OPTIMAL DESIGN OF A STAND-ALONE HYBRID SYSTEM CONSISTING OF PV/WT/FC TECHNOLOGY

Touraj Qanatir
Master Student
Department of Electrical Enginnering
Amirkabir University of Technology
Tehran, Iran
Email: Touraj.Qanatir@aut.ac.ir

Gholam H. Riahy
Associate Professor
Department of Electrical Enginnering
Amirkabir University of Technology
Tehran, Iran
Email: Gholam@aut.ac.ir

Abstract— **Hybrid renewable energy systems, consisting of different types of technologies, have been proposed as an eco-friendly energy system for stand-alone remote area. Comparing traditional off-grid systems, using diesel generator with renewable energy systems, it is found that the latter offers technical, economic and environmental advantages. In this study, a hybrid renewable energy system using hydrogen storage system is considered for satisfying the sample load pattern for Rafsanjan in Iran. Wind turbine site matching is very crucial for having a cost-effective energy system. Wind probability density function of the region is used to estimate capacity factor for four wind turbines and the turbine with the highest capacity factor is selected. A hybrid system consisting of wind turbine, photovoltaic panel, fuel cell is considered. This system is modeled, optimally sized, and compared with a diesel-alone generation system in terms of the total annual cost and environmental pollutants.**

Keywords: Hybrid renewable system; Wind turbine; Photovoltaic; Fuel cell; Probability density function

I. INTRODUCTION

In recent years, the world has faced a serious challenge in terms of providing energy which is one of the most necessary requirements of humankind. Today, a great portion of the energy demand all around the world is supplied from conventional energy sources [1]. On the other hand, electrification to the remote areas at minimal cost and low emission is a significant issue when future energy concepts are discussed [2]. Hybrid energy systems are best suited to reduce dependence on fossil fuel and without causing greenhouse gases using available wind speed and solar irradiation. Among the renewable energy sources, photovoltaic (PV) panels and wind turbines (WTs) are the most promising technologies to satisfy the load demand in remote areas [3].

For a renewable hybrid system, it is necessary to provide an energy storage system. The storage system meets the remaining load demand when the output power of renewable energy sources has low energy. With regarding hydrogen tank (HT) as a storage system, the fuel cell (FC) with electrolyser system can be considered as a backup power source when the load is greater than power which is generated by renewable sources. When hydrogen is extracted from water by using excess electricity obtained from the renewable energy resources, it can be regarded as an eco-friendly fuel. Use of such energy sources can reduce the emission of CO_2 to nearly zero [4].

Selecting an optimal combination in hybrid energy systems is one of the most important issues for enjoying a cost-effective energy system. Literature study represents that there are many attempts based on probabilistic, analytical and heuristic methods for appropriate sizing of hybrid energy system. The sizing of a hybrid system considering the loss of power supply probability (LPSP) and the levelized cost of energy (LCE) concepts, is presented in [5]. The optimum generation capacity and storage needed are determined for an autonomous hybrid wind/PV system for an experimental site [6]. In [7] optimal design of a reliable hydrogen-based stand-alone wind/PV system is studied. The interest of a hybrid solar energy system, including a lithium-based batteries bank and a hydrogen chain (electrolyser, gas storages and fuel cell), is investigated for an off-grid application [8]. Computation of wind turbine capacity factor at the planning step is important issue for wind turbine site matching. In [9] two models of wind turbine is considered and wind turbine with the most annual energy production is selected. A nonlinear optimization model for planning wind turbine installations is introduced [10]. The simulation results in HOMER indicate that hybrid system would be a feasible solution at remote locations [11]. The other methods for sizing of hybrid system are heuristic algorithms such as genetic algorithm and harmony search [12-13].

In this paper, a mathematical model is introduced for each system component and then, Rafsanjan's wind data is used to select appropriate wind turbine. Particle swarm optimization (PSO) technique is used to optimally size the hybrid system consisting of wind turbine, photovoltaic panel and fuel cell in order to satisfy the load pattern.

II. SYSTEM CONFIGURATION

The output power of PV panel and WT is variable inasmuch as it is dependent on the variation of the resources (sun and wind). Also, because of the load demand fluctuation the main attribute of such hybrid system is the ability of satisfying the demand at any time and storing the excess energy for the later time in deficit conditions.

Figure.1 shows the configuration of the hybrid system consisting of PV, WT, FC and HT to store excess energy and improve the system reliability. In this system, electrolyser produces hydrogen by excess electrical energy of the PV and WT and fills the HT. The hydrogen can then be used to supply a FC which is considered as a backup power source when the load demand is high.

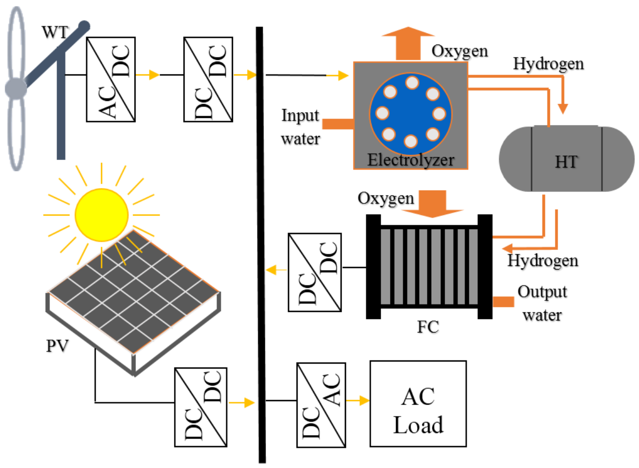

Figure 1. Schematic of the PV/WT/FC hybrid system

III. MODELING THE SYSTEM COMPONENT

A. Wind Turbine

The output power of a wind turbine is expressed with (1) as a function of wind speed at the height of turbine hub:

$$p_{WT}(v)=\begin{cases}0; & v\le v_{cut-in}, v\ge v_{cut-out}\\ (p_{WT,rated})\times\dfrac{v-v_{cut-in}}{v_r-v_{cut-in}}; & v_{cut-in}\le v\le v_r\\ p_{WT,rated} & v_r\le v\le v_{cut-out}\end{cases} \quad (1)$$

Where v is the wind speed, $P_{WT,rated}$ is the rated power of the wind turbine, and v_{cut-in}, $v_{cut-out}$ and v_r are cut-in, cut-out and rated speed of the wind turbine, respectively. The measured wind speed can be transformed to wind speed at the height of turbine hub, by using (2).

$$v=v_{measure}\times\left(\frac{H_{hub}}{H_{measure}}\right)^{\zeta} \quad (2)$$

which $v_{measure}$ is the measured wind speed at the height of $H_{measure}$ and H_{hub} is the height of turbine hub. ζ is varying between 0.10 for flat land and more than 0.25 for heavily forested landscapes. A proper amount of ζ for a land which is far away from trees and high buildings, is equal to 0.14. This ζ has been considered in this study [14]. Parameters, which are related to the four intended turbines, has been shown in Table1.

B. Photvoltaic Panel

The hourly information of solar irradiation is required for a proper design of hybrid system. Using (3), the output power of each PV is obtained as a function of solar irradiation power.

Table 1. TECHNICAL CHARACTERISTICS OF WIND TURBINES

Turbine	v_{cut-in} (m/s)	v_r (m/s)	$v_{cut-out}$ (m/s)	$v_{WT,\max}$ (kW)	H_{hub} (m)
1	3.1	12.5	24	1	20
2	2.1	9	20	2.5	20
3	3	12	25	7.5	25
4	3	14	25	10	25

$$p_{PV}(R)=p_{PV,rated}\times\left(\frac{R}{R_{ref}}\right)\times[1+N_T(T_c-T_{ref})] \quad (3)$$

which p_{pv} and p_r are the produced power of each PV and the rated power of PV, respectively. Also R is solar irradiation in W/m^2. R_{ref} is the solar irradiation at reference conditions, which is usually considered to be 1000 W/m^2. T_{ref} is the cell temperature at reference conditions and set usually as 25 ℃. N_T is the temperature coefficient of the PV and it equals -3.7×10^{-3} (1/C). T_c is the cell temperature, can be calculated by (4).

$$T_c=T_{air}+\left[\frac{(NOCT-20)}{800}\times R\right] \quad (4)$$

where T_{air} is the ambient air temperature in °C, R is the solar irradiation and NOCT is the nominal operating cell temperature in °C. It is one of the PV module specifications and it has been considered as 48 °C.

C. Electrolyser

When the total output power of WT/PV is greater than the load demand, the surplus power is delivered to the electrolyser to fill the hydrogen tanks. The energy of hydrogen stored in the tank at time t is obtained by the following equation:

$$E_{HT}(t)=E_{HT}(t-1)+\left[(E_{WT}+E_{PV}(t))-\frac{E_{load}(t)}{\eta_{Inv}}\right]\times\eta_{Elect} \quad (5)$$

where $E_{HT}(t)$ and $E_{HT}(t-1)$ are the energy stored in the HTs at time t and $(t-1)$, respectively. η_{Elect} is electrolyser's efficiency which is assumed to be constant for all operating states.

When the load demand is greater than the energy produced by the WT/PV, the FC is used to satisfy the load demand. In this case, the energy of hydrogen stored in the tank at time t is obtained by

$$E_{HT}(t) = E_{HT}(t-1) - \frac{[\frac{E_{load}(t)}{\eta_{Inv}} - (E_{WT} + E_{PV}(t))]}{\eta_{FC}} \quad (6)$$

Due to low working temperature (80–100 ◦C) and fast dynamic response, PEM fuel cells are best suited for residential applications. In [15], the FC efficiency curve, which is a function of the part load ratio (PLR), has been developed. Mathematical expression has been proposed in [15] to approximate the curve as follows:

$$\begin{aligned} &\text{If PLR} < 0.05 \quad \eta_{FC} = 0.2716 \\ &\text{If PLR} \geqslant 0.05 \\ &\eta_{FC} = 0.9033\times \text{PLR}^5 - 2.9996\times \text{PLR}^4 + 3.6503\times \text{PLR}^3 \\ &\quad - 2.0704\times \text{PLR}^2 + 0.4623\times \text{PLR} + 0.3747 \end{aligned} \quad (7)$$

where PLR can be obtained by

$$\text{PLR} = \frac{\text{Generated Electrical Power}}{\text{Rated Power}} \quad (8)$$

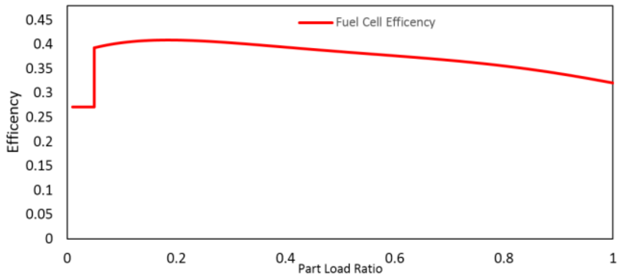

Figure 2. Performance Curves of FC

The mass of stored hydrogen is calculated as follows:

$$m_{HT}(t) = \frac{E_{HT}(t)}{HHV_{H2}} \quad (9)$$

where the Higher Heating Value (HHV) of hydrogen is equal to 39.7 kWh/kg. It is not feasible that the mass of stored hydrogen exceeds the rated tank capacity. On the other hand, due to hydrogen pressure drop, a small fraction of the hydrogen (here, 5%) may not be extracted [7].

IV. INVESTIGATION OF WIND STATISTIC DATA

A method that is used to determine the Annual Energy Production (AEP) of a WT, is the calculation of production amount regarding the region wind speed distribution. Considering the stochastic nature of wind and calculating the number of occurrences frequencies per year, wind speed distribution has been obtained according to hourly data and represented in Figure 3.

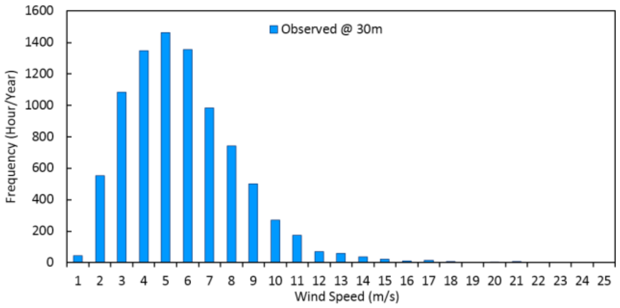

Figure 3. Wind Speed Distribution According To Hourly Data

The Weibull probability density function has a high matching with the wind speed data. This function is a particular case of Gamma Distribution and expressed as follows:

$$f(v) = (\frac{k}{c})(\frac{v}{c})^{(k-1)} \exp[-(\frac{v}{c})^k] \quad (10)$$

$$F(v) = 1 - \exp[-(\frac{v}{c})^k] \quad (11)$$

where $f(v)$ and $F(v)$ are Probability Distribution (PDF) and Cumulative Distribution (CDF) Functions, respectively. c and k are scale and shape parameters, respectively in the Weibull model of region wind speed. There are different methods to calculate the Weibull function parameters. In this study Maximum Likelihood method have been investigated.

A. Maximum Likelihood Method for Calculation the Weibull Model Parameters

In this method, the Weibull model parameters are obtained by using two equations (12) and (13):

$$\frac{1}{k} - \frac{\sum_{i=1}^{n} v_i^k \ln v_i}{\sum_{i=1}^{n} v_i^k} + \frac{1}{n}\sum_{i=1}^{n} \ln v_i = 0 \quad (12)$$

$$c = \left(\frac{1}{n}\sum_{i=1}^{n} v_i^k\right)^{\frac{1}{k}} \quad (13)$$

where $v_1, v_2, \ldots, v_n$ is a random sample of probability density function which has n members. c can be obtained from (13) by calculating k by using iterative numerical methods. In the following, this method has been used in order to obtain the Weibull model parameters. Results of this method has been shown in Table 2.

Table 2. PARAMETERS OF THE WEIBULL DISTRIBUTION FUNCTION OF WIND SPEED

Evaluation Method	k	c
Maximum Likelihood	2.11	5.991

The obtained Weibull model by using Maximum Likelihood method similar to real data, as it can be seen in Figure 4.

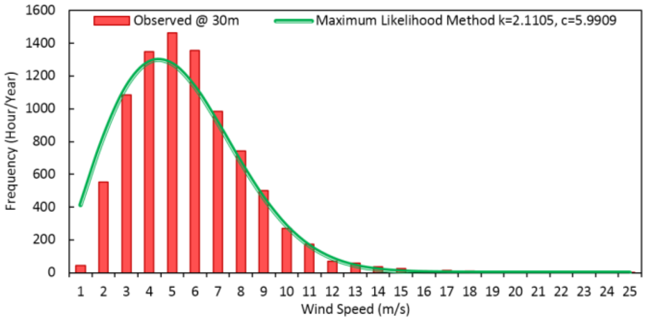

Figure 4. Wind Speed Probability Density Function

B. *Investigating Harvestable Energy from Wind Turbine*

Annual energy production of a turbine is calculated by using (14):

$$AEP = T\int_{0}^{\infty} p_{WT}(v)\cdot f(v)dv = T\int_{v_{cut-in}}^{v_{cut-out}} p_{WT}(v)\cdot f(v)dv \qquad (14)$$

which $f(v)$ is the Weibull probability density function of wind and $T = 8760$ is the number of hours during a year. The integral in (14) can be calculated by using numerical integration methods.

Capacity factor (CF) is an important index in production power of a WT and expressed with (19):

$$CF = \frac{AEP}{E_R} = \frac{1}{p_{WT,rated}} \int_{v_{cut-in}}^{v_{cut-out}} p_{WT}(v)\cdot f(v)dv \qquad (19)$$

In the above equation, E_R is equals

$$E_R = T \cdot p_{WT,rated} \qquad (20)$$

which E_R is the maximum amount of harvested energy by turbine, while the turbine operates in its rated power during period of T. CF for intended turbines has been shown in Table3.

Table 3. CALCULATED CAPACITY FACTOR FOR WIND TURBINES

Turbine	$p_{WT,rated}$ (kW)	CF (%)
1	1	23.04
2	2.5	41.98
3	7.5	26.45
4	10	21.73

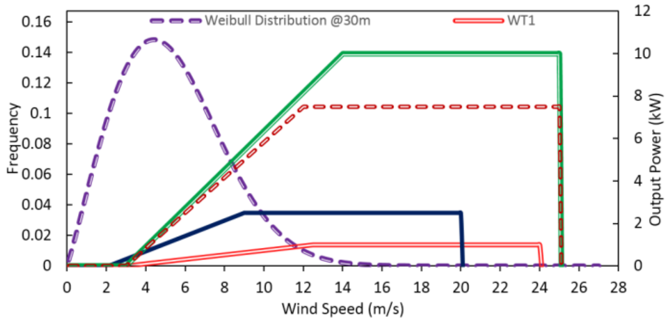

Figure 5. Characteristic of Turbine Output Power and Wind Speed Probability Density Function

As it can be seen in Table 3, the maximum of CF is obtained for second WT. In the following, this turbine is used for optimal design of the intended combination system.

V. COST MODELING

In this section, the objective function of the optimum design problem is the minimization of the total annual cost (C_T). The C_T consists of the annual capital cost ($C_{Capital}$) and the annual operating and maintenance cost ($C_{O\&M}$). In order to optimal design of the hybrid energy system, the optimization technique should minimize (21).

$$\text{Minimize} \quad C_T = C_{Capital} + C_{O\&M} \qquad (21)$$

In order to convert initial capital cost to the annual capital cost, capital recovery factor (CRF), defined by (22) is used.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (22)$$

where i is the interest rate and n indicates the life span of the system.

Because of life span constraints, Some components of PV/WT/FC system must be replaced several times during the project operation time. In this study, the life span of FC and electrolyser is assumed to be 5 years. By using single payment present worth factor, (23) can be calculated.

$$C_{FC/Elect} = P_{FC/Elect}(1 + \frac{1}{(1+i)^5} + \frac{1}{(1+i)^{10}} + \frac{1}{(1+i)^{15}}) \qquad (23)$$

where $C_{FC/Elect}$ is the present worth of FC/electrolyser system and $P_{FC/Elect}$ is FC/electrolyser price.

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

$$C_{Conv/Inv} = P_{Conv/Inv} \times (1 + \frac{1}{(1+i)^{10}}) \qquad (24)$$

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

For this system, total annual capital cost are obtained by

$$C_{Capital} = CRF[N_{WT} \times C_{WT} + N_{PV} \times C_{PV} + N_{HT} \times C_{HT} + C_{FC} + C_{Elect} + N_{Conv/Inv} \times C_{Conv/Inv}] \quad (25)$$

where C_{WT} is unit cost of wind turbine, C_{PV} is unit cost of PV panel, N_{HT} is the number of storage tanks, C_{HT} is unit cost of hydrogen storage tank, $N_{Conv/Inv}$ is the number of converter/inverter.

For obtaining the annual maintenance cost of the system components, (26) is used:

$$C_{O\&M} = N_{WT} \times C_{WT}^{O\&M} + N_{PV} \times C_{PV}^{O\&M} + C_{FC}^{O\&M} + C_{Elect}^{O\&M} \quad (26)$$

where $C_{WT}^{O\&M}$, $C_{PV}^{O\&M}$, $C_{FC}^{O\&M}$ and $C_{Elect}^{O\&M}$ are the annual maintenance costs of PV, wind turbine, fuel cell and electrolyser.

VI. CONSTRAINTS

For the WT/PV/FC system, the constraints of the maximum available number of WT, PV panels and HT should be satisfied. For the hydrogen tank, because of hydrogen pressure drop, a small fraction of the hydrogen may not be extracted. Also, the mass of stored hydrogen should not exceed the rated capacity of the hydrogen tank.

$$M_{HT}^{\min} \le M_{HT} \le M_{HT}^{\max} \quad (27)$$

where $M_{HT}^{\min}$ (assumed to be 5% of rated capacity of HT) and $M_{HT}^{\max}$ denote the minimum and maximum storage capacity of the hydrogen tank, respectively.

VII. PARTICLE SWARM OPTIMAIZATION ALGORITHM (PSO)

PSO is a population-based metaheuristic algorithm attempting to realize the global solution of an optimization problem by inspiring from the nature social behavior and dynamic movements with communication of insects, birds and fish. In this context, the population is known as swarm and each individual of the population is called particle. Each particle moves with an adaptable velocity within the search space and retains in its memory the best position it ever encountered. The global variant of PSO the best position ever attained by all individuals of the swarm is communicated to all the particles. The general principles for the PSO algorithm are stated as follows.

$$V_i^{k+1} = \omega \times V_i^k + C_1 \times rand_1 \times (P_{best} - X_i^k) + C_2 \times rand_2 \times (g_{best} - X_i^k) \quad (28)$$

where X_i is the position of ith particle. Particle i remembers the best position it visited so far, referred to as P_{best}, and the best position of the best particle in swarm is called g_{best}. V_i is the velocity of ith particle and ω is the inertia coefficient which is employed to manipulate the impact of the previous history of velocities on the current velocity. C_1 and C_2 represent the cognitive and social parameters.

Each particle adjust its position in next iteration with respect to (32):

$$X_i^{k+1} = X_i^k + \gamma \times V_i^{k+1} \quad (29)$$

where γ is constriction factor, which is used to limit velocity.

VIII. RESULTS

In this research, the experimental data used for wind speed and solar insolation is obtained from Rafsanjan, in Iran. The solar irradiation and wind speed (20 m above the ground) profiles for one week are plotted in Figure 6. The hourly mean values of ambient temperature is shown in Figure 7. The parameters related to the components have been given in Table 4. Figure 8 shows the average hourly load demand.

In order to optimally size the components of PV/WT/FC system MATLAB environment is used to implement PSO technique.

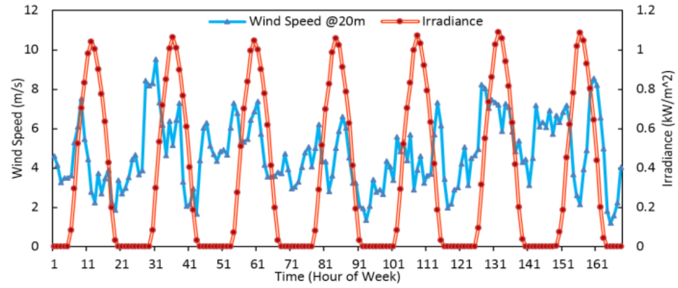

Figure 6. Hourly Profiles of Solar Irradiation and Wind Speed

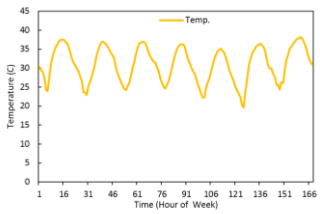

Figure 7. Hourly Ambient Temperature

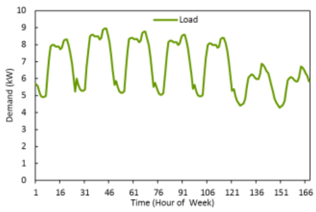

Figure 8. Hourly Load Demand

Summary of the results obtained by PSO has been listed in Table 5. The total annual costs for PV/WT/FC system is found 33769.74$.

Figure 9 indicates the convergence process of the PSO algorithm for finding the appropriate size of the system. Figure 10 illustrates the energy flow in hydrogen-based storage system as well as output power of FC is shown in Figure 11.

The total annual costs for PV/WT/FC system is 33769.74$ while this value for diesel system is 41578.9$. Table 5 shows the amount of the pollutants (CO_2, SO_2, NO_X and CO) resulted from the fuel combustion in the diesel generator during one year of operation for the system in which the diesel works.

Table 4. Component parameters

Component	Capital cost	O&M cost	Life time (year)	Efficiency	Unit
PV Panel	312 $	2% of Capital Cost per Year	20	-	260 W
Wind Turbine	8000 $	2% of Capital Cost per Year	20	-	2.5 kW
Converter	1000 ($/kW)	-	10	95%	1 kW
Electrolyser	2700 ($/kW)	4% of Capital Cost per Year	5	75%	1 kW
Hydrogen Tank	500 ($/kg)	-	10	-	1 kg
Fuel Cell	4000 ($/kW)	5% of Capital Cost per Year	5	-	1 kW
Diesel	1713.15 $	1.24 ($/L)	1	-	1.9 kW
System parameter					
Interest rate (i)	6%				
System life span	20 years				

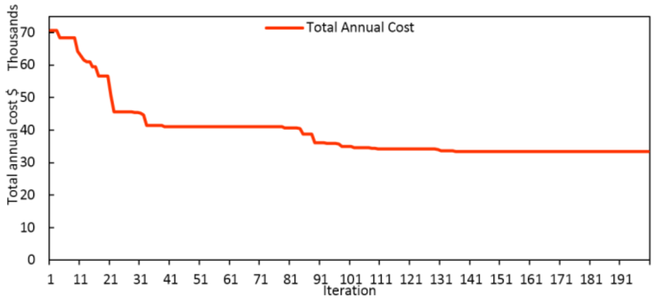

Figure 9. Convergence Process of PSO For Finding the Optimum Size of the Hybrid System

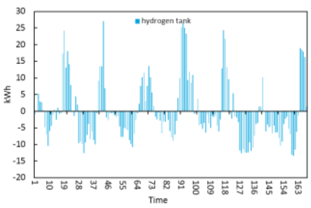

Figure 10. Energy Flow in Hydrogen-Based Storage System

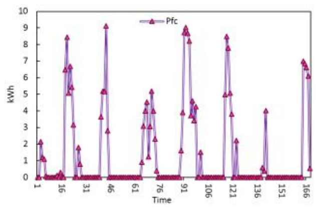

Figure 11. Output Power of FC

Table 5. Summary of the Results

Hybrid system	N_{WT}	N_{PV}	N_{HT}	P_{FC}	Total Cost$
Optimal Combination	52	7	8	10 kW	33769.7413

Table 6. Emissions of Diesel Alone System

Fuel	Emission (kg/kWh)			
	CO2	SO2	NOx	CO
Petroleum	0.85	0.0005	0.0025	0.0002
Total Emission of Diesel-alone System	49943.149 (kg/year)	29.37 (kg/year)	146.89 (kg/year)	11.75 (kg/year)

IX. CONCLUSION

This paper presents a stand-alone hybrid system consisting of WT/PV/FC for electrification to a remote area located in Rafsanjan, Iran. The components of hybrid energy system is mathematically formulated. Wind probability density function of the region is used to estimate capacity factor for four wind turbines and appropriate wind turbine with highest capacity factor is selected. Then, the optimal sizing of the system is found by PSO algorithm and the result compared with diesel-alone system. It is found that using PV/WT/FC is more cost-effective than diesel alone system.

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