# Size Optimization of New Hybrid Stand-alone Renewable Energy System Considering a Reliability Index

M. Bashir, *Student Member, IEEE*, J. Sadeh, *Member, IEEE*

*Abstract:* **Over last two decades, solar and wind energies have become an alternative to traditional energy sources. These alternative energy sources are non-polluting, free in their availability and are renewable. Another alternative is tidal energy, which is related to falling and rising ocean water levels. Tidal behavior can be predicted easily and this means that if it is enable to harness tidal energy, it can be produced power for specific periods of time. In this paper, a new hybrid combination of renewable energy sources is considered. The combination of wind, photovoltaic and tidal is taken into account as a primary and battery as an auxiliary source. The aim of design is to minimize the annualized cost of the generation system over its 20 years of operation. Determining the capacity of hybrid wind, photovoltaic, tidal and battery is formulated as an optimization problem. The objective function is the minimization of the cost with the constrain having specific reliability index. To evaluate the system reliability level, the Equivalent Loss Factor (ELF) has been used as an index. Comparison between hybrid wind, solar and battery and new combination of renewable energy is done and it is shown that the combination of wind, solar, tidal and battery is more economical. Particle Swarm Optimization (PSO) is used for optimal sizing the system. Simulation results are carried out by MATLAB software. It is shown that hybrid system is the best configuration that has minimum cost and can satisfy all constrains.**

**Keyword:** Renewable energy, wind and photovoltaic power, reliability evaluation, tidal, particle swarm optimization.

## I. INTRODUCTION

Nowadays, political and economic crisis, limitation of fossil reserves, environmental concerns, population and economic growth resulted in an increase in the use of renewable energy resources. However, the main problem of renewable energy is dependence of these sources to the weather conditions. Therefore, there are oscillations in their outputs. To solve this problem, these generation units are used together. In the recent year, various combinations of renewable and nonrenewable energy sources have been considered. Some of these combinations can be expressed as:

- ✓ wind – solar – battery
- ✓ wind – micro turbine
- ✓ wind – solar – diesel
- ✓ wind – fuel cell
- ✓ solar – biomass

Wind and solar energy has become a common, because a requirement weather condition is available in many locations and technology needed to use this energy is provided.

Yang et al. [1] proposed a new sizing method for a hybrid wind, solar and battery. In this method hourly data of wind speed and solar radiation are used. The reliability factor is Loss of Power Supply Probability (LPSP) and for assessment the cost, Levelised Cost of Energy (LCE) model is used. The sizing problem is solved by genetic algorithm.

Borowy and Salameh [2] develop a graphical construction technique for determining the optimal sizes of the battery bank and the PV array in a hybrid wind and solar system. Only paired combinations of the three subsystems were considered in the optimization process. In [3] the downhill simplex method is utilized to size hybrid photovoltaic-microhydro power. The cost of a renewable generation system, integrated with electrolysers and fuel cells are also taken into account. A methodology for optimal unit sizing of hybrid power generation systems using multiobjective optimization is presented in [4]. Mousa et al. [5] designed a hybrid wind and solar power generator system. The aim was minimizing the cost, and constrain was the power generated being larger than consumption. GAMS is used for solving the problem.

In this paper, a new hybrid stand-alone renewable energy system is introduced. The sizing determination topic is defined as an optimization problem. The aim is to minimizing cost so the objective function consists of the cost of capital, replacement, operation and maintenance for wind, solar, tidal and battery energy sources. The hourly data of wind speed, solar radiation and water velocity are used for simulations. Considered constrain is reliability of the system. To evaluate reliability of the system, the Equivalent Loss Factor (ELF) index has been used.

The particle swarm optimization (PSO) algorithm is used for determining the requirement sizes of wind, solar, tidal and battery for supply the load with ELF=0.1 at least and minimum cost.

M. Bashir is M.Sc student with Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran (e-mail: mohsenbashir@ieee.org).

J. Sadeh is Associate professor with Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran (e-mail: sadeh@ieee.org).

Comparison between new hybrid of renewable energy and the combination of wind, solar and battery is expressed and effect of ELF value and changing water speed at the optimization problem are investigated.

## II. MODEL OF HYBRID COMPONENTS

In Fig 1, hybrid system consists of wind, solar, tidal and battery is shown. In this combination, four major power sources (wind, solar, tidal and battery) are considered. In the following section, model and the cost of these power sources are described.
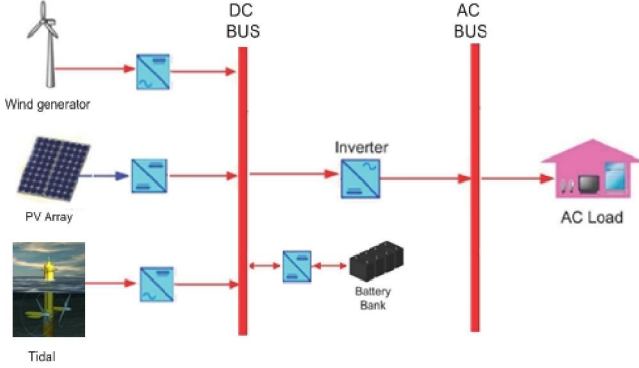


Fig. 1. Hybrid system consist of wind, solar, tidal and battery

### A. Wind

Choosing the suitable model for wind turbine is very important. According to type of wind turbine and rated power, power output characteristic can be different. In this paper, the output power of wind turbine ($p_{wind}$) in terms of wind speed is shown in equation (1) [6]:

$$p_{wind} = \begin{cases} 0 & v < v_{cutin}, v > v_{cuout} \\ p_{max}\left(\dfrac{v - v_{cutin}}{v_{rated} - v_{cutin}}\right)^3 & v_{cutin} \le v < v_{rated} \\ p_{max} + \left(\dfrac{p_{furl} - p_{max}}{v_{cutout} - v_{rated}}\right) & v_{rated} \le v \le v_{cutout} \end{cases} \quad (1)$$

where, $v$, $v_{cutin}$, $v_{cutout}$ and $v_{rated}$ are the wind speed in the current time step, cut-in, cut-out and rated speed (m/s) of wind turbine, respectively. $p_{max}$ and $p_{furl}$ are the maximum output power and output power at cut-out speed (kW), respectively.

In this paper, Bergey wind power's BWC Excel-R/48 is used. The rated capacity of this turbine is 7.5(kW) and provides 48V dc as output.

Considered life time of wind turbine is 20 years. The total cost of wind turbine consists of capital, replacement, operation and maintenance costs. The cost and other parameters of BWC Excel-R/48 wind turbine is described in Table I [6,7].

The measurement of wind speed was at height 30 meters and the wind turbine hub height is 19.9526(m), it is important to adjust the measured wind speed to the hub height. This can be done using equation (2):

$$\frac{v(h_2)}{v(h_1)} = \left(\frac{h_2}{h_1}\right)^\alpha \quad (2)$$

where $v(h2)$ is the wind speed at the desired height $h_2$ and $v(h_1)$ is the wind speed measured at a known height $h_1$ and $\alpha$ is a coefficient known as the wind shear exponent. The wind shear exponent varies with pressure, temperature and time of day. A commonly used value is $(\frac{1}{7})$ [7].

| TABLE I WIND TURBINE PARAMETERS | | |
|---|---|---|
| Cut-in Speed | $v_{cutin}$ | 3(m/s) |
| Cut-out Speed | $v_{cutout}$ | 25(m/s) |
| Rated Speed | $v_{rated}$ | 15(m/s) |
| Maximum Output Power | $p_{max}$ | 8.1(kW) |
| Capital Cost | $CC_W$ | 16400($/Unit) |
| Replacement Cost | $RC_W$ | 13000($/Unit) |
| Operation & Maintenance Cost | $MC_W$ | 75($/Unit) |

### B. Photovoltaic

Photovoltaic system is highly influenced by weather conditions. There are some equations which can use to compute the output power of photovoltaic system. In this paper, equation (3) is considered for output power of photovoltaic ($p_{pv}$) system [7,8].

$$p_{pv} = \frac{G}{G_{STC}} p_{ratedpv} \eta_{pv} \quad (3)$$

where, $G$ is the solar radiation incident on the photovoltaic array in the current time step ($W/m^2$), $G_{STC}$ is the incident radiation at standard test condition and equal to 1000 ($W/m^2$), $p_{ratedpv}$ is a rated power of each array (kW) and $\eta_{pv}$ is the efficiency of PV's DC/DC converter and Maximum Power Point Tracking (MPPT).

In this paper, rated power of each photovoltaic array is considered to be 1 (kW) and the life time of the photovoltaic array is assume to be 20 years. The cost and other parameters of the photovoltaic array is described in Table II [6,7].

| TABLE II PHOTOVOLTAIC PARAMETERS | | |
|---|---|---|
| efficiency | $\eta_{pv}$ | 90% |
| Capital Cost | $CC_S$ | 7000($/Unit) |
| Replacement Cost | $RC_S$ | 6000($/Unit) |
| Operation & Maintenance Cost | $MC_S$ | 20($/Unit) |

### A. Tidal

Marine energy is divided into four parts: tidal, wave, ocean thermal energy and energy from salinity gradients (osmosis). Tidal power plants due to similarities with hydro power plants and usage their technology have rapid develop. For the generating electricity from tidal energy, two ways can be used:
- ✓ By building a tidal barrage across an estuary or a bay in high tide areas.
- ✓ By extracting energy from free flowing water (tidal kinetic energy). Usually, tidal barrage is not used due to the impact on the environmental conditions.

As a renewable resource, tidal current flow is very predictable, to within 98% accuracy for decades. Weather conditions such as wind, fog, rain, and clouds have no effect on tidal current. This is one of the advantages of tidal current because these factors can influence on another alternative energy like the wind and solar. Global marine current is influenced by tides and to a lesser extent by thermal and density of water.

The tides cause water to flow inwards twice each day (flood tide) and seawards twice each day (ebb tide) with a period of approximately 12 h and 24 min (a semidiurnal tide), or once both inwards and seawards in approximately 24 h and 48 min (a diurnal tide). In most locations, the tides are a combination of the semidiurnal and diurnal effects, with the tide being named after the most dominant type.

The strength of the currents varies, depending on the proximity of the moon and sun relative to earth. The magnitude of the tide-generating force is about 68% moon and 32% sun due to their respective masses and distance from earth [9].

In this paper, tidal current flow is used for generating power. Tidal turbines are different types. In this paper horizontal axis turbines is used. The power output of tidal turbine ($p_{tidal}$) can be calculated with using equation (4) [10]:

$$p_{tidal} = 0.5\rho A C_p v_{tide}{}^3 \qquad (4)$$

where, $\rho$ is the fluid density ($^{kg}/_{m^2}$), $A$ is the cross-sectional area of the turbine ($m^2$), $C_p$ is the power coefficient and $v_{tide}$ is the fluid velocity ($^m/_s$).

$C_p$ is essentially the percentage of mechanical power that can be extracted from the fluid stream by the turbine and takes into account its efficiency. For marine turbines, it is estimated to be in the range 0.35–0.5 [9].

In tidal turbine, when water speed is less than $v_{cutin.tide}$ or more than $v_{cutout.tide}$ the output power is become zero. If water speed is more than $v_{cutin.tide}$ or less than $v_{rated.tide}$ the output power is computed using equation (4) and if water speed is more than $v_{rated.tide}$ or less than $v_{cutout.tide}$ the output power is equal to rated power of turbine.

In this paper, the rated capacity of tidal turbine is considered to be 10(kW). Considered life time of tidal turbine is assumed to be 20 years. The cost and other parameters of tidal turbine is described in Table III [11,12].

TABLE III
TIDAL TURBINE PARAMETERS

| Cut-in Speed | $v_{cutin.tidal}$ | 0.7(m/s) |
|---|---|---|
| Rated Speed | $v_{rated.tidal}$ | 2.4(m/s) |
| cross-sectional area | $A$ | 3.006(m$^2$) |
| power coefficient | $C_p$ | 0.47 |
| Capital Cost | CC$_T$ | 25000 ($/Unit) |
| Replacement Cost | RC$_T$ | 17000 ($/Unit) |
| Operation & Maintenance Cost | MC$_T$ | 100 ($/Unit) |

*B. Battery*

Renewable energy sources such as wind and solar are depending to weather conditions, so an energy storage device should be considered to have a better reliability. There are many types of energy storage such as battery, capacitor banks, super conducting magnetic energy storage (SMES) and fuel cell.

Battery bank is a traditional approach to store electrical energy with high efficiency. It's discharging level cannot exceed a minimum limit defined as depth of discharge and charging level cannot exceed a rated capacity of battery.

The lifetime of the battery bank is influenced by charge and discharge factor.

In this paper, battery bank is considered as the storage device. Surrette-6CS25P model with nominal voltage of 6 volt and energy rated of 6.94 (kWh) is considered.

Considered life time of a battery bank is 4 years and depth of discharge is about 20%. The cost and other parameters of the mentioned battery bank describe in Table IV [7].

TABLE IV
BATTERY BANK PARAMETERS

| Charging Efficiency | $\eta_{charge}$ | 0.7(m/s) |
|---|---|---|
| Discharging Efficiency | $\eta_{discharge}$ | 2.4(m/s) |
| Capital Cost | CC$_B$ | 1250 ($/Unit) |
| Replacement Cost | RC$_B$ | 1100($/Unit) |
| Operation & Maintenance Cost | MC$_B$ | 20  ($/Unit) |

## III. PROBLEM FORMULATION

The aim of this paper is to obtain the optimal number of renewable sources (wind, solar, tidal and battery) for supplying the load with considering a minimum cost and satisfying a defined reliability index. The lifetime of the project is considered to be 20 years. Determining the sizing of hybrid wind, photovoltaic, tidal and battery is formulated as an optimization problem. The objective function is minimizing the cost and the constrain having specific reliability.

The cost function consists of capital, replacement operation and maintenance costs. In this paper, for calculation of system cost, Net Present Cost method (NPC) is considered.

NPC method is formulated like equation (5) [13]:

$$NPC = \sum_{i=1}^{L} N_i (CC_i + RC_i * K_i + MC_i * PWA(ir, R)) \qquad (5)$$

$L$ is the number of renewable sources, in this analysis it is equal to four. $N_i$ is a number of each renewable energy source, which evaluate from an optimization algorithm. $CC$, $RC$ and $MC$ are capital, replacement, operation and maintenance costs of each renewable source, respectively. The replacement cost is the cost of replacing a component at the end of its lifetime, for converting this cost to present, $K_i$ is considered, which is calculated according to the following equation:

$$K_i = \sum_{n=1}^{l1} \frac{1}{(1+ir)^{n*l2}} \qquad (6)$$

$l1$ and $l2$ are number of times, which the renewable unit replace and total life time of renewable unit, respectively. For sources, that is lifetime is equal to the lifetime of total project, $K_i$ is equal to zero. $ir$ is interest rate, and in this paper $ir$ it is considered to be 0.06.

$PWA(ir, R)$ is used to convert annual cost of maintenance and operation cost to present cost, which can be calculated using equation (7):

$$PWA(ir, R) = \frac{(1+ir)^R - 1}{ir(1+ir)^R} \qquad (7)$$

$R$ is lifetime of total system. The aim of optimization method is minimizing the NPC.

There are many indices for reliability evolution such as Loss of Power Supply probability (LPSP), Equivalent Loss Factor (ELF), Loss of Load Probability (LOLP) and etc.

In this paper, Equivalent Loss Factor (ELF) is used for calculating the reliability. ELF is calculated using the following equation [14]:

$$ELF = \frac{1}{H} \sum_{i=1}^{H} \frac{Q(i)}{D(i)} \qquad (8)$$

$H$, is the total number of step time, in this analysis $H$ is equal to 8760. $Q(i)$ and $D(i)$ are total loss load and total load demand at each step time, respectively. ELF $\leq 0.1$ is considered for this optimization problem.

## IV. OPERATION STERATEGY

For supplying electrical energy of load with hybrid renewable source, appropriate power management is needed. In this paper power management is divided to three states:

In state 1, wind, solar and tidal generations are assumed to be equal to load demand. In this state, all the power generations are consumed in a load and battery state of charge (SOC) is not changed.

In state 2, wind, solar and tidal generations are greater than the load demand. In this state, some of the power generated by wind, solar and tidal are consumed in load. If SOC of battery isn't 100%, surplus power of generation is charged the battery. If SOC of battery is 100% or become 100% after minutes of charging, the surplus of power is consumed in a dump load.

In state 3, wind, solar and tidal generations are less than the load demand. In this state, all the power generated with the wind, solar and tidal are used for supplying the load. If SOC of battery is greater than depth of discharge, shortage of power generation is supplied from battery and if the battery could not supply the shortage of generation, the load will be shed.

## V. OPTIMIZATION ALGORITHM

Particle swarm optimization (PSO) is a population based stochastic optimization technique. PSO is inspired from the swarming behavior of animals and human social behavior. In PSO, the feasible solutions, called particles, fly through the problem space by following the current optimum particles. The particle adjusts its position according to its own experience and the experience of the neighboring particles.

The best previous position explored by the $n$th particle is recorded and denoted as $p_{best}$. Another value that is recorded by the particle swarm optimizer is the best value obtained so far by any particle in the population. This best value is a global best and is known as $g_{best}$. Each particle tries to modify its position using the current velocity and its distance from $p_{best}$ and $g_{best}$. The modification can be represented by the concept of velocity and can be calculated as shown in the equations (9) and (10). Let $x$ and $v$ denote the particle's position and its velocity in the search space [15].

$$v_{i+1} = wv_i + c_1 rand(p_{best} - x_i) + c_2 rand(g_{best} - x_i) \quad (9)$$

$$x_{i+1} = x_i + v_{i+1} \qquad (10)$$

The first term in (9) represents the inertia of the particle, while the second and third terms represent the memory and the cooperation between particles, respectively. The constants $c_1$ and $c_2$ represent the learning rate or the acceleration term that pulls each particle towards $p_{best}$ and $g_{best}$ positions. The inertia weight $w$ governs how much of the previous velocity should be retained from the previous time step. In this work a linearly decreasing inertia weight is used, as equation (11):

$$w = w_{max} - \frac{w_{max} - w_{min}}{itr_{max}} *itr \qquad (11)$$

where, $w_{max}$ and $w_{min}$ are the maximum and minimum weight values that are constant and $itr$ is the iteration number.

In this paper a modified PSO is presented. In this modified PSO, if the constraints are not satisfied, then updating process are done with equation (12). Again the constraints are checked. If again the constraints are not satisfied, updating is done by equation (13).

$$\begin{aligned} v_{i+1} &= c_2 rand(g_{best} - x_i) \\ x_{i+1} &= x_i + v_{i+1} \end{aligned} \qquad (12)$$

$$\begin{aligned} v_{i+1} &= 0 \\ x_{i+1} &= p_{best} \end{aligned} \qquad (13)$$

The parameters of PSO algorithm considered in this paper are shown in Table V.

| TABLE V PSO PARAMETERS | |
|---|---|
| $c_1$ | 1.5 |
| $c_2$ | 1.5 |
| $w_{min}$ | 0.1 |
| $w_{max}$ | 1 |
| iteration | 40 |
| population | 30 |

## VI.  SIMULATION RESULTS

In this paper, hourly wind speed, the data of solar radiation and water speed of one year is used for simulation. Data of each hour is obtained from the average of sixteen years hourly data of state Oregon of United States. Hourly data of wind speed, solar radiation and water speed are shown in Fig. 2, 3 and 4 respectively. Hourly load data of one year is shown in Fig. 5. Peak load is considered to be 500kW.
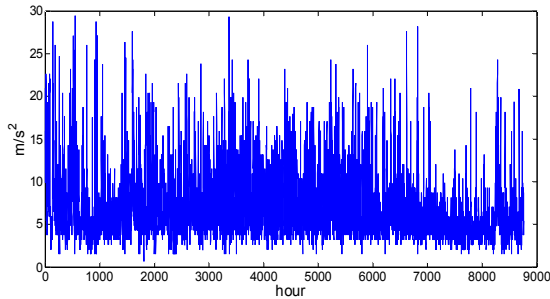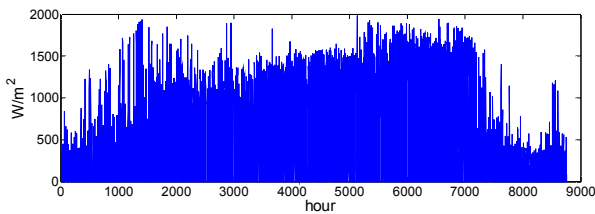


Fig. 2. Hourly wind speed of 1 year
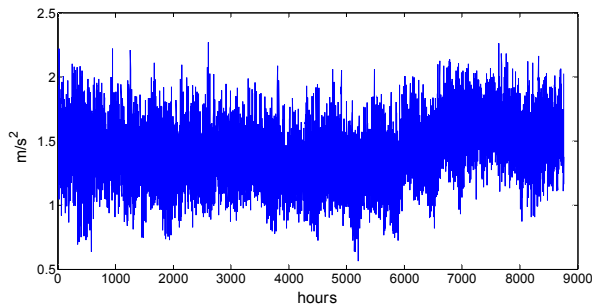


Fig. 3. Hourly solar radiation of 1 year



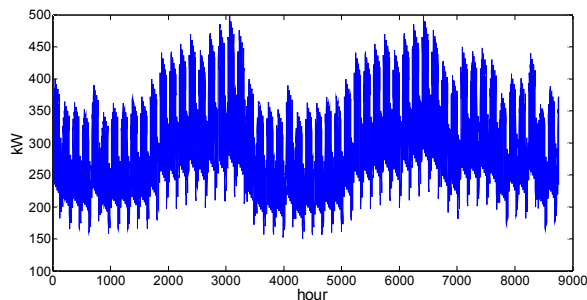Fig. 4. Hourly water speed of 1 year



Fig. 5. Hourly load data of 1 year

Population is generated with PSO algorithm. The decision variable in the optimized procedure is numbers of wind, solar, tidal and battery.  For each population, reliability factor is calculated, if ELF>0.1, PSO update each of population again. For all rows of population, the objective function is calculated

then each of population that has a minimum of cost and defined reliability is selected.

Sizing of hybrid wind, solar, tidal and battery is investigated, and the best sizing selected. Some results of analysis are shown in Figs. 6, 7 and 8. Figs. 7 and 8 are zoomed for better showing the details.
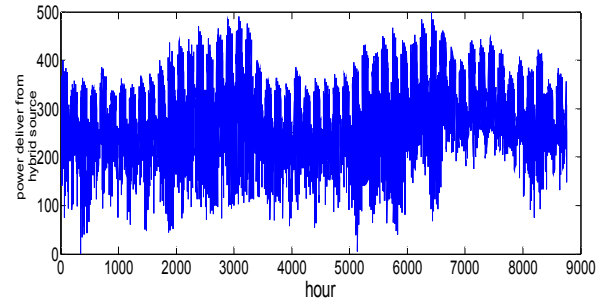


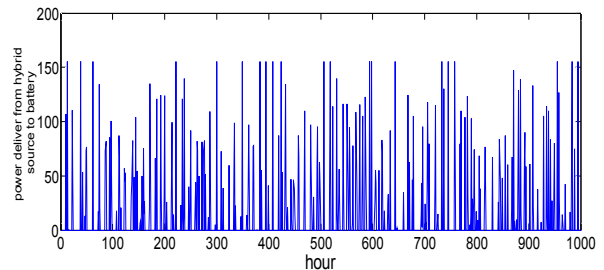Fig. 6. Power deliver from hybrid system



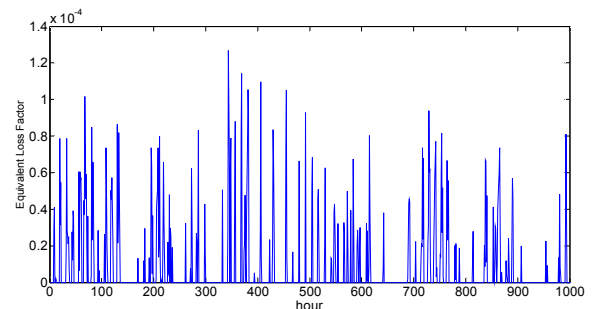Fig. 7. Power delivered from hybrid renewable sources to battery



Fig. 8. Equivalent Loss Factor

The convergence of PSO algorithm is shown in Figs. 9 and the best combination of renewable sources is shown in Table VI.
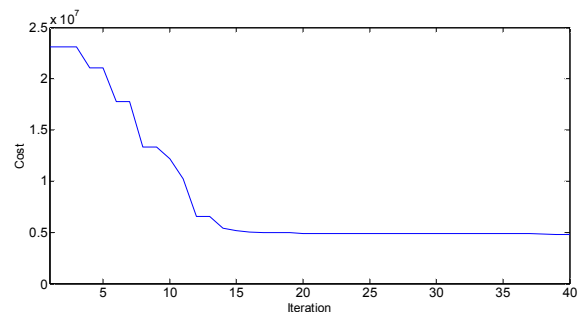


Fig. 9. Convergence of PSO algorithm

**TABLE VI**
**OPTIMIZED PARAMETERS**

| Number of Wind Turbine | Number of Solar Array | Number of Tidal Turbine | Number of Battery | Total Cost |
|---|---|---|---|---|
| 24 | 85 | 143 | 28 | 0.4813e+7 |

Again, all the simulation is repeated with hybrid wind, solar and battery. The convergence of PSO for this hybrid is shown in Fig. 10 and Table VII.
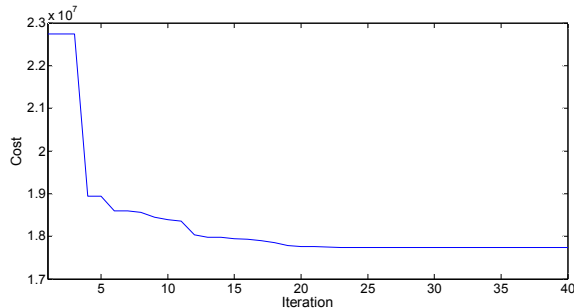


Fig. 10. Convergence of PSO algorithm for hybrid wind, solar and battery

**TABLE VII**
**OPTIMIZED PARAMETERS OF HYBRID WIND, SOLAR AND BATTERY**

| Number of Wind Turbine | Number of Solar Array | Number of Battery | Total Cost |
|---|---|---|---|
| 23 | 2003 | 713 | 1.7744e+7 |

It is obvious that combination of wind, solar, tidal and battery is more economical. Combination of wind, solar, tidal and battery has a one problem. This combination only used in place near the sea. Other analysis is done at the hybrid wind, solar, tidal and battery and hybrid wind, solar and battery system. The results are shown in Table VIII and IX.

**TABLE VIII**
**EFFECT OF ELF ON THE OPTIMIZATION PARAMETERS**

| ELF | Number of Wind Turbine | Number of Solar Array | Number of Tidal Turbine | Number of Battery | Total Cost |
|---|---|---|---|---|---|
| 0.1 | 24 | 85 | 143 | 28 | 0.4813e+7 |
| 0.05 | 37 | 0 | 152 | 104 | 0.50311e+6 |
| 0.1 | 23 | 2003 | — | 713 | 1.7744e+7 |
| 0.05 | 401 | 1879 | — | 695 | 2.33e+7 |

**TABLE IX**
**EFFECT OF WATER SPPED ON THE OPTIMIZATION PARAMETERS**

| Water Speed | Number of Wind Turbine | Number of Solar Array | Number of Tidal Turbine | Number of Battery | Total Cost |
|---|---|---|---|---|---|
| primary | 24 | 85 | 143 | 28 | 0.4813e+7 |
| Increase 0.3(m/s$^2$) | 0 | 68 | 79 | 140 | 0.3120e+7 |

Table VIII, shows the effect of reliability index on the total cost of the system. The result shows that increase reliability of the system to two times cause an increase at the total cost. In combination of wind, solar, tidal and battery increase on the total cost is lesser than the combination of wind, solar and battery. Table IX, shows the effect of increase in water speed on total cost.

## VII. CONCLUSION

In this paper a new hybrid renewable resources is introduced. Hourly data of wind speed, solar radiation, water speed and load are used for simulation. The lifetime of the system considered 20 years. NPC method used for calculating Cost of system and reliability factor which used is ELF. Particle swarm optimization method is used to obtain the number of wind turbine, solar array, tidal turbine and battery that have minimum cost and satisfy reliability. The new combination of renewable energy is compared to the hybrid wind, solar and battery and it is shown that the new hybrid is more economical than hybrid wind, solar and battery.

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## IX.  BIOGRAPHIES

**Mohsen Bashir** was born in Mashhad, Iran, in 1985. He received the B.Sc. degree (Hons). in electrical engineering from azad university of Birjand, Birjand, Iran and now he is a graduate student in department of electircal engineering of Ferdowsi University of Mashhad, Mashhad, Iran. His resarch intereses are power system protection, power system operation, renewable energy and distributed generation.

**Javad Sadeh** (M'08) was born in Mashhad, Iran, in 1968. He received the B.Sc. and M.Sc. degrees (Hons). in electrical engineering from Ferdowsi University of Mashhad, Mashhad, Iran, in 1990 and 1994, respectively, and the Ph.D. degree in electrical engineering from Sharif University of Technology, Tehran, Iran with the collaboration of the Electrical Engineering Laboratory of the Institut National Polytechnique de Grenoble (INPG), Grenoble, France, in 2001. Since then, he has been an Associate Professor at the Ferdowsi University of Mashhad. His research interests are power system protection, dynamics, and operation.