

Optimization and Techno-Economic Analysis of Autonomous Photovoltaic/Fuel Cell Energy System

Saeed Jalilzadeh¹, Hossein Kord², and Ahmad Rohani³, Non-members

ABSTRACT

This paper introduces a method to unit sizing hybrid Photovoltaic/Fuel Cell generation system for a typical domestic load that is not located near the electric grid. In this configuration the combination of a battery, an electrolyser, and a hydrogen storage tank are used as the energy storage system. The aim of this design is finding the configuration, among a set of systems components, which meets the desired system reliability requirements, with the lowest value of levelized cost of energy over 20 years of operation. An energy based modelling has been developed using Matlab/Simulink to observe evolution of the system during a typical day, and the results are reported and discussed in the paper. An overall power management strategy is designed for the proposed system to manage power flows among the different energy sources and the storage unit in the system. The results show that a system composed with a photovoltaic generator, a fuel cell, an electrolyser and a battery can deliver energy in a stand-alone installation with an acceptable cost.

Keywords: Hybrid energy system, Optimization, Reliability, Simulation, Unit sizing

1. INTRODUCTION

Mankind needs energy to overcome the difficulties on the earth throughout the history, so energy is a key element in the interactions between nature and society. However, energy production, transportation and consumption activities bring some problems which are more apparently today. These problems related to energy may be classified as below [1]:

- depletion of fossil fuel resources,
- growth in energy demand,
- global warming (climate change),
- global unrest,
- local pollution,

- fluctuating oil and natural gas prices, etc.

The aforementioned limitations, have led the research community to seek for alternative Renewable Energy Sources (RES). Special emphasis has been given on the development and implementation of fuel cell (FC) systems, for both academic purposes and industrial applications. Fuel cells may be considered as continuous chemical reactors which convert fuel and oxidant chemical potential into electrical energy. The key advantages of fuel cells compared to the conventional electrical power generation technologies are: higher efficiency, especially when the waste heat is used for co-generation, quiet operation suitable for residential applications, and almost zero levels of produced pollutant gases. The most important drawback concerning fuel cell technology is that the basic fuel they use (hydrogen) does not exist free in nature [2].

The major application of a stand-alone power system is in remote areas where utility lines are uneconomical to install due to terrain, the right-of-way difficulties or the environmental concerns. According to the World Bank, more than 2 billion people live in villages that are not yet connected to utility lines [3]. These villages are the largest potential market of the hybrid stand-alone systems. Many alternative energy sources including wind, photovoltaic (PV), FC, diesel system, gas turbine, and micro turbine can be used to build a hybrid energy system [4-11].

In previous studies, the optimal sizing problem is solved for wind-fuel cell hybrid system [9], and for wind-solar-fuel cell hybrid system [10]. Furthermore the optimal sizing of wind-solar-battery hybrid system is performed by means of genetic algorithm [11].

In this paper, a stand-alone hybrid alternative energy system consisting of PV, FC, electrolyser, and battery is proposed for stand-alone applications. PV is the primary power source of the system, and the FC-electrolyser combination is used as a backup and a long-term storage system. A battery bank is also used in the system for short-time backup to supply transient power. The details of the major system components, system reliability and economical model are also discussed in the paper.

An overall power management strategy is designed for the system to coordinate the power flows among the different energy sources. Simulation studies have been carried out to verify the system performance

Manuscript received on July 31, 2009 ; revised on October 14, 2009.

¹ The author is with Electrical Engineering Department, Zanzan University, Iran, E-mail: jalilzadeh@znu.ac.ir

² The author is with Young Researchers Club, Islamic Azad University, Zanzan Branch, Zanzan, Iran, E-mail: kord@znu.ac.ir

³ The author is with Young Researchers Club, Islamic Azad University, Shiraz Branch, Shiraz, Iran, E-mail: rohani@znu.ac.ir

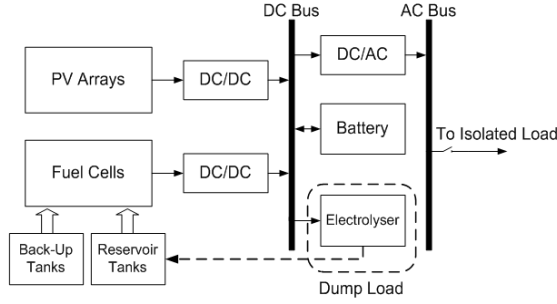


Fig. 1: Photovoltaic/Fuel cell Hybrid System

using practical load profile and real weather data from Shiraz area in south-west Iran. It is to mention that there are many similar regions around the world with this typical situation that can be expanded.

The paper is organized as follows: Firstly, the mathematical model of hybrid PV/FC system (HPFS), including PV modules, FC stack, electrolyser and battery storage, is developed. Secondly, the system reliability model, which is based on loss of power supply probability (LPSP) technique, and the system economical model, based on the levelized cost of energy (LCE) concept, is presented. Section 5 describes power management strategy. Lastly, the simulation results and conclusion are presented.

2. MODELING OF THE HYBRID PV/FC SYSTEM COMPONENTS

As shown in Fig. 1 this paper develops the hybrid system consisting of proton exchange membrane (PEM) FC and PV modules that uses battery to store the energy and electrolyser to produce hydrogen (H₂). The hydrogen can be produced, during the surplus of energy production, from water by electrolysis and stored in a container for further use. Indeed the electrolyser in this model is used as a dump load.

2.1 PV Model

As the operation and the performance of a PV generator is interested in its maximum power, the models describing the PV module's maximum power output behaviours are more practical for PV system assessment. In this paper, a mathematical model for estimating the power output of PV modules is used. The estimation is carried out using a computer program, which uses a subroutine for determining the power output of a PV module. Using the solar radiation available on the tilted surface, the ambient temperature and the manufacturer's data for the PV modules as model inputs, the power output of the PV generator (PPV) can be calculated according to the following equation [12]:

$$P_{PV} = \eta_g N A_m G_t \quad (1)$$

Where η_g is the instantaneous PV generator efficiency, A_m the area of a single module used in a system (m²), G_t the global irradiance incident on the titled plane (W/m²) and N is the number of modules used in system. All the energy losses in a PV generator, including connection losses, wiring losses and other losses, are assumed to be zero. The instantaneous photovoltaic generator efficiency is represented by the following equation [13].

$$\eta_g = \eta_r \eta_{pt} [1 - \beta_t (T_c - T_r)] \quad (2)$$

Where η_r is the PV generator reference efficiency, η_{pt} the efficiency of power tracking equipment, which is equal to 1 if a perfect maximum power point tracker is used, T_c the temperature of PV cell (°C), T_r the PV cell reference temperature and β_t is the temperature coefficient of efficiency, ranging from 0.004 to 0.006 (per °C).

Based on the energy balance proposed by [14], the PV cell temperature can be expressed as follows:

$$T_c = T_a + G_t \left(\frac{\tau \alpha}{U_L} \right) \quad (3)$$

Where T_a is the ambient temperature (°C), U_L is the overall heat loss coefficient (W/m² per °C), τ and α represent, respectively, the transmittance and absorptance coefficients of PV cells. The overall heat loss coefficient ($\tau \alpha / U_L$) can be estimated from the nominal operating cell temperature (NOCT) as follows [15]:

$$\left(\frac{\tau \alpha}{U_L} \right) = \frac{NOCT - 20}{800} \quad (4)$$

Consequently, the instantaneous PV generator efficiency can be expressed as follows:

$$\eta_g = \eta_r \eta_{pt} \times \left\{ 1 - \beta_t (T_a - T_c) - \beta_t G_t \left(\frac{NOCT - 20}{800} \right) (1 - \eta_r \eta_{pt}) \right\} \quad (5)$$

Where η_{pt} , η_t , NOCT, A_m are parameters that depend on the type of module, and given by the manufacturer of the modules. Note that 800 in (5) is in (W/m²), and NOCT (°C) ranges from 40 to 70 (°C) [16].

2.2 Electrolyser Model

The electrolyser is simply considered as a constant gain corresponding to the electrolyser (η_{ELEC}) and an integrator to determine the amount of produced hydrogen. The amount of hydrogen consumed by the FC is also determined. The difference between both gives the amount of available stored hydrogen, following (6).

$$SOC_{ELEC} = \int (P_{ELEC} \times \eta_{ELEC}) dt - \int \frac{P_{FC}}{\eta_{FC}} \quad (6)$$

Where SOC_{ELEC} is the state of charge electrolyser, P_{ELEC} is electrolyser power, PFC is FC power and η_{FC} is the efficiency of FC stack.

2.3 FC Model

The FC supplies the system during critical periods when solar insolation is very weak and the lamp consumption is very high (winter season). The PEMFC is particularly well suitable for this work. It produces electricity from the hydrogen without any greenhouse emission, if hydrogen comes from a clean source like an electrolysis process associated with renewable energy. PEM fuel cell has reliable performance under intermittent supply and is commercially available at large industrial scale capacities. This kind of fuel cell is suitable for large-scale stationary generation and has fast dynamic response with a power release response time of only 1 to 3 seconds [17]. This model permits to calculate hydrogen consumption according to the delivered power. It should be noticed that the FC auxiliary system needs around 20% of the FC net power (for cooling and air pressurization) [18].

2.4 Battery Model

The battery input power (P_{BAT}) can be positive or negative depending on the charge or discharge mode of operation. The battery power is obtained from (7).

$$P_{BAT} = P_{PV} + P_{FC} - P_{LOAD} \quad (7)$$

The state of charge (SOC_{BAT}) is deduced from the battery power and efficiency [18,19]:

$$SOC_{BAT} = \int (P_{BAT,charging} \times \eta_{BAT} - P_{BAT,decharging}) dt \quad (8)$$

The FC is activated when the battery SOC is lower than a threshold value. On the contrary, FC is stopped and the electrolyser starts up when SOC is higher to a threshold value. The battery power given in (7) becomes the electrolyser power following (9).

$$P_{ELEC} = P_{PV} - P_{LOAD} \quad (9)$$

At any hour, the storage capacity ($C_{BAT}(t)$) is subject to the following constraints:

$$C_{BAT,min} \leq C_{BAT}(t) \leq C_{BAT,max} \quad (10)$$

Where $C_{BAT,max}$ and $C_{BAT,min}$ are the maximum and minimum allowable storage capacity, respectively. Using for $C_{PBAT,max}$ the storage nominal capacity ($C_{BAT,n}$), then:

$$C_{BAT,min} = DOD \times C_{BAT,n} \quad (11)$$

Where, $DOD(\%)$ represents the maximum permissible depth of battery discharge.

3. MODELING OF SYSTEM RELIABILITY

Several approaches are used to achieve the optimal configurations of hybrid systems in terms of technical analysis. In this study, the technical sizing model for the HPFS is developed according to the concept of LPSP to evaluate the reliability of hybrid systems [20]. The methodology used can be summarized in the following steps:

The total power (P_{tot}), generated by the PV generator and FC at hour t is calculated as follows:

$$P_{tot}(t) = P_{PV}(t) + P_{FC}(t) \quad (12)$$

Then, the inverter input power ($P_{inv}(t)$), is calculated using the corresponding load power requirements, as follows:

$$P_{inv}(t) = \frac{P_{LOAD}(t)}{\eta_{inv}} \quad (13)$$

Where $P_{LOAD}(t)$ is the power consumed by the load at hour t, η_{inv} is the inverter efficiency (95% in this study). It should be noticed that the electrolyser power is added to P_{LOAD} when it is activated. Three states may be appearing:

- a) The total power generated by the PV and FC is greater than the power needed by the load, P_{inv} . In this case, the energy surplus is stored in the batteries and the new storage capacity is calculated using (8) until the full capacity is obtained. The remainder of the available power is dedicated to the electrolyser to produce hydrogen.
- b) The total PV and FC power is less than the power needed by the load (P_{inv}), the energy deficit is covered by the storage and a new battery capacity is calculated using (8).
- c) In case of inverter input and total power equality, the storage capacity remains unchanged.

In case (a) when the batteries capacity reaches a maximum value ($C_{BAT,max}$), the control system stops the charging process. The wasted energy, defined as the energy produced and not used by the system, for hour t is calculated as follows:

$$WE(t) = P_{tot}(t) \Delta t - \left(\frac{P_{LOAD}(t)}{\eta_{inv}} \Delta t + \left(\frac{C_{BAT,max} - C_{BAT}(t-1)}{\eta_{cha}} \right) \right) \quad (14)$$

In case (b), if the batteries capacity decreases to its minimum level ($C_{BAT,min}$), the control system disconnects the load and the energy deficit, loss of power supply for hour t can be expressed as follows [21]:

$$LPS(t) = P_{LOAD}(t)\Delta t - ((P_{PV}(t) + P_{FC}(t))\Delta t + C_{BAT}(t-1) - C_{BAT,min})\eta_{inv} \quad (15)$$

Where Δt is the step of time used for the calculations (in this study $\Delta t = 1$ h). During that time, the power produced by the PV and FC is assumed constant. So, the power is numerically equal to the energy within this time step.

The loss of power supply probability, for a considered period T , can be defined as the ratio of all the $LPS(t)$ values over the total load required during that period. The LPSP technique is considered as technical implemented criteria for sizing a hybrid PV/FC system employing a battery bank and an electrolyser. The technical model for hybrid system sizing is developed according to the LPSP technique [22].

$$LPSP = \frac{\sum_{t=1}^T LPS(t)}{\sum_{t=1}^T P_{LOAD}(t)\Delta t} \quad (16)$$

Where T is the operation time (in this study, $T = 1$ year). One more concept can be introduced too. The concept is the energy excess percentage, which is defined as the wasted energy divided by the total energy produced by the PV and FC during the considered period.

$$EXC(T) = \frac{WE(T)}{E_{tot}(T)} \quad (17)$$

For a given LPSP value and a defined period, many configurations can technically meet the required reliability demand of power supply. The optimal configuration can be identified finally from these set of configurations by achieving the lowest LCE. This can be performed by applying an economical model developed in Section 4.

4. ECONOMICAL MODEL

There are different financial analysis models based on “discounted cash flow analysis” such as, net present value, required revenues analysis, profitability index, internal rate of return and levelized cost [16]. These analysis models are termed as financial indicators and are used for comparison of different projects. The choice of model would depend on the sector for which the analysis is being performed. As the project is related to electricity generation, it was categorized as a private utility sector project. In this section, an economic sizing model is developed for the HPFS according to the levelized cost of energy concept. The LCE is defined as [23]:

Table 1: Details of Components

PV Array	
Technology	Polycrystalline
Maximum Power	120W
Efficiency	12%
Module unit	1.07m ²
Short circuit current	7.74A
Open circuit voltage	21V
Capital cost	4.84US\$/W _{peak}
Lifetime	20 year
Fuel cell array	
Technology	PEMFC
PEMFC stack	100W
Efficiency	50%
Operating Temperature	80 ^o c
Capital cost	8 US\$/W
Replacement cost	6 US\$/W
Lifetime	5000 hour
Electrolyser	
Technology	Alkaline
Efficiency	74%
Capital cost	20 US\$/W
Lifetime	20 year
Battery	
Technology	Lead-acid
Capital cost	20 US\$/W
Lifetime	5 year
Charging efficiency	80%

$$LCE = \frac{TPV \times CRF}{E_{LOAD}} \quad (18)$$

Where E_{LOAD} is the yearly output in (KWh), TPV and CRF are the total present value of actual cost of all system components and the capital recovery factor, respectively, which can be expressed as follows [23]:

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (19)$$

$$TPV = C_{PV} + C_{FC} + C_{ELEC} + C_{BAT} \quad (20)$$

Where i is the annual discount rate, n is the system lifetime in years, C_{PV} the sum of present value of capital and maintenance costs of the PV generator in system life, C_{FC} the sum of present value of capital and maintenance costs of the FC in system life, C_{ELEC} the sum of present value of capital and maintenance costs of the electrolyser in system life and C_{BAT} is the sum of present value of capital and replacement costs of battery bank in system life. The configuration with the lowest LCE is taken as the optimal one from the set of configurations, which guarantee the required LPSP. The annual discount rate is considered as 10%, system lifetime is 20 years and the

details of proposed hybrid system components can be found in table 1 [10,18,24,25].

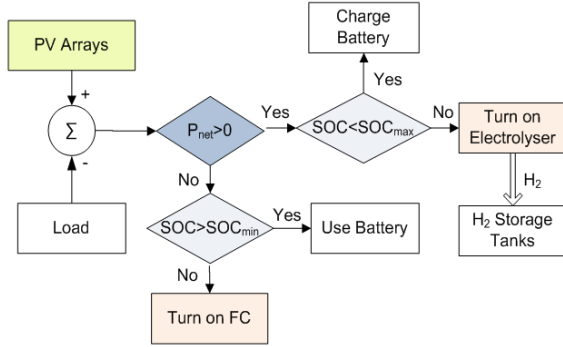


Fig.2: Block Diagram of the Overall Control Scheme for the Proposed Hybrid Alternative Energy System

5. POWER MANAGEMENT STRATEGY

An overall control strategy for power management among different energy sources in a multi-source energy system is needed. Fig. 2 shows the block diagram of the overall control strategy for the proposed hybrid alternative energy system. The power difference between the generation sources and the load demand is calculated as:

$$P_{Net} = P_{PV} - P_{LOAD} - P_{SC} \quad (21)$$

Where, P_{SC} is the self-consumed power for the system operation. The governing control strategy is that, at any time, any excess PV generated power ($P_{Net} > 0$) is supplied to the battery or the electrolyser to generate H2 that is delivered to the hydrogen storage tanks through a gas compressor. Therefore the power balance equation given in (21) can be written as:

$$P_{PV} = P_{LOAD} + P_{BAT,Charging} + P_{SC}, \quad (SOC < SOC_{MAX}) \quad (22)$$

$$P_{PV} = P_{LOAD} + P_{ELEC} + P_{SC}, \quad (SOC = SOC_{MAX}) \quad (23)$$

When there is a defect in power generation ($P_{NET} < 0$), the battery and/or the FC stack begins to produce energy for the load. Therefore, the power balance equation for this situation can be written as:

$$P_{PV} + P_{BAT,Discharging} = P_{LOAD} + P_{SC}, \quad (SOC > SOC_{MIN}) \quad (24)$$

$$P_{PV} + P_{FC} + P_{BAT,Discharging} = P_{LOAD} + P_{SC}, \quad (SOC < SOC_{MIN}) \quad (25)$$

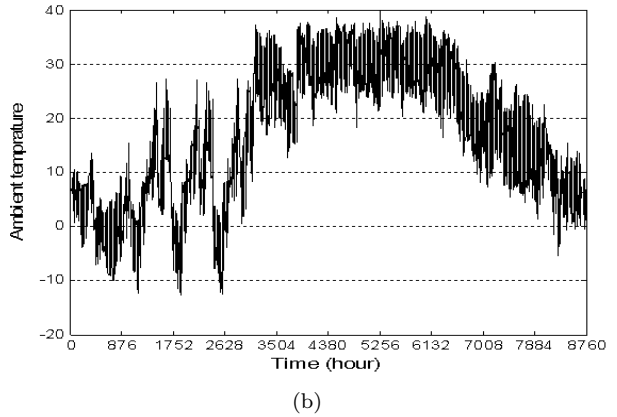
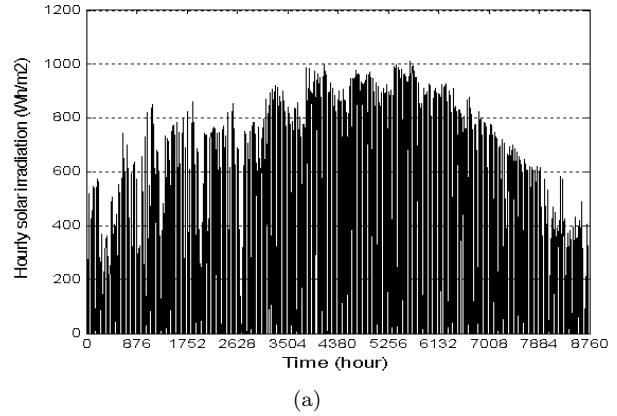


Fig.3: Hourly Values of Meteorological Parameters: (a) Solar Irradiation, (b) Ambient Temperature

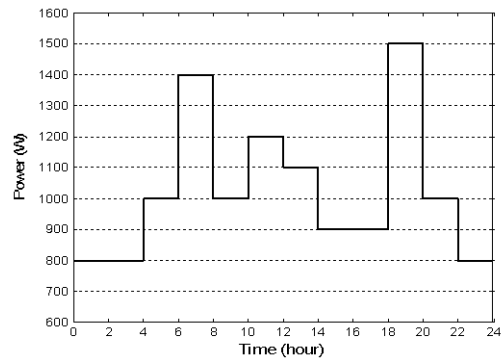


Fig.4: Hourly Load Profile.

6. RESULTS AND DISCUSSIONS

The simulations are computed using 1 year of hourly global solar irradianations on tilted plane (45°), as well as hourly mean values of ambient temperature, given in Fig. 3. The estimated hourly load profile is shown in Fig. 4. The load average in a day is 1(KW).

In this section, several simulations have been made by considering different combinations taking into account, the power of PV and FC and the capacity storage. Fig. 5 shows the great search results, based on the LPSP concept, for an allowable LPSP and a load profile defined in this study, performed on a Pentium-

Table 2: *Optimized Values*

Parameter	Number of PV panels	Batteries Capacity	FC power	LPSP	EXC	LCE	Total cost
Optimum value	45	18KWh	500 W	0.6%	19.5%	1.125\$/KW	86698US\$

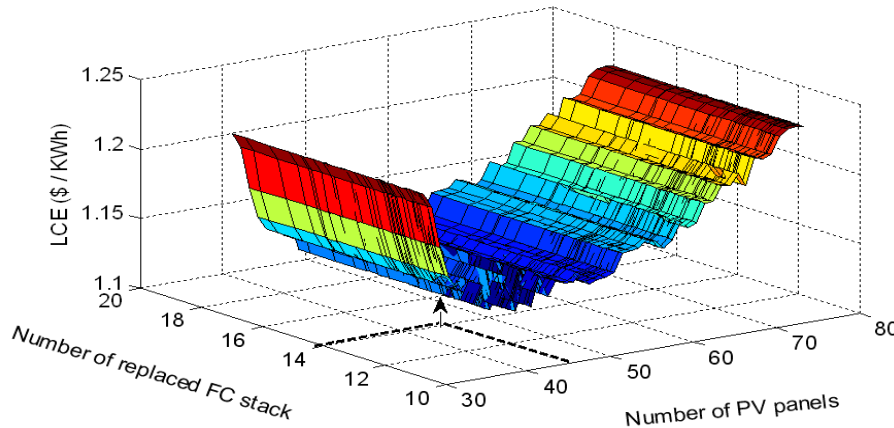


Fig.5: *Cost Optimization of the Proposed Configuration*

IV PC with 3.2 (GHz) processor speed, 1 (GB) RAM and WinXP operating system. Out of limitations on sketch dimensions, only two parameters of optimization parameters are presented in the figure. The optimized parameters are presented in table 2.

In Fig. 6, the LCE is given as a function of excess energy part, according to these results; it is observed that for a minimum value of LCE, an optimal value of excess energy part is exists. For the system configuration considered in this study, this value is about 20%. A reduction in the excess energy part, with the same conditions of the system reliability, increases the LCE. Also the LCE is given as a function of number of PV panels in Fig. 7. The lowest LCE is obtained for 45 PV panel according to Fig. 7. It can be presented similar explanations for two other parameters too that is neglected. The total cost of the system through 20 years of operation is 86698 (US\$) and the breakdown of cost analysis of configuration is depicted in Fig. 8.

In order to inspection to operation of system according to power management strategy, Fig. 9 is presented. In this figure, operation of system in a typical day and normal weather condition on 24 hours term is shown. The parameters are optimum values that are given in table 2. For a start, the FC does not work because the battery SOC is high enough and the solar power is weak, thus the load is supplied by the battery (see Fig. 9 (a)). When the battery SOC is lower than the nominal value, the FC is activated and the load is supplied. But the FC is unable to supply the load more than 500 W, thus in spite of low SOC, battery supplies surplus of the load.

As long as the solar power rises during the day, load is mainly supplied by PV and battery is in charg-

ing mode. When the battery SOC reaches its maximum allowable value, the battery charging is stopped and the electrolyser is activated. On condition that the FC is working, it supplies the load up to 500 (W); over this value, either PV supplies the additional load or the battery supplies it at the time of the solar radiation does not exist.

During the day, PV charges battery and when battery reaches its nominal SOC, FC is stopped. The battery SOC in different modes of battery operation is shown in Fig. 9 (b). Also the battery SOC in a one year period is presented in Fig. 10.

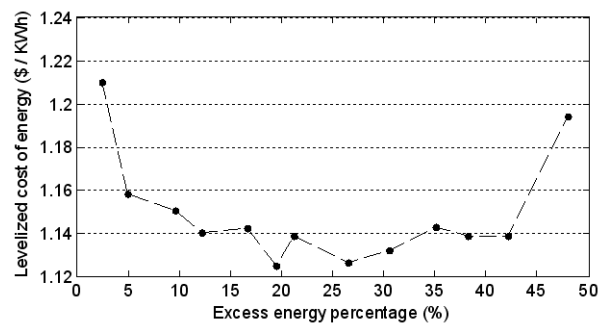


Fig.6: *Levelized Costs of Energy as a Function of Energy Excess Part for Optimal System Configurations*

7. CONCLUSIONS

The optimal sizing of autonomous hybrid PV/FC system, using an optimization model, has been developed in this work. The system configurations can be obtained in terms of a system power supply reliability requirement by using the LPSP concept. The one

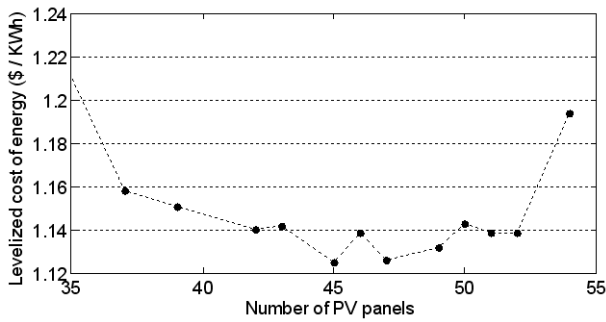


Fig.7: Levelized Costs of Energy as a Function of Number of PV Panels for Optimal System Configurations

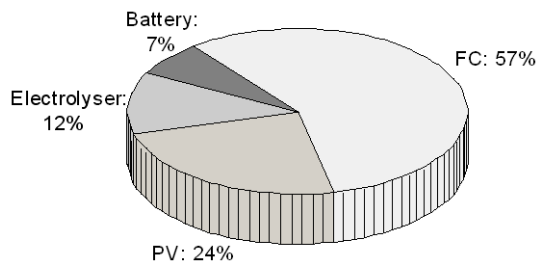
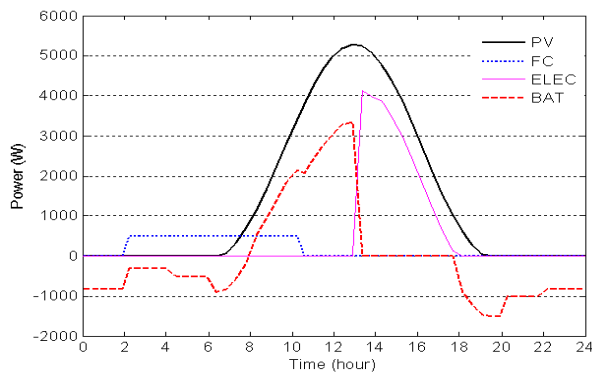
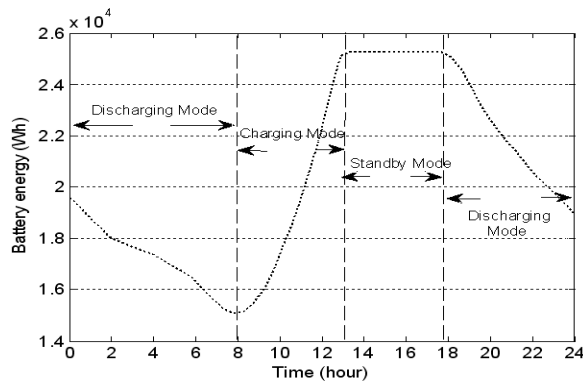


Fig.8: Breakdown of Cost Analysis of Configuration



(a)



(b)

Fig.9: Operation of System: (a) Powers Evolutions During 24Hours, (b) Energy of Battery During 24Hours.

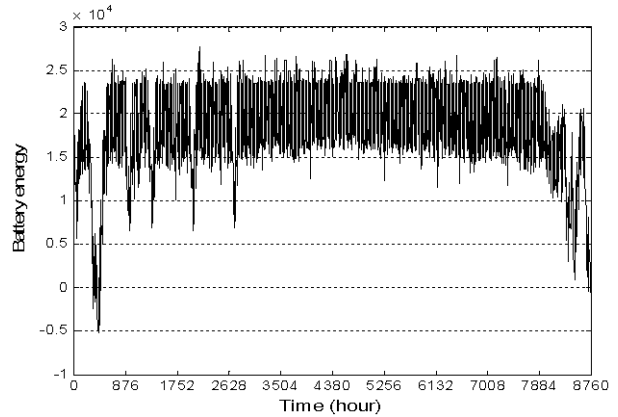


Fig.10: Energy of Battery During 1 Year.

with the lowest levelized cost of energy is considered as the economical optimal configuration.

The system devices choice represents an important step in the optimal sizing of the hybrid PV/FC system. Including economical consideration, the hybrid system consisting 45 PV panels, 500 (W) FC power and 18 (KWh) of batteries capacity found better than others. However, the lowest LCE is obtained by about 20 percent of excess energy. The use of a third energy source (i.e. diesel generator) maybe leads to a configuration with lower excess energy.

References

- [1] E. Cetin, A. Yilanci, Y. Oner, M. Colak, I. Kasikci, and H.K. Ozturk, "Electrical analysis of a hybrid photovoltaic/hydrogen/fuel cell energy system in Denizli, Turkey," *International Journal of Energy and Buildings*, Vol. 41, pp. 975-981, 2009.
- [2] J. Larminie, and A. Dicks, *Fuel Cell Systems Explained*, 2nd ed., JohnWiley & Sons, Ltd., New York, 2003.
- [3] Patel MR, *Wind and solar power systems*, CRC Press, USA, 1999.
- [4] K. Agbossou, M. Kolhe, J. Hamelin, and T.K. Bose, "Performance of a Stand-Alone Renewable Energy System Based on Energy Storage as Hydrogen," *IEEE Trans. on Energy Conversion*, Vol. 19, No.3, 2004.
- [5] F. Bonanno, A. Consoli, A. Raciti, B. Morgana, and U. Nocera, "Transient Analysis of Integrated Diesel- Wind-Photovoltaic Generation Systems," *IEEE Trans. on Energy Conversion*, Vol. 14, No.2, 1999.
- [6] S. Diaf, D. Diaf, M. Belhamel, M. Haddadi, and A. Louche, "A methodology for optimal sizing of autonomous hybrid PV/wind system," *International Journal of Energy Policy*, Vol. 35, pp. 5708-5718, 2007.
- [7] T. Zhou, and B. Francois, "Modeling and control design of hydrogen production process for

- an active hydrogen/wind hybrid power system,” *International Journal of Hydrogen Energy*, Vol. 34, pp. 21-30, 2009.
- [8] D. Ipsakisa, S. Voutetakis, P. Seferlis, F. Stergiopoulos, and C. Elmasides, “Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage,” *International Journal of Hydrogen Energy*, pp. 1-15, 2008.
- [9] Z. Samaras, D. Zafeiris, “Optimization of a wind-power fuel cell hybrid system in an autonomous electrical network environment,” *International Journal of Renewable Energy*, Vol. 32, pp. 57-79, 2007.
- [10] C.Wang, and M.H. Nehrir, “Power Management of a Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System,” *IEEE Trans. on Energy Conversion*, Vol. 23, No.3, 2008.
- [11] D. Kolokotsa, et al, “Methodology for optimal sizing of stand-alone photovoltaic/wind/generator systems using genetic algorithms,” *International Journal of Solar Energy*, Vol. 80(9), pp. 1072-1088, 2006.
- [12] T. Markvard, *Solar Electricity*, 2nd. ed. John Wiley, USA, 2000.
- [13] M.A. Habib, S. Said, M.A. El-Hadidy, and I. Al-Zaharna, “Optimization procedure of a hybrid photo-voltaic/wind energy system,” *International Journal of Energy*, Vol. 24, pp. 919-929, 1999.
- [14] J.A. Duffie, and W.A. Beckman, *Solar Engineering of Thermal Process*, 2nd ed. John Wiley, New York. 1991.
- [15] R. Chedid, and Y. Saliba, “Optimization and control of autonomous renewable energy systems,” *International Journal of Energy Research*, Vol. 20, pp. 609-624. 1996.
- [16] B.D. Shakyaa, Lu. Ayea, and P. Musgraveb, “Technical feasibility and financial analysis of hybrid wind-photovoltaic system with hydrogen storage for Cooma,” *International Journal of Hydrogen Energy*, Vol. 30, pp. 9-20. 2005.
- [17] R.S. Garcia, and D. Weisser, “A wind/diesel system with hydrogen storage: Joint optimization of design and dispatch”, *IEEE International Conference on Renewable Energy*, Vol. 31, pp. 2296-2320, 2006.
- [18] J. Lagorse, M.G. Simões, A. Miraoui, and P. Costerg, “Energy cost analysis of a solar-hydrogen hybrid energy system for stand-alone applications,” *International Journal of Hydrogen Energy*, Vol. 33, pp.2871-2879, 2008.
- [19] B. Pattipati, K. Pattipati, and J.P. Christopher, “Automotive Battery Management Systems,” *IEEE AUTOTESTCON*, pp.581-586, 2008.
- [20] Yang Lu, L. Burnett, and J.H.X, “Investigation on wind power potential on Hong Kong islands-an analysis of wind power and wind turbine characteristics,” *International Journal of Renewable Energy*, Vol. 27, pp.1-12, 2002.
- [21] S.B. Bogdan, and Z.M. Salameh, “Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system,” *IEEE Trans. on Energy Conversion*, Vol. 11, pp. 367-375, 1996.
- [22] A. Bin, Y. Hongxing, H. Shen, and L. Xianbo, “Computer aided design for PV/Wind hybrid system,” *International Journal of Renewable Energy*, Vol. 28, pp. 1491-1512. 2003.
- [23] A.L. Athanasia, and D.P. Anastassios, “The economics of PV standalone residential households: a case study for various European and Mediterranean locations,” *International Journal of Solar Energy Materials and Solar Cells*, Vol. 62, pp. 411-427, 2000.
- [24] NASA Surface Meteorology and Solar Energy. (<http://www.nasa.gov>)
- [25] Solar Energy Research and Consultancy (SERC). (<http://www.solarbuzz.com>)



Saieed Jalilzadeh was born in Salmas, Iran, in 1962. He received his B.Sc. and M.Sc. degrees from Tabriz University, Iran, in 1986 and 1991, respectively And the PhD degree from Iran University of Science and Technology (IUST), Tehran, Iran, in 2006 all in Electrical Engineering. He is currently an Assistant Professor with Department of Electrical Engineering, Zanjan, Iran. His research interests include renewable energies, stability, and dynamic power system.



Hossein Kord was born in Zanjan, Iran, in 1985. He received his B.Sc. degree in Electrical Engineering from KNT University, Tehran, Iran, in 2008. He is currently pursuing the M.Sc. degree from Department of Electrical Engineering, Zanjan, Iran. He is a member of Young Researchers Club (YRC), Zanjan, Iran. His research interests include renewable energies and power system planning.



Ahmad Rohani was born in Shiraz, Iran, in 1984. He received the B.Sc. degree in Electrical Engineering from IAU, Bushehr branch, Iran, in 2007. He is currently a M.Sc. student in the Department of Electrical Engineering, Zanjan, Iran. He is a member of Young Researchers Club (YRC), Shiraz, Iran. His research interests include renewable energies and network expansion planning.