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Cost related sensitivity analysis for optimal operation of a grid-parallel PEM fuel cell power plant

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Abstract

Fuel cell power plants (FCPP) as a combined source of heat, power and hydrogen (CHP&H) can be considered as a potential option to supply both thermal and electrical loads. Hydrogen produced from the FCPP can be stored for future use of the FCPP or can be sold for profit. In such a system, tariff rates for purchasing or selling electricity, the fuel cost for the FCPP/thermal load, and hydrogen selling price are the main factors that affect the operational strategy. This paper presents a hybrid evolutionary programming and Hill–Climbing based approach to evaluate the impact of change of the above mentioned cost parameters on the optimal operational strategy of the FCPP. The optimal operational strategy of the FCPP for different tariffs is achieved through the estimation of the following: hourly generated power, the amount of thermal power recovered, power trade with the local grid, and the quantity of hydrogen that can be produced. Results show the importance of optimizing system cost parameters in order to minimize overall operating cost.

Keywords: Fuel cell economics; PEM fuel cell; Evolutionary programming; Sensitivity analysis

1. Introduction

Fuel cell power plants (FCPP) are commonly accepted as one of the most promising technologies to generate clean power. Fuel cell power plants are capable of generating power and heat as well as hydrogen. In such combined heat, power, and hydrogen (CHP&H) generation mode, the energy conversion efficiency of the FCPP is expected to increase while decreasing the overall operational cost significantly. To obtain maximum benefits from the FCPP, an appropriate energy conversion strategy must be established. Developing an optimal operational strategy for the FCPP helps in reducing the overall operational cost. The cost of fuel, selling price of hydrogen, and the tariff relating to the buying/selling of electrical and thermal energy are factors that significantly affect the operation strategy.

Since the cost model is constructed based on production cost, generation level and power trade, the energy management strategy is sensitive to change in tariffs.

This paper focuses on analyzing the sensitivity of the operational strategy to cost parameters.

In [1,2] a cost model has been introduced to estimate the optimal output power from the FCPP while satisfying system operational constraints. In this paper the cost model presented in [1,2] has been extended to include the effect of storing hydrogen for future use. The cost model is constructed as a cost optimization problem subject to system and operational constraints. To estimate the daily optimal operational strategy for the FCPP a hybrid technique based on evolutionary programming (EP) and Hill–Climbing (HC) method [1,3] is used. Evolutionary programming is employed to search for the near optimal solution while the HC method is used to ensure feasibility during the solution process.

The paper is organized as follows: Section 2 introduces a cost model for a fuel cell system. Section 3 presents the solution methodology. Test and results are presented in Section 4. Section 5 presents the conclusions.

2. Fuel cell cost model

The cost model presented in this paper includes the utilization of the recovered thermal energy and production/storage of hydrogen.

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Nomenclature

$C_{el,p}$	tariff for purchasing electricity ($\$\,kWh^{-1}$)
$C_{el,s}$	tariff for selling electricity ($\$\,kWh^{-1}$)
C_{Hs}	hydrogen selling price ($\$\,kg^{-1}$)
C_{n1}	price of natural gas for FCPP ($\$\,kWh^{-1}$)
C_{n2}	fuel price for residential loads ($\$\,kWh^{-1}$)
C_{pump}	hydrogen storing cost ($\$\,kWh^{-1}$)
F	a conversion factor (kg of hydrogen kW^{-1} of electric power), where $F=1.05\times10^{-8}\,{\nu_{cell}}^{-1}$ and ν_{cell} is cell operating voltage, $\nu_{cell}=0.6$ V
$L_{el,j}$	electrical load demand at interval j (kW)
$L_{th,j}$	thermal load demand at interval j (kW)
MDT	minimum down-time (number of intervals)
MUT	minimum up-time (number of intervals)
$n_{start\text{–}stop}$	number of start–stop events
N^{max}	maximum number of start–stop events
OM	daily operation and maintenance cost ($)
P_a	power for auxiliary devices (kW)
ΔP_D	lower limit of the ramp rate
$P_{H,end}$	available stored hydrogen at the end of the day (kWh)
P_{H_j}	equivalent electric power for hydrogen production (kW)
$P_{Hst,j}$	stored hydrogen power at interval j (kW)
$P_{H\_usage,j}$	secondary hydrogen stream amount in kW at interval j
P_j	electrical power produced at interval j (kW) less the power for auxiliary devices.
P^{max}	maximum limit of generating power (kW)
P^{min}	minimum limit of generating power (kW)
$P_{th,j}$	thermal load produced at interval j (kW)
P_{Tj}	total power produced at interval j, where $P_{T_j}=P_j+P_a+P_{H_j}$
ΔP_u	upper limit of the ramp rate
PLR	part load ratio
r_{TE}	thermal energy to electrical energy ratio
T	length of time interval (h)
t_{off}	time the FCPP has been off (h)
T^{off}	FCPP off-time (number of intervals)
T^{on}	FCPP on-time (number of intervals)
U	FCPP on–off status, $U=1$ for running, $U=0$ for stopping

Greek symbols

α,β	hot and cold start up cost, respectively
η_j	fuel cell electrical efficiency at interval j
η_{st}	hydrogen storage efficiency
ν_{cell}	cell operating voltage, $\nu_{cell}=0.6$ (V)
τ	fuel cell cooling time constant (h)

2.1. Recovered thermal energy calculation

At all load conditions, the FCPP produces thermal energy as a byproduct [4]. In PEM FCPP thermal energy is recovered mainly from the reformer where the temperature rises to about 365 °C. The recovery from the stack is neglected due to the lower operating temperature (70–80 °C). This paper considers thermal load (space heating and hot water) as part of the loading of the PEM FCPP along with electric loads. The thermal load is satisfied by utilizing the recovered thermal energy from the FCPP, and if necessary through the direct use of natural gas. Mathematical expressions to approximate the efficiency and the thermal output of the FCPP have been developed in Ref. [4] as follows:

For $PLR_j < 0.05$

$$\eta_j = 0.2716, \qquad r_{TE,j} = 0.6801 \tag{1}$$

For $PLR_j \geq 0.05$

$$\eta_j = 0.9033PLR_j^5 - 2.9996PLR_j^4 + 3.6503PLR_j^3 - 2.0704PLR_j^2 + 0.4623PLR_j + 0.3747 \tag{2}$$

$$r_{TE,j} = 1.0785PLR_j^4 - 1.9739PLR_j^3 + 1.5005PLR_j^2 - 0.2817PLR_j + 0.6838 \tag{3}$$

The efficiency and the thermal to electrical energy ratio are functions of PLR. In this case, the thermal power recovered from the FCPP based on the electrical power output can be calculated as follows:

$$P_{th,j} = r_{TE}(P_j + P_a + P_H) \tag{4}$$

2.2. Hydrogen management strategy

The hydrogen production strategy is based on the difference between the maximum capacity of the FCPP and the generated electric power at each interval.

To include the hydrogen in the FCPP cost model, an equivalent electric power for the generated hydrogen at each interval is considered P_{H_j}. The equivalent electric power is considered at the fuel cell stack output as shown in Fig. 1. Fig. 1(upper figure) reflects the electric power output and hydrogen output locations in the FCPP stages. Fig. 1(lower figure) shows the location of P_{H_j} in the FCPP. Considering P_{H_j} at the stack terminals makes it possible to quantify the production of hydrogen ($kg\,s^{-1}$) in terms of electrical power. The hydrogen production in $kg\,s^{-1}$ can be calculated using P_{H_j} as follows [5]:

$$(H_2)\,\text{amount} = 1.05\times10^{-8}\,\frac{P_{H_j}}{\upsilon_{cell}} \tag{5}$$

In this paper hydrogen storage cost is equal to the hydrogen pumping cost and does not include any storage infrastructure or technology cost. The hydrogen reservoir is assumed to be leak-proof with 95% storage efficiency. The hydrogen management strategy is as follows: the hydrogen production level can vary in the range of zero and the difference between the maximum capacity and the generated electric power. The hydrogen generated at high thermal demand intervals is stored in a hydrogen tank. During the low thermal demand interval the stored hydrogen along with the hydrogen produced from the reformer are

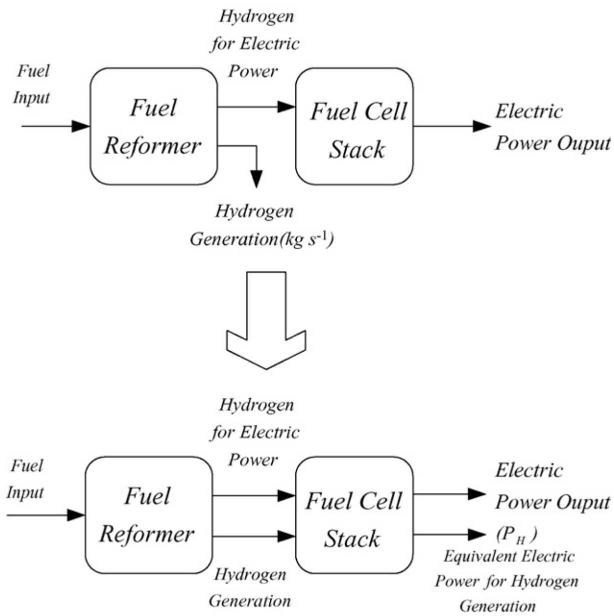

Fig. 1. Hydrogen insertion in the FCPP cost model.

used to produce electricity. At the end of the day, the unused hydrogen is sold. This strategy is expected to reduce the overall cost and increase the overall system efficiency.

Two hydrogen streams are considered in this strategy as shown in Fig. 2. The secondary hydrogen stream produces electric power only. In this paper the thermal energy is recovered from the reformer due to generation of the main and excess hydrogen streams. The recovered thermal energy from the stack is neglected.

The stored hydrogen amount $P_{\text{Hst},j}$ at interval j can be calculated as follows:

$$P_{\text{Hst},j} = P_{\text{Hst},j-1} + P_{\text{H},j}\eta_{\text{st}} - P_{\text{H\_usage},j} \tag{6}$$

2.3. FCPP cost-based model

In Refs. [1,2] the authors introduced a cost model for the FCPP operating strategy. In this paper, the model has been extended to include the economic aspects of hydrogen production/storage. The model considers the electrical power output, the thermal power recovery, hydrogen production, and the power trade with the local grid. This model can be represented as a cost optimization problem subject to system and operational constraints, which can be summarized as follows:

$$\text{Objective Function} = \min\left(\sum \text{Cost} - \sum \text{Income}\right) \tag{7}$$

where

$$\begin{aligned}\sum \text{Cost} = {} & C_{n1}T\sum_j\left(\frac{P_j + P_a + P_{\text{H}}}{\eta_j}\right) \\ & + C_{\text{el,p}}T\sum_j \max(L_{\text{el},j} - P_j - P_{\text{H\_usage},j}, 0) \\ & + C_{n2}T\sum_j \max(L_{\text{th},j} - P_{\text{th},j}, 0) \\ & + \alpha + \beta(1 - \mathrm{e}^{-(t_{\text{off}}/\tau)}) + \text{OM} + C_{\text{pump}}T\sum_j P_{\text{H},j}\eta_{\text{st}}\end{aligned} \tag{8}$$

$$\begin{aligned}\sum \text{Income} = {} & C_{\text{el,s}}T\sum_j \max(P_j + P_{\text{H\_usage},j} - L_{\text{el},j}, 0) \\ & + C_{\text{Hs}}P_{\text{H,end}}\end{aligned} \tag{9}$$

Subject to:

$$P^{\min} \leq P_{Tj} \leq P^{\max} \tag{10}$$

$$P_{Tj} - P_{Tj-1} \leq \Delta P_{\text{u}} \tag{11}$$

$$P_{Tj-1} - P_{Tj} \leq \Delta P_D \tag{12}$$

$$(T_{j-1}^{\text{on}} - \text{MUT})(U_{j-1} - U_j) \geq 0.0 \tag{13}$$

$$(T_{j-1}^{\text{off}} - \text{MDT})(U_j - U_{j-1}) \geq 0.0 \tag{14}$$

$$n_{\text{start–stop}} \geq N^{\max} \tag{15}$$

First term of Eq. (8) is the daily fuel cost for producing electricity and hydrogen ($). Second term is the daily cost of electrical energy purchased if the demand exceeds the electrical energy produced ($). The third term is the daily cost of purchased

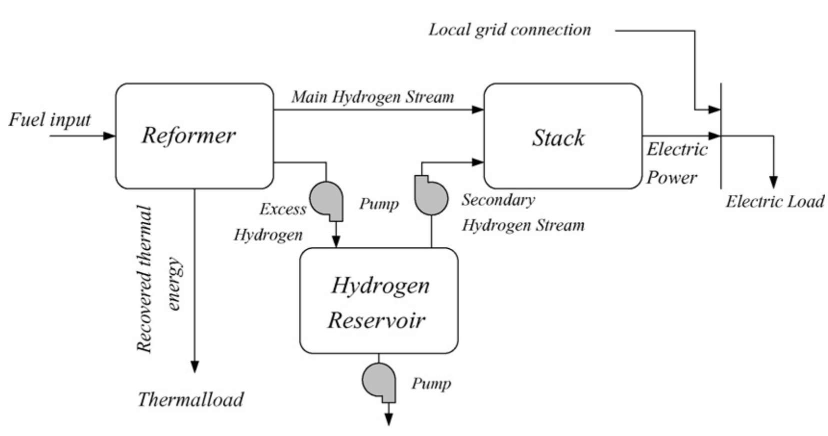

Fig. 2. Hydrogen flow in the FCPP system.

gas for residential thermal loads if the thermal energy produced is not enough to meet the thermal energy demand ($). The forth term is the operation and maintenance cost of the FCPP ($). The fifth term is the start up cost ($). The last term is the daily hydrogen storage cost ($). The first term in Eq. (9) represents the daily income from electrical energy sale if the electrical energy produced exceeds the demand ($). The second term represents the income from selling the remaining hydrogen in the tank at the end of the day ($).

3. Evolutionary programming-based solution methodology

Evolutionary programming can be traced back to the early 1950s when Turing discovered a relationship between machine learning and evolution. During the 1980s, advances in computer technology permitted the use of evolutionary programming to solve difficult real-world optimization problems [6–9]. The general scheme for solving optimization problems using evolutionary programming can be summarized as follows.

3.1. Initialization

An initial population of uniform randomly distributed solutions is selected.

3.2. Mutation

A Gaussian random variable is added to all the current generation individuals using Eq. (16) with uniform probability:

$$S_{i+m,j} = S_{i,j} + N(0, \beta_i v(S_i) + z_j), \quad j = 1, \ldots, k \tag{16}$$

where m is the number of individuals in the current generation, $v(S_i)$ the fitness score, S_i the jth element of the ith individual, $N(\mu,\sigma^2)$ the Gaussian random variable with mean μ and variance σ^2, β_i is a constant of probability to scale $v(S_i)$, z_j is an offset to guarantee a minimum amount of variance, i is the individual number, and k is the number of variables in each individual.

3.3. Competition

A probabilistic selection scheme is used to assign a weight to each offspring individual according to a comparison between current individual and a randomly chosen one. The weights are calculated as follows:

$$W_i = \sum_{j=1}^{N} W_{i,j} \tag{17}$$

where N is the competition number generated randomly, and $W_{i,j}$ is either 0 or 1 depending on the competition of the individual with another individual selected randomly from the population. The value of $W_{i,j}$ can be calculated as follows:

$$W_{i,j} = \begin{cases} 1 & \text{if } v(S_i) \le v(S_p) \\ 0 & \text{otherwise} \end{cases} \tag{18}$$

where $p = [2\,\mathrm{m}u_1 + 1]$, $p \ne i$, $u_1 \sim U(0,1)$

The above mentioned EP procedure is used to search for the optimal operational strategy for the FCPP. The Hill–Climbing technique (HC) [9] is used to watch for the infeasibility of the solutions during the search process. HC as explained in [9] is a local search technique that can be used to search for the local optimum. In this paper the HC search ability is used to move the infeasible solution to the feasible region to help EP to converge more rapidly towards the global optimal.

4. Tests and results

The proposed cost model has been applied to a 250 kW grid-parallel FCPP that supplies a residential neighborhood. The IEEE-RTS load profile with a peak of 250 kW [10] is used to simulate the hourly electrical load profile of the system. In this test system, the weekly, daily and hourly peak load values are given in percent of annual, weekly and daily peak loads, respectively. Thermal load profile is estimated based on hot water usage and space heating rates for the winter in Atlanta, Georgia [4]. The thermal load is used along with the electrical load profile to simulate total hourly operation of the FCPP. The gas prices, hydrogen selling price, and the parameters of the FCPP and the EP for all test cases are given in Table 1.

Case 1. In this case, the effect of fuel price on the FCPP optimal operation is tested. The fuel price for the FCPP is increased from $ 0.02 to $ 0.06 with an increment of $ 0.01. Cost/income components for different fuel prices are given in Table 2. Figs. 3–5 show the following: the electrical/thermal load and generation, the purchased/sold electrical power to/from the grid, and the hydrogen power production/storage usage. The curves in Figs. 3–5 reflects fuel prices of $ 0.02, $ 0.04, and $ 0.06.

Examining the fuel cost in Table 2, it is clear that initially the fuel cost increases with the increase of fuel price. Beyond fuel price of $ 0.05 the fuel cost decreases. This is because of the

Table 1
FCPP and evolutionary program default parameters

Maximum limit of generating power, P^{max} (kW)	250
Minimum limit of generating power, P^{min} (kW)	0.0
Length of time interval, T (h)	0.25
Upper limit of the ramp rate, ΔP_u (kW s^{-1})	20
Lower limit of the ramp rate, ΔP_D (kW s^{-1})	25
Price of natural gas for FCPP, C_{n1} ($ kWh^{-1})	0.04
Tariff for purchasing electricity, $C_{el,p}$ ($ kWh^{-1})	0.13
Tariff for selling electricity, $C_{el,s}$ ($ kWh^{-1})	0.08
Fuel price for residential loads, C_{n2} ($ kWh^{-1})	0.05
Hydrogen selling price, C_{Hs} ($ kg^{-1})	1.80
Hot start up cost, α ($)	0.05
Cold start up cost, β ($)	0.15
The fuel cell cooling time constant, τ (h)	0.75
Minimum up-time, MUT (number of intervals)	2
Minimum down-time, MDT (number of intervals)	2
Maximum number of start–stop time, N^{max}	5
Hydrogen storage efficiency, η_{st} (%)	95
Hydrogen storing cost, C_{pump} ($ kWh^{-1})	0.01
Maximum number of evolutionary generation	20000
Number of individuals	150

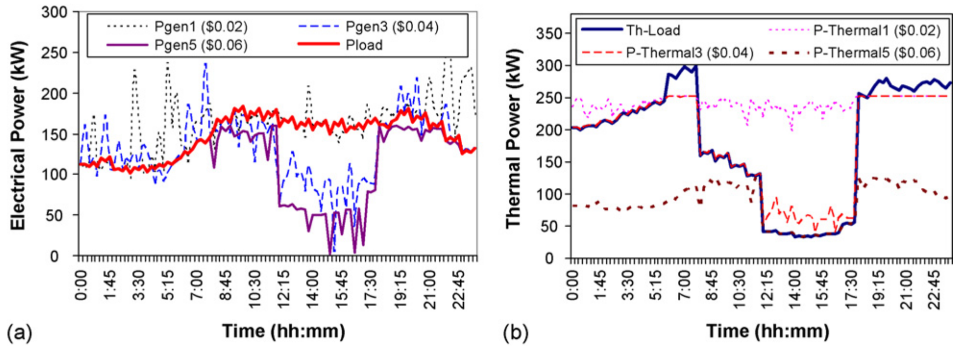

Fig. 3. Case 1, load and generation (a) electric and (b) thermal.

Table 2
Cost/income component for Case 1

Daily cost/income components ($)	Fuel price, C_{n1} ($ kWh^{-1})				
	0.02	0.03	0.04	0.05	0.06
Fuel cost	360.71	467.49	552.2	509.13	431.55
Cost of electricity purchased	0	0	0	0	100.07
Income from electricity sold	30.71	28.43	11.34	0.01	0
Cost of residential natural gas	10.37	10.37	10.47	79.73	137.8
Hydrogen selling income	209.34	146.85	104.13	16.08	0
Hydrogen storing cost	19.19	15.28	14.87	9.36	0.54
Total cost	169.44	336.14	477.59	595.83	683.49

fact that, it would be cheaper to buy part of the electric energy from the grid rather than produce all of the energy from the FCPP with high production cost. The increase in the amount of the purchased energy at a fuel price of $ 0.06 can be seen from Fig. 4b. At a fuel price of $ 0.05 the system produces enough electric energy (from the main and secondary hydrogen streams, Fig. 5b) to satisfy the electric load. In this case, the purchased energy is zero as shown in Fig. 4b. Table 2 and Fig. 4a show that the system is selling energy to the grid when the fuel price is lower than $ 0.05. It is also clear from Table 2 that the income from selling power to the grid decreases until it reaches zero when the fuel price is $ 0.06.

The cost for residential natural gas increases with the increase of the fuel cost (Table 2 and Fig. 3b). This is due to the reduced amount of electric energy and hydrogen production at higher fuel price as shown in Table 2 and Fig. 5. This results in decrease of the amount of recovered thermal energy and increase in the natural gas usage to satisfy the thermal load.

The electrical power, recovered thermal power, hydrogen production, and hydrogen usage are sensitive to fuel price particularly at low thermal load and high fuel price as shown in

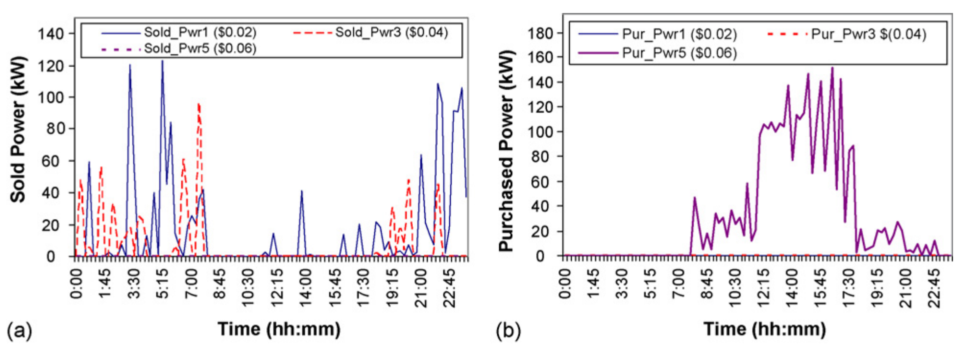

Fig. 4. Case 1, power trade with grid (a) purchased and (b) sold.

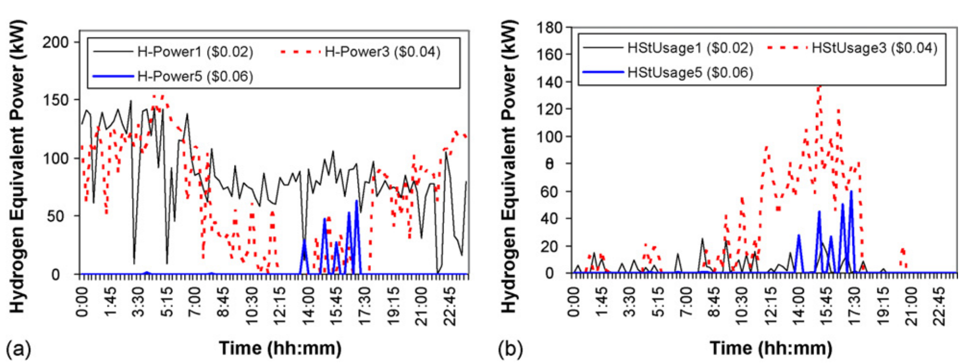

Fig. 5. Case 1, hydrogen (a) produced and (b) usage from tank.

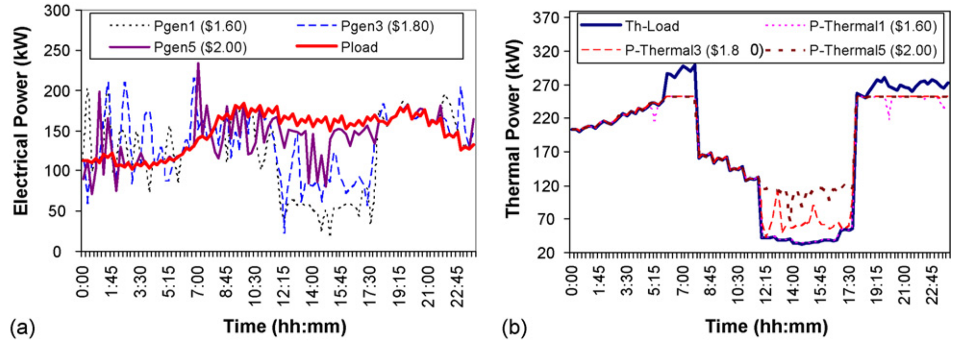

Fig. 6. Case 2, load and generation (a) electric and (b) thermal.

Figs. 3–5. Power trade with the grid is also sensitive to the change in fuel price. The system sells more energy during periods of high thermal load and low fuel price; but buys energy at low thermal load and high fuel price.

Case 2. In this case, the effect of hydrogen selling price on the FCPP optimal operation is evaluated. The system is tested with the price of hydrogen in the range of $ 1.60–2.00 in increments of $ 0.10. The change in the cost/income components are shown in Table 3. Figs. 6–8 show the electrical/thermal load and generation, power trade with the grid, and hydrogen production/storage.

Table 3 shows that the production cost is increased by $ 59.58 for the change of hydrogen price from $ 1.60 to $ 2.00. Hydrogen price does not have noticeable effect on the cost of buying energy from the grid. Hydrogen price has greater impact on the

Table 3
Cost/income component for Case 2

Daily cost/income components ($)	Hydrogen selling price, C_{Hs} ($\$\,kWh^{-1}$)				
	1.60	1.70	1.80	1.90	2.00
Fuel cost	529.78	537.08	552.8	565.12	589.36
Cost of electricity purchased	0	0	0	0	0.73
Income from electricity sold	10.5	11.25	14.93	12.2	7.6
Cost of residential natural gas	12.43	10.45	10.5	10.42	10.42
Hydrogen selling income	73.57	82.73	99.82	122.21	162.8
Hydrogen storing cost	15.08	15.85	14.56	15.26	15.65
Total cost	487.66	483.7	478.82	472.29	462.5

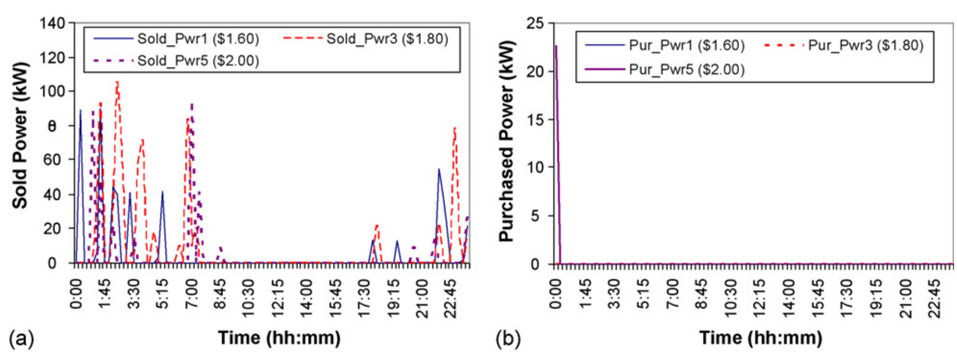

Fig. 7. Case 2, power trade with grid (a) purchased and (b) sold.

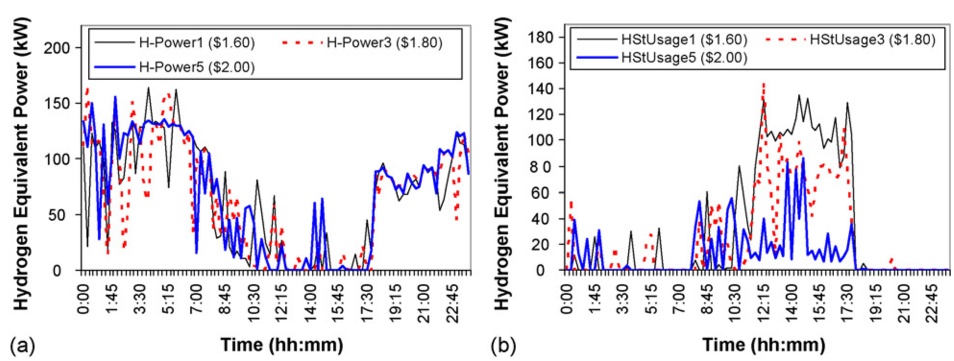

Fig. 8. Case 2, hydrogen (a) produced and (b) usage from tank.

income from selling energy to the grid. Table 3 shows that the income from selling electrical energy increases with the increase of hydrogen price up to \$ 1.80. For hydrogen price higher than \$ 1.80 the income decreases. For hydrogen price in the range of \$ 1.60–1.80 it is more profitable to the system to produce more electric energy for sale to the grid. For hydrogen price in excess of \$ 1.80, it is beneficial for the system to sell more hydrogen than electric energy. Cost of residential natural gas is almost constant with the change in the hydrogen price. This is because at high thermal demand the sum of the produced electrical and hydrogen energy is close to the maximum capacity of the FCPP. This also supports the fact that the amount of the hydrogen produced for a price greater than \$ 1.70 is almost constant. The increase in the income from the sale of hydrogen comes mostly from increase in the hydrogen selling price.

Examining Figs. 6–8 shows that, at low thermal demand the electric/thermal power are sensitive to the change in the hydrogen price. Also during this period, hydrogen production is insensitive to the change in the hydrogen price. Further, during the low thermal demand period, hydrogen usage from the tank decreases with the increase of hydrogen price. At high thermal load, the power trade with the grid is sensitive to the hydrogen price as explained previously.

Case 3. In this case, the effect of the price of purchased electrical energy on FCPP operation is tested. The price of electrical energy purchased is varied in the range of \$ 0.12–0.16 in increments of \$ 0.01.

The change in the daily cost/income is shown in Table 4. Figs. 9–11 show the electrical/thermal load and generation,

Table 4
Cost/income component for Case 3

Daily cost/income components (\$)	Purchasing electricity price, $C_{el,p}$ (\$ kWh^{-1})				
	0.12	0.13	0.14	0.15	0.16
Fuel cost	552.3	555.17	548.6	549.17	545.3
Cost of electricity purchased	0.56	0.56	0	0	0
Income from electricity sold	10.78	7.98	5.26	7.23	6.27
Cost of residential natural gas	11.16	10.45	10.51	10.47	10.7
Hydrogen selling income	105.9	112.2	108.37	106.28	103.47
Hydrogen storing cost	15.2	15.23	15.94	15.65	16.28
Total cost	477.92	476.7	476.21	476.76	477.01

power trade with the grid, and hydrogen production/storage. As shown in Table 4 and Figs. 9–11, the price of electrical energy purchased does not have significant effect on the system cost/income components. This is due to the near full capacity operation of the FCPP.

Case 4. In this case, the effect of the sale price of electrical energy on the FCPP optimal operation is tested. This sale price is changed from \$ 0.06 to \$ 0.10 with increments of \$ 0.01. The change in the cost/income component is shown in Table 5. Figs. 12–14 show the electrical/thermal load and generation, power trade with the grid, and hydrogen production/storage.

It is clear from Table 5 and Figs. 13–15 that the sale price of electrical energy has considerable effect on the income from the sale of electricity and hydrogen. The income from electrical energy sold increases with the increase of its sale price. On

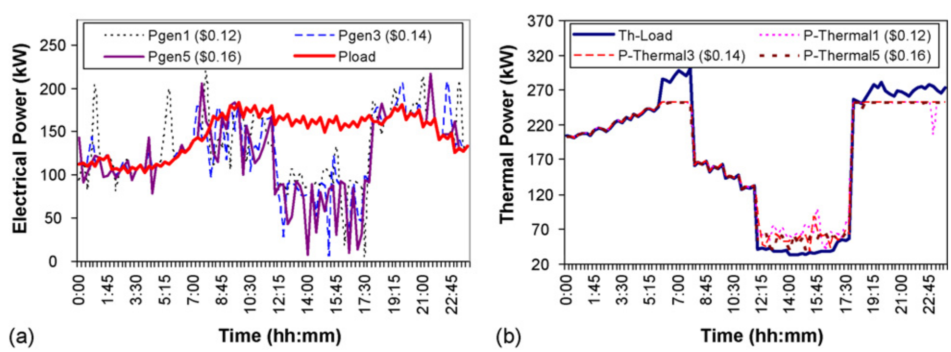

Fig. 9. Case 3, load and generation (a) electric and (b) thermal.

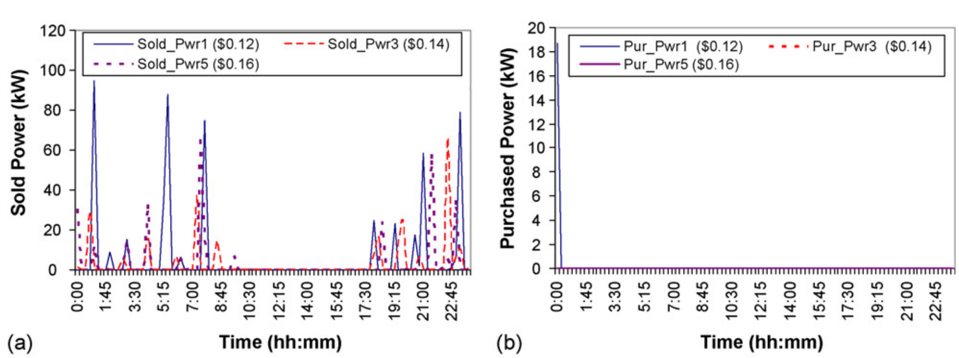

Fig. 10. Case 3, power trade with grid (a) purchased and (b) sold.

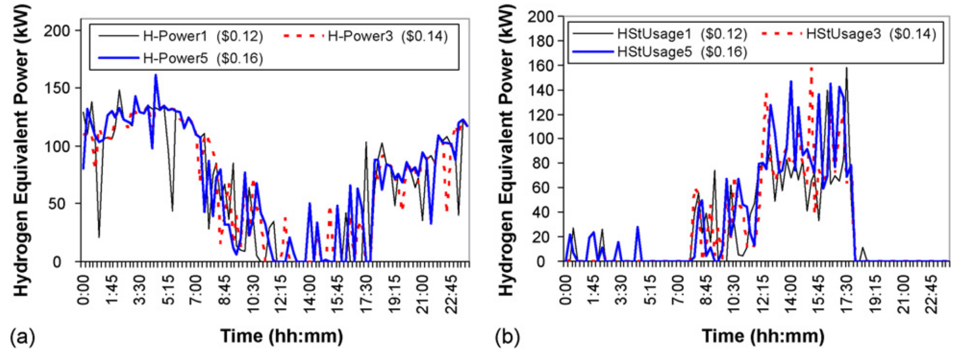

Fig. 11. Case 3, hydrogen (a) produced and (b) usage from tank.

Table 5
Cost/income component for Case 4

Daily cost/income components ($)	Selling electricity price, $C_{el,s}$ ($ kWh^{-1})				
	0.06	0.07	0.08	0.09	0.1
Fuel cost	547.49	547.34	552.28	552.4	553.2
Cost of electricity purchased	0	0.34	0.38	0	0
Income from electricity sold	0	0.05	8.26	40.96	75.88
Cost of residential natural gas	10.41	10.42	10.9	10.43	10.39
Hydrogen selling income	113.61	113.65	108.93	70.58	38.15
Hydrogen storing cost	17.64	17.65	15.51	11.92	9.74
Total cost	475.78	475.89	477.1	480.3	477.58

the other hand, the amount of hydrogen production decreases, which decreases the income from selling hydrogen. It is also clear from Figs. 13a and 14a that increasing the sale price of electrical energy decreases the hydrogen production level and increases the amount of electrical energy sold to the grid.

Case 5. In this case, the effect of residential natural gas price on the FCPP optimal operation is examined. The residential natural gas price is changed in the range of $ 0.05–0.09 with increments of $ 0.01. The change in the daily cost/income is shown in Table 6. Figs. 15–17 show the electrical/thermal load and generation, power trade with the grid, and hydrogen production/storage.

As shown in Table 6, the production cost, and the income from selling electricity are increased with the increase of natu-

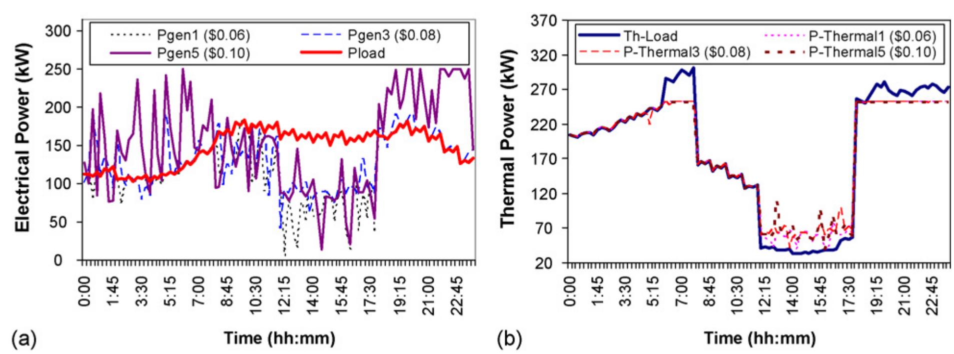

Fig. 12. Case 4, load and generation (a) electric and (b) thermal.

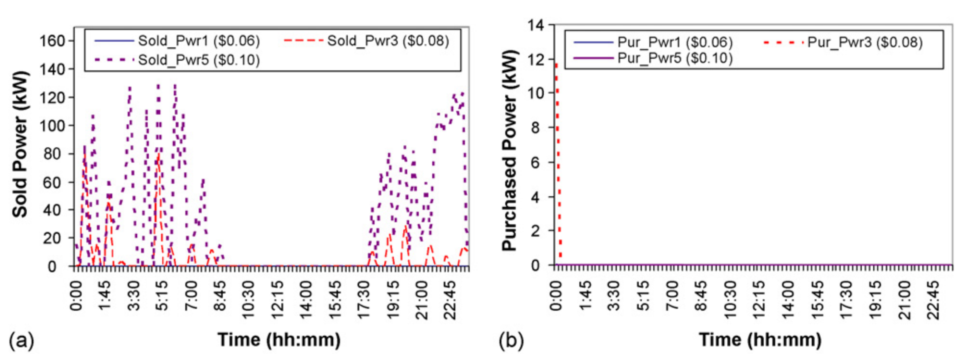

Fig. 13. Case 4, power trade with grid (a) purchased and (b) sold.

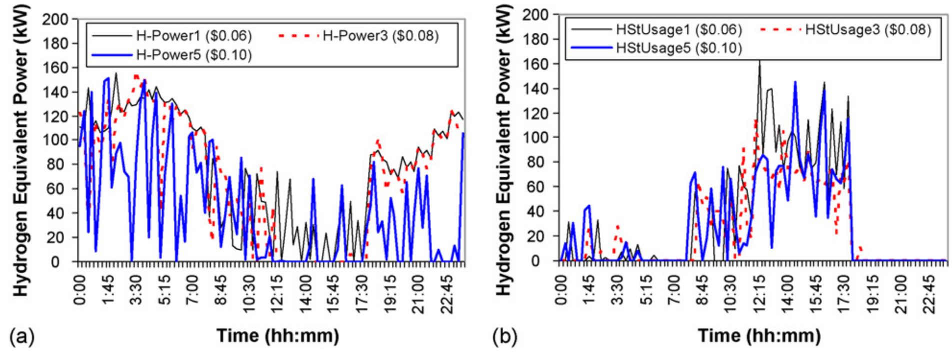

Fig. 14. Case 4, hydrogen (a) produced and (b) usage from tank.

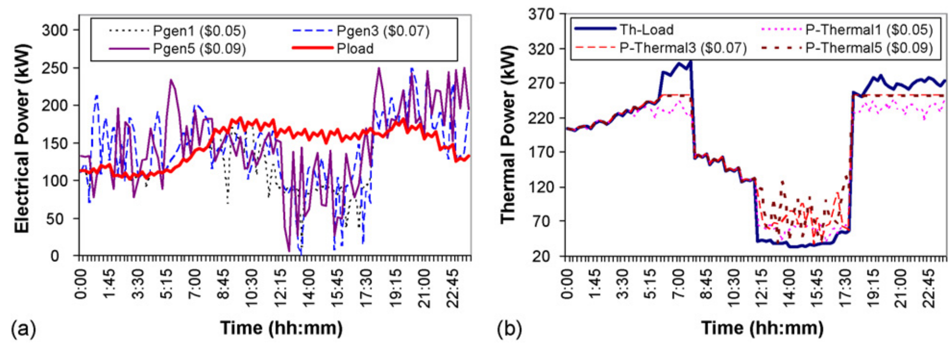

Fig. 15. Case 5, load and generation (a) electric and (b) thermal.

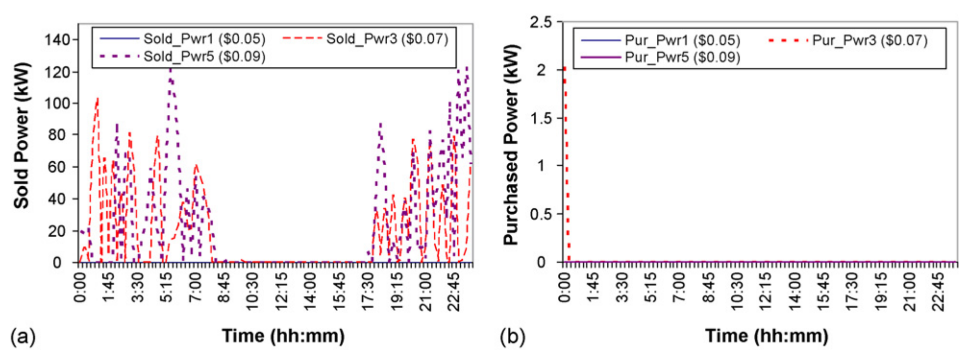

Fig. 16. Case 5, power trade with grid (a) purchased and (b) sold.

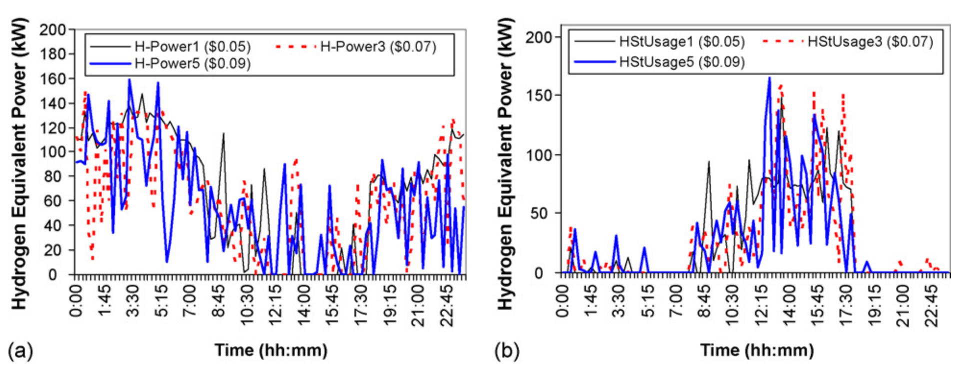

Fig. 17. Case 5, hydrogen power (a) produced and (b) usage from tank.

Table 6
Cost/income component for Case 5

Daily cost/income components ($)	Fuel price for residential loads, C_{n2} ($ kWh^{-1})				
	0.05	0.06	0.07	0.08	0.09
Fuel cost	530.95	551.07	558.74	561.64	568.52
Cost of electricity purchased	0	0	0.07	0	0
Income from electricity sold	0	13.29	31.38	38.7	42.56
Cost of residential natural gas	17.43	10.47	12.14	13.85	15.57
Hydrogen selling income	105.8	100.27	83.19	75.94	77.33
Hydrogen storing cost	15.73	14.82	13.43	12.53	12.45
Total cost	472.76	478.3	486.38	490.53	494.15

ral gas price. The income from the sale of hydrogen decreases with the increase of natural gas price. The reason for the decrease of hydrogen income is due to the excessive use of hydrogen from the tank to produce electric power, which decreases the production of thermal energy during low thermal demand periods as shown in Fig. 17b. During high thermal load period, the system produces more electric power and less hydrogen as the natural gas price increases (Figs. 15a, 16a, and 17a).

5. Conclusions

In this paper, the impact of price/tariff change on the optimal cost of operation of a PEM FCPP operating in a grid-parallel mode is presented. The cost model of the operational cost of the FCPP includes power trade with the local grid, thermal recovery, and hydrogen production/storage. The model is evaluated using IEEE test system load profile. The results show the effect of changing the fuel price, hydrogen selling price, electric energy purchase/sale price, and residential natural gas price on the optimal electrical, thermal, and hydrogen production levels and different cost/income components. From the results, it can be concluded that fuel price, hydrogen selling price, and residential gas price have significant effects on system operational strategy. In addition, thermal load level has impact on sensitivity of production levels due to price/tariff changes. For example, some of the production levels and cost components are sensitive to price change during low thermal demand periods, while others are sensitive during high thermal load periods.

The figures presented in this paper are based on generic load profiles. Therefore, region-specific load profiles and tariffs would yield results that necessarily differ from those presented in this paper. The paper does not present a discussion on the technology or the capital cost of production and storage of hydrogen.

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