proposed method in solving nonlinear problems as well as benefits of the wind-solar hybrid system to meet electricity of highways and street considering economic and reliability aspects.

2. Climate criteria and weather assessment of case study

Tabriz city can be mentioned as one of the most polluted provinces and cities in Iran. The reason is that there many industrial and agriculture facilities located in the area that absorb a significant amount of fossil fuels in this area. In addition, the high amount of energy consumption has intensified air pollution. The population of Tabriz city in the year 1385 was 1.378935 million. It has raised by 8.24 % in 1390 and reached the number of 1.494988 million and 1558693 million in 1395 (the last census). Fig. 1 shows the geographical situation of Azerbaijan province and Tabriz city.

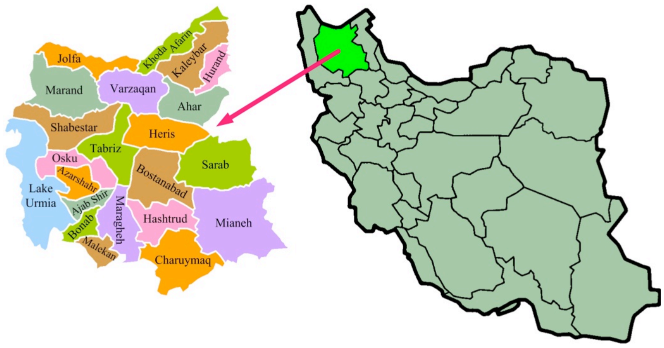

Fig. 1. Geographical situation of Azerbaijan province and Tabriz city

Tabriz is located in the middle of the Azerbaijan border and the northeast part of Urmia lake. The latitude and longitude of Tabriz are 38° 7' 86" *N* and 46° 28' 8" *E* and the average altitude is 1351.4 meters. It takes 619 kilometers to the west of Tehran and 150 kilometers to the south of Jolfa, surrounded by Iran and Azerbaijan's border. This town is surrounded by Pokechin and Onebneali mountains from the north, Gavazni and Bababaghi Mountains from the northeast, Payan Col from the east, and Sahand mountain range from the south. Tabriz climate is dry steppe along with hot and dry summers and cold winters. Cold weather in winters is the effect of high altitude and the mountainous topography of that region. The weather of this city is dry and hot in summers, although the weather moderates due to proximity to Sahand Mountains and a large number of gardens nearby.

Investigation of wind direction, with regard to cardinal directions, speed, amount, and the percentage of wind repetition shows that local winds, either intensified or weak, is blowing to this city from whole directions. Between those directions, the wind that blows from the east and from northeast constitutes the main direction of Tabriz air stream. The southwest and west winds are in the next step. These winds are resisted less and moderate in amount. The northern, southern, southeastern, and northeastern winds have less amount of blowing and they are not very important.

Weather forecasting assessments related to the radiation of sun and wind speed in different months corresponded with Tabriz city since last 20 years (shown in Fig. 2 and 3) illustrates that this city has annual average radiation of 4.65 (kWh/m^2.day) and mean wind speed of 6.1 (m/s). These quantities show that Tabriz is one of the best places for application of hybrid energy systems [50].

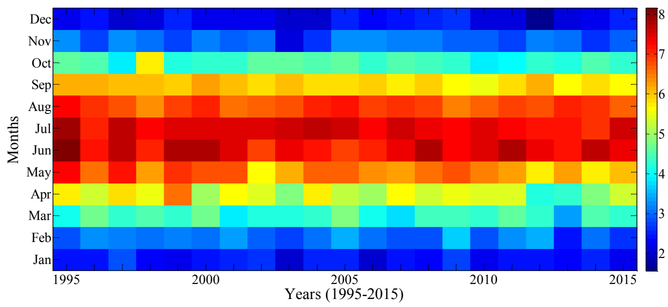

Fig. 2. The amount of solar radiation of different months of the year in Tabriz City (from 1995 to 2015) in *KWh/m^2*

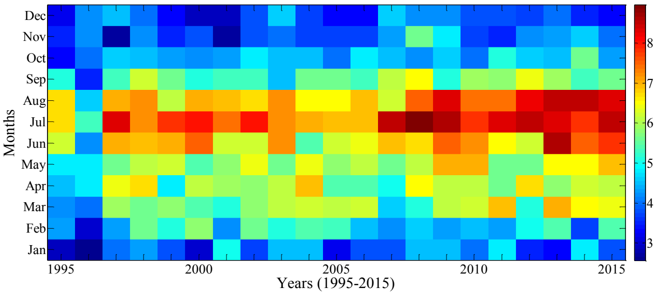

Fig. 3. The wind speed of different months of the year on the Tabriz City (from 1995 to 2015) in *m/s*

3. Hybrid System

Solar-wind hybrid systems take advantages of two renewable energy resources simultaneously, which helps to enhance the efficiency of the system [51]. In this system, with regard to the presence of two generation resources, the size of storage will be decreased for isolated systems. Fig. 4 illustrates the general configuration of the hybrid solar-wind system used in this study.

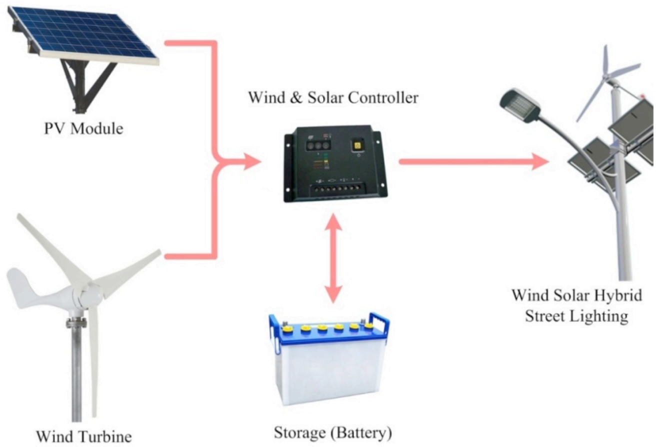

Fig. 4. General configuration of hybrid system for highways and street lighting

3.1. Hybrid System Components

The main components of the hybrid system are wind, solar, battery. There are some presumptions for the operation of these parts. It is assumed that the mean hourly speed of the wind farm is selected to estimate the wind generation and the intra-hour fluctuations are neglected. In addition, the wind generation model is supposed to be quadratic, which appropriately describes the behavior of the wind generation. In solar modeling, the instantaneous fluctuations in weather parameters are ignored, and the mean hourly radiation and temperature are employed. Besides, other influential factors such as emission, dust, and any type of hydrophilic or hydrophobic surface coating in photovoltaic systems are neglected. For the battery modeling, with respect to the long-term sizing, the charge/discharge intervals are supposed to be one hour that effectively shows the required capacity of the battery. Hence, more accurate battery operation patterns are not necessary to be used in the model. The efficiency of the battery is considered to be 80%. One of the fundamental assumptions is that the hybrid system is completely isolated from the grid and cannot exchange power with the grid.

3.1.1. Wind Turbine

Stochastic nature of wind has caused that wind units do not have continuous characteristics and controllability. Wind units' power generation depends on wind speed and wind turbine characteristics. In wind turbines, the generated power is calculated according to Eq. (1). Moreover, the values of A, B, and C are corresponded with the turbine's characteristics and can be calculated by Eq. (2) to (4).

$$P_{WT}=\begin{cases}0 & 0\le V<V_{ci}\\ \left(A+BV+CV^2\right)P_r & V_{ci}<V<V_r\\ P_r & V_r<V<V_{co}\\ 0 & V>V_{co}\end{cases} \tag{1}$$

$$A=\frac{P_r}{\left(V_{ci}-V_r\right)^2}\left[V_{ci}(V_{ci}+V_r)-4(V_{ci}\times V_r)\left[\frac{V_{ci}+V_r}{2V_r}\right]^3\right] \tag{2}$$

$$B=\frac{P_r}{\left(V_{ci}-V_r\right)^2}\left[4(V_{ci}+V_r)\left[\frac{V_{ci}+V_r}{2V_r}\right]^3-(3V_{ci}+V_r)\right] \tag{3}$$

$$C=\frac{1}{\left(V_{ci}-V_r\right)^2}\left[2-4\left[\frac{V_{ci}+V_r}{2V_r}\right]^3\right] \tag{4}$$

In above equations, V_{ci} is defined as cut-in speed; V_r means rated velocity; V_{co} represents cut-out speed. P_r is the rated power of wind turbine. Thus, the output power generation can be calculated using Eq. (5):

$$P_{WG}=P_W\eta_W \tag{5}$$

In the aforementioned equations, η_w represents the combined efficiency of the gearbox, generator and electronic devices [52].

3.1.2. Photovoltaic Panel

The output power of photovoltaic panels can be calculated using Eqs. (6)-(8). This model includes the effects of solar radiation and panel temperature on the output power of photovoltaic panels. The equations that compute maximum output power point are as below:

$$P_{PV}=V_{mpp}.I_{mpp} \tag{6}$$

$$V_{mpp}=V_{mpp,ref}+P_{v,oc}(T_c-T_{c,ref}) \tag{7}$$

$$I_{mpp}=I_{mpp,ref}+I_{SC,ref}(G_T/G_{ref})+P_{I,SC}(T_c-T_{c,ref}) \tag{8}$$

In which, P_{pv} is panel power, V_{mpp} is voltage at the optimum point of power generation, $V_{mmp,ref}$ is as same as V_{mpp} in standard condition. I_{mpp} is the panel current and $I_{sc,ref}$ is the short circuit in standard condition. G_T represents the average daily radiation of sun (W/m^2), and G_{ref} is equal to 1000 for the standard condition. $P_{V,oc}$ and $P_{I,sc}$ temperature coefficients for open-circuit voltage (V/°C) and short circuit current (*A/°C*). $T_{c,ref}$ denotes the panel temperature in standard condition, which assumed to be 25 (*°C*), and $Tc(t)$ is the operating temperature of the photovoltaic panel that can be calculated as below:

$$T_c(t)=T_a(t)+\frac{NOCT-20}{800}\times G_T \tag{9}$$

$T_a(t)$ is the surroundings temperature (°C). *NOCT* (normal operating cell temperature) is assumed to be between 40 and 46 (°C) with the radiation of 500 (W/m^2) and a surroundings temperature equal to 20 (*°C*) [53].

3.1.3. Battery

The input power of the battery can be either positive or negative regard to charging/discharging state of the battery and can be calculated according to Eq. (10). Moreover, state of charge (*SOC*) of the battery can be calculated using Eq. (11), considering power and efficiency of the battery.

$$P_{BAT} = P_{WG} + P_{PV} - P_{Load} \tag{10}$$

$$SOC_{BAT} = \int \left(P_{BAT,charging} \times \eta_{BAT} - P_{BAT,discharging} \right) dt \tag{11}$$

Note that battery capacity $C_{bat}(t)$ (in every hour) is limited according to Eq. (12).

$$C_{BAT,\min} \leq C_{BAT}(\mathrm{t}) \leq C_{BAT,\max} \tag{12}$$

In which, $C_{bat,max}(t)$ and $C_{bat,min}(t)$ are respectively the maximum and the minimum of the storable capacity of battery [54, 55].

3.2. Optimization Problem Formulation

3.2.1. Strategy of System Energy Management

The profit and reliability are two important factors related to energy management strategies in size determination of optimization problem. Hence, in order to achieve an optimum practical result, a comprehensive energy management scheme for integration of various types of resources is needed. The power difference between generating resources and demand can be achieved by Eq. (13):

$$P_{Net}(\mathrm{t}) = P_{WT}(\mathrm{t}) + P_{PV}(\mathrm{t}) - P_D(\mathrm{t}) \tag{13}$$

In the above equation, P_D (t) is the consumed power at hour t. The control system operation method is that the surplus of generated power by wind turbines and photovoltaic panels (P_{net}>0) should be stored in the battery while needed. Hence, the power equations are as Eq. (14) and (15):

$$P_{WT} + P_{PV} = P_D + P_{BAT,charging}, \quad \left(C_{BAT} < C_{BAT,MAX} \right) \tag{14}$$

$$\left(P_{WT} \times WPC \right) + P_{PV} = P_D, \quad \left(V_{BAT} = V_{BAT,MAX} \right) \tag{15}$$

In (15), *WPC* implies the turbine's power control system. In this case, the excess power should be decreased by the control system of wind turbines. Otherwise, the turbines without controllability of gearbox should be shut down to maintain the power equality constraints.

If generating resources were not able to supply the required energy (P_{net}<0), the battery starts to supply the required electricity. Thus, the power equality equations, in this case, are according to Eq. (16) and (17):

$$P_{WT} + P_{PV} + P_{BAT,discharging} = P_D, \quad \left(C_{BAT} > C_{BAT,MIN} \right) \tag{16}$$

$$P_{WT} + P_{PV} = P_D + \text{Load Shedding}, \quad \left(C_{BAT} < C_{BAT,MIN} \right) \tag{17}$$

Based on the aforementioned explanations, it is possible to have three different operating modes.

A- P_{net}>0: In this case, the surplus power is being stored in the battery. After the battery is fully charged, the excess power will be decreased by a control system of wind turbines through a gearbox-oriented mechanism or it should be disconnected from the network (curtailment).

B- P_{net}<0: In this case, the deficiency of power is provided by the battery, and otherwise the load shedding should be implemented. In this hybrid system, the utilized LED projector lamp is a kind of lamps that is able to work in two or more lighting intensities so that the LED rows are divided into two or more parallel sections that can separately be ON or OFF. Thus, in case of necessity for load shedding, any separate section can be turned off. That means that the LED projector lamp stays on but with lower Lux of luminous emittance.

C- P_{net} =0: In this case, the battery capacity remains unchanged.

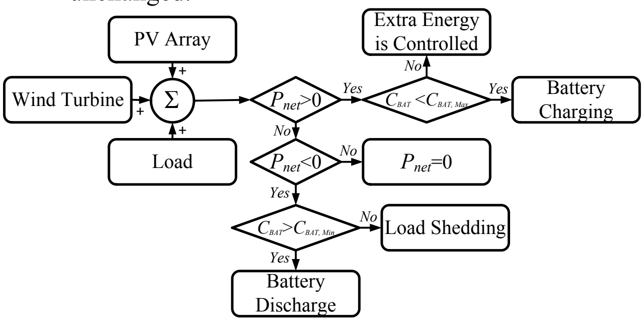

Fig. 5. The block diagram of the proposed hybrid energy system

Fig. 5 illustrates the structure of the energy management model of the proposed hybrid system, which indicates the operation in three modes.

3.2.2. Reliability Constraints Modeling

In this paper, the *LPSP* index is used to calculate reliability. When P_{net}>0 reached to its maximum value ($V_{BAT,Max}$), the control system stops the charging of the battery, and the excess power at time *t* can be calculated using (18):

$$WEP(\mathrm{t}) = P_{total}(\mathrm{t})\Delta\mathrm{t} - \left(\frac{C_{BAT,Max} - C_{BAT}(t-1)}{\eta_{BAT}} \right) \tag{18}$$

In the above equation, P_{total} is the total generated power in the system, η_{BAT} is the battery efficiency (which is considered to be 80% in this paper), and Δt denotes the time interval adopted for this paper.

When P_{net}<0, if the battery capacity reached its minimum level ($V_{BAT,Min}$), the battery disconnects from the network. Unsupplied load (where we need to implement load shedding) at time t can be calculated using Eq. (19):

$$LPS(\mathrm{t}) = P_D(\mathrm{t})\Delta\mathrm{t} - \left(\begin{matrix} \left(P_{WT}(\mathrm{t}) + P_{PV}(\mathrm{t}) \right)\Delta\mathrm{t} \\ + C_{BAT}(t-1) - C_{BAT,Min} \end{matrix} \right) \eta_{BAT} \tag{19}$$

Time interval of simulation equals to one hour, the generated power by *WT* and *PV* during this interval is assumed to be fixed. Thus the power and energy are adequate during an interval. Thus, the *LPSP* index is defined according to Eq. (20) during an interval. This index is a technical criterion which is a notable term for designing and hybrid system size determination.

$$LPSP = \sum_{t=1}^{T} LPS(\mathrm{t}) \Bigg/ \sum_{t=1}^{T} P_D(\mathrm{t})\Delta\mathrm{t} \tag{20}$$

Many constraints, restrictions, and parameters can affect *LPSP* in hybrid systems design. In this paper, the levelized energy cost parameter (*LEC*) is employed which will be explained in the following parts. This parameter helps to achieve the desired structure, size, and *LPSP*. In addition, excess energy can be calculated using Eq. (21) within operating time of *T*.

$$XE(\mathrm{T}) = \frac{WEP(\mathrm{T})}{E_{total}(\mathrm{T})} \tag{21}$$

In the above equation, E_{total} is the total generated energy in the system during the defined period of time.

3.2.3. Economic Modeling of the System

One of the main factors in an optimized renewable energy system implementation is the costs and financial issues. In this section, an economic model is presented to achieve the optimum size of the hybrid system based on *LEC*. In addition, the implementation expenditures and operation costs of hybrid system are investigated. *LEC* is defined in Eq. (22):

$$LEC = \frac{NPV \times CRF}{E_{Load}} \tag{22}$$

In the above equation, E_{load} is the annual output energy in (*KWh*), *NPV* is the net present value of construction, implementation, and operation for all components of the system. *CRF* is the capital recovery factor which is mentioned in Eq. (23) and (24):

$$NPV = C_{WT} + C_{PV} + C_{BAT} \tag{23}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{24}$$

Where, C_{WT}, C_{PV}, C_{BAT} are the current cost of construction and operation of wind turbines, photovoltaic panels and battery respectively. The interest rate is defined by *i*, and *n* denotes the lifetime of the system (yr.). As mentioned before, the structure with lower *LEC* is introduced as the best selection. It will result in the desired *LPSP*. In this paper, the annual interest rate is 10% and effective lifetime assumed 20 years [56]. Fig. 6 shows the flowchart of the proposed method in this paper.

4. Bat Optimization Algorithm

Bats are wonderful animals. They are the only mammals that are able to fly, and also most of them have advanced ability of positioning using sounds wave. Bats use a particular frequency range of sound in order to indicate positions. Among all types of bats, small bats are a famous example of using sounds as a tool for positioning. Small bats propagate long sound pulses from themselves and then they process the reflections.

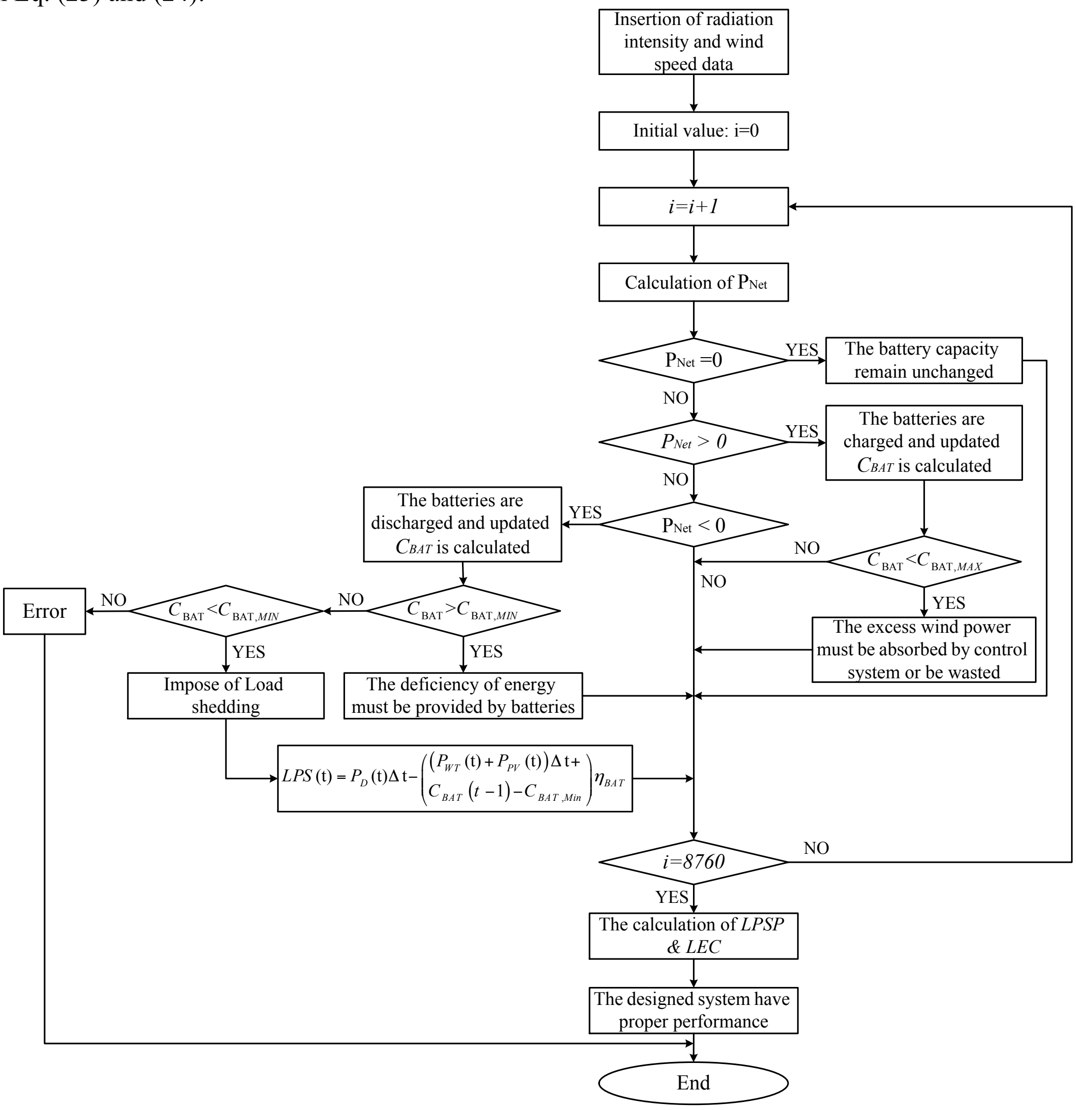

Fig. 6. The proposed method flowchart

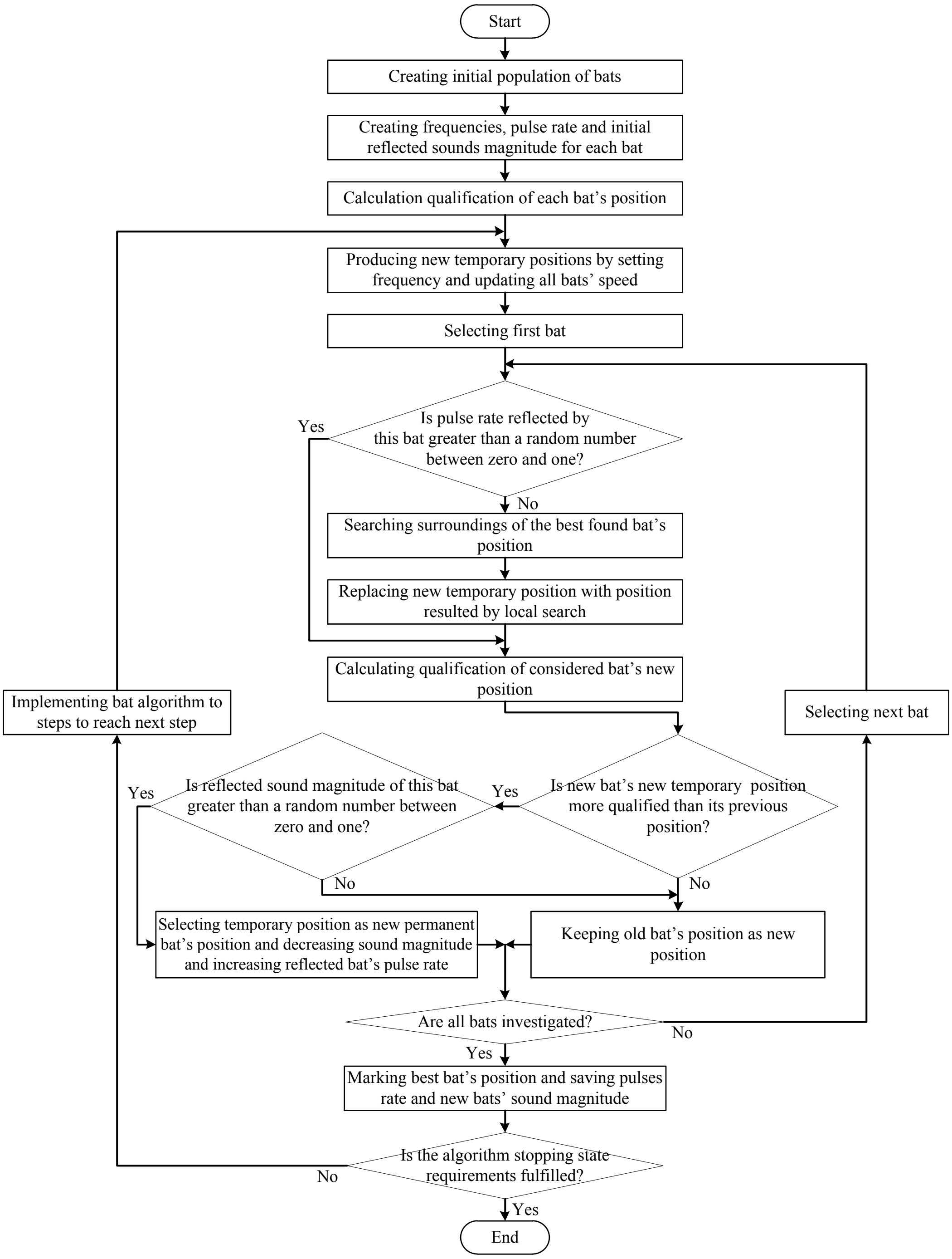

Fig. 7. Complete steps of bat optimization algorithm

The bat optimization algorithm, presented in 2010 by *Xin-She Yang* for the first time, is an inspiration of tracking characteristic of small bats in searching for hunts [57]. In order to expand this optimization algorithm, general rules have been used which is pointed below:

First rule: all bats distinguish and recognize the distance by reflection, and also all of them know the difference between reflected sound resulted by whether food or surrounding objects.

Second rule: bats follow their hunts randomly with the velocity of v_i, the position of p_i, the constant frequency of f_{min}, using different wavelengths and sound magnitude of R. Bats can set up their wavelength and their sent pulses ($[0,1] \in r$) considering their distance to their hunt.

Third rule: although the magnitude of sound can be different in most states, however, it is supposed that these changes are limited by the maximum amount of R_0 to the minimum amount of R_{min}.

Regard to described rules above, in order to have mathematical modeling for each virtual bat of i in a d-dimension search space, the position of p_i and velocity of v_i can be used in each iteration of the algorithm according to the following equation:

$$f_i = f_{min} + \left(f_{max} - f_{min}\right)\beta \tag{25}$$

$$v_i^{\tau+1} = v_i^{\tau} + \left(p_i^{\tau} - p_*\right) f_i \tag{26}$$

$$p_i^{\tau+1} = p_i^{\tau} + v_i^{\tau} \tag{27}$$

In the above equation, τ is counter of algorithm iteration and β is a random number with a uniform distribution between zero and one. P^* is the best current position which is chosen after comparing with new positions of virtual bats in each iteration. Furthermore, at each iteration, the local search can be performed based on a random search around the position of the best bat can be calculated by Eq. (28):

$$p_{new} = p_{old} + \varepsilon R^{\tau} \quad (28)$$

In the above equation, R^{τ} is the average sound's length for all bats involved in the iteration, R_i represents the sound's length, and $\varepsilon \in [-1,1]$ are presented in order to limit random search steps. The rate of r sends a pulse in each iteration that can be shown as Eqs. (29) and (30).

$$R_i^{\tau+1} = \alpha R_i^{\tau} \qquad \forall\ 0 \le \alpha \le 1 \quad (29)$$

$$r_i = \left[1 - exp\left(-\gamma\tau\right)\right] \qquad \forall\ \gamma \ge 0 \quad (30)$$

By observing equation 30, it is obvious that the variation range of r is between zero and one. The number zero indicates no pulse sending state and the number one means maximum pulse sending. The total schema of bat optimization algorithm illustrated in Fig.7. Note that usage of pulse rate (r_i) is exactly retrieved from what happens in reality. If the bat approaches its target, it sends more pulses in order to monitor its hunt position better. Simulation of this behavior in optimization algorithm is possible by setting r_i parameter. As this rate is closer to 1, surroundings local search around the best position happens with more possibility and vice versa. Note that by putting $r_i=R_i=0$, this algorithm operates similar to particle swarm optimization algorithm (PSO) or by putting $r_i=Ri=0.7$, this algorithm behaves like harmony search algorithm. It's worth mentioning that the algorithm stops working when it reaches to a specific number of iterations [58].

5. Numerical Study and Simulation Results

5.1. Investigation of Hybrid Case Study System

In this section, technical and economic characteristics of hybrid under study system are evaluated. The understudy hybrid system includes: 1-wind turbines 2-photovoltaic panel 3-battery. In this research, the study is segregated into three scenarios as follows.

1. Scenario 1: the hybrid system consists of a 100W wind turbine
2. Scenario 1: the hybrid system consists of a 300W wind turbine
3. Scenario 1: the hybrid system consists of a 600W wind turbine

The results of each independent usage will be compared to others. Technical and economical parameters of wind turbines, photovoltaic panels and battery are illustrated in Table 1.

5.2. Load, Radiation and Wind Speed of the understudy hybrid system

Electricity consumption in 1390 in Tabriz was 2756376 *MWh*. It is raised by 17% (3333292 *MWh*) until 1394. The lighting of highways and streets constitutes the amount of 133332 *MWh* of this consumption.

There are various methods to decrease costs and electricity consumption in the lighting of streets. In this study, *LED* lights are used which is provided to maintain 20 Lux in installation height of 12 meter. The forecasted load profile of the understudy system (each light) for a year (8760 hours) is shown in Fig. 8.

Table 1.b. Technical characteristics of the photovoltaic unit

PV panel	
power range	0.08 KW ~ 0.48 KW
Panel efficiency (%)	15%
operating temperature (°C)	-40˚C ~ +85˚C
power fluctuation percentage	-2% ~ +2%
initial cost per watt	$ 1.6
replacement cost per watt	$ 1.4
maintenance cost	$ 20

Table 1.c. Technical characteristics of the battery unit

Battery	
rated capacity	200 Ah
rated voltage	12 V
charge-discharge efficiency	80 %
minimum state of charge	40 %
estimated lifetime	4 ~ 10 years
maximum charge rate	1 A/Ah
maximum current charge	60
initial cost	$ 360
replacement cost per watt	$ 340
maintenance cost	$ 4

Table 1.a. Technical characteristics of the wind unit

Wind turbine			
Turbine model	100W	300W	600W
structure	3 blades	3 blades	3 blades
cut-in speed	3 m/s	3 m/s	3 m/s
cut-out speed	60 m/s	60 m/s	60 m/s
rated power	0.10 KW in12.6 m/s	0.3 KW in12.6 m/s	0.6 KW in11 m/s
maximum output power	0.11 KW	0.36 KW	0.69 KW
output voltage	12-24 V-DC	12-24 V-DC	12-24 V-DC
turbine diameter	928 mm	1200 mm	1700 mm
effective lifetime	Min 15 years	Min 15 years	Min 15 years
initial cost	$ 225	$ 320	$ 417
replacement cost	$ 200	$ 300	$ 390
maintenance cost	$ 20	$ 20	$ 20

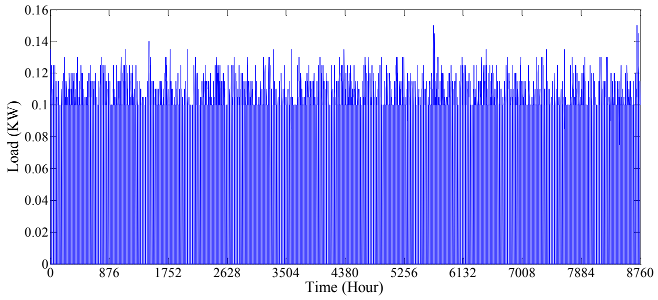

Fig. 8. Forecasted load profile of under study system (each light) for a year

In order to validate the results of simulation and to evaluate the condition and amount of generated power by the hybrid system, the data of wind speed and radiation is required. Hence, the weather data and radiation of the last 20 years (from 1995 to 2015) for Tabriz city which is provided through synoptic stations of the meteorological organization of East Azerbaijan province is used. In order to estimate annual profile (8760 hours) of radiation and wind speed, the hourly data of the last 20 years have been averaged. It has two main advantages; the first advantage is that results have more validity. And the second advantage is that due to the fact that the simulation is performed in 8760 steps, analyzing of generated and consumed the energy of each hybrid system section is possible. Annual profile of radiation and wind speed which is resulted by the last 20 years' data of the area is shown in Fig. 9 and 10:

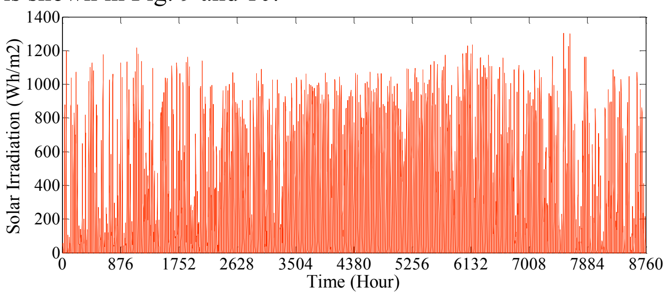

Fig. 9. Annual hourly profile of radiation

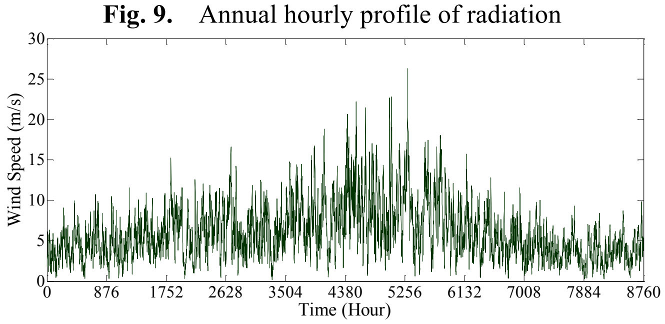

Fig. 10. Annual hourly profile of wind speed

In this simulation, we used Matlab software using a personal computer with the following hardware specifications: Core^{TM} i5, *CPU* 2.4 GHz ~ 3.0 GHz, and 8 GB DDR3 RAM. The Pareto solutions based on simultaneous optimization of objective function and reliability index after 10 iterations for each algorithm is shown in Table 2. Table 2 illustrates the perfect performance of the suggested algorithm, optimum combination of renewable resources and the cost of the hybrid system. To show the effectiveness of BA algorithm for solving the proposed optimization method, the results of optimization is compared with GA and PSO algorithm. Figs. 11 to 13 show the algorithms convergence trend in three different power ranges of the wind turbine. Based on the optimization results, it can be understood that GA and PSO algorithms are very similar in terms of the convergence to the optimum solution. But in terms of time, PSO algorithm converges to the optimum point faster due to its simplicity and lack of some operators like mutation and crossover. Regard to the Figs. 11 to 13, the results of the bat algorithm for all three scenarios indicate that even though this algorithm not only have more accurate responses, but also have higher run speed in all scenarios. It also has converged to the final optimum result in less iteration. This fact expresses that it is less likely for PSO to trap in local minimum.

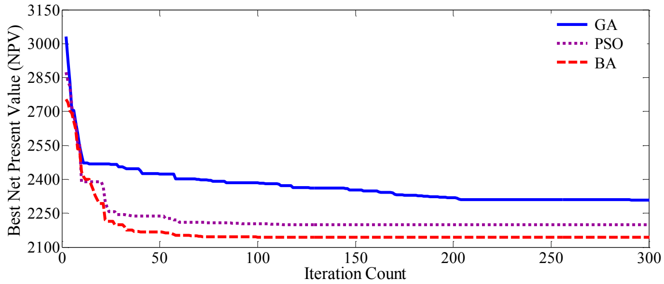

Fig. 11. Convergence trend of implemented algorithms to hybrid system in scenario 1

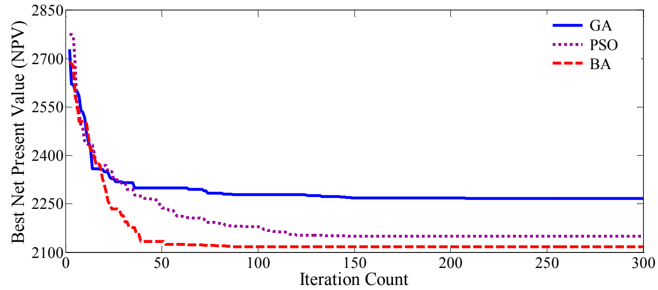

Fig. 12. Convergence trend of implemented algorithms to hybrid system in scenario 2

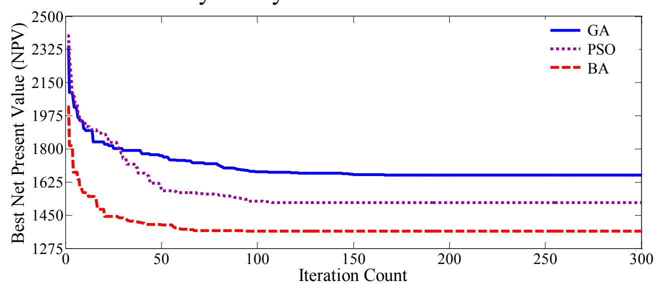

Fig. 13. Convergence trend of implemented algorithms to hybrid system in scenario 3

According to Table 2, the results show that the least initial cost of the optimized hybrid system belongs to bat algorithm in scenario 3 with the amount of 905$. The reason why this scenario has the lowest cost is the fact that the minimum amount of battery and the lowest capacity of the solar panel are adopted. In addition, the wind capacity is increased which has a lower initial investment cost ($/W). The maximum initial cost is related to GA in case of 300 W with the cost of 1552$. The reason for this increase is that the number of batteries and capacity of panels has their corresponding maximum boundaries within all optimization scenarios. Similarly, the *NPV* of bat algorithm in scenario 3 has the lowest value. It is because that the lowest initial cost, operation cost, and maintenance cost is related to this case.

As it is obvious in Table 2, the maintenance cost in scenario 3 hybrid system optimized with bat algorithm has the lowest value. As it is mentioned, this scenario has the lowest initial cost, operational and replacement cost which is the reason for the lowest electricity cost of this scenario. According to Table 2, the lowest value of the index of *LPSP* is related to scenario 1 and 2 hybrid system optimized by GA, which provides higher reliability. The reason is that the capacity of solar panels and batteries are increased in these two cases. The presence of much more capacity of storage makes the system to more reliable. As it was discussed in the objective function, the lowest amount of *LPSP* is not considered to be minimized. The objective is that minimize the *LEC* subject to decrease the *LPSP*. Thus, as it can be seen in scenario 3 hybrid system optimized by bat algorithm, the *LEC* has the lowest value and *LPSP* is close to the best solutions.

According to what is discussed above, a hybrid system in accordance with the third scenario is a much more reasonable choice in comparison with other options to implement a hybrid solar-wind system to supply required electricity of street lights in Tabriz. This turbine has lower costs (initial cost, net final cost, maintenance cost, electricity cost) in comparison with other choices. According to calculations, the wind turbine has a crucial role in supplying and generating energy in this hybrid system. Therefore, according to Tabriz climate, the increment in wind turbines capacity in this hybrid system can improve the performance and reduce net final cost. Table 3 shows all suggested hybrid power generation systems with all wind turbine power ranges using BA, GA and PSO algorithms.

As it is clear in Table 3, the contribution of PV panels in supplying required electricity in the optimized system is demonstrated. As it is discussed, the hybrid system in accordance with the 3rd scenario is optimized by bat algorithm is the best option, in which the contribution of wind turbines is %86 whereas the share of PV panels is %14. This matter shows that extraction of electricity from wind resources is more affordable compared with solar resources. However, this fact does not indicate that all of the demand should be met by wind energy, because according to the Figs. 14 and 15, there are some moments, when the wind turbines are unable to generate electricity due to lack of sufficient or appropriate wind speed. In other words, the presence of PV panels ensures the adequate reliability of the hybrid system and prevents deficiency of electricity for supplying the demand. According to the results of Tables 2 and 3, the total generated energy in the selected hybrid system (hybrid system in the 3rd scenario optimized through BA algorithm) is equal to 2316 KWh/year. In this case, the unsupplied electric load of the system equals to 13.76 KWh/year (about 1%). In Figs. 14 and 15 the annual power generation profile of PV and WT are shown.

Table 2. The results of BA in comparison with GA and PSO

parameters	Optimized quantities and values								
	Scenario 3			Scenario 2			Scenario 1		
	BA	PSO	GA	BA	PSO	GA	BA	PSO	GA
Population Size	100	100	100	100	100	100	100	100	100
Number of Iterations	300	300	300	300	300	300	300	300	300
Number of Wind Turbines	1	1	1	1	1	1	1	1	1
PV Panel Capacity	0.08	0.16	0.24	0.24	0.40	0.32	0.24	0.40	0.32
Number of Batteries	1	1	1	2	1	2	2	1	2
Initial Cost	905	1033	1161	1424	1320	1552	1329	1225	1457
Net Present Value (NPV)	1372	1515	1657	2113	2145	2257	2139	2191	2297
Maintenance Costs ($/year)	55	57	58	81	97	83	95	113	99
Electricity Cost ($/KWh)	0.446	0.491	0.535	0.685	0.710	0.728	0.702	0.719	0.742
LPSP	0.005	0.006	0.004	0.004	0.016	0.003	0.009	0.02	0.003
Excess Energy (KWh/yr)	1930	2050	2170	675	921	794	274	515	387
LEC	0.4411	0.4871	0.5328	0.6794	0.6897	0.7257	0.6877	0.7045	0.7385

Table 3. Amount and portion of generated energy by *PV* and *WT* at optimized point using *BA*, *GA* and *PSO*

Parameter	Algorithm	*Scenario 3*	*Scenario 2*	*Scenario 1*
PV Generation (KWh/year)	GA	364	485	485
	PSO	242	606	606
	BA	121	364	364
Energy supply share of PV%	GA	14%	40%	60%
	PSO	10%	46%	35%
	BA	5%	34%	53%
WT Generation (KWh/year)	GA	2195	721	324
	PSO	2195	721	324
	BA	2195	721	324
Energy supply share of WT%	GA	86%	60%	40%
	PSO	90%	54%	65%
	BA	95%	66%	47%

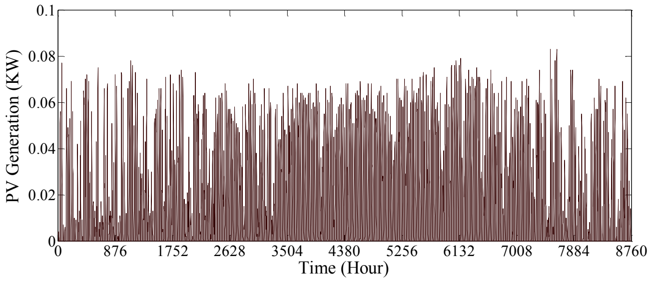

Fig. 14. Annual generation variation graph using *PV* in selected hybrid system

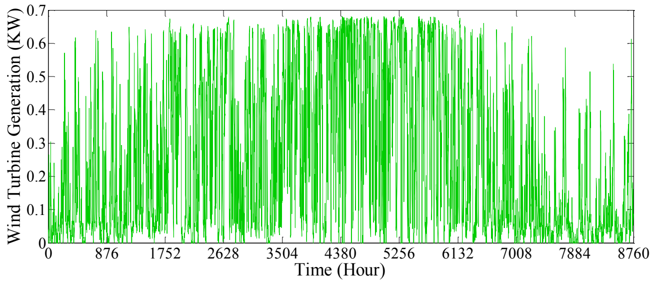

Fig. 15. Annual generation variation graph using *WT* in selected hybrid system

In this system, the battery is responsible for storing excess generated power of WT and PV. It also must provide the required energy to prevent load shedding (peak hours or when the system encounters generation deficiency). Fig. 16 shows the battery set annual charge/discharge changes.

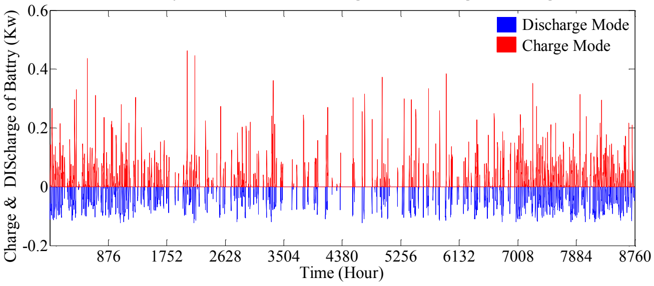

Fig. 16. The battery set annual charge/discharge changes for selected hybrid system

As it is shown in Fig. 16, the battery storage system has a substantial role in providing electricity and improving the reliability of the system. It is particularly obvious when sufficient electricity is not provided by wind turbines and PV panels. According to Figs. 14 and 15, on October, November, December, January, February, and March (that is equivalent with fall and winter seasons in Iran), the generation of wind turbines and PV panels usually decreases. During these months, the role of the battery storage system is more prominent. Hence, the charging and discharging amount of battery is increased within this period. As well, in seasons of spring and summer, due to prolongation of daylong and increase in seasonal wind speed in Tabriz, the generations of wind and solar resources are adequate so that the necessity of operation of the battery system is reduced. The battery energy storage not only improves the reliability of the hybrid system but also prevents the increase in the size of other components of the hybrid system (PV panels and wind turbine).

6. Conclusion

In this paper, a smart energy management scheme and a comprehensive control strategy are proposed for a hybrid solar-wind system with battery energy storage to supply required electricity for street lightings using low-power lights. In order to choose the best configuration of the hybrid system to minimize costs and market demand coverage in different weather situations and load variations, bat optimization algorithm (BA) is employed. Moreover, in order to optimize cost function and the reliability index of *LPSP* simultaneously, Pareto principle variation analysis is used. The case study is categorized into three scenarios in which the hybrid system has different schemes. Three sizes of wind turbines (100 W, 300 W, and 600 W) are utilized in this model. Economic analysis of the results confirms the advantages of the designed hybrid system clearly. In addition, the results of comparing the designed hybrid system through three scenarios imply that the 3rd scenario, which contains a 600 W wind turbine, has the lowest operation cost (*NPV*, initial cost, O&M cost, electricity cost, *LEC)* and the a sensible level of *LPSP* in comparison with the other two scenarios which delineate the higher level of reliability. In this study, in order to solve the optimization problem, the bat algorithm (BA) is used and the results are compared with GA and PSO algorithms. The suggested algorithm shows better accuracy and speed. Thus, it can converge to the optimum result in a very short time and in less iteration. This fact shows that the suggested method can be employed for operation purposes, where the accuracy, cost, and speed are highly important.

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