International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2013 Issue 14 Volume 5 Number 1 Pages 74-81

ECONOMIC AND OPTIMAL OPERATION OF THE NETWORK CONNECTED PV-FC HYBRID SYSTEM IN SUPPLYING RESIDENTIAL LOADS

M. Partovi M. Mohammadian

International Center for Science, High Technology and Environmental Sciences, Electrical Engineering Department
Shahid Bahonar University of Kerman, Kerman, Iran, m_prtv@yahoo.com, m.mohammadian@uk.ac.ir

Abstract- This paper presents an economic model and helps an evolutionary approach to evaluate the impact of PV-FC hybrid system on the performance and operational costs which is network-connected. The using of wind and solar energies in the form of individual units, due to the low reliability and intermittent nature of these energies is not so much economical. Therefore, the combination of these technologies in the form of combined heat and power (CHP) system can be considered as a potential option to reduce the operational costs. In this paper, the integrated PV-FC cost model includes production costs of power, output thermal power from the reformer, power produced by PV, power trade with the network, and maintenance costs. In addition, the different tariff rates for purchasing and selling electricity in each hour of a day are considered. In order to estimate the optimal operational strategy for the hybrid system the genetic algorithm (GA) is used. At last, the simulation results show the reduction of operational costs in different conditions of utilization from the proposed system.

Keywords: PEM Fuel Cell, Photovoltaic, Economical Model, Hybrid System, Genetic Algorithm.

I. INTRODUCTION

In recent years, using of renewable energy system applications, such as wind turbine (WT), photovoltaic (PV) array and fuel cell (FC) due to factors including the low costs and no loss of power transmission as the renewable energy sources have been grown. The PEMFC due to the lower operating temperature (80-100^{o}C), fast start-up, higher efficiency than the conventional power plants, extremely low emission, flexible structure, and ability to produce both of electrical and thermal energies are the best candidates for residential and vehicular applications. [1] However, each of these technologies has disadvantages too. For example, the PV and WT are highly depending on the weather conditions and also the required amount of FC fuel is too expensive. But the combination of these technologies can be considered as a hybrid system with high reliability to satisfy both the electrical and thermal loads [2, 3].

Also several research works have been done for selecting the parameters such as the size of hybrid systems [4]. The hybrid system can either be connected to the main network or work autonomously with respect to the network-connected mode or islanded mode, respectively. In the network-connected mode, when the consumable load changes, the power supplied by the main network and hybrid system must be properly changed. In this situation the power delivered from the hybrid system as well as network must be coordinated to meet consumable load [5].

The management of the distributed generation (DG) units requires an accurate economic model to describe the operating costs taking into account the output power produced. In [9-14] references, FC economic models as well as the system operational limitations have been presented, so the optimum output power from the FC has been estimated. In this model, the possibility of exchanging power with the local network and the utilization of output thermal power from the reformer in supplying thermal load have been provided.

Energy management is one of the most important issues in the DG systems. The different strategies to manage the output power from the DG's can be considered. Also, by choosing the appropriate share of these components in supplying the consumable loads, the objective function of cost optimization problem minimized and has practically caused the substructures of this system to operate at their maximum efficiency. Accordingly, in this paper the energy management of desired hybrid system in the form of an optimization problem, in order to get minimum operational costs has been performed. Here, the combination of FC and PV systems connected to the network is used to satisfy both the electrical and thermal loads. The genetic algorithm (GA) is employed to determine the parameters of the system for optimal operation during a day. In order to reach realistic results, the different electrical tariff rates in each hour a day have been considered.

This paper is organized firstly as the economic model of proposed hybrid system, including PEMFC and PV is developed. Section III applies the methodology to energy management of the proposed hybrid system. The GA as an evolutionary search algorithm is described in section IV. The simulation results are discussed in Section V and concluded in section VII.

II. SYSTEM MODELING

The proposed hybrid system consisting of 250 KW FC and 50 KW PV units which are used as the main sources connected to the network shown in Figure 1. This system can be extended and if necessary, according to the conditions of desired region, we can add other available energy sources to it. The rated power of the PV panel, and the number of panels used are free inputs to the program and can be changed. A robust energy management strategy is the key in minimizing the operational costs. In this paper, the most important point to choose an energy management strategy is the economic performance of proposed hybrid system. Since the output thermal power of the reformer is function of the part load ratio (*PLR*) and as a by-product [6], it can effect on the energy management. In order to design an optimum energy management and to see the performance of the designed system in various conditions, we should have sufficient information about component structures. In this section we investigate and introduce all sub systems of the main system.

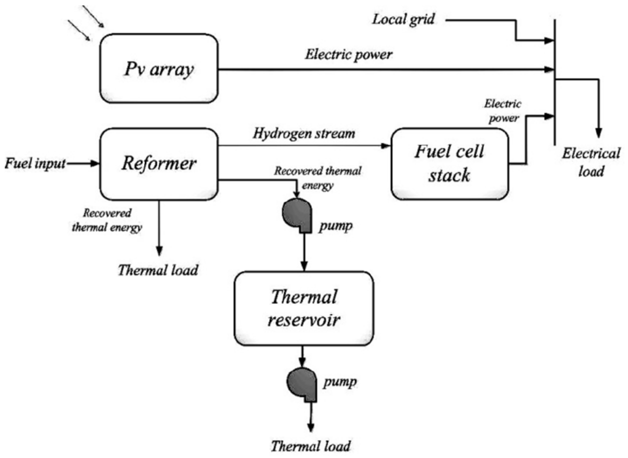

Figure 1. The configuration of the network connection proposed hybrid system

A. Mathematical Model of Solar Array

The model used in this paper is the double diode model whose equivalent circuit is shown in Figure 2.

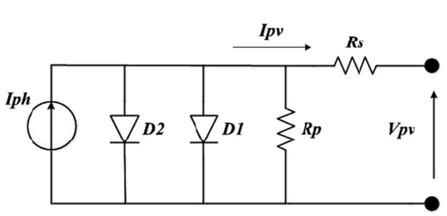

Figure 2. Equivalent electric diagram of a solar array [7]

The proposed model consists of 150 arrays with maximum capacity of 50KW which every of arrays includes 18 series and 70 parallel modules. The electrical output power of the PV array, $P_{pv,j}$ at interval j with respect to temperature $T_j(^{\circ}\mathrm{K})$ and radiation $E_j(\mathrm{w/m^2})$, can be determined by the following equations [7]:

$$I^{out}_{pv,j} = N_p\,[I_{ph,j} - I_{s1,j}\,[e^{e.(\frac{V_{pv,j}}{N_s}+\frac{I_{pv,j}R_{s,j}}{N_p})/KT_j} -1] - I_{s2,j}\,[e^{e.(\frac{V_{pv,j}}{N_s}+\frac{I_{pv,j}R_{s,j}}{N_p})/KA_jT_j} -1] - \frac{V_{pv,j}}{N_sR_{p,j}} - \frac{I_{pv,j}R_{s,j}}{N_pR_{p,j}}] \tag{1}$$

$$P_{pv,j} = I^{out}_{pv,j} \times V^{out}_{pv,j} \tag{2}$$

$$I_{ph,j} = k_0\, E_j\,\left(1{+}k_1T_j\right) \tag{3}$$

$$I_{s1,j} = k_2\, T_j^{3}\, e^{\frac{k_3}{T_j}} \tag{4}$$

$$I_{s2,j} = k_4\, T_j^{\frac{3}{2}}\, e^{\frac{k_5}{T_j}} \tag{5}$$

$$A_j = k_6 + k_7\, T_j \tag{6}$$

$$R_{s,j} = k_8 + \frac{k_9}{E_j} + k_{10}\, T_j \tag{7}$$

$$R_{p,j} = k_{11}\, e^{k_{12}T_j} \tag{8}$$

where I_{s1} and I_{s2} correspond to the reverse-saturation current of the solar cell, q is the electron charge and has value of 1.6×10^{-19} C, K is the Boltzmann's constant and has value of 1.38×10^{-23} J/K. The other constants for the solar cell are given in Table 1.

Table 1. The constants of a solar array [7]

parameter	Constant values	
I_{ph}	$k_0 = -5.729\times10^{-7}$	$k_1 = -0.1098$
I_{s1}	$k_2 = 44.5355$	$k_3 = -1.264\times10^{4}$
I_{s2}	$k_4 = 11.8003$	$k_5 = -7.3174\times10^{3}$
R_s	$k_8 = 1.47$	$k_9 = 1.6126\times10^{3}$ $k_{10} = -4.474\times10^{-3}$
R_p	$k_{11} = 2.303\times10^{6}$	$k_{12} = -2.812\times10^{2}$
A	$k_6 = 2$	$k_7 = 0$

B. Recovered Thermal Power of the Reformer

In this system, the output thermal power of the reformer is used to supply thermal load where the temperature of output power reaches to about 365 °C, and if necessary it can be done through the direct use of natural gas. Since the performance temperature of the FC is too low (70-80 °C), the output thermal power of the FC is ignored [9]. This output thermal power can be used to supply residential thermal loads such as cooking, space and water heating, and etc. If the thermal power generation is more than the thermal demand, the surplus thermal power can be sold to other residential consumers or can be stored and reused in the other hours of a day. In order to determine the efficiency and thermal to electrical ratio the *PLR* is used, and they can be calculated as follow [10]:

if $PLR_j < 0.05$

$$\eta_j = 0.2716\ ,\ r_{TE,j} = 0.6801 \tag{9}$$

$$\text{if} \quad PLR_j \ge 0.05$$

$$\begin{cases} \eta_j = 0.9033 \times PLR_j^5 - 2.9996 \times PLR_j^4 \\ +3.6503 \times PLR_j^3 - 2.0704 \times PLR_j^2 \\ +0.4623 \times PLR_j + 0.3747 \\ r_{TE,j} = 1.0785 \times PLR_j^4 - 1.9739 \times PLR_j^3 \\ +1.5005 \times PLR_j^2 - 0.2817 \times PLR_j + 0.6838 \end{cases} \tag{10}$$

The thermal power received from the reformer is calculated as follows:

$$P_{th,j} = r_{TE,j}\ (P_j + P_a) \tag{11}$$

where $P_{th,j}$ is the output thermal power from the reformer at interval j (KW) and P_a is the power for auxiliary equipments (KW).

C. Cost Function of the Hybrid System

In this paper, the proposed model in [6, 11] references along with the PV system has been spread and also is developed regarding the fact that the tariff rate of electricity is different in each hour of a day. This makes the model more realistic. The recommended objective function of the cost optimization problem subject to operational constraints is considered as below:

$$\text{ObjFun} = \min\Big(\sum_j Cost_j - \sum_j Income_j\Big) \tag{12}$$

subject to:

$$P^{\min} \le P_j \le P^{\max} \tag{13}$$

$$P_j - P_{j-1} \le \Delta P_u \tag{14}$$

$$P_{j-1} - P_j \le \Delta P_D \tag{15}$$

$$(T_{j-1}^{on} - MUT)\big(U_{j-1} - U_j\big) \ge 0 \tag{16}$$

$$(T_{j-1}^{off} - MDT)\big(U_j - U_{j-1}\big) \ge 0 \tag{17}$$

$$n_{start-stop} \le N^{\max} \tag{18}$$

The objective function consists of two main parts. The first term is the performance costs of the hybrid system that includes fuel cost, and cost of purchasing power (electrical/thermal) if the power generated is less than the demand. Besides, startup cost, the performance and maintenance cost of the hybrid system are also included in the first term. The second term of the objective function includes the system revenues that are obtained from the sale of surplus electrical and thermal power.

III. ENERGY MANAGEMENT STRATEGY

In this section, the most important purpose of applying energy management is to supply consumable electrical and thermal loads with minimum cost. In this paper the performance of the proposed hybrid system is connected to the network and there is the possibility of purchasing and selling electricity to the network. Therefore, the control strategy must be adopted in a manner that the proposed hybrid system provides the demand in the most economic mode. For this the cost of each one of the components must be considered in the proposed model. The formulation of objective function consists of cost of power purchased from the network and the revenues from selling surplus electricity to the network. They are introduced as follow [1]:

A. Fuel Cost

This term that is the fuel cost for electrical power produced by the FC can be written as the following:

$$C_{FUEL,j} = c_f \frac{P_j + P_a}{\eta_j} \tag{19}$$

where c_f is the price of natural gas for FC ($/KWh), T is the length of time interval (h), P_j is the electrical power produced by FC at interval j (KW).

B. Cost of Purchasing Power from the Network

If the demand is more than the electrical power produced, the hybrid system can purchase power from the network to meet both the electrical and thermal loads. The following equation can be used to compensate the shortage of electrical load from the network:

$$C_{EL-p,j} = c_{el-p,j}\ T \max(L_{el,j} - P_j - P_{pv,j}, 0) \tag{20}$$

where $c_{el-p,j}$ is the tariff rate for purchasing electricity at interval j ($/KWh) which is different in each hour of a day, L_{el} is the electrical demand (KW).

If the thermal load is more than the output thermal power from reformer, the thermal generation shortfall can be calculated as follows:

$$C_{GAS-p,j}^{(1)} = c_g\ T \max(L_{th,j} - P_{th,j}, 0) \tag{21}$$

where c_g is the fuel price for residential loads ($/KWh), $L_{th,j}$ is the thermal demand at interval j (KW), and $P_{th,j}$ is the output thermal power from reformer at interval j (KW).

If the surplus thermal power is stored and reused at the other hours, the cost of purchasing natural gas can be calculated as follows:

$$C_{GAS,j}^{(2)} = c_g\ T \max(L_{th,j} - P_{th-storage,j} - P_{th,j}, 0) \tag{22}$$

where $P_{th-storage,j}$ is the amount of stored thermal power at interval j.

C. Start-up and Maintenance Cost

The operation and maintenance cost (COM) as a function of electrical power are calculated. Start-up cost is also proportional to the temperature and duration of inactivity FC (t_{off}) and can be defined as follows:

$$C_{SUP} = \alpha + \beta(1 - e^{-t_{off}/\tau}) \tag{23}$$

where α, β are the hot and cold start-up cost respectively, t_{off} is the off time of the FC (h), and τ is the FC cooling time constant (h).

D. Revenue of Selling Surplus Electrical Power

In this case, the possibility of selling surplus electrical power to the network is provided. When the total electrical output power from the hybrid system is more than the electrical demand, the daily revenue from selling surplus electrical power to the network is calculated as follows:

$$I_{EL-S,j} = c_{el-s,j}\ T_{\max}(P_j + P_{pv,j} - L_{el,j}, 0) \tag{24}$$

where c_{el-s} is the variable tariff for selling electricity at interval j (\$/KWh).

E. Revenue of Selling Surplus Thermal Power

If the output thermal power from reformer is more than the thermal load, this surplus power can be sold to the other residential consumers and the daily revenue from the sale of surplus thermal power (\$) is:

$$I_{TH-S,j} = c_{th-s,j}\ T_{\max}(p_{th,j} - L_{th,j}, 0) \tag{25}$$

where c_{th-s} is tariff for selling thermal power (\$/KWh). The revenue from the sale of unused thermal power to the other residential consumers at the end of the day is:

$$I_{TH,S} = c_{th,s}\ P_{th-end} \tag{26}$$

where P_{th-end} is the daily saving from selling surplus thermal power at the end of a day (\$).

IV. COST OPTIMIZATION PROBLEM IN GA

In this paper the genetic algorithm (GA) is implemented to define the optimal settings by minimizing the cost objective function (12) subjected to the constraints given by (13-18). The GA differs from other search methods in several ways. The most important difference is that a GA works on a population of possible solutions, while other heuristic methods use a single solution in their iterations [15].

The major steps of GA are as follows: First, The operation of GA begins with an initial population of chromosomes. Then the fitness of each chromosome is defined by the objective function. The selection operator chooses the chromosomes with better fitness among the population by randomized methods and forms a mating pool. Using crossover and mutation operators, a new population is produced. The iterative loop is executed until the termination condition is satisfied [16, 17].

In order to determine the number of variables (chromosomes), the hours of a day is divided into 0.1-hour time intervals. In this case the length of each string or chromosome is 240. Each chromosome presents the power generation of FC in the related step time. For the studied problem in this paper, the GA parameters are selected as Table 2.

V. SIMULATION RESULTS AND DISCUSSION

In this section, the proposed model has been applied to a 250 KW FC and 50 KW PV connected to the network, which has been tested for supplying both electrical and thermal load profiles [2]. The hourly solar irradiance data for a sunny day is shown in Figure 3.

The FC parameters, gas prices and GA default parameters are according to Table 2. Table 3 gives different tariff rates for purchasing and selling electricity in each hour of a day. In this paper the output thermal power from the reformer is used besides the electrical power to supply thermal load. In order to give incentive to other residential consumers to use this energy, its price should be lower than other ways of supplying thermal load [1]. In this research, the results are compared with a base case (without considering the FC and PV units).

The Figures 4 and 5 show the electrical and thermal load profiles (with a peak of 300 KW) that are used to simulate total hourly operation of proposed hybrid system.

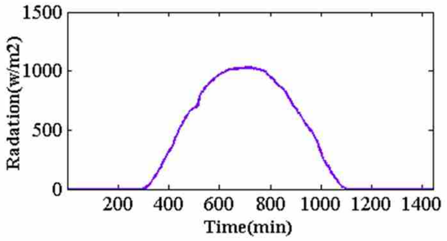

Figure 3. Irradiance data for a sunny day

Table 2. FC and GA parameters [9]

Maximum limit of generating power, $P^{\max}$(KW)	250
Minimum limit of generating power, $P^{\min}$(KW)	0.0
Hot start up cost, α(\$)	0.05
Cold start up cost, β(\$)	0.15
The FC cooling time constant, τ(h)	0.75
Minimum up-time, MUT (number of intervals)	2
Minimum down-time, MDT (number of intervals)	2
Lower limit of the ramp rate, ΔP_D(KW)	20
Upper limit of the ramp rate, ΔP_U(KW)	25
Length of time interval, T(h)	0.1
Fuel price for residential load, c_g (\$/kWh)	0.06
Price of natural gas for FC, c_f (\$/kWh)	0.04
Thermal power selling price, $c_{th,s}$ (\$/kWh)	0.04
Thermal storage efficiency, $c_{st,th}$ (%)	90
Maximum number of start-stop, $N^{\max}$	5
Maximum number of evolutionary generation	8000
Number of individuals	450

Table 3. Tariff rates for purchasing and selling electricity

Time, (h)	Purchasing Tariff $C_{el,p}$ (\$/KWh)	Selling Tariff $C_{el,s}$ (\$/KWh)
0-6	0.05	0.03
6-8	0.07	0.05
9	0.09	0.07
10-11	0.1	0.07
12-16	0.11	0.08
17	0.13	0.09
18-19	0.14	0.1
20	0.17	0.14
21	0.15	0.1
22	0.1	0.07
23	0.07	0.05

A. Base Case (without FC and PV)

In this case, only the network and natural gas is used to meet the both electrical and thermal loads and other resources are not considered. The daily cost components for supplying residential loads without running FC and PV units are given in Table 4. The simulation results show that the daily cost for providing electrical and thermal loads is \$ 708.40.

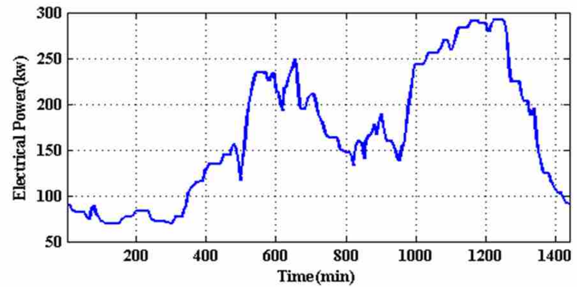

Figure 4. Electrical load profile

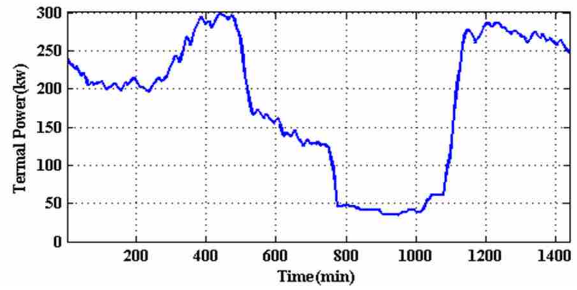

Figure 5. Thermal load profile

Table 4. Cost components for base case

Daily cost/revenue components ($)	Base case
Purchased electricity cost	445.39
Sold electricity revenue	0.00
Residential natural gas cost	263.01
Revenue from sale of thermal power	0.00
Total cost	708.40

B. Case 1

In this case, the model is tested without considering PV unit and the FC in terms of network connectivity which is used to supply electrical and thermal loads. A summary of test results is given in Table 5. It is clear from the table that using FC in combination with the network results in a lower overall cost compared to the cost of previous case. The power trade with the network and electrical/thermal output power from the FC are shown in Figures 6, 7 and 8 respectively. As Figure 7 depicts, in the first hours of the day (12 pm to 6 am), when the purchasing tariff rate is low; production by FC is not economically advantageous. Therefore, the most of consumable load is met by the purchased power from the network. From 6 am to 4 pm, the production of FC is more significant and the electrical/thermal power produced by the hybrid system follows up the electrical load and a part of the thermal load. The results show that using of the FC saves the system $ 53244.55 annually compared to the case of supplying load without running FC and PV.

Table 5. Cost components for strategy 1

Daily cost/revenue components ($)	Case 1
Fuel cost	408
Purchased electricity cost	44.46
Sold electricity revenue	6.14
Residential natural gas cost	128.31
Revenue from sale of thermal power	30.57
FC O&M cost	18.47
Total cost	562.53

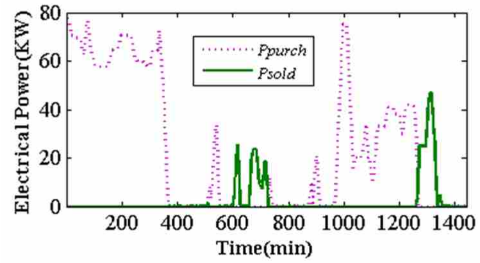

Figure 6. Electrical power trade with the network for case 1

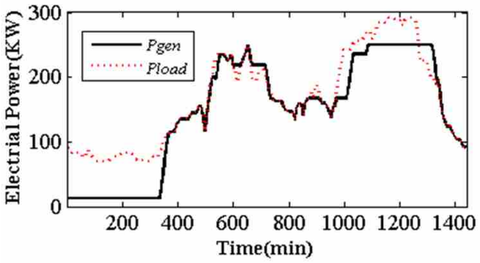

Figure 7. Electrical load and power generation for case 1

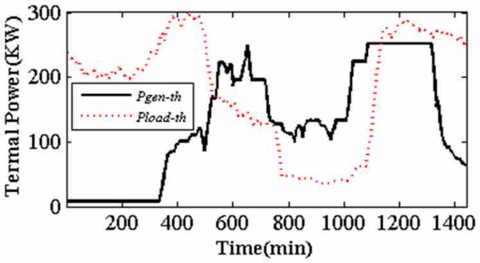

Figure 8. Thermal load and generation for case 1

C. Case 2

This case is like the case 1 with the difference that the surplus thermal output power from the reformer is stored and reused in each hour of a day. The stored thermal power will be sold to other domestic consumers at the end of the day. The test results are shown in Table 6. This table shows that storing and reusing thermal power saves the system $ 57989.95 annually compared to the base case.

It can be concluded from the findings that storing thermal power along with gas compensation results in a lower overall cost than selling thermal power. The electrical power trade with the network and the electric load/generation are shown in Figures 9 and 10, respectively. Figure 11 shows the thermal load/generation which is recovered from the reformer. According to Figure 9 in the first hours of the day, the system purchased more power from the network due to low tariff rate of energy. So, FC must produce a lower amount of power.

During low thermal demand periods (9 am to 7 pm) the output power from the FC has been more influenced by the thermal load and the system storing the surplus thermal power. In this case, the required amount of electrical power can be purchased from the network or met by natural gas. During the high thermal load period (after 7 pm) the hybrid system a use stored thermal power, and produces enough electrical power to satisfy the electrical load.

Comparing this case with the case 1 shows that the strategy of storing the surplus thermal power makes the system obtain $ 3354.35 annually. In conclusion, the storing of thermal power is better than the selling of it in terms of the overall cost and total savings.

Table 6. Cost components for strategy 2

Daily cost/revenue components ($)	Case 2
Fuel cost	310.56
Purchased electricity cost	106.21
Sold electricity revenue	4.78
Residential natural gas cost	124.36
Revenue from sale of thermal power	0.00
FC O&M cost	13.18
Total cost	549.53

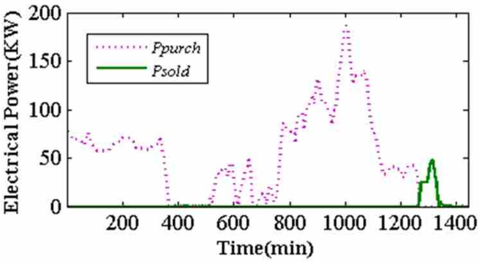

Figure 9. Electrical power trade with the network for case 2

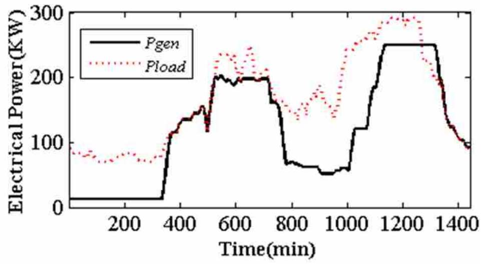

Figure 10. Electrical load and power generation for case 2

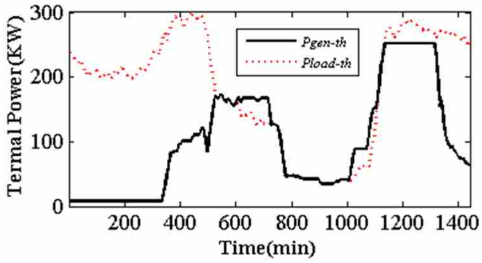

Figure 11. Thermal load and generation for case 2

D. Case 3

In this test case, in addition to the FC stack the model is tested by using of 50 kW PV system, which is operated at its full capacity all the time [2]. The obtained revenues and costs of components are given in Table 7. The power trade with the network, and the electrical load and output power from the FC and PV are shown in Figures 12 and 13, respectively. The thermal load and output thermal power from the reformer are given in Figure 14. According to Figure 11, due to the production of PV in the mid-day hours, the output power from the FC at this time has decreased and the possibility of selling surplus electrical power to the network is provided by the FC.

Table 7. Cost components for strategy 3

Daily cost/revenue components ($)	Case 3
Fuel cost	372.62
Purchased electricity cost	41.13
Sold electricity revenue	16.3
Residential natural gas cost	133.11
Revenue from sale of thermal power	23.89
FC O&M cost	17.15
PV O&M cost	2.69
Total cost	526.51

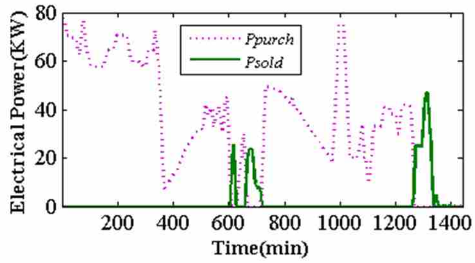

Figure 12. Electrical power trade with the network for case 3

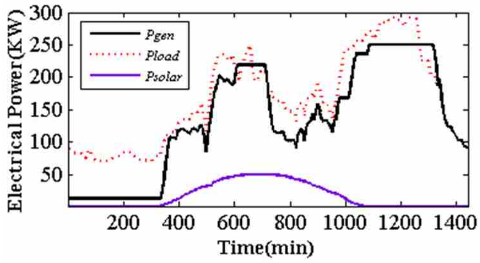

Figure 13. Electrical load and power generation for case 3

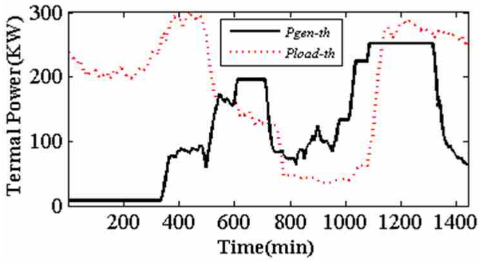

Figure 14. Thermal load and generation for case 3

E. Case 4

In this case, the effect of storage and reuse of the surplus thermal power on the optimal operation of proposed hybrid system is evaluated. The obtained results show that the combination of FC and PV units along with storing thermal power results in the lowest operational cost and the highest efficiency. The purchasing/selling electrical power from/to the network, the electrical load and power output from the FC and PV, and the thermal load and generation are given in Figure 15, 16 and 17, respectively. Cost and revenue components are given in Table 8. It is clear from the results that the daily cost of components with a significant reduction of $ 193.87 compared to the base case is equivalent to 517.32.

In summary, the daily cost for different strategies are shown in Table 9. Comparing costs for all strategies reveals that Strategy 4 gives a lower cost over entire year.

Table 8. Cost components for strategy 4

Daily cost/revenue components ($)	Case 4
Fuel cost	295.50
Purchased electricity cost	82.04
Sold electricity revenue	7.64
Residential natural gas cost	131.23
Revenue from sale of thermal power	0.00
FC O&M cost	13.5
PV O&M cost	2.69
Total cost	517.32

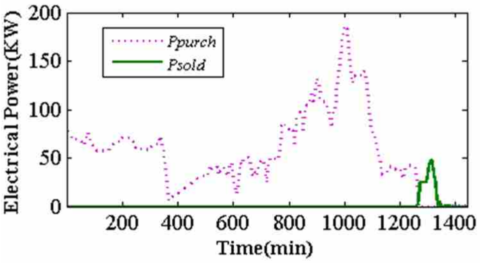

Figure 15. Electrical power trade with the network for case 4

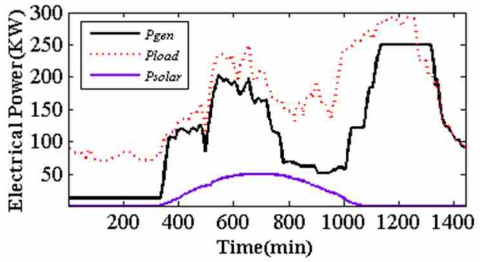

Figure 16. Electrical load and power generation for case 4

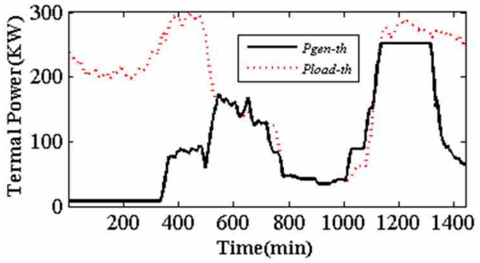

Figure 17. Thermal load and generation for case 4

Table 9. Costs and savings summary for all strategies

	Daily total cost ($)	Yearly savings ($)
Base case	708.40	0.0
Case 1	562.53	53,242.55
Case 2	549.53	57,987.55
Case 3	526.51	66,389.85
Case 4	517.32	69,744.2

The total efficiency of the FC is calculated according to the following equation [18]:

$$\eta_{total,j} = \frac{P_j + P_a + \min(P_{th,j}, L_{th,j})}{[(P_j + P_a)/\eta_j]} \qquad (27)$$

The Figure 18 shows the total efficiency for the strategies 1, 2, 3 and 4. It is clear that considering the thermal storage increasing the efficiency to as high as 55%–60%. The results of numerical optimization show that the strategies 2 and 4 due to the use of thermal energy storage enhance the total efficiency, especially at the low thermal demand periods.

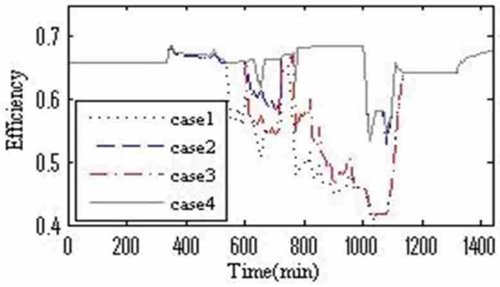

Figure 18. Total efficiency curves for all strategies

VII. CONCLUSIONS

In this paper, the combination of FC and PV as a hybrid system is studied in an economic model. This model is used as a CHP system to supply residential loads. The paper considers the economic model which includes output thermal power from the reformer and electrical power trade with the network. Based on the maximum power received from the PV system, the FC satisfies both electrical and thermal loads which are network connected. During each hour a day, the different tariff rates for purchasing and selling electrical power is assumed. In order to estimate the daily optimal operational strategy for the hybrid system and to minimize the operating costs, the GA is used. The simulation results show the combination of FC and PV units along with the storing surplus thermal power considered as the best strategy in reducing the overall costs and savings per year. This case saves the system $193.87 daily or $70762.55 annually compared to the base case.

ACKNOWLEDGMENT

The authors would like to thank the International Center for Science, High Technology and Environmental Sciences for helpful support. This paper has been done as a part of research contract no. 1.952 dated June 12, 2010 with mentioned international center.

NOMENCLATURES

P_j : The electrical power produced by FC

P_{pv} : The electrical power produced by PV

η : The electrical efficiency of FC

r_{TE} : The thermal to electrical power ratio

$P^{\max}$: The maximum limit of generated power

$P^{\min}$: The minimum limit of generated power

ΔP_U : The upper limit of the ramp rate

ΔP_D : The lower limits of the ramp rate

T^{on} : The FC on-time (number of intervals)

T^{off} : The FC off-time (number of intervals)

MUT : The minimum up-time (number of intervals)

MDT : The minimum down-time (number of intervals)

PLR : The part load ratio ($P_j / P^{\max}$)

U : The FC on-off status (where U = 1 for running and U = 0 for stopping)

$n_{start-stop}$: The number of start-stop events

$N^{\max}$: The maximum number of start-stop events
T : The ambient temperature
E : The intensity of solar radiation
I_{ph} : The light generated current of PV
R_s : The series resistance
R_p : The parallel resistance
A : The ideality factor
N_s : The number of cells connected in series
N_p : The number of parallel modules

REFERENCES

[1] M.S. Alam, "Smart Energy Management and Control for Fuel Cell Based Micro-Grid Connected Neighborhoods", Year Three Final Report, University of South Alabama, March 16, 2006.
[2] M.Y. El Sharkh, M. Tanrioven, A. Rahman, M.S. Alam, "Optimal Operation of a Wind and Fuel Cell Power Plant Based CHP System for Grid-Parallel Residential Micro-Grid", WSEAS Conference, Athens, Greece, 12-14 July 2005.
[3] H.A. Shayanfar, G. Derakhshan, A. Ameli, "Optimal Operation of Microgrids Using Renewable Energy Resources", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 10, Vol. 4, No. 1, pp. 97-102, March 2012.
[4] A. Ahmarinezhad, A. Abbaspour Tehranifard, M. Ehsan, M. Fotuhi Firuzabad, "Optimal Sizing of a Stand Alone Hybrid System for Ardabil Area of Iran", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 12, Vol. 4, No. 3, pp. 118-125, September 2012.
[5] P. Pradeep Kumar, B. Kiran Babu, "Power-Management Strategies for a Grid-Connected PV-FC Hybrid System by Using Fuzzy Logic Controller", International Journal of Modern Engineering Research (IJMER), Vol. 2, Issue 2, pp. 358-364, Mar.-Apr. 2012.
[6] M.Y. El-Sharkh, A. Rahman, M.S. Alam, "Evolutionary Programming Based Methodology for Economical Output Power from PEM Fuel Cell for Microgrid Application", J. Power Sources, Vol. 139, No. 1-2, pp. 165-169, 2005.
[7] J. A. Gow, C.D. Manning, "Development of a Photovoltaic Array Model for Use in Power Electronics Simulation Studies", IEEE Proc. on Electric Power Applications, Vol. 146, No. 2, pp. 193-200, Mar. 1999.
[8] F.M. Gonzalez Longatt, "Model of Photovoltaic Module in Matlab", 2nd Spanish American Congress of Electrical Engineering Studies, 2005.
[9] M.Y. El Sharkh, M. Tanrioven, A. Rahman, M.S. Alam, "Cost Related Sensitivity Analysis for Optimal Operation of a Grid Parallel PEM Fuel Cell Power Plant", Journal of Power Sources, Vol. 161, Issue 2, pp. 1198-1207, 2006.
[10] F. Barbir, T. Gomez, "Efficiency and Economics of Proton Exchange Membrane (PEM) Fuel Cell", International Journal of Hydrogen Energy, Vol. 21, No. 10, pp. 891-901, 1996.
[11] S. Ahmed, M. Azmy, I. Erlich, "Online Optimal Management of PEM Fuel Cells Using Neural Networks", IEEE Trans. on Power Del., Vol. 20, No. 2, pp. 1051-1058, April 2005.
[12] M.Y. El Sharkh, M. Tanrioven, A. Rahman, M.S. Alam, "Impact of Hydrogen Production on Optimal Economic Operation of a Grid Parallel PEM Fuel Cell Power Plant", J. Power Sources, Vol. 153, pp. 136-144, 2006.
[13] G. Erdmann, "Future Economics of the Fuel Cell Housing Market", International Journal of Hydrogen Energy, Vol. 28, No. 7, pp. 685-694, 2003.
[14] M.B. Gunes, "Investigation of a Fuel Cell Based Total Energy System for Residential Applications", Master of Science Thesis, Department of Mechanical Engineering, Virginia Polytechnic Institute and State University, 2001.
[15] T.V. Mathew, "Genetic Algorithm", Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, www.civil.iitb.ac.in/tvm/2701_dga/2701-ga-notes/gadoc/gadoc.html, January 18, 2005.
[16] D.E. Goldberg, "Genetic Algorithm in Search Optimization and Machine Learning", Massachusetts, Addison-Wesley, 1989.
[17] M. Alqedra, M. Arafa, M. Ismail, "Optimum Cost of Presented and Reinforced Concrete Beams Using Genetic Algorithms", Journal of Artificial Intelligence, Vol. 4, No. 2, pp. 76-88, 2011.
[18] M.Y. El Sharkh, M. Tanrioven, A. Rahman, M.S. Alam, "Economics of Hydrogen Production and Utilization Strategies for the Optimal Operation of a Grid Parallel PEM Fuel Cell Power Plant", Int. Journal of Hydrogen Energy, Vol. 35, No. 16, pp. 8804-8814, 2010.

BIOGRAPHIES

Mojtaba Partovi was born in Kerman, Iran in May 1987. He received his B.Sc. and M.Sc. degrees in Electrical Engineering Department, Shahid Bahonar University of Kerman, Iran, in 2009 and 2012, respectively. His research interests include renewable energies, hybrid energy power generation systems, power system planning, and optimization. Currently, he is working on hybrid and CHP power systems.

Mohsen Mohammadian received his B.Sc. degree in Electrical Engineering from Sharif University of Technology, Tehran, Iran, and his M.Sc. and Ph.D. degrees in Electrical Engineering from K.N. Toosi University of Technology, Tehran, Iran. He is as an Assistant Professor in the Electrical Engineering Department, Shahid Bahonar University of Kerman, Kerman, Iran. His current research interest includes non-linear control, intelligent control and control of complex systems, such as hybrid electric vehicles and power systems.