DEVELOPMENT OF AN ECONOMICAL OPERATION STRATEGY TO IMPROVE FUEL CELL POWER PLANT COMPETITVENESS

A Thesis

Submitted to the Graduate Faculty of the University of South Alabama in partial fulfillment of the requirements for the degree of

Master of Science

in

Electrical Engineering

by

Khaled Al-Saadi
B.S. University of South Alabama, 2003
December 2005

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THE UNIVERSITY OF SOUTH ALABAMA
COLLEGE OF ENGINEERING

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LIST OF SYMBOLS

Symbol	Definition
A_{profit}	The annual profit
$AFL^{\cos t}$	Airflow loop cost
$AC^{\cos t}$	Ancillary components cost
$B^{\cos t}$	Battery cost
$C^{\cos t}$	Converter cost
$CFL^{\cos t}$	Coolant flow loop cost
DSA	Daily saving amount
$E_{\cos t}^{pur}$	Cost of purchasing electricity
E_{profit}^{sel}	Profit of selling electricity
$FCPP$	Fuel cell power plant
$FCOC$	Fuel cell operation cost
$FC_{capital}^{\cos t}$	Fuel cell capital cost
$FU_{\cos t}$	Fuel usage cost
F	A conversion factor (kg of hydrogen /kW of electrical power)
J	Number of intervals

$HYL^{\cos t}$	Hydrogen loop cost
$HML^{\cos t}$	Humidification loop cost
H_{profit}^{gen}	Profit from generated hydrogen
i	Number of ancillary components
$I^{\cos t}$	Inverter cost
$i\%$	The interest rate
L_J^{el}	Electrical load demand
L_J^{tl}	Thermal load demand
l	The life time of FCPP
$MEA^{\cos t}$	Membrane electrodes assembly cost
$NRC^{\cos t}$	Non-repeat components cost
n	Number of components
$OP_{tot}^{\cos t}$	Operation cost function
OP_J^{profit}	Total cost due to system operations
$OP_{tot}^{\cos t}$	Total saving amount due to excess thermal energy
$OC^{\cos t}$	Overall controller cost
PEM	Proton exchange membrane
$PC^{\cos t}$	Power conditioning cost
$PC^{\cos t}$	Power conditioning cost
P_{output}^{fc}	Fuel cell output power

$P_{st,J}^{th}$	The stored excess thermal energy at interval J
$P_{st,J-1}^{th}$	The stored excess thermal energy at the previous interval J-1
$P_{st,J}^{th,usage}$	The used storage amount of thermal energy at interval J
$P_{st,end}^{th}$	The neglected storage amount at the end of time horizon
$P_{FC}^{\max}$	The maximum capacity of FCPP
P_{J}^{el}	Fuel cell electrical produced power
P_{J}^{th}	Fuel cell thermal energy
P_{J}^{H}	The equivalent electrical power from hydrogen production
P_{J}^{L}	Lost power
P_{J}^{Urr}	Upper ramp rate power
P_{J}^{Lrr}	Lower ramp rate power
PW_{profit}	Present worth of profit
P/A	The present worth based on the annual benefit
$RC^{\cos t}$	Repeat components cost
$R^{\cos t}$	Reformer cost
r_{TE}^{fc}	FCPP thermal to electrical ratio
rte_{l-side}	Thermal to electrical ratio for the load side
$SA^{\cos t}$	Stack assembly cost
$S^{\cos t}$	Stack cost

$Th_{\cos t}^{pur}$	Cost of purchasing thermal energy
$Th_{profit}^{neglect}$	Profit of neglecting excess thermal energy
Th_{profit}^{sel}	Profit of selling excess thermal energy
$Th_{\cos t}^{store}$	Cost of storing thermal energy
Th_{profit}^{pur}	Profit of selling the unused stored excess thermal energy
T	Time duration
t_f	Fuel usage tariff
t_{el}^{pur}	Electricity purchasing tariff
t_{el}^{sel}	Electricity selling tariff
t_{gas}^{pur}	Gas purchasing tariff
t_{gas}^{sel}	Gas selling tariff
t_h^{sel}	Hydrogen selling tariff
v_c	The cell operating voltage
VP_{level}	Volume production level
η_J	Fuel cell efficiency
ΔP_u	Upper ramp rate
ΔP_l	Lower ramp rate

ABSTRACT

Al-Saadi, Khaled, M.S. University of South Alabama, December 2005. Development of an Economical Operation Strategy to Improve Fuel Cell Power Plant Competitiveness. Chair of the Committee: Dr. Mohammad S. Alam.

A fuel cell is a new technology that is being seriously considered as a potential candidate for generating electric power. Due to its high efficiency, fast load response, pollution and noise free operation, modularity and cogeneration potential, the fuel cell power plant (FCPP) shows excellent potential as an alternative source of energy. The main purpose of this research is to develop an economical operational strategy for enhancing the competitiveness of FCPPs. This research addresses the following issues: the initial installation cost for a proton exchange membrane (PEM) FCPP based on varying output power requirements; possible PEM fuel cell operational cost (FCOC) strategies; electrical and hydrogen production levels based on rte_{l-side} (ratio of thermal to electrical energy for the load side); and a cost sensitivity analysis test based on various tariff parameters. Finally, several economic parameters such as net profit, net cost, and payback period are evaluated based on the savings obtained from each of the operational strategies.

CHAPTER 1

INTRODUCTION

The fuel cell is an electrochemical device that converts the chemical energy of the hydrogen and oxygen into electrical energy, water and heat [1]. This electrical energy can be used to run electrical devices in automobiles, residences, industries, and space applications. The fuel cell has two electrodes, the anode (positive) and the cathode (negative). Every fuel cell contains an electrolyte, which carries electrically charged particles from one electrode to the other, and a catalyst, which speeds up the reactions at the electrodes. Figure 1.1 shows the components of a typical fuel cell stack.

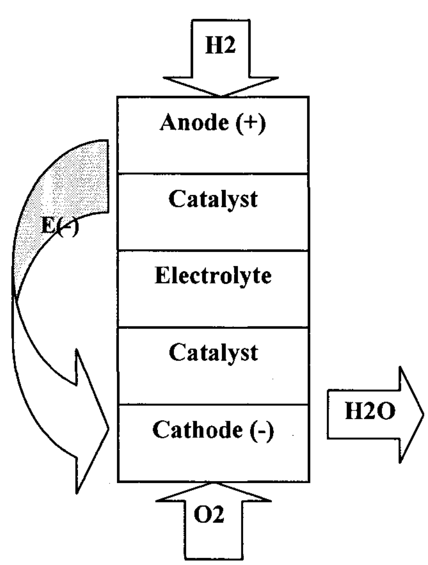

Figure 1.1 Generalized fuel cell operation diagram.

There are several types of fuel cells such as alkali fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), PEM fuel cell, and solid oxide fuel cell (SOFC) [2]. The PEM fuel cell provides the widest range of power (0.1-250 kW) [3], a 40 to 50% efficiency, and a low operating temperature of 80^{o} C (175^{o} F) [4]. These characteristics make PEM fuel cell more reliable than other types of fuel cells. However, if the heat produced during the fuel cell operation is properly utilized, then the efficiency of operation may increase up to 60 to 80% [5].

1.1 Present Research and New Contributions

In this thesis, several fuel cell operational strategies are considered: excess electric energy strategy, hydrogen production strategy, excess hydrogen storage and its utilization strategy, and heat recovery strategy in order to minimize fuel cell operational cost. A suitable combination of these operating strategies allows comparison of different operating costs depending on the system load profiles [6]. If the excess thermal energy produced in an FCPP is properly utilized, it decreases the FCOC. Furthermore, an optimum solution for electric and hydrogen production levels based on rte_{l-side} load profiles is developed. A sensitivity test analysis of purchase and selling tariffs for electricity, gas, and hydrogen has also been performed. The FCPP economic model in this research is based on an economic model developed in Reference [7] to find the optimal output power for a 4 kW and 50 kW PEM FCPP using an evolutionary programming-based methodology. Finally, several economic parameters such as net profit, net cost, and pay back period are calculated in this thesis.

1.2 Structure of the Thesis

Chapter 1 gives a brief introduction about the fuel cell structure, fuel cell types, PEM fuel cell in terms of efficiency, fuel cell operation strategies, and the present research. Chapter 2 discusses the fuel cell components and their functions. In Chapter 3 PEM fuel cell cost components are derived, the fuel cell capital cost for a 50 kW PEM FCPP is calculated. Chapter 4 summarizes fuel cell operational strategies, fuel cell cost components, and overall operational cost functions. Chapter 5, the first section discusses the algorithm for optimum operational strategy and explains the methodology to reach the optimum solution. In Section II of Chapter 5, the results for fuel cell operational strategies are shown. The strategies include: electrical, hydrogen, and thermal output powers for FCPP, power trade with the network, thermal compensation amount, thermal storage amount, and fuel cell optimum operational cost. In addition, a cost sensitivity analysis is carried out for all fuel cell operational strategies. In the third section, an optimum solution is given for electric and hydrogen production levels using rte_{l-side} based load profiles. In the last section, an economic analysis is extended for several economic parameters such as payback period, net profit, and net cost. Chapter 6 starts with a cost comparison of all fuel cell operation strategies, followed by concluding remarks, and recommendations for future work.

CHAPTER 2

FUEL CELL COMPONENTS AND PEM FUEL CELL SYSTEM

2.1 Introduction

The fuel cell consists mainly of a reformer, a stack, ancillary components, and a power conditioning system. The reformer is the fuel energy source that produces hydrogen for the fuel cell system. The stack mainly consists of two parts, the stack repeat components and the stack non-repeat components. The stack repeat components contain membrane electrode assembly (MEA), bipolar plates, separator, cooler plate, and gasket [8]. The stack non-repeat components are endplates, insulator set, current collector set and tie-rods. The ancillary components are distributed between four loops and the overall controller. The four loops are listed as follows: a hydrogen flow loop, an airflow loop, a coolant flow loop, and a humidification loop. The last part is the power conditioning system that includes a DC/DC converter, a DC/AC inverter, and the energy storage unit (battery) [9].

Figure 2.1 shows the FCPP components: the fuel processor that produces hydrogen (H_2) from natural gas; the stack that produces heat, water and DC power; and finally the power inverter that converts the DC power to AC power which makes power available for the user.

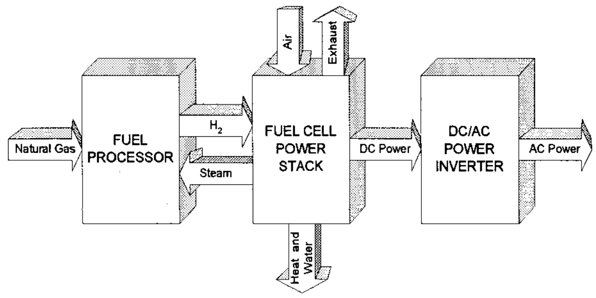

Figure 2.1 Fuel cell components.

2.2 Fuel Processor (Reformer)

The steam reformer is used to extract hydrogen from methanol [10]. The reformer is the energy source for the fuel cell that provides hydrogen to the fuel cell stacks where the electrochemical reaction takes place.

2.3 Stack & Ancillary Components

The tasks of ancillary components are to balance the temperature of the stack and provide the stack with the required level of humidity to keep it up and running. In addition, the ancillary components keep the hydrogen and the airflow rates constant using the overall controller.

2.3.1 Stack

The stack mainly consists of two parts; the stack repeat components and the stack non- repeat components. The stack repeat components include a membrane electrode assembly (MEA), bipolar plates, a cooler plate, and gaskets. The membrane electrode assembly, shown in Figure 2.2, contains a membrane, a catalyst, and electrodes. The membrane is the main functional part of the stack, which allows the proton (H^+) to pass through the stack and stop the electrons (e^-) from going through. The electrodes are current carbon paper, which provides electrical conductivity and structural strength. The bipolar plate consists of multiple MEA as shown in Figure 2.3. The bipolar plate is made of a metallic hardware that could be a stainless steel, a titanium, a nickel or other coating metals such as gold which has a function to connect the stacks in series. The selection of the material depends on the corrosion-resistance to ensure long service life. The nickel is considered a decent choice due to its proven corrosion resistance, and cost effectiveness [11].

The cooler plate is a cooling cell used to get rid of the stack waste heat from the fuel cell stack and to maintain a uniform temperature across the MEA. The gasket is an injection mold that contains a number of cavities, which determine the number of parts produced per cycle of the machine shot size and clamping force. The gasket is inserted between the bipolar plates to prevent cooling water leakage. Figures 2.2 and 2.3 show the MEA and the repeat components of the stack.

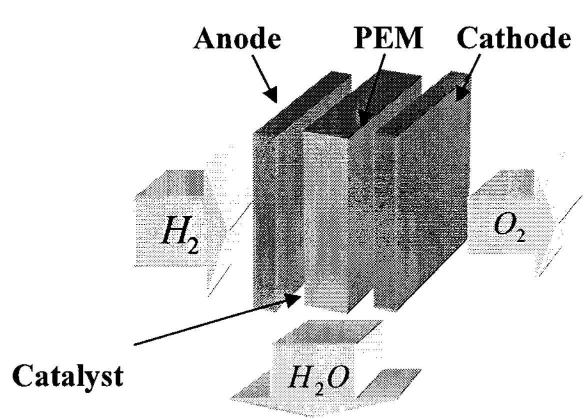

Figure 2.2 Membrane electrode assemblies (MEA).

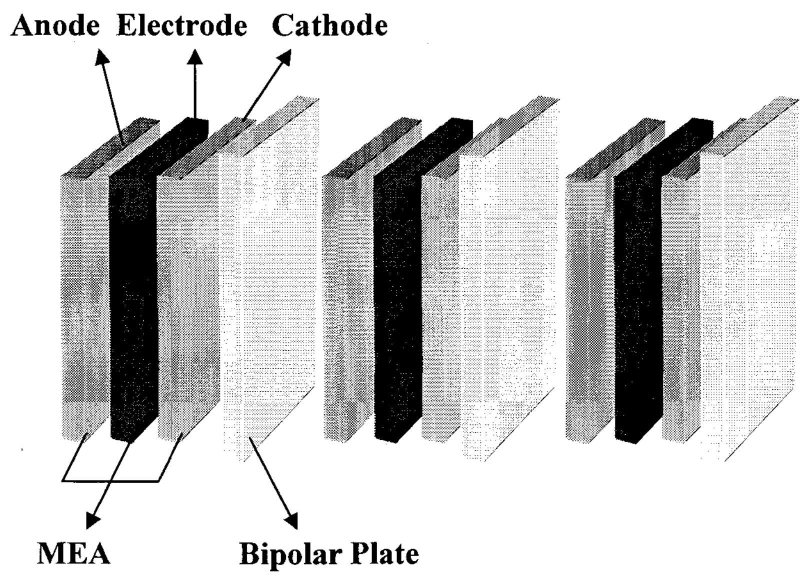

Figure 2.3 Stack repeat components.

The stack non-repeat components include a stack housing, endplates, insulators, current collectors and tie-rods. The stack housing is a two-part injected molded polymer unit, which provides structural stiffness, protection for stack elements, and acts as an electrical insulation shield for safety. Two endplates are required for each stack. The endplates are used to serve as structural members for both fuel cell stacks, supply attachment points for reactant and coolant, and supply mounting points between the stacks and the system structure. Two electrical insulators are required for each stack to isolate the endplates from the electrically charged current collectors of the stack. The current collectors allow the attachment of external leads to draw electrical power form stacks which connect two parallel stacks of electrochemical cells in series electrically. Tie-Rods are used to help seal the stacks and provide additional structural rigidity to stack. Figure 2.4 shows the stack non- repeat components.

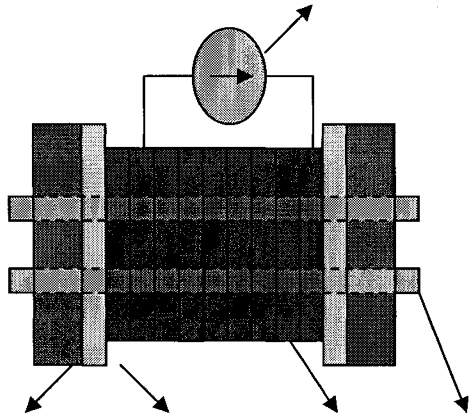

Figure 2.4 Stack non-repeat components.

2.3.2 Ancillary Components

The ancillary components are divided into four loops and the overall controller. The four loops are hydrogen, airflow, coolant, and humidification loop. Each loop includes some of the ancillary components as described in the next sections.

2.3.2.1 Hydrogen Loop. The hydrogen loop includes a humidifier, a hydrogen tank, and a hydrogen circulation pump. The humidifier is a water spray injection device, which provides appropriate amount of humidification to the air and hydrogen flow streams.

2.3.2.2 Airflow Loop. The air loop includes a humidifier which provides humidified air, a cooler, a compressor, an air input, and a motor. The air blower is modeled as oil-less regenerative blower or centrifugal blower powered by AC electric motors. The compressor's function is to increase the pressure of the air.

2.3.2.3 Coolant Flow Loop. The coolant loop includes a radiator, a coolant pump and a temperature control. There are two pumps with a driver and electric motors, which are needed for the radiator of fuel cell system. A de-ionized water pump is used for circulating fuel cell coolant. A regular non-de-ionized water pump is used for carrying the heat away. These two pumps constitute the pump system of the coolant loop. The radiator of the fuel cell system is based on a stainless steel plate liquid-to-liquid heat exchange. The stainless steel construction is necessary to handle the corrosive de-ionized water coolant.

2.3.2.4 Humidification Loop. The humidification loop includes a water separator, a water tank, and a humidity control. The humidification loop uses the water sources to humidify both hydrogen and air.

2.3.2.5 Overall Controller. The overall controller's task is to balance the functions of all four loops mentioned earlier. It contains four controllers: a hydrogen flow controller, an airflow controller, a temperature controller, and a humidifier controller. The hydrogen flow controller corresponds to the loop to maintain the hydrogen circulation pump at a prescribed level. The airflow controller relates to the loop that controls air circulation at a prescribed pressure. The temperature controller system adjusts the temperature for the fuel cell. Finally, the humidifier controller helps to keep the humidification at the desired level for the fuel cell.

2.4 Power Conditioning System

The power conditioning unit includes a DC/DC converter, a DC/AC inverter, and an energy storage unit i.e. (battery). The DC/DC converter acts as regulator for the DC voltage produced from the stack to ensure a constant level of DC voltage. The DC-to-AC inverter converts the DC output voltage to AC. The battery acts as an energy storage that can be used to meet overload for a short period. Figure 2.5 shows a detailed diagram of fuel cell system components.

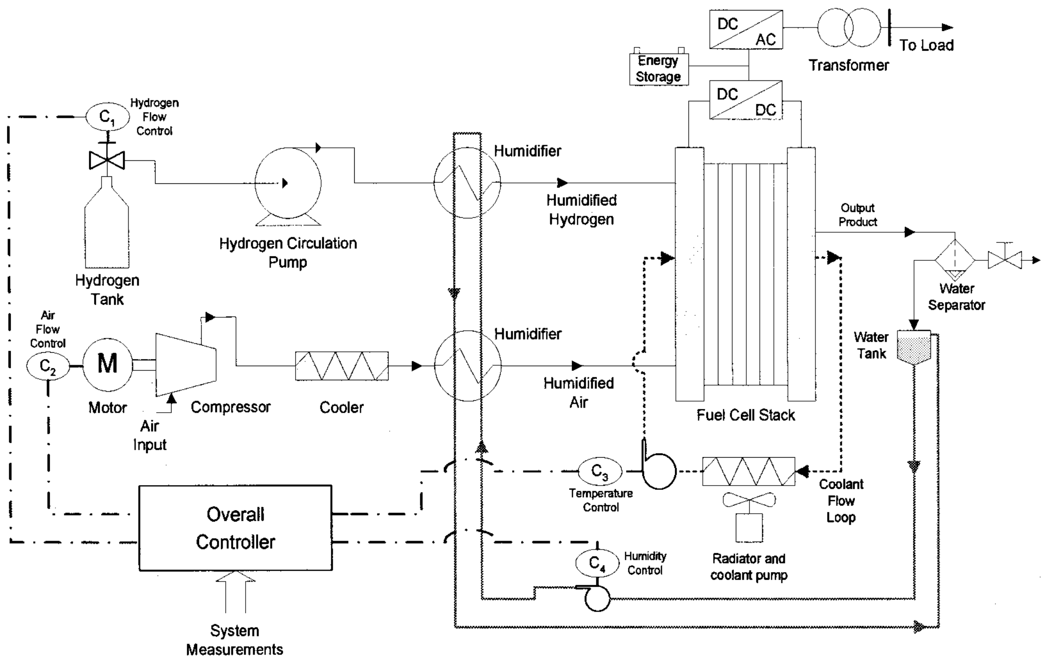

Figure 2.5 Fuel cell system components.

In summary, the PEM fuel cell components were described in this chapter. The next chapter details the capital cost of a PEM FCPP.

CHAPTER 3

FUEL CELL CAPITAL COST ESTIMATION

3.1 Cost Estimates of Fuel Cell Components

The main reason that is hindering the widespread use of FCPPs is the high price. In this section, both linear and quadratic functions for FCPP cost components are derived using curve fitting technique in order to minimize FCPP capital cost. The general fuel cell component cost function includes the cost of reformer, stack, ancillary components, and power conditioning. The following equation summarizes the general FCPP component cost function:

$$FC_{capital}^{\cos t} = \sum_{i=1}^{n} FC_i^{\cos t} = \sum_{i=1}^{n} (R_i + S_i + AC_i + PC_i)^{\cos t}, \tag{3.1}$$

where n is the number of components, $FC_{capital}^{\cos t}$ is the fuel cell capital cost (\$), $R^{\cos t}$ is the reformer cost (\$), $S^{\cos t}$ is the stack cost (\$), $AC^{\cos t}$ is the ancillary components cost (\$), and $PC^{\cos t}$ is the power conditioning unit cost (\$).

3.1.1 Reformer Cost Estimate

The reformer supplies the hydrogen to the fuel cell. The input fuel requirement of the reformer needed for a 50kW FCPP is about 40 kg/day. Using the mathematical model given in the Directed Technologies, Inc (DTI) report for 6000 unit production levels, the reformer equations are derived for both 100 and 10,000 units from 6000 units based on the progress ratio method [12]. The estimated cost for the steam methane reformer for a 50kW FCPP based on 100 production units is given by

$$R^{cost} = \$5,682 + \$104 \times P_{output} \tag{3.2}$$

The estimated cost for 10,000 production units is given by

$$R^{cost} = \$5,057 + \$92.8 \times P_{output} \tag{3.3}$$

Table 3.1 provides the cost estimates for various FCPP output power requirements.

Table 3.1 Reformer cost estimate comparison.

	Production Units	**Cost of Different FCPP Output Powers [$]**			
Reformer		**5kW**	**10kW**	**25kW**	**50kW**
	100	6,202	6,722	8,282	10,882
	10,000	5,521	5,985	7,377	9,697

3.1.2 Stack Cost Estimate

The cost of stack components such as electrodes, bipolar plates and peripherals is independent of power density. However, the performance of the membrane and the weight of platinum have a strong relationship with power density [13]. The material cost has the largest impact on the cost of the fuel cell [14]. In addition, there are other costs such as a manufacturing cost, a markup cost, a material cost, and an assembly cost for repeat components that should be considered.

The estimated stack cost for 50 kW output power is $8,040 based on 100 production units. The cost will be lower for higher production levels. The total estimated stack cost for 10,000 production units is $4,186. The general cost formula for the stack is given by

$$S^{\cos t} = \sum_{i=1}^{n} S_i^{\cos t} = \sum_{i=1}^{n} (MEA_i + RC_i + NRC_i + SA_i)^{\cos t}, \tag{3.4}$$

where $MEA^{\cos t}$ is the membrane electrode assembly cost ($), $RC^{\cos t}$ is the repeat components cost ($), $NRC^{\cos t}$ is the non-repeat components cost ($), and $SA^{\cos t}$ is the stack assembly cost ($). The fuel cell stack cost based on fuel cell output power [$/kW] may be expressed as

$$S^{\cos t} = \frac{(MEA + RC + NRC + SA)^{\cos t}}{P_{output}} \tag{3.5}$$

Based on Equation 3.4, the cost of a 50 kW fuel cell stack is included in Table 3.2.

Table 3.2 Fuel cell stack components cost comparison.

Stack Components	**100 Units [$]**	**10,000 Units [$]**
MEA	5,352	3,543
RCS	1,484	424
NRCS	1,095	164
SAC	109	55
Total Cost	8,040	4,186
Cost/kW	161	83.72

The quadratic equation for the stack based on 100 production units is given by

$$S^{\cos t} = \$1{,}422.3 + \$113.92 * P_{output} + \$0.36869 * P^2{}_{output}, \qquad (3.6)$$

while the quadratic equation for the stack based on 10,000 production units is given by

$$S^{\cos t} = \$380.62 + \$79.002 * P_{output} - \$0.066041 * P^2{}_{output}. \qquad (3.7)$$

Table 3.3 Fuel cell stack cost estimate comparison.

Stack	Production Units	Cost of Different Fuel Cell Sizes [$]			
		5kW	10kW	25kW	50kW
	100	2,000	2,600	4,500	8,040
	10,000	774	1,164	2,314	4,165

3.1.3 Ancillary Components Cost Estimates

The overall ancillary component cost for a 50 kW FCPP is $5,424 for 100 production units and $4,820 for 10,000 production units. The cost of ancillary components drops further for large production volume (usually above 50,000 production units per year). In general, the cost for ancillary components can be expressed as

$$AC^{\cos t} = \sum_{i=1}^{n} AC_i^{\cos t} = \sum_{i=1}^{n} (HYL + AFL + CFL + HML + OC)_i^{\cos t}, \qquad (3.8)$$

where i is the number of ancillary components, $HYL^{\cos t}$ is the hydrogen loop cost ($), $AFL^{\cos t}$ is the airflow loop cost ($), $CFL^{\cos t}$ is the coolant flow loop cost ($), $HML^{\cos t}$ is the humidification loop cost ($), and $OC^{\cos t}$ is the overall controller cost ($). The ancillary component cost estimates for a 50kW FCPP is summarized in Table 3.4.

Table 3.4 Ancillary components cost estimates.

Ancillary Components	100 Units [$]	10,000 Units [$]
Air Blower	774	773
Humidifier	115	110
Radiator	606	510
Stain Steel Pump	452	381
Iron Pump	136	128
Control Electronics	88	70
Actuation & misc	2,782	2,504
Piping & Valves	275	220
Total	5,228	4,656

The ancillary component cost equation based on 100 production units is given by

$$AC^{\cos t} = \$3{,}442.3 + \$39.8 * P_{output} \quad (3.9)$$

The ancillary components cost equation based on 10,000 production units is given by

$$AC^{\cos t} = \$3{,}055.6 + \$35.45 * P_{output} \quad (3.10)$$

Table 3.5 Ancillary components cost estimate comparison.

Ancillary Components	Production Units	Cost of Different Fuel Cell Sizes [$]			
		5kW	**10kW**	**25kW**	**50kW**
	100	3,630	3,841	4,457	5,424
	10,000	3,222	3,411	3,960	4,820

3.1.4 Power Conditioning Cost Estimate

The average cost of the fuel cell battery considering high volume is \$120 /kWh [15]. The cost of the energy storage estimated for 50 kW is \$1,920 for both 100 and 10,000 production units. The converter cost for a 10 kW fuel cell is \$1,460 for 100 units. The estimated DC/AC inverter cost for 50 kW output power is \$10,109 for 100 units and \$8,992 for 10,000 units. The power conditioning system cost estimate is given by

$$PC^{cost} = \sum_{i=1}^{n} PC_i^{cost} = \sum_{i=1}^{n} (B_i + C_i + I_i)^{cost}, \tag{3.11}$$

where PC^{cost} is the power conditioning cost (\$), B^{cost} is the battery cost (\$), C^{cost} is the converter cost (\$), and I^{cost} is the inverter cost (\$).

The quadratic equation for the power conditioning system based on 100 units becomes

$$PC^{cost} = \$609 + \$374.4 \times P_{output} + \$5.6425 \cdot e^{-15} * P_{output}^2, \tag{3.12}$$

while the quadratic equation for the power conditioning system based on 10,000 units is

$$PC^{cost} = \$542.49 + \$332.86 * P_{output} + \$0.00136 * P_{output}^2. \tag{3.13}$$

Table 3.6 depicts a summary of the power conditioning system component cost estimates for various levels of FCPP output powers.

Table 3.6 Power system components cost estimates.

Power System Components	Production Units	Cost of Different Fuel Cell Sizes [$]			
		5kW	10kW	25kW	50kW
Battery	100	192	384	960	1,920
	10,000	171	341	853	1,707
Converter (DC/DC)	100	730	1,460	3,650	7,300
	10,000	649	1,298	3245	6490
Inverter (DC/AC)	100	1,559	2,509	5,359	10,109
	10,000	1,387	2,232	4,767	8,992
Total	100	2,481	4,353	9,969	19,329
	10,000	2,207	3,871	8,865	17,189

3.2 Capital Cost for FCPP

The estimated overall cost of a 50kW FCPP is $43,675 based on 100 production units. The fuel cell system cost drops for higher production levels, which is estimated to be $35,875 for 10,000 production units. Table 3.7 summarizes the overall cost of 50 kW fuel cell systems for both production levels.

Table 3.7 Total cost of 50 kW FCPP system.

Components	100 Units [$]	10,000 Units [$]
Reformer	10,882	9,697
Stack	8,040	4,168
Ancillary Components	5,424	4,820
Power System	19,329	17,189
Total Cost	43,675	35,874

The initial cost [$] of a FCPP based on 100 units may be expressed as

$$FC^{\cos t} = \$10{,}990 + \$652.78 * P_{output}. \quad (3.14)$$

Similarly, the initial cost [$] of a FCPP based on for 10,000 units is given by

$$FC^{\cos t} = \$9325.8 + \$533.99 * P_{output} \quad (3.15)$$

Table 3.8 shows the overall cost for various FCPP output powers for both 100 and 10,000 production units.

Table 3.8 Cost comparison between FCPP output powers.

Components Prices	**Production Units**	**Cost of Different Fuel Cell Sizes [$]**			
		5kW	**10kW**	**25kW**	**50kW**
Reformer	100	6,202	6,722	8,282	10,882
	10,000	5,521	5,985	7,377	9,697
Stack	100	2,000	2,600	4,500	8,040
	10,000	750	1,200	2,300	4,168
Ancillary Components	100	3,630	3,841	4,457	5,424
	10,000	3,222	3,411	3,960	4,820
Power System	100	2,481	4,353	9,969	19,329
	10,000	2,309	4,076	9,377	17,189
Total Cost per kW	100	2,863	1,752	1,088	874
	10,000	2,360	1,467	921	718
Total Cost	100	14,313	17,516	27,208	43,675
	10,000	11,802	14,672	23,014	35,874

Figure 3.1 summarizes the capital cost for various FCPP output power ranges.

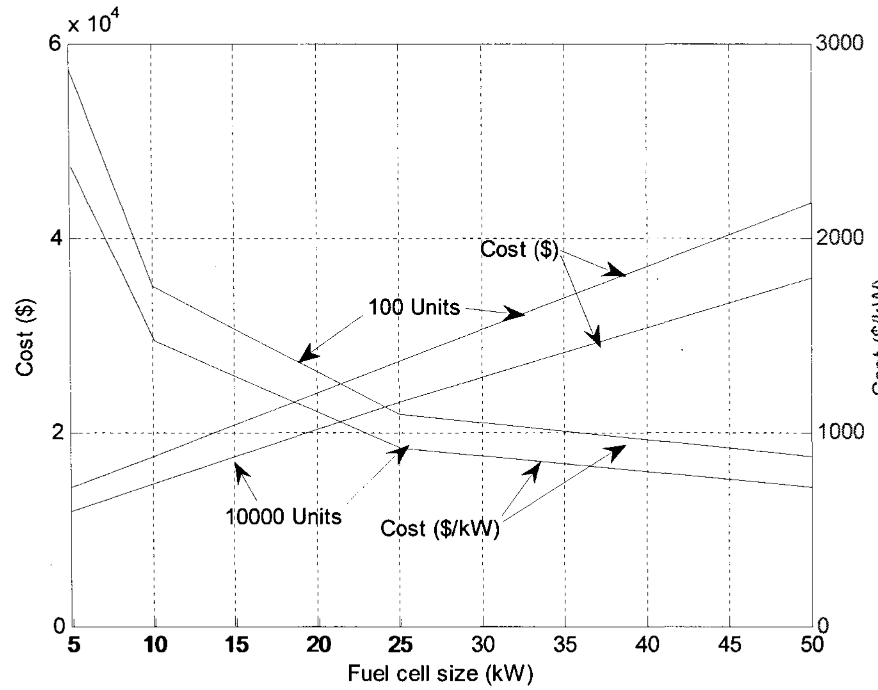

Figure 3.1 Cost comparison of the FCPP output powers.

This study shows that the cost of any FCPP decreases as the volume production level (VP_{level}) increases. Thus,

$$FC_{capital}^{cost} \propto \frac{1}{VP_{level}} \tag{3.16}$$

This chapter showed that the cost of the fuel cell is directly related to the fuel cell output power. The capital cost of FCPP increases with the increase of the fuel cell output power. However, the unit cost of FCPP ($/kW) drops gradually with increasing fuel cell output power. In the next chapter, different FCOC strategies are discussed in order to minimize the FCPP cost.

CHAPTER 4

FUEL CELL OPERATIONAL STRATEGIES AND OVERALL OPERATIONAL COST FUNCTIONS

4.1 Fuel Cell Operational Strategies

Different fuel cell operational costs are developed in this chapter in order to satisfy certain fall/spring load profiles [16]. These load profiles represent electrical and thermal load demands over a 24 hour period for a generic house, and are obtained from real life data as shown in Figure 4.1 [17]. The FCPP is used to satisfy the electrical and thermal load demands are given in the load profiles. The FCPP also considers hydrogen. The FCPP produces electrical power that can be used to satisfy the electrical load demand or it can sell the excess amount of electrical power produced to the local grid. In addition, the FCPP produces thermal energy that can be used to satisfy the thermal load demand, sell the excess amount of thermal energy produced to the neighborhood, or store it for later use. The FCPP hydrogen can be stored for later use or it can be sold in order to reduce the FCOC. The FCPP cost components that are considered to calculate the FCOC are summarized as follows: fuel cost, electricity/thermal energy usage, purchase or sale, hydrogen production/consumption or sale, and a fixed operation and maintenance cost. Natural gas is considered as a fuel to run the FCPP and usually the fuel usage cost depends on the fuel cell production level. These FCPP cost components are explained in greater detail in subsequent pages. The proposed algorithm yields the lowest operational cost for the all-electric home, gas supplied thermal load, and combination of all-electric and gas supplied thermal load profiles [18].

Four models have been developed based on these cost components in order to calculate the fuel cell operational cost. All possible combinations to calculate FCOC are summarized in Figures 4.2.a and 4.2.b. The first model is the Base Model: FCOC based on electricity usage to produce thermal energy. The other three models are – Model I: FCOC based on gas usage for the compensation of thermal energy shortage with no hydrogen production; Model II: FCOC based on electricity usage for the thermal energy compensation with hydrogen production; and Model III: FCOC based on gas usage for compensation of thermal energy shortage with hydrogen production [19].

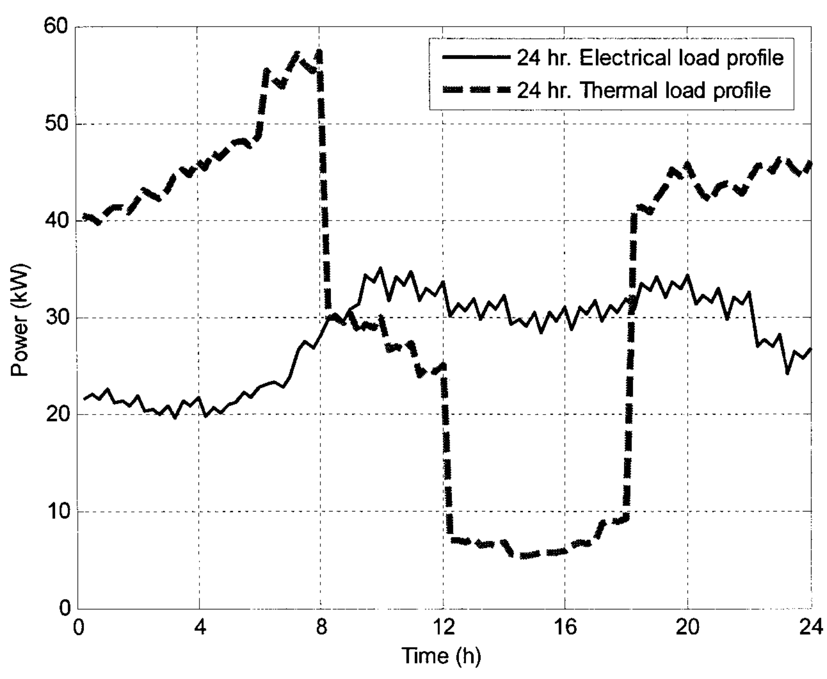

Figure 4.1 Fall/spring load profile.

The Base Model and Model II deal with two strategies: wasting the excess thermal energy or selling the excess thermal energy. The third strategy, storing excess thermal energy, is not considered for these models since electricity used for thermal energy cannot be stored. Models I and Model III deal with three strategies for utilizing the excess thermal energy either by wasting the excess thermal energy, selling the excess thermal energy, or storing the excess thermal energy for later use. Figure 4.2 shows two flowcharts for the base model and the other FCOC models including the possible strategies.

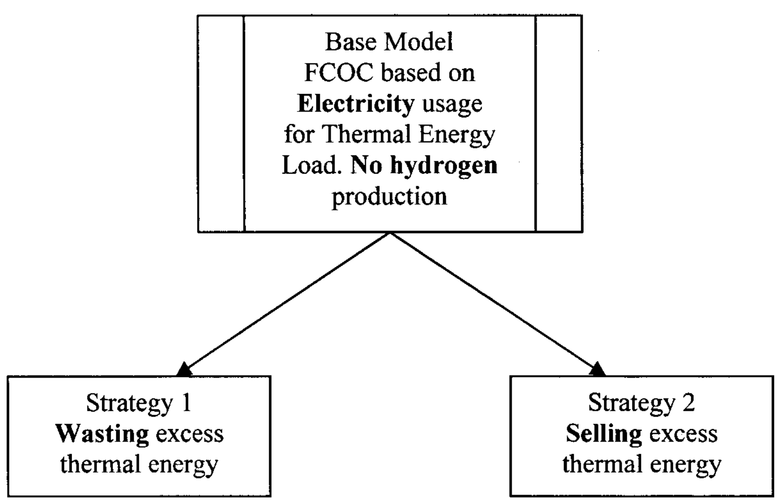

Figure 4.2.a Flowchart for the base model.

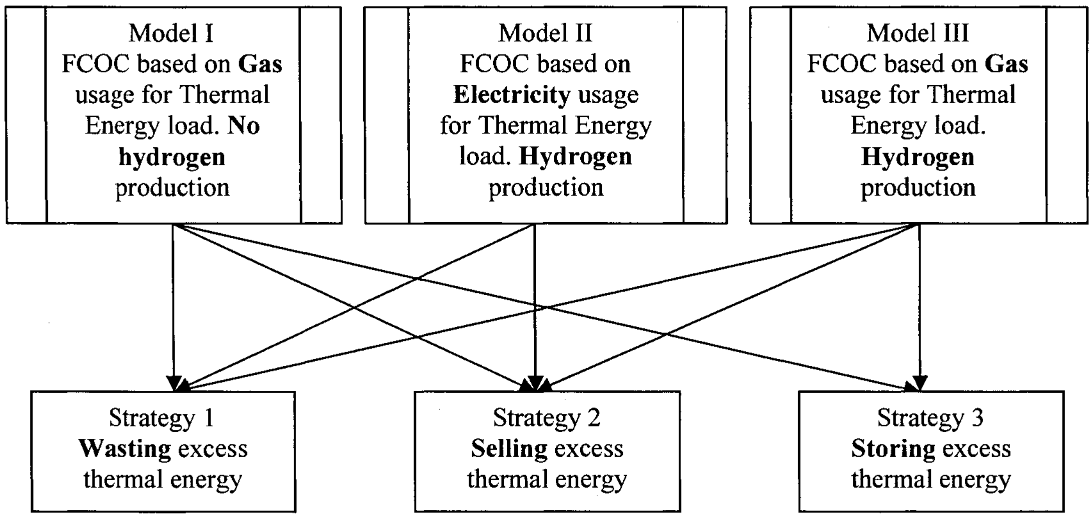

Figure 4.2.b Flowchart illustrating possible FCOC strategies.

4.2 Fuel Cell Cost Components

There are five components associated with the calculation of FCOCs – a fuel cost, an electricity usage, a thermal energy usage, a hydrogen production, and an operation and maintenance cost.

4.2.1 Fuel Cost

Fuel consumption relates to FCPP output levels. The higher the fuel cell output power, the greater the amount of fuel needed. Since a 50 kW fuel cell is considered in this study, the maximum fuel consumption occurs at 50 kW output. The minimum output level is assumed to be 2.5 kW for the fuel cell. Therefore, the lowest fuel consumption occurs at 2.5 kW. The fuel usage cost function contains fuel cell generated electric power, hydrogen production (if hydrogen is considered), power losses, and fuel cell efficiency. The power losses for the transformer, the DC/DC converter, and the DC/AC inverter are approximately 5% of the fuel cell generated electric power. The fuel cell efficiency varies depending on the fuel cell generation power. The FCPP operates with approximately 40% efficiency. The fuel usage tariff is assumed to be \$0.05/kWh. Thus the daily fuel cost function can be expressed as

$$FU_{\cos t} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^{H} + P_J^{L}}{\eta_J} * T * t_f, \tag{4.1}$$

where $FU_{\cos t}$ is the fuel usage cost (\$), J indicates 96 intervals based on 15 minute sampling intervals (0.25 h) for a 24 hour period. P_J^{el} is the FCPP output power (kW), P_J^{H} is the equivalent electric power for hydrogen production (kW), P_J^{L} represents the power losses (kW), η_J is the fuel cell efficiency, T is the time duration (T=0.25 h), and t_f is the fuel usage tariff (\$/kWh).

4.2.2 Electricity Usage

The electricity usage function is separated into two functions based on the values of the load profile and fuel cell output power at interval J. Equation 4.2, expresses the cost of daily amount of electricity needed to be purchased from the grid in order to satisfy the load if the fuel cell electric energy output is less than the load demand.

$$E_{\cos t}^{pur} = \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} \tag{4.2}$$

where $E_{\cos t}^{pur}$ represents the cost of electricity purchased (\$), L_J^{el} represents the electrical load demand at interval J (kW), and t_{el}^{pur} represents the electricity purchasing tariff (\$/kWh).

Equation 4.3, determines the income obtained from selling the excess amount of electricity produced to the local grid if the fuel cell production exceeds the load demand.

$$E_{profit}^{sel} = \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el}) * T * t_{el}^{sel} \quad (4.3)$$

where E_{profit}^{sel} represents the profit of selling electricity ($), t_{el}^{sel} represents the electricity selling tariff.

4.2.3 Thermal Energy Usage

To calculate thermal energy, the following parameters need to be considered: a fuel cell electric generation power, a hydrogen production power (if hydrogen is considered), power losses, an auxiliary power (neglected in this study) and a fuel cell thermal to electric energy ratio (r_{TE}^{fc}). The power losses for the transformer, the DC/DC converter, and the DC/AC inverter are approximately 5% of the fuel cell electric generation power. The thermal energy can then be calculated as follows:

$$P_J^{th} = r_{TE}^{fc} * (P_J + P_J^H + p_J^L) \quad (4.4)$$

where P_J^{th} represents the thermal energy (kW).

Equation 4.5 expresses the fuel cell thermal to electric energy ratio:

$$r_{TE}^{fc} = 1.08 * \left(\frac{P_J}{50}\right)^4 - 1.97 * \left(\frac{P_J}{50}\right)^3 + 1.51 * \left(\frac{P_J}{50}\right)^2 - 0.28 * \left(\frac{P_J}{50}\right) + 0.68 \quad (4.5)$$

The thermal energy function is separated into two functions based on the values of the load profile and fuel cell thermal energy P_J^{th} at interval *J*. Equation 4.6, expresses the cost of daily amount of thermal energy needed to be purchased in order to satisfy the load profile if the fuel cell thermal energy production is less than the thermal load.

Electricity or gas could be used to calculate the thermal energy, which is discussed later in further detail from the point of view of economic. Unit costs of 0.06 and 0.04 ($/kWh) are assumed as purchasing and selling gas tariffs ($t_{el,gas}^{pur}$), respectively.

$$Th_{cost}^{pur} = \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{el,gas}^{pur} \tag{4.6}$$

Equation 4.7 expresses the cost function if excess thermal energy is wasted.

$$Th_{neglect}^{profit} = 0 \tag{4.7}$$

Equation 4.8 determines the income obtained from selling the excess thermal energy to the grid if the fuel cell thermal energy exceeds the thermal load demand. This excess amount of thermal energy produced can be reused in order to reduce the FCOC either by selling it to other neighborhoods or storing the excess thermal energy for later use. This helps to reduce the operational cost, which is proven in the next chapter.

$$Th_{profit}^{sel} = \sum_{J=1}^{96} \max(P_J^{th} - L_J^{th}) * T * t_{el,gas}^{sel} \tag{4.8}$$

Equation 4.9 calculates the cost for the case of storing the excess thermal energy. The results discussed in the next chapter show this strategy as the most efficient strategy regarding the fuel cell operational cost.

$$Th_{profit}^{store} = \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th} - P_{st,J}^{th}) * T * t_{el,gas}^{pur} \tag{4.9}$$

The stored excess thermal energy can be used in the intervals of high thermal demand where the thermal load is lower than produced thermal energy. The rest of the stored excess thermal energy can be sold to other neighborhoods at the end of the day. The stored thermal energy at interval J can be calculated as follows:

$$P^{th}_{st,J} = P^{th}_{st,J-1} + \sum_{J=1}^{96} \max(P^{th}_J - L^{th}_J) - P^{th,usage}_{st,J} \quad (4.10)$$

The profit made after selling the unused stored excess thermal energy at the end of the day can be expressed as follows:

$$Th^{store}_{profit} = P^{th}_{st,end} * t^{sel}_{el,gas}, \quad (4.11)$$

where $P^{th}_{st,J}$ is the stored excess thermal energy at interval J (kW), $P^{th}_{st,J-1}$ is the stored excess thermal energy at the previous interval J-1 (kW), $P^{th,usage}_{st,J}$ is the amount of thermal energy used from storage at interval J (kW), Th^{store}_{profit} represents the profit made after selling the unused stored excess thermal energy, and $P^{th}_{st,end}$ is the unused storage amount at the end of the day.

4.2.4 Hydrogen Income

The amount of hydrogen produced can be used to reduce the FCOC. Equation 4.12 calculates the cost of fuel cell hydrogen production:

$$H^{gen}_{profit} = \sum_{J=1}^{96} (P^H_J * F) * T * t^{sel}_h \quad (4.12)$$

F is a conversion factor (kg of hydrogen/kW of electric power):

$$F = \frac{1.05 * 10^{-8}}{v_c} \quad (4.13)$$

The amount of generated hydrogen varies between the maximum capacity and the generated power level of the fuel cell, which is given by the following equation:

$$P^H_J = P^{max}_{FC} - P_J - P_L, \quad (4.14)$$

where H^{gen}_{profit} is the generated hydrogen income (\$), $P^{\max}_{FC}$ is the maximum capacity of FCPP, where $P^{\max}_{FC}$=50 kW, F is a conversion factor (kg of hydrogen /kW of electric power), and v_c is the cell operating voltage, where $v_c = 0.6\ Volt$ [20]. The daily operation and maintenance costs are considered constant, which is $1.97/day.

4.3 FCOC Functions

The general FCOC function is summarized as follows:

$$OP^{\cos t}_{tot} = \sum_{J=1}^{96}(OP^{\cos t}_{J} - OP^{profit}_{J}) \tag{4.15}$$

where $OP^{\cos t}_{tot}$ represents the general FCOC function (\$), $OP^{\cos t}_{J}$ represents total FCPP cost due to systems operation, demand, and maintenance, and OP^{profit}_{J} represents total FCPP saving due to excess energy strategies such as storage/sale of hydrogen, thermal, and electrical energy.

Ten FCOC functions are derived according to the model and strategy that follows.

4.3.1 Base Model (electricity compensation)

Two FCOC functions are derived for this model according to the excess thermal energy strategy.

4.3.1.1 Strategy 1(wasting excess thermal energy). The equation below calculates the cost of FCPP of the Base Model when wasting the excess thermal energy.

$$OP_{cost} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^{H} + P_J^{L}}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el})$$

$$* T * t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{el}^{pur} + OM_{cost} \qquad (4.16)$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy, and the last term represents the operation and maintenance cost.

4.3.1.2 Strategy 2 (selling the excess thermal energy). The following equation expresses the overall cost function of FCPP for the Base Model when selling the excess thermal energy.

$$OP_{cost} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^{H} + P_J^{L}}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el})$$

$$* T * t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{th} - L_J^{th}) * T * t_{el}^{sel} + OM_{cost} \qquad (4.17)$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on electricity usage, the fifth term corresponds to the profit made selling excess thermal energy, and the last term represents the operation and maintenance cost.

4.3.2 Model I (gas compensation)

Three FCOC functions are derived for this model according to the excess thermal energy strategy.

4.3.2.1 Strategy 1 (wasting the excess thermal energy). The equation below calculates the cost of the FCPP of model I when wasting the excess thermal energy.

$$OP_{\cos t} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^H + P_J^L}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el})$$
$$* T * t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{gas}^{pur} + OM_{\cos t} \qquad (4.18)$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on gas usage, and the last term represents the operation and maintenance cost.

4.3.2.2 Strategy 2 (selling excess thermal energy). The equation below calculates the cost of the FCPP of model I when selling the excess thermal energy.

$$OP_{\cos t} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^H + P_J^L}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el})$$
$$* T * t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{gas}^{pur} - \sum_{J=1}^{96} \max(P_J^{th} - L_J^{th}) * T * t_{gas}^{sel} + OM_{\cos t} \qquad (4.19)$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on gas usage, the fifth term corresponds to the profit made selling excess thermal energy, and the last term represents the operation and maintenance cost.

4.3.2.3 Strategy 3 (storing excess thermal energy). The equation below calculates the cost of the FCPP of model I when storing the excess thermal energy.

$$OP_{cost} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^{H} + P_J^{L}}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el}) * T *$$
$$t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th} - P_{st,J}^{th}) * T * t_{gas}^{pur} - P_{end}^{th} * t_{gas}^{sel} + OM_{cost} \quad (4.20)$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on gas usage and thermal storage, the fifth term corresponds to the profit made selling the unused excess thermal energy at the end of the day, and the last term represents the operation and maintenance cost.

4.3.3 Model II (electricity compensation and hydrogen production)

Two FCOC functions are derived for this model according to the excess thermal energy.

<u>**4.3.3.1 Strategy 1 (wasting excess thermal energy)**</u>. The equation below calculates the cost of FCPP for model II when wasting the excess thermal energy.

$$OP_{cost} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^{H} + P_J^{L}}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el})$$
$$* T * t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{el}^{pur} - \sum_{J=1}^{96} (P_J^{H} * F) * T * t_h^{sel} + OM_{cost} \quad (4.21)$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on electricity usage, the fifth term corresponds to the profit made selling hydrogen production, and the last term represents the operation and maintenance cost.

4.3.3.2 Strategy 2 (selling excess thermal energy). The equation below calculates the cost of FCPP model II when selling the excess thermal energy.

$$OP_{\text{cost}} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^{H} + P_J^{L}}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el})$$
$$* T * t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{th} - L_J^{th}) * T * t_{el}^{sel} - \sum_{J=1}^{96} (P_J^{H} * F) * T$$
$$* t_h^{sel} + OM_{\text{cost}} \tag{4.22}$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on electricity usage, the fifth term corresponds to the profit made selling excess thermal energy, the sixth term corresponding to the profit made selling hydrogen production, and the last term represents the operation and maintenance cost.

4.3.4 Model III (gas compensation and hydrogen production)

Three FCOC functions are derived in this model according to the excess thermal energy.

4.3.4.1 Strategy 1 (wasting excess thermal energy). The equation below calculates the cost of FCPP for model III when wasting the excess thermal energy.

$$OP_{\text{cost}} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^{H} + P_J^{L}}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el})$$
$$* T * t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{gas}^{pur} - \sum_{J=1}^{96} (P_J^{H} * F) * T * t_h^{sel} + OM_{\text{cost}} \tag{4.23}$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on gas usage, the fifth term corresponding to the profit made selling hydrogen production, and the last term represents the operation and maintenance cost.

4.3.4.2 Strategy 2 (selling excess thermal energy). The equation below calculates the cost of FCPP of model III when selling the excess thermal energy.

$$OP_{\text{cost}} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^H + P_J^L}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el}) * T * t_{el}^{sel}$$
$$+ \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th}) * T * t_{gas}^{pur} - \sum_{J=1}^{96} \max(P_J^{th} - L_J^{th}) * T * t_{gas}^{sel} - \sum_{J=1}^{96} (P_J^H * F) * T * t_h^{sel} + OM_{\text{cost}} \quad (4.24)$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on gas usage, the fifth term corresponds to the profit made selling excess thermal energy, the sixth term corresponding to the profit made selling hydrogen production, and the last term represents the operation and maintenance cost.

4.3.4.3 Strategy 3 (storing excess thermal energy). The equation below calculates the cost of FCPP of model III when storing the excess thermal energy.

$$OP_{\text{cost}} = \sum_{J=1}^{96} \frac{P_J^{el} + P_J^H + P_J^L}{\eta_J} * T * t_f + \sum_{J=1}^{96} \max(L_J^{el} - P_J^{el}) * T * t_{el}^{pur} - \sum_{J=1}^{96} \max(P_J^{el} - L_J^{el})$$
$$* T * t_{el}^{sel} + \sum_{J=1}^{96} \max(L_J^{th} - P_J^{th} - P_{st,J}^{th}) * T * t_{gas}^{pur} - P_{st,end}^{th} * t_{gas}^{sel} - \sum_{J=1}^{96} (P_J^H * F) * T * t_h^{sel} + OM_{\text{cost}} \quad (4.25)$$

where the first term corresponds to the fuel usage cost, the second term corresponds to the cost of electricity purchased, the third term corresponds to the profit made selling electricity, the fourth term corresponds to the cost of purchasing thermal energy based on gas usage and thermal energy storage, the fifth term corresponds to the profit made selling the unused excess thermal energy at the end of the day, the sixth term corresponding to the profit made selling hydrogen, and the last term represents the operation and maintenance cost.

In Chapter 5, the algorithm for choosing an optimal operation strategy is determined based on the FCOC functions discussed in Chapter 4. In addition, the next chapter includes cost sensitivity and an economical analysis for the results obtained from the fuel cell operation strategies.

CHAPTER 5

ALGORITHM FOR OPTIMUM OPERATIONAL STRATEGY AND RESULTS

5.1 Algorithm for Optimum Operational Strategy

Fourteen steps, which summarize the algorithm for choosing the optimum operation strategy, are given in this section. In Figure 5.1, a flow chart is given to explain these steps and the methodology used to reach the near optimum operation solution.

The minimum and maximum output power for FCPP is set between 2.5 and 50 kW. Table 5.1 summarizes all FCPP system parameters.

Table 5.1 FCPP system parameters.

FCPP System Parameters	
Maximum limit of generating power, $P^{\max}$ (kW)	2.5, 50
Minimum limit of generating power, $P^{\min}$ (kW)	50
Length of time interval, T (h)	0.25
Upper limit of the ramp rate, ΔP_U (kW)	25
Lower limit of the ramp rate, ΔP_D (kW)	30
Fuel price for residential loads, t_f (\$ $kW^{-1}h^{-1}$)	0.05
Tariff for purchasing electricity, t_{el}^{pur} (\$ $kW^{-1}h^{-1}$)	0.13
Tariff for selling electricity, t_{el}^{sel} (\$ $kW^{-1}h^{-1}$)	0.07
Tariff for purchasing gas, t_{gas}^{pur} (\$ $kW^{-1}h^{-1}$)	0.06
Tariff for selling gas, t_{gas}^{pur} (\$ $kW^{-1}h^{-1}$)	0.04
Tariff for selling hydrogen, t_h^{sel} (\$ $kW^{-1}h^{-1}$)	1.9

The following steps explain the methodology used to reach the optimum solution:

Step 1: Read electric and thermal load powers from the load profiles.

Step 2: Start the "for" loops; three "for" loops are used for this algorithm. All loops are based on 15 minute sampling intervals for a 24 hour period. The first loop is the time interval to read the load power ($j = 1,2,\ldots,96$). The second loop is fuel cell operating level represented by index of "i" to produce fuel cell electric generated power and production of thermal energy level, which is calculated in the next steps. If the hydrogen production is taken into consideration, the loop represented by counter "k" will be involved to generate hydrogen level.

Step 3: Calculate the fuel cell generated power starting from 2.5 kW to 50 kW with an increment of 0.5 kW. This interval can be selected for a value less than 0.5 kW in order to get more accurate results.

Step 4: Check all system constraints such as lower and upper ramp rates.

Step 5: Calculate the cost of electricity needed to purchase from the grid to satisfy the load power and the profit of selling excess electricity to other neighborhoods.

Step 6: Calculate the power loss.

Step 7: Calculate hydrogen generated power and the profit made from selling the produced hydrogen.

Step 8: Calculate fuel cell total output power.

Step 9: Calculate the cost of the purchased thermal energy needed to satisfy the thermal load power and the profit of selling the excess thermal energy based on the strategies that could be used such as wasting, selling, or storing excess thermal energy.

Step 10: Calculate fuel cost.

Step 11: Calculate maintenance and operation costs.

Step 12: Calculate total FCOCs.

Step 13: End of the three "for" loops.

Step 14: Determine optimal FCOC.

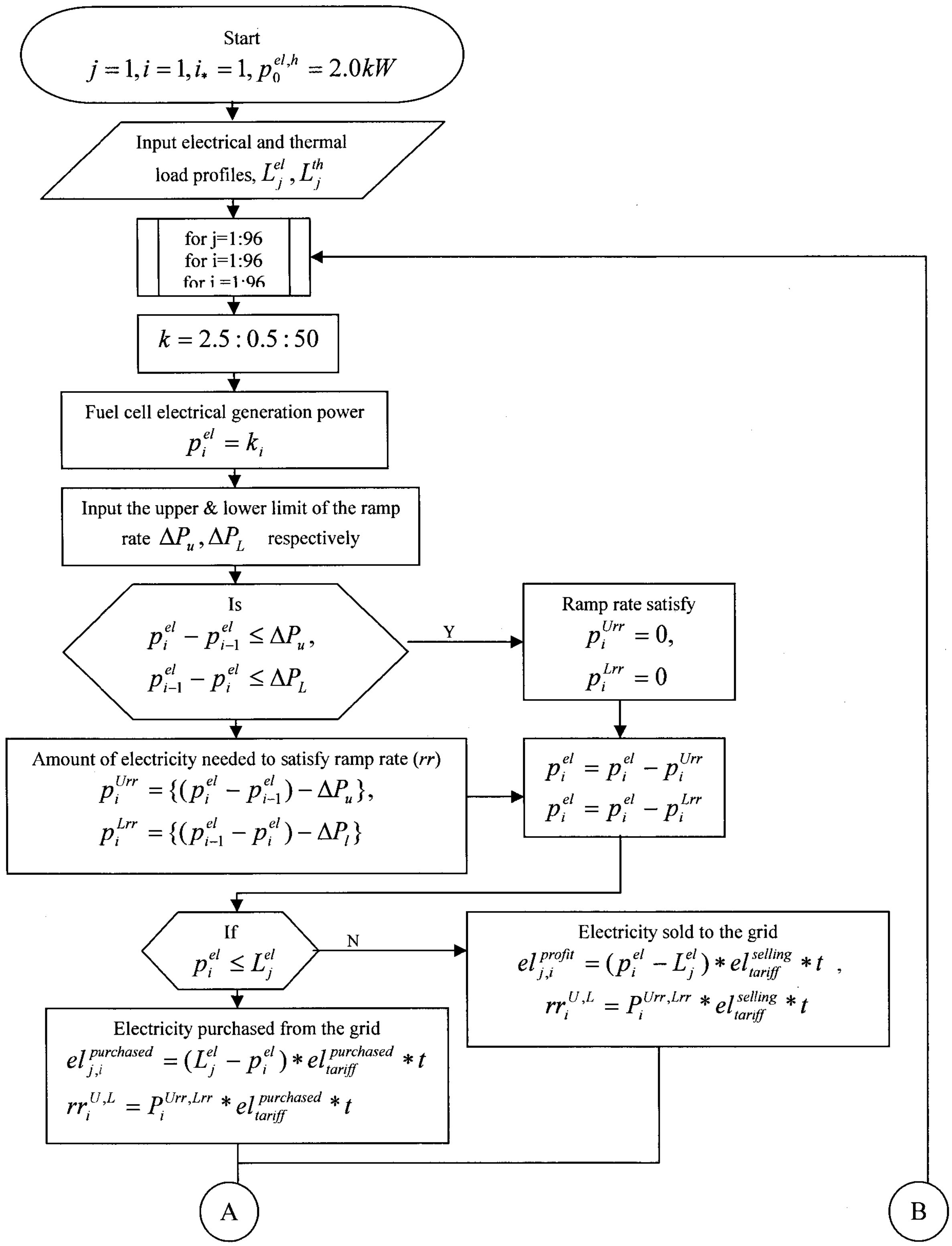

Figure 5.1 Flow chart for FCPP algorithm

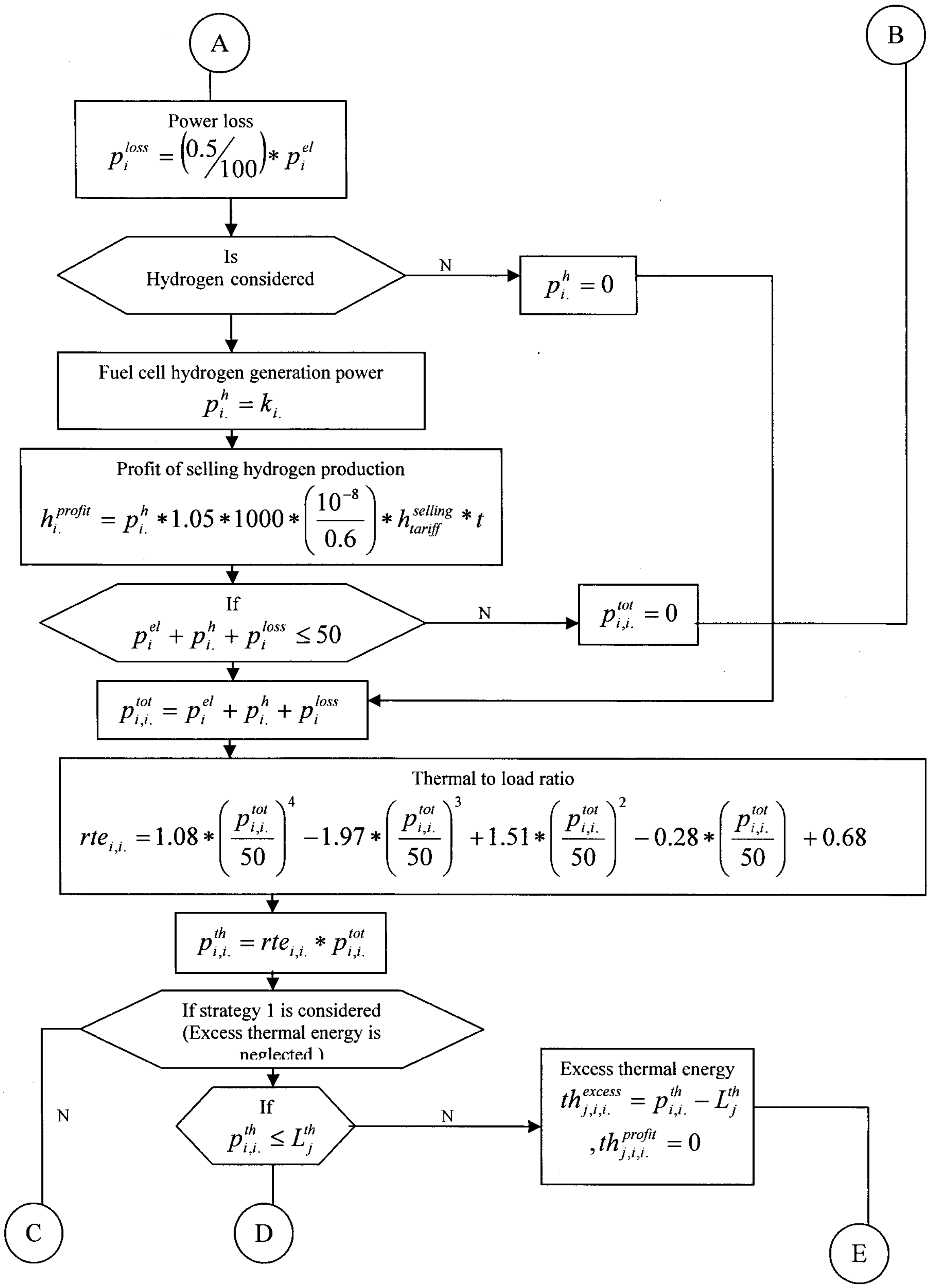

Figure 5.1 Continued

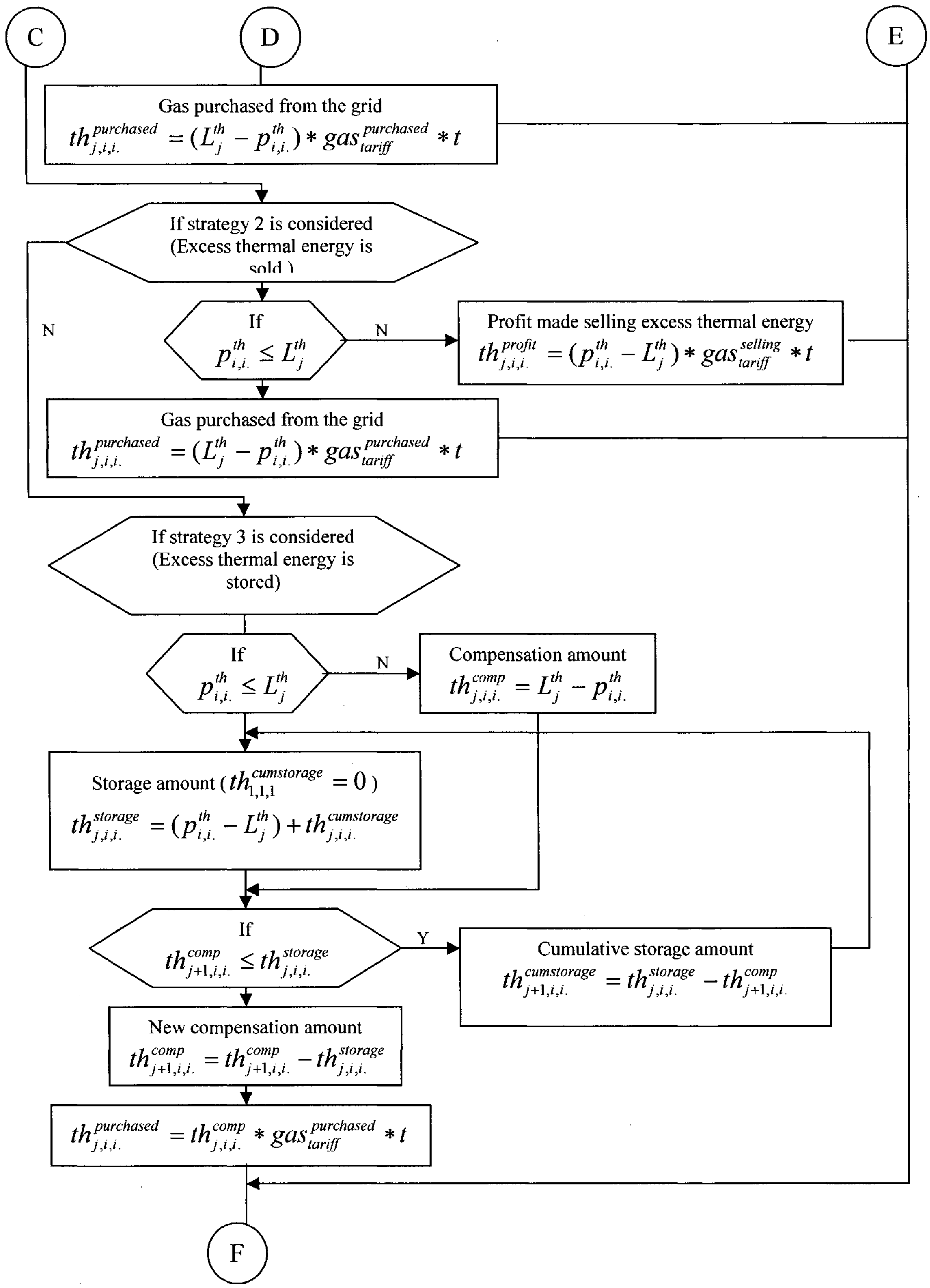

Figure 5.1 Continued

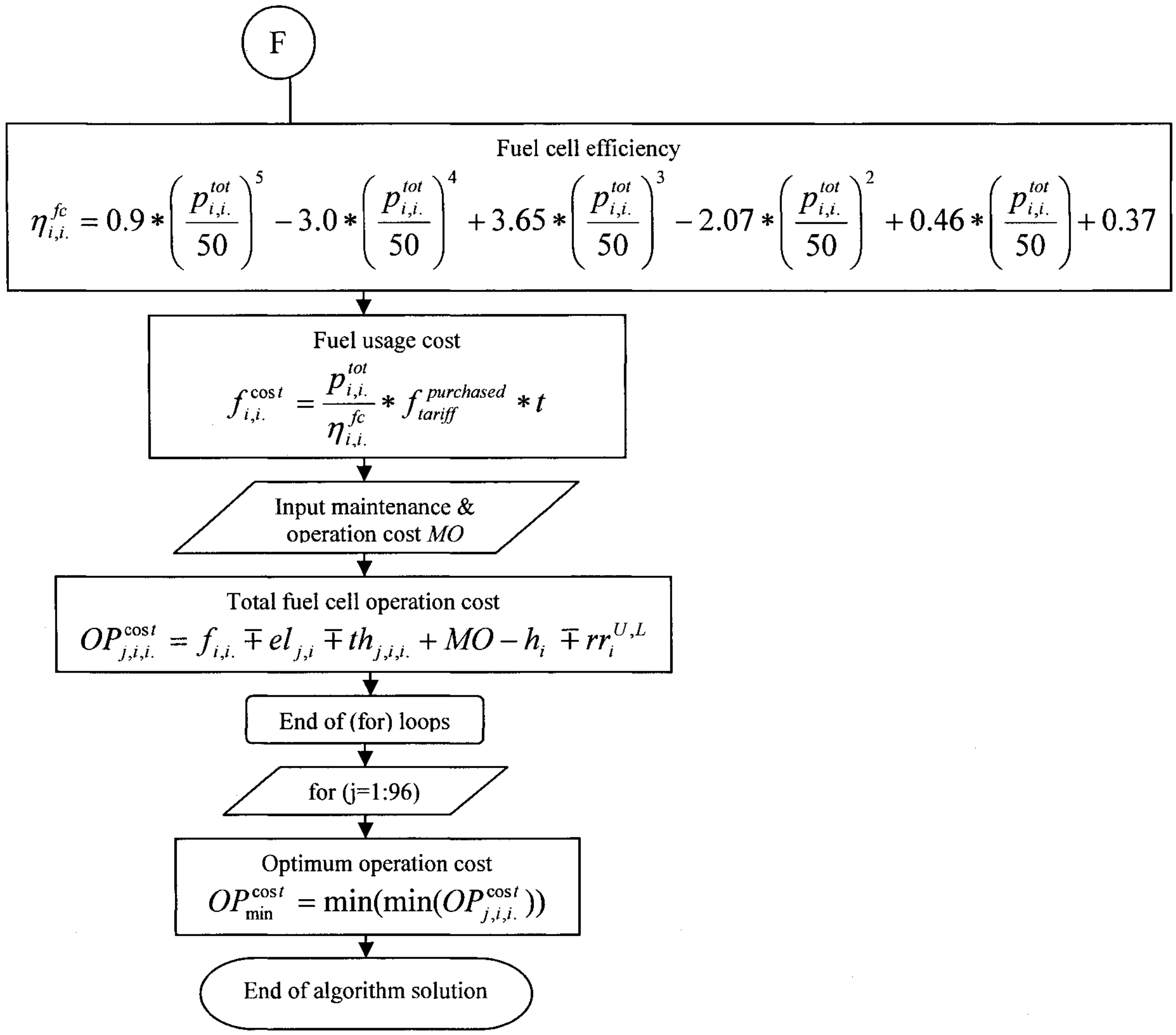

Figure 5.1 Continued

5.2 Case Studies

Simulation results for fuel cell operational models are obtained using algorithms written in MATLAB. Possible fuel cell operational strategies results for a 50 kW PEM fuel cell include the following figures: the fuel cost, the electricity/thermal energy usage, purchase or sale, the hydrogen production/consumption or sale, the power trade with the grid, the thermal compensation amounts, the thermal storage amounts, and the fuel cell optimal operational costs.

In addition, a cost sensitivity analysis is carried out for all fuel cell operational strategies using various purchase and sale tariffs. FCOC is varied based on purchase and sale tariffs for certain models and strategies. Electricity, gas, and hydrogen tariffs are the parameters considered in the cost sensitivity analysis. Increasing the purchase tariffs for any of these parameters increases the FCOC.

5.2.1 Base Model (electricity compensation)

The base model discusses the operational costs in terms of electricity used for thermal energy compensation. The excess thermal energy produced help to reduce the operational cost of FCPP by either selling it to other neighborhoods or storing and reusing it to satisfy the thermal demand. There are two strategies to deal with the excess thermal energy produced which are explained in the next section.

5.2.1.1 Strategy 1(wasting excess thermal energy).

5.2.1.1.1 Test and Results. The optimal daily cost components of the FCPP system for the base model while wasting excess thermal energy are summarized in Table 5.2.

Table 5.2 Component costs for 50 kW FCPP.

Component Costs for 50 kW FCPP	**[$]**
Daily fuel cost	131.36
Daily cost of purchased electricity	0
Daily profit of selling electricity	4.01
Daily cost of residential natural gas	0
Operation and maintenance cost	1.97
Electricity purchased to satisfy the ramp rate	0.42
Hourly cost per (kWh)	8.82
Total daily cost	**128.90**

Figures 5.2 and 5.3 show the FCPP electric and thermal outputs power when compared to the load power respectively.

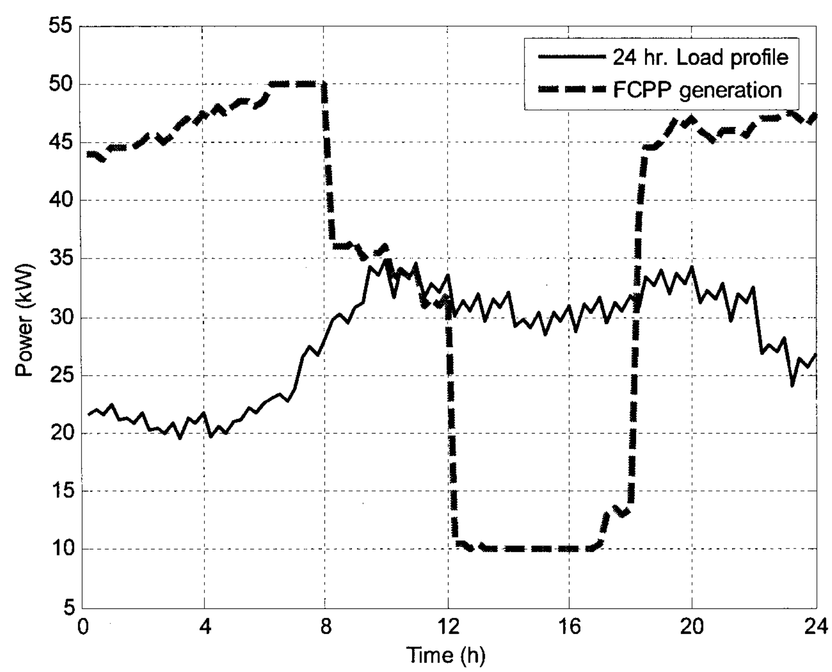

Figure 5.2 Electrical output power of the FCPP.

The fuel cell generates power higher than the load in the first period of interval J due to the high thermal demand as illustrated in Figure 5.3. In addition, the fuel cell generates the maximum power of 50 kW at the end of the first period in order to produce the highest thermal power to satisfy the thermal demand. Afterward, the fuel cell generated power drops to 10 kW due to the low thermal demand in this period.

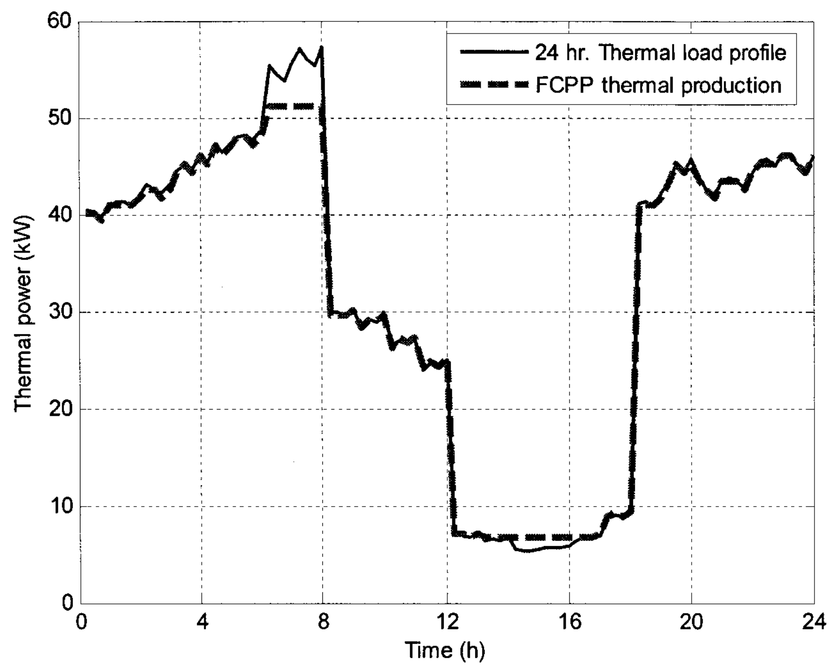

Figure 5.3 Thermal output power of the FCPP.

Figure 5.4 illustrates the electrical power trade with the local grid.

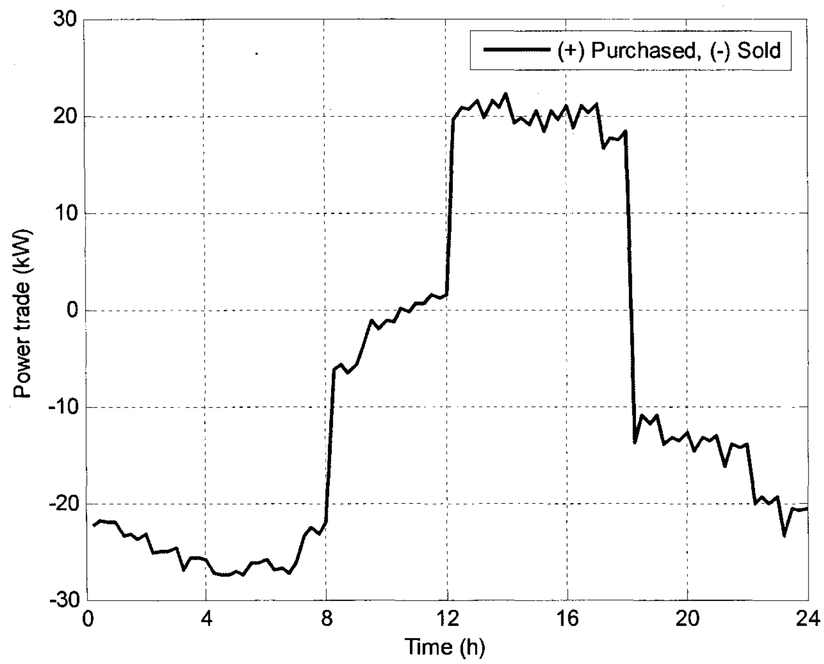

Figure 5.4 Power trade with the network.

The first and last parts of Figure 5.4 indicate the excess amount of electricity that can be sold to other neighborhoods due to the higher power production of the fuel cell compared to the electric load. The shortfall of electricity needed to satisfy the load is purchased from the grid. Figure 5.5 represents the thermal power compensation amount.

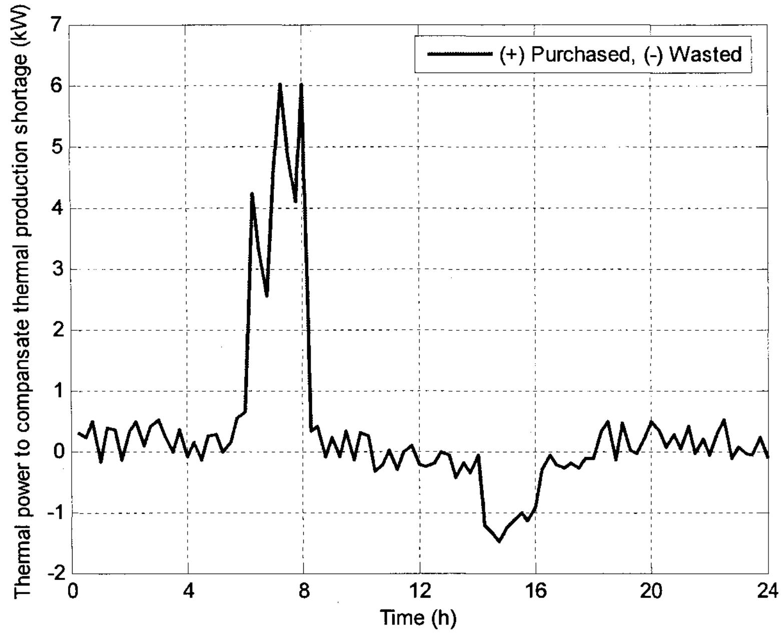

Figure 5.5 Thermal power compensation amounts.

The shortfall of thermal power is purchased from the grid since electricity is used to meet the thermal load. Finally, Figure 5.6 shows the optimum operational costs for FCPP.

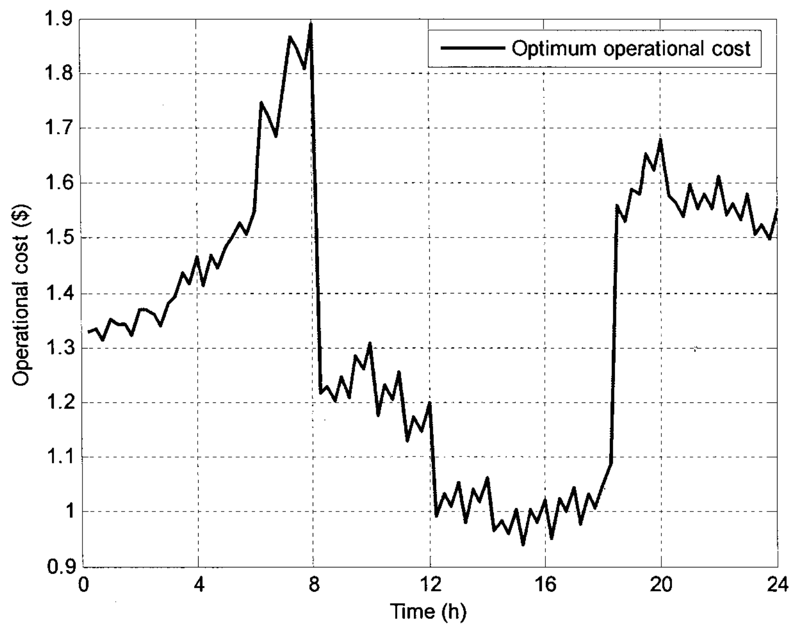

Figure 5.6 Optimum operational cost.

The highest FCOC is at the end of the first period of interval J due to the high thermal power produced in this period. During these periods, the fuel cell generates more power to satisfy the thermal demand.

__5.2.1.1.2 Cost Sensitivity Analysis and Evaluation__. Table 5.3 shows FCOC sensitivity based on electricity purchasing and selling tariffs.

Table 5.3 FCOC based on electricity tariffs.

Purchasing Electricity Tariff[$]	Selling Electricity Tariff [$]	Daily Total Operational Cost	
		[$]	[$/kWh]
0.13	0.07	128.90	8.82
	0.08	125.81	8.61
	0.09	122.72	8.40
0.11	0.07	126.18	8.64
	0.08	123.10	8.43
	0.09	120.01	8.21
0.09	0.07	122.25	8.37
	0.08	120.25	8.02
	0.09	117.25	8.02

Figures 5.7, 5.8, and 5.9 show the daily FCOC, the daily fuel usage cost, and the daily profit of selling electricity versus purchasing and selling tariffs.

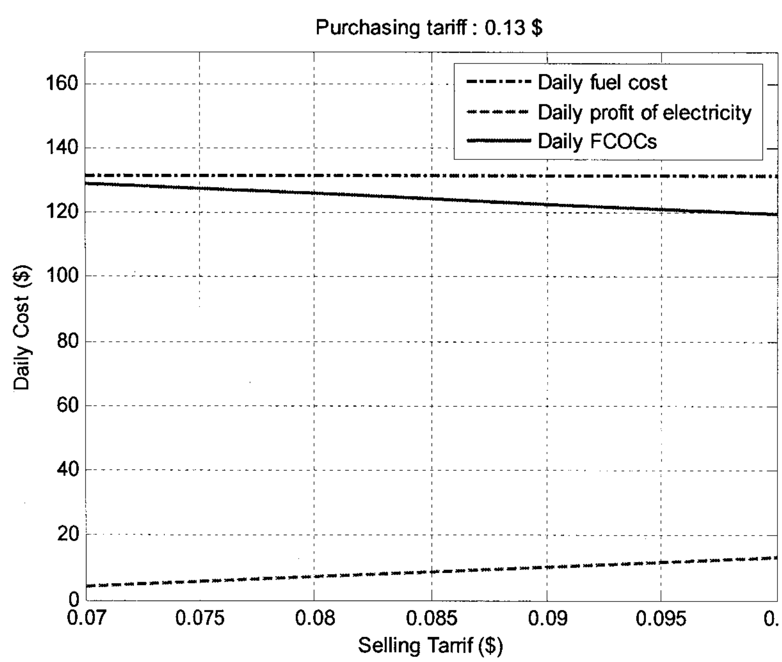

Figure 5.7 Daily cost versus selling electricity tariffs.

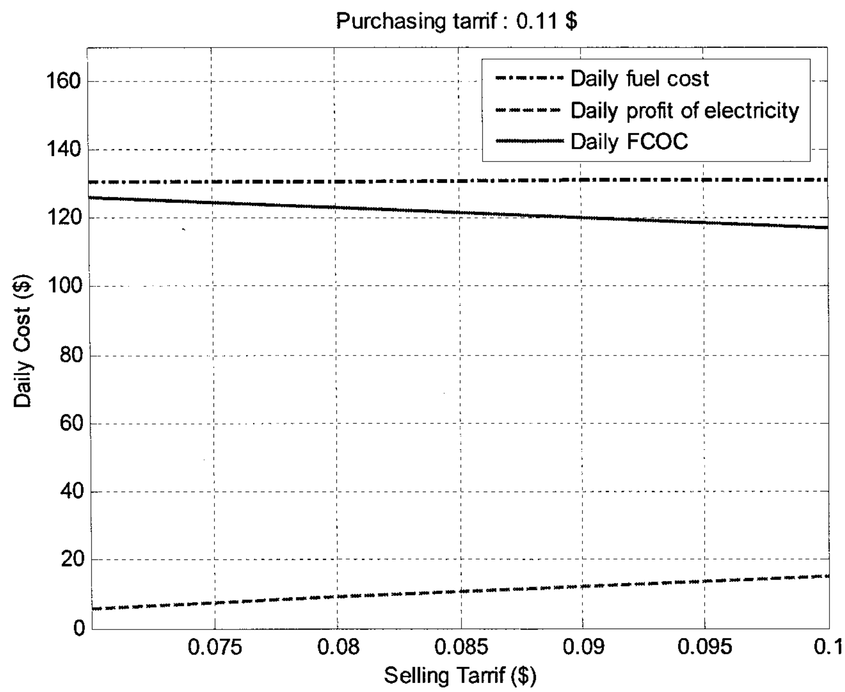

Figure 5.8 Daily cost versus selling electricity tariffs.

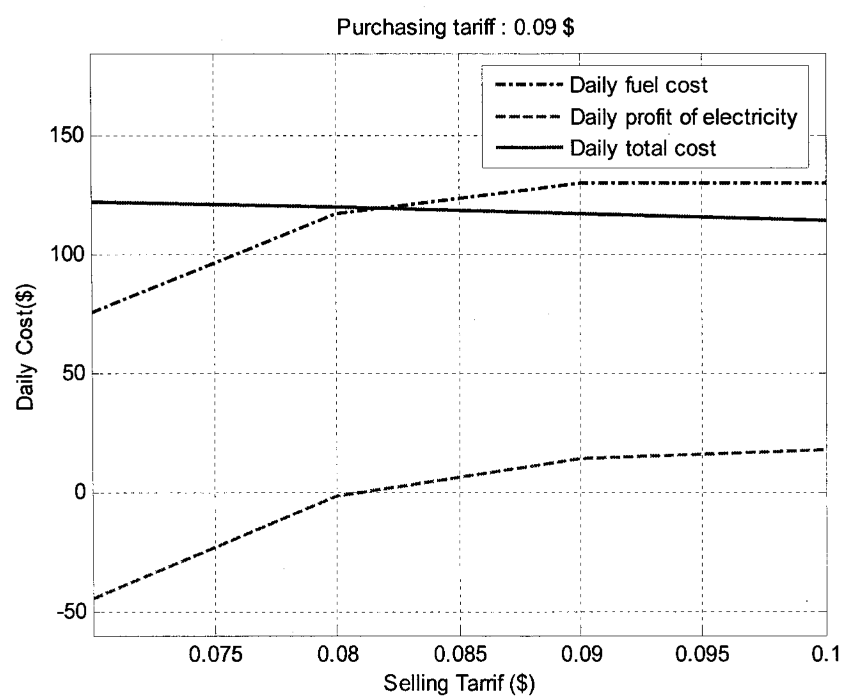

Figure 5.9 Daily cost versus selling electricity tariffs.

The sensitivity cost figures show that the FCOC decrease with the increase of the selling tariffs, or the decrease of the purchasing tariffs. In addition, the fuel cost and the profit of selling electricity are relatively related to the FCOC.

5.2.1.2 Strategy 2 (selling excess thermal energy).

5.2.1.2.1 Test and Results. The optimal daily cost components for the FCPP system for the base model while selling excess thermal energy are summarized in Table 5.4.

Table 5.4 Component costs for 50 kW FCPP.

Component costs for 50 kW FCPP	**[$]**
Daily fuel cost ($)	149.52
Daily cost of purchased electricity($)	0
Daily profit of selling electricity($)	27.48
Daily cost of residential natural gas ($)	0
Operation and maintenance cost ($)	1.97
Hourly cost per (kWh)	8.49
Total daily cost ($)	**124.00**

Figures 5.10 and 5.11 show the FCPP electrical and thermal outputs power compared to the load power respectively.

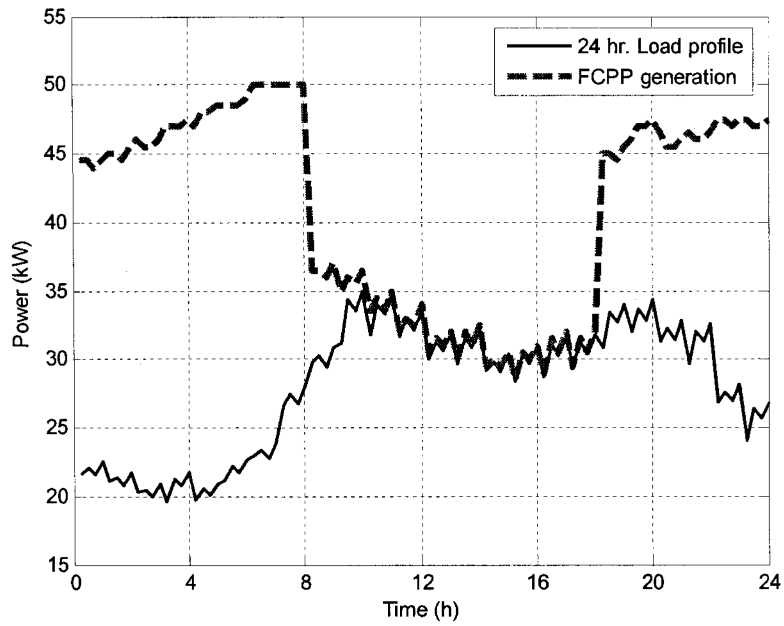

Figure 5.10 Electrical output power of the FCPP.

The fuel cell generated power is very high compared to the electric load at the first 30 intervals *J* due to the high thermal production needed to satisfy the thermal load as illustrated in Figure 5.11 below. Afterward, the fuel cell generated power drops, but it does not go below the load power at any interval *J*. Due to the usage of the second strategy, the fuel cell thermal production increases to maximize the benefit of selling the excess thermal energy. Therefore, the fuel cell generated power increases in order to produce more thermal energy.

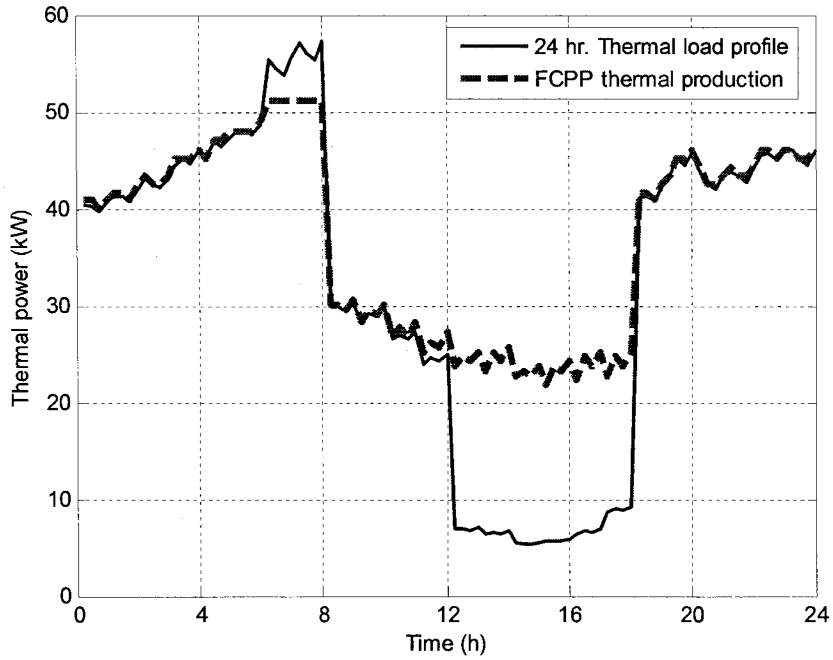

Figure 5.11 Thermal output power of the FCPP.

Figure 5.12 shows the excess amount of electricity that can be sold to the grid due to the higher fuel cell power production compared to the power demand. In this strategy, the benefit of selling the excess thermal energy is maximized in order to minimize the FCOC. Figure 5.13 shows the thermal power needed to compensate thermal production shortage.

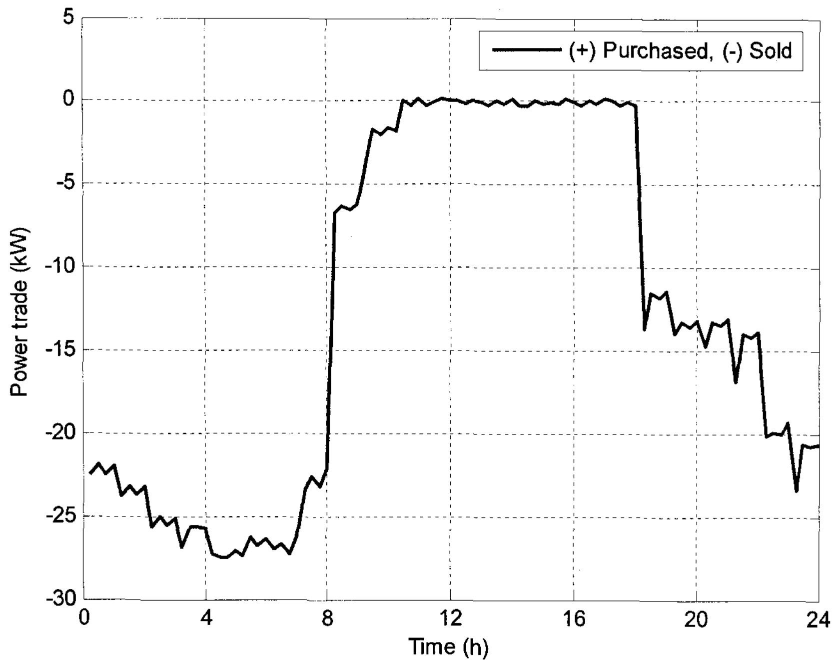

Figure 5.12 Power trade with the network.

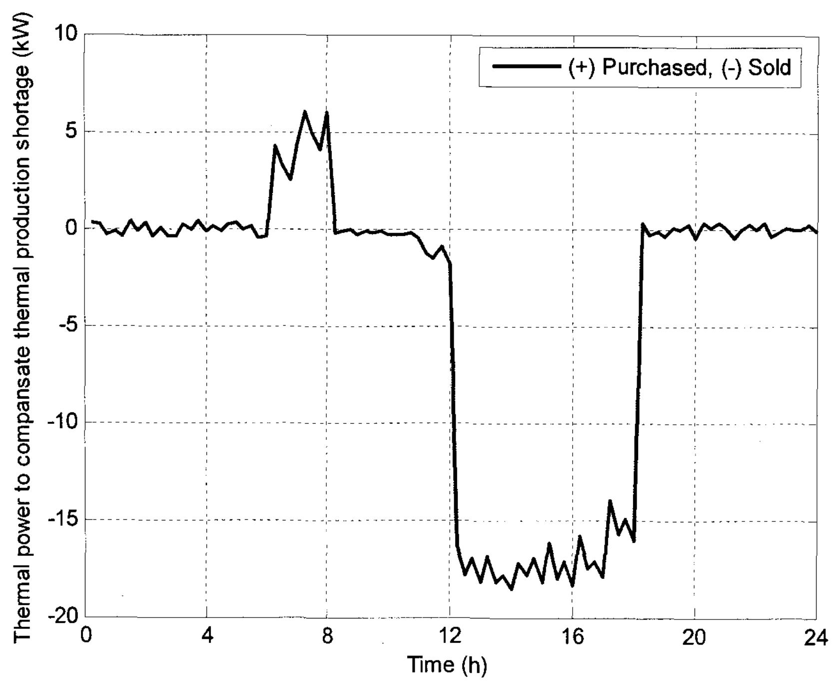

Figure 5.13 Thermal power compensation amounts.

Finally, Figure 5.14 shows the optimum operational costs for FCPP.

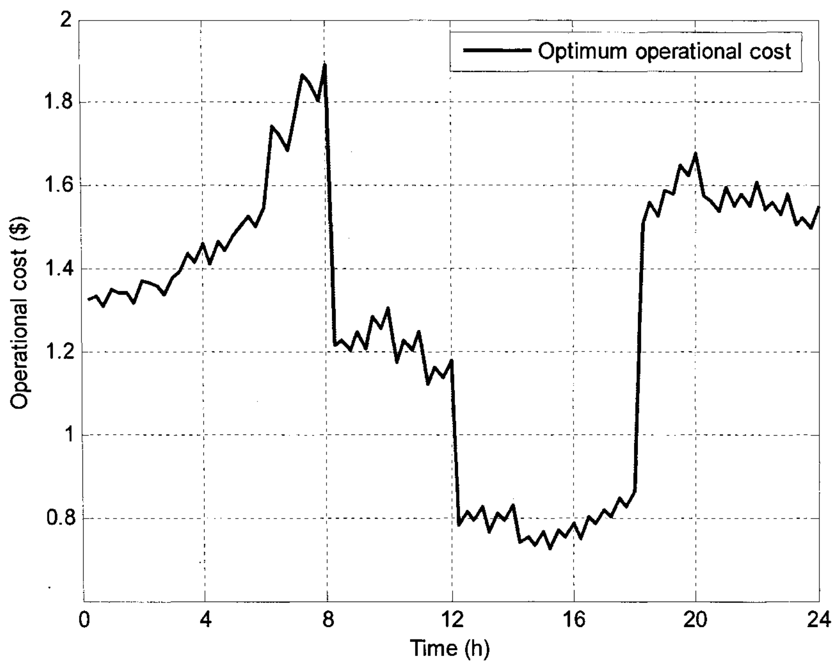

Figure 5.14 Optimum operational cost.

Although the fuel consumption in this strategy is higher than the fuel consumption in the first strategy, the operational cost is still cheaper in this strategy. This is due to the increased profit from selling the excess thermal energy.

5.2.1.2.2 Cost Sensitivity Analysis and Evaluation. Table 5.5 shows FCOC based on electricity purchasing and selling tariffs.

Table 5.5 FCOC based on various electricity tariffs.

Purchasing Electricity Tariff [$/kWh]	Selling Electricity Tariff [$/kWh]	Daily Total Cost (includes maintenance) [$]	Daily Total Cost (includes maintenance) [$/kWh]
0.13	0.07	124.00	8.49
	0.08	119 .85	8.20
	0.09	113.08	7.74
0.11	0.07	123.77	8.47
	0.08	119.66	8.19
	0.09	112.90	7.73
0.09	0.07	121.91	8.34
	0.08	119.36	8.17
	0.09	112.72	7.71

Figures 5.15, 5.16 and 5.17 illustrate the daily FCOC, the daily fuel cost, and the daily profit of selling electricity versus purchasing and selling electricity tariffs.

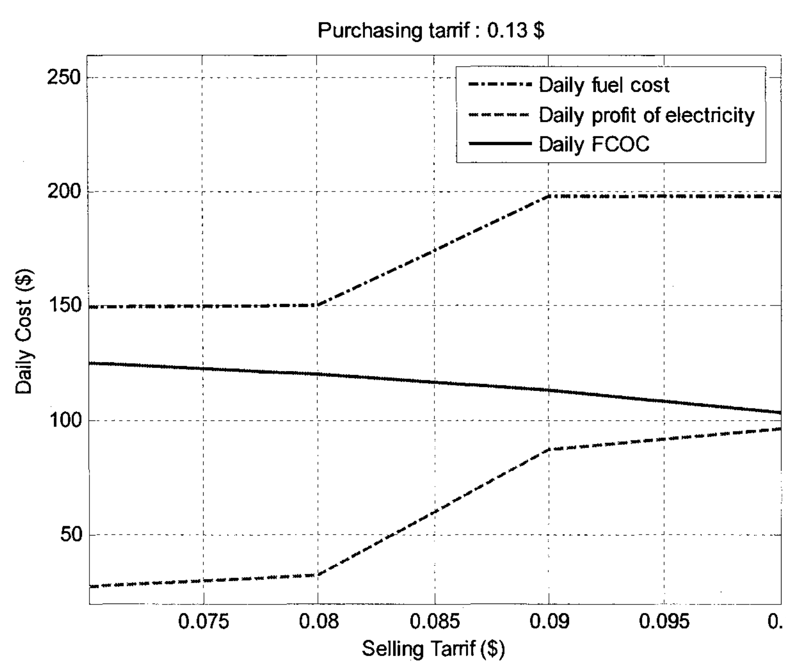

Figure 5.15 Daily cost versus selling electricity tariffs.

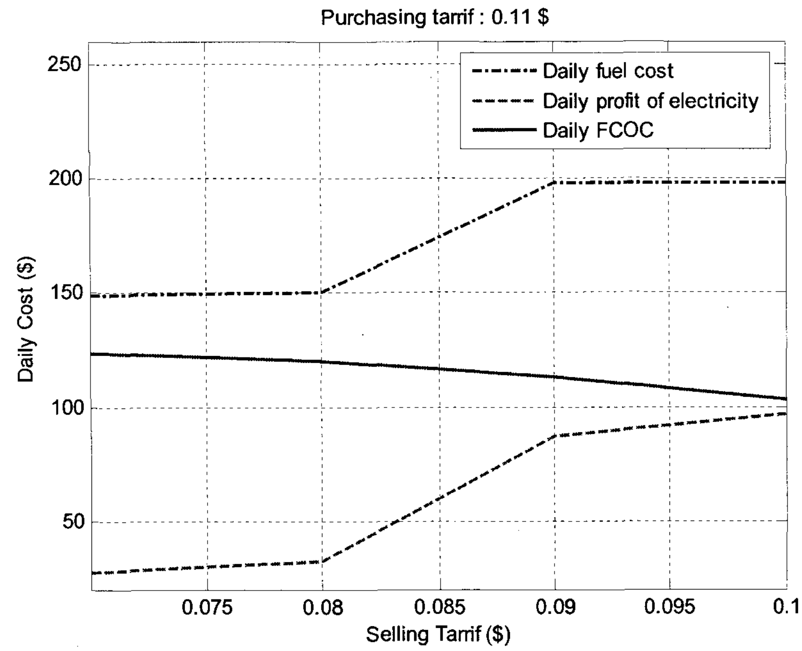

Figure 5.16 Daily cost versus selling electricity tariffs.

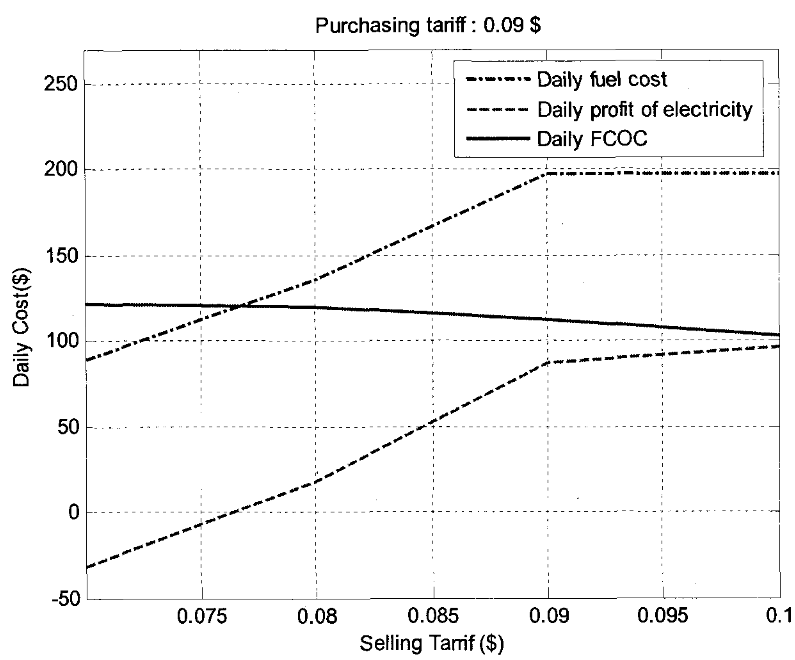

Figure 5.17 Daily cost versus selling electricity tariffs.

5.2.2 Model I (gas compensation)

Model I discusses the operational costs in terms of gas usage for thermal energy compensation. The excess thermal energy helps in reducing the operational cost of FCPP by either selling it to other neighborhoods, or storing and reusing it when there is shortage of thermal generation. Three strategies are considered regarding excess thermal energy.

5.2.2.1 Strategy 1 (wasting the excess thermal energy).

5.2.2.1.1 Test and Results. The optimum daily cost components for the FCPP system while wasting excess thermal energy are summarized in Table 5.6.

Table 5.6 Component costs for 50 kW FCPP.

Component costs for 50 kW FCPP	**[$]**
Daily fuel cost	75.77
Daily cost of purchased electricity	15.71
Daily profit of selling electricity	0
Daily cost of residential natural gas	22.56
Operation and maintenance cost	1.97
Total hourly cost per (kWh)	7.94
Total daily cost	**116.00**

Figures 5.18 and 5.19 show the FCPP electrical and thermal outputs power versus the load power, respectively.

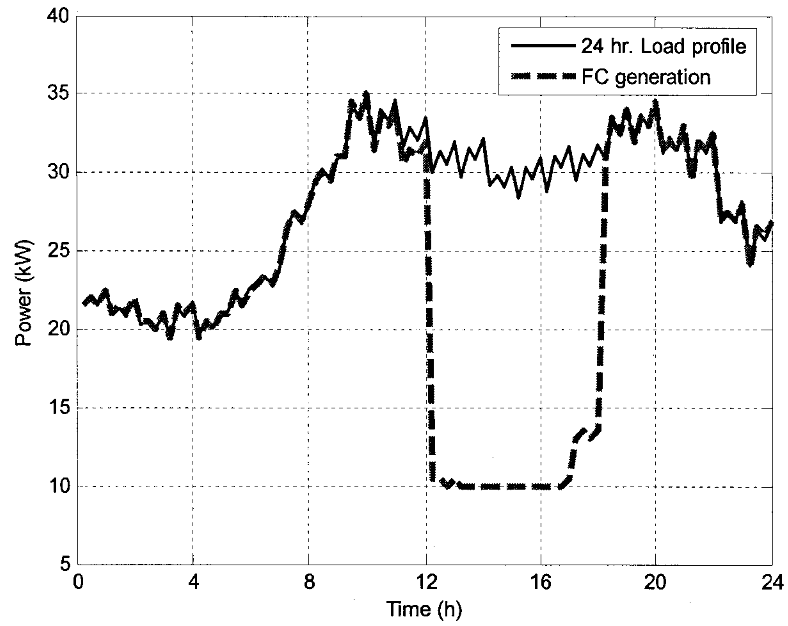

Figure 5.18 Electrical output power of the FCPP.

In this model, the thermal production is based on gas usage instead of electricity, which was the case in the base model. This makes the fuel cell generated power in Figure 5.18 independent of the thermal production in Figure 5.19. The fuel cell generated power almost satisfies the electric demand. At some intervals, there is shortage of electricity that can be satisfied by buying electricity from the grid. There is almost no excess electricity that can be sold back to the grid.

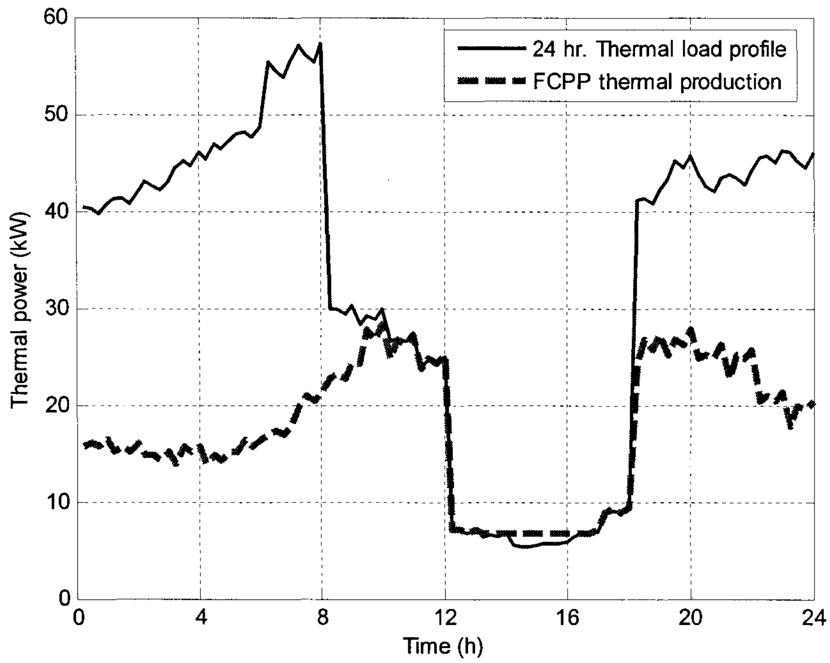

Figure 5.19 Thermal output power of the FCPP.

As shown in Figure 5.19, there is a large shortage of thermal energy production that would require purchasing natural gas.

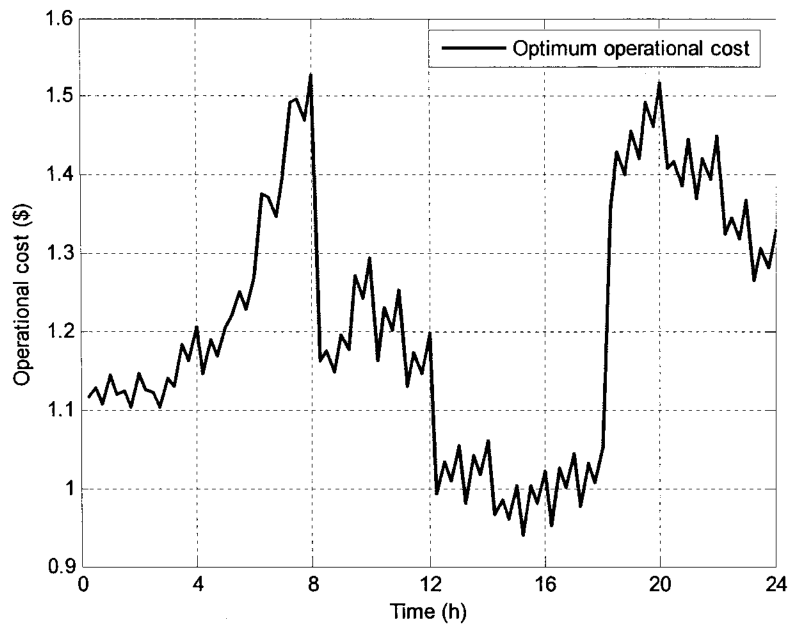

Figure 5.20 Optimum operational cost.

The FCOC for this model is cheaper than the FCOC in the base model because of the use of natural gas instead of electricity to meet the thermal demand. Since there is a cheaper purchasing tariff for natural gas compared to electricity, the FCOC is reduced to \$116.00 from \$128.90 in the base model.

5.2.2.1.2 Cost Sensitivity Analysis and Evaluation. Table 5.7 shows FCOC based on electricity purchasing and selling tariffs.

Table 5.7 FCOC based on various electricity tariffs.

Purchasing Electricity Tariff [$/kWh]	Selling Electricity Tariff [$/kWh]	Daily Fuel Cost [$]	Daily Cost of Purchasing Electricity [$]	Daily Cost of Natural Gas [$]	Daily Total Cost (include maintenance)	
					[$]	[$/kWh]
0.13	0.07	75.77	15.71	22.56	116.00	7.940
	0.08	75.93	15.60	22.50	116.00	7.939
	0.09	76.08	15.48	22.44	115.97	7.937
	0.10	84.23	10.10	19.59	115.88	7.931
0.11	0.07	74.70	14.08	22.74	113.49	7.767
	0.08	74.89	13.95	22.67	113.48	7.767
	0.09	75.12	13.79	22.59	113.48	7.767
	0.10	83.57	8.23	19.62	113.40	7.761

Table 5.8 shows FCOC based on gas purchasing and selling tariffs.

Table 5.8 FCOC based on various gas tariffs.

Purchasing Gas Tariff [$/kWh]	Selling Gas Tariff [$/kWh]	Daily Fuel Cost [$]	Daily cost of Purchasing Electricity [$]	Daily Cost of Natural Gas [$]	Daily Total Cost (include maintenance)	
					[$]	[$/kWh]
0.06	0.04	75.93	15.60	22.50	116.00	7.939
	0.05	75.93	15.60	22.50	116.00	7.939
	0.06	75.93	15.60	22.50	116.00	7.939
	0.07	75.93	15.60	22.50	116.00	7.939
0.04	0.04	75.30	16.04	15.15	108.45	7.422
	0.05	75.30	16.04	15.15	108.45	7.422
	0.06	75.30	16.04	15.15	108.45	7.422
	0.07	75.30	16.04	15.15	108.45	7.422

Table 5.7 shows that the FCOC decrease slightly as the selling tariffs increase and the purchasing tariffs decrease. In addition, the fuel cost is relatively related to the FCOC. Table 5.8 shows the daily FCOC, the daily fuel cost, the daily cost of buying electricity, and the daily cost of purchasing natural gas based on various gas tariffs.

5.2.2.2 Strategy 2 (selling excess thermal energy).

5.2.2.2.1 Test and Results. The optimal daily cost components for the FCPP system while selling excess thermal energy are summarized in Table 5.9.

Table 5.9 Component costs for 50 kW FCPP.

Components cost for 50 kW FCPP	**[$]**
Daily fuel cost	93.16
Daily cost of purchased electricity	0.24
Daily profit of selling electricity	0
Daily cost of residential natural gas	18.46
Operation and maintenance cost	1.97
Total hourly cost per (kWh)	7.79
Total daily cost	**113.84**

Figures 5.21 and 5.22 show the FCPP electrical and thermal outputs power compared to the load power, respectively.

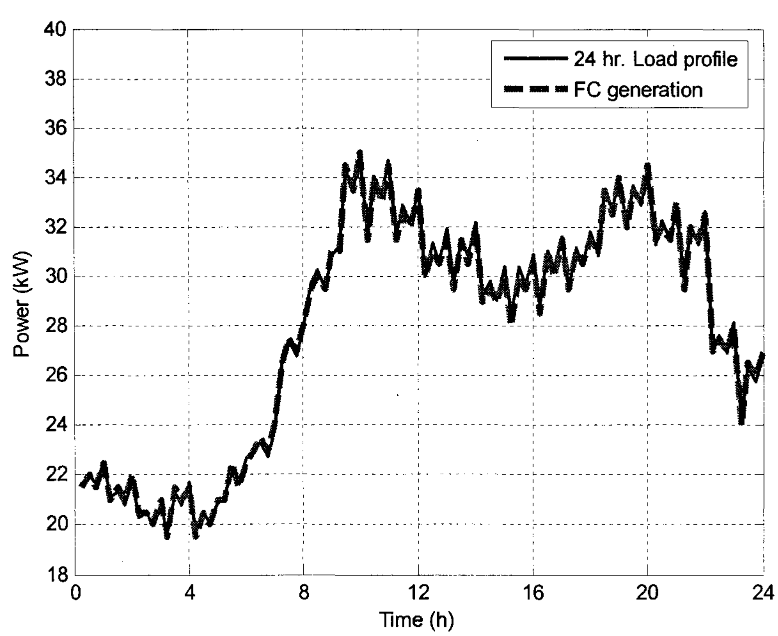

Figure 5.21 Electrical output power of the FCPP.

Figure 5.22 shows an almost perfect example of fuel cell generated power that satisfies the load demand.

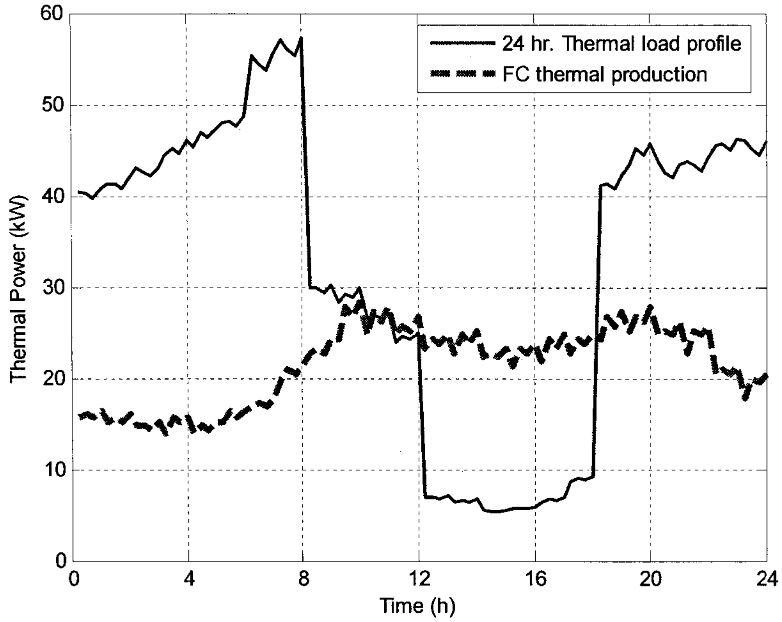

Figure 5.22 Thermal output power of the FCPP.

The fuel cell thermal productions almost follow the same pattern as the fuel cell generated power. Figure 5.23 shows the optimal FCOC for model I while selling excess thermal energy.

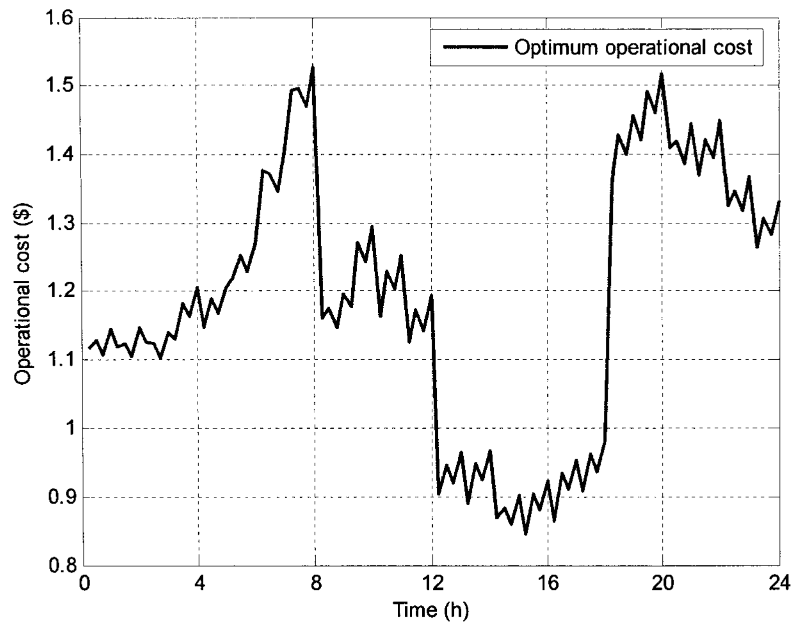

Figure 5.23 Optimum operational cost.

5.2.2.2.2 Cost Sensitivity Analysis. Table 5.10 shows the daily FCOC, the daily fuel cost, the daily cost of buying electricity, and the daily cost of purchasing natural gas versus electricity purchasing and selling tariffs.

Table 5.10 FCOC based on various electricity tariffs.

Purchasing Electricity Tariff [$/kWh]	Selling Electricity Tariff [$/kWh]	Daily Fuel Cost [$]	Daily Cost of Purchasing Electricity [$]	Daily Cost of Natural Gas [$]	Daily Total Cost (include maintenance) [$]	Daily Total Cost (include maintenance) [$/kWh]
0.13	0.07	93.16	0.24	18.46	113.84	7.791
	0.08	93.36	0.10	18.40	113.82	7.789
	0.09	93.53	-0.04	18.34	113.80	7.788
0.11	0.07	80.09	9.69	21.55	113.30	7.754
	0.08	80.28	9.56	21.48	113.30	7.754
	0.09	80.51	9.41	21.40	113.29	7.753

Table 5.11 shows the daily FCOC, the daily fuel usage cost, the daily cost of buying electricity, and the daily cost of purchasing natural gas based on various gas tariffs.

Table 5.11 FCOC based on various gas tariffs.

Purchasing Gas Tariff [$/kWh]	Selling Gas Tariff [$/kWh]	Daily Fuel Cost [$]	Daily cost of Purchasing Electricity [$]	Daily Cost of Natural Gas [$]	Daily Total Cost (include maintenance) [$]	[$/kWh]
0.06	0.04	93.36	0.10	18.40	113.82	7.789
	0.05	93.48	0.01	17.34	112.79	7.719
	0.06	93.60	-0.07	16.26	111.75	7.648
	0.07	93.72	-0.14	15.17	110.72	7.577
0.04	0.04	92.75	0.52	11.04	106.29	7.274
	0.05	92.88	0.43	9.98	105.26	7.20
	0.06	92.97	0.37	8.91	104.22	7.13
	0.07	93.10	0.29	7.82	103.18	7.061

5.2.2.3 Strategy 3 (storing excess thermal energy).

5.2.2.3.1 Test and Results. The optimal daily cost components of the FCPP system while storing excess thermal energy are summarized in Table 5.12.

Table 5.12 Component costs for 50 kW FCPP.

Component costs for 50 kW FCPP	**[$]**
Daily fuel cost	69.91
Daily cost of purchased electricity	21.22
Daily cost of residential natural gas	15.29
Operation and maintenance cost	1.97
Total hourly cost per (kWh)	7.42
Total daily cost	**108.40**

Figures 5.24 and 5.25 show the FCPP electrical and thermal outputs power compared to the load power, respectively.

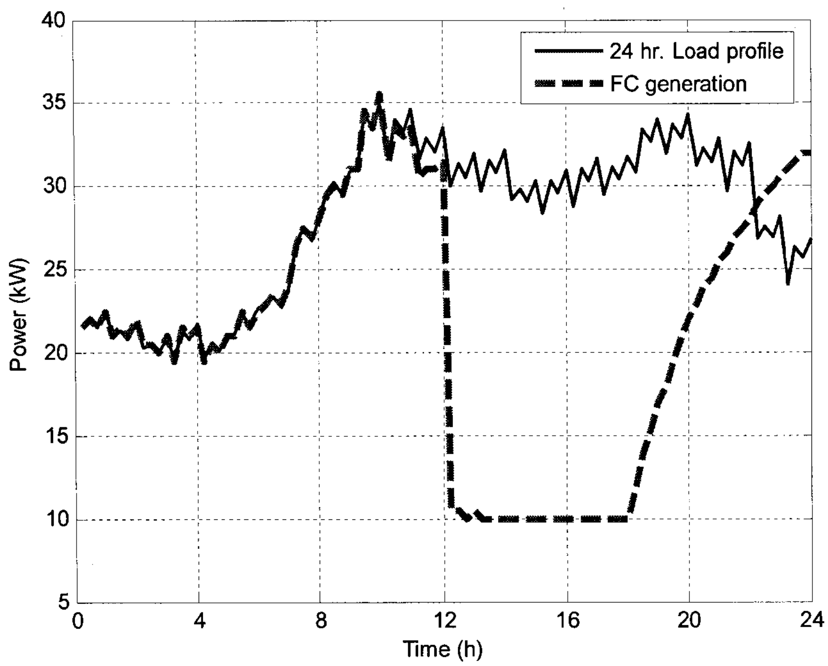

Figure 5.24 Electrical output power of the FCPP.

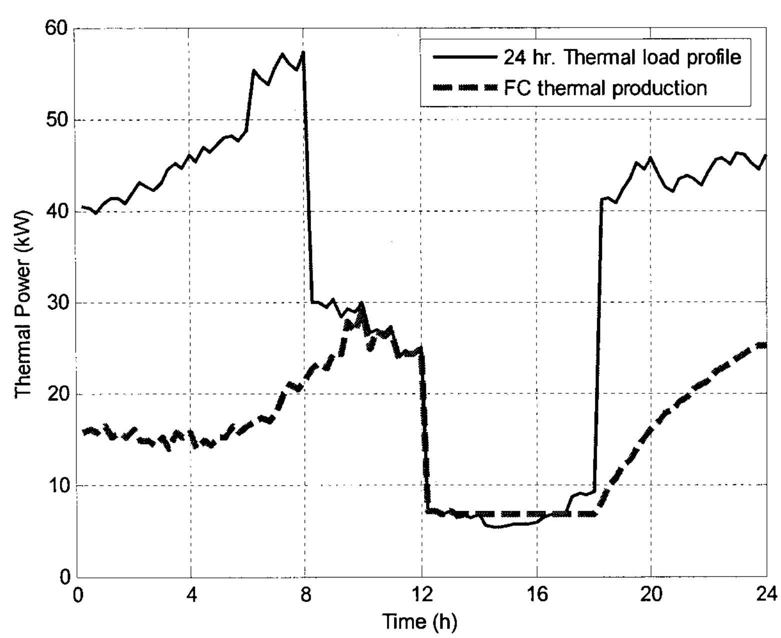

Figure 5.25 Thermal output powers of the FCPP.

Figure 5.26 shows the thermal compensation and the storage amount in each interval. Initially, there is no excess thermal energy stored, which indicates that the thermal demand is always higher than the thermal production.

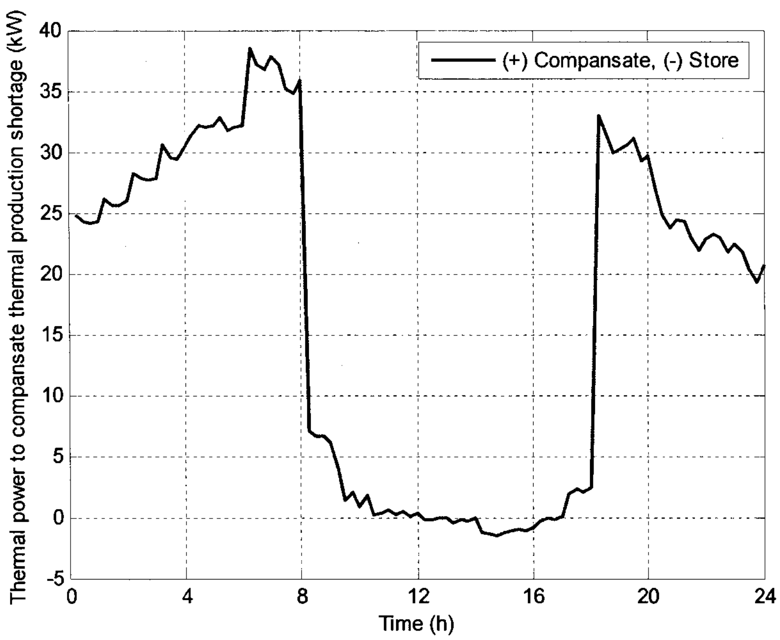

Figure 5.26 Thermal power compensation and storage amounts.

Figure 5.27 shows the optimal FCOC for model I while using the third strategy.

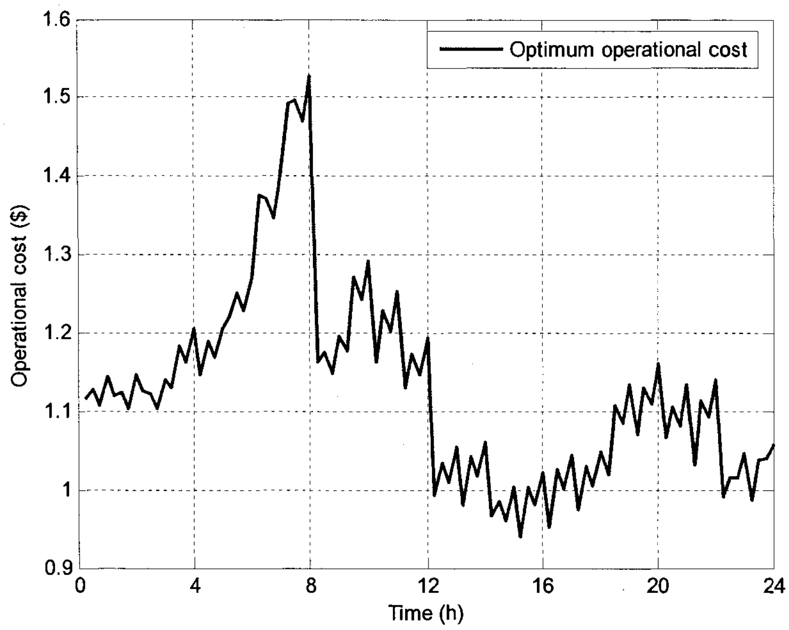

Figure 5.27 Optimum operational cost.

5.2.2.3.2 Cost Sensitivity Analysis and Evaluation. Table 5.13 includes the daily FCOC, and the daily cost of purchasing gas based on various electricity tariffs.

Table 5.13 FCOC based on electricity tariffs.

Purchasing Elect Tariff [$]	Selling Elect Tariff [$]	Daily Total Cost (include maintenance) [$]	Daily Total Cost (include maintenance) [$/kWh]
0.13	0.07	108.40	7.42
	0.08	108.23	7.41
	0.09	108.05	7.39
	0.10	107.43	7.35
0.11	0.07	104.92	7.18
	0.08	104.83	7.17
	0.09	104.59	7.16
	0.10	103.98	7.12

Table 5.14 includes the daily FCOC, and the daily cost of purchasing gas versus various gas purchasing and selling tariffs.

Table 5.14 FCOC based on gas tariffs.

Purchasing Gas Tariff [$/kWh]	Selling Gas Tariff [$/kWh]	Daily Total Cost (include maintenance) [$]	[$/kWh]
0.06	0.04	108.40	7.42
	0.05	108.40	7.42
	0.06	108.40	7.42
	0.07	108.40	7.42
0.04	0.04	103.27	7.07
	0.05	103.27	7.07
	0.06	103.27	7.07
	0.07	103.27	7.07

5.2.3 Model II (electricity compensation and hydrogen production)

Model II discusses the operation cost in terms of electricity used for thermal energy compensation. The excess thermal energy produced helps to reduce the operational cost of FCPP by either selling it to other neighborhoods, or storing and reusing it when there is a shortfall in thermal production. In addition, the hydrogen production power is considered in this model, which helps to decrease the FCOC. There are three strategies in terms of dealing with the excess thermal energy produced. The next section explains the test and results for these strategies.

5.2.3.1 Strategy1 (wasting excess thermal energy).

5.2.3.1.1 Test and Results. The optimal daily cost components of the FCPP system while wasting excess thermal energy are summarized in Table 5.15.

Table 5.15 Component costs for 50 kW FCPP.

Component costs for 50 kW FCPP	[$]
Daily fuel cost	128.03
Daily cost of purchased electricity	18.07
Daily profit of selling electricity	0
Daily cost of residential natural gas	0
Daily profit of selling hydrogen	39.36
Operation and maintenance cost	1.97
Total hourly cost per (kWh)	7.43
Total daily cost	**108.64**

Figures 5.28 and 5.29 show the FCPP electrical and thermal outputs power compared to the load power.

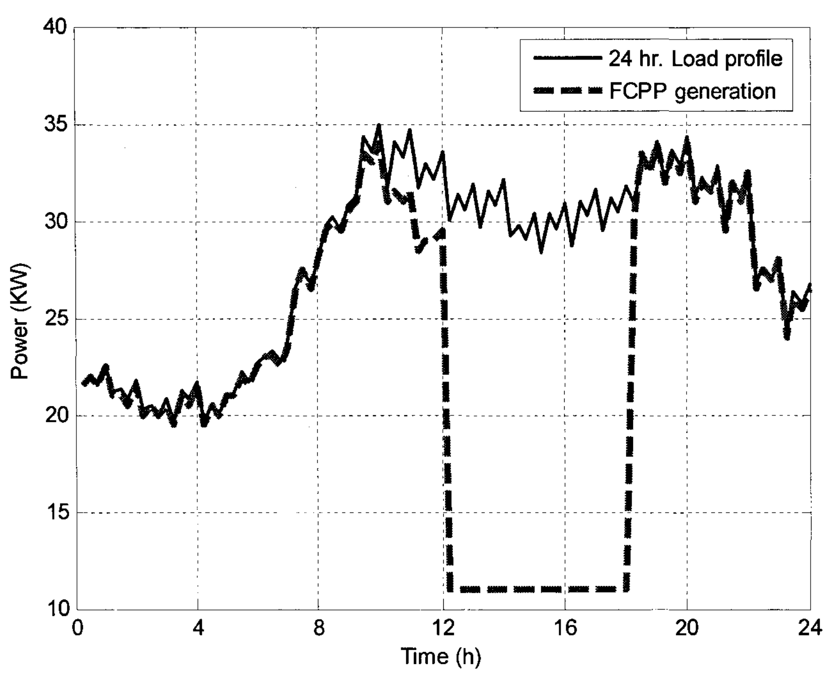

Figure 5.28 Electrical output power of the FCPP.

Figure 5.28 shows that initially the fuel cell output power is high in order to produce high thermal power to satisfy the thermal demand. Figure 5.29 shows a lack of thermal energy at the first part, and then it shows an excess amount of thermal energy. In general, the fuel cell thermal output power satisfies the thermal demand production levels.

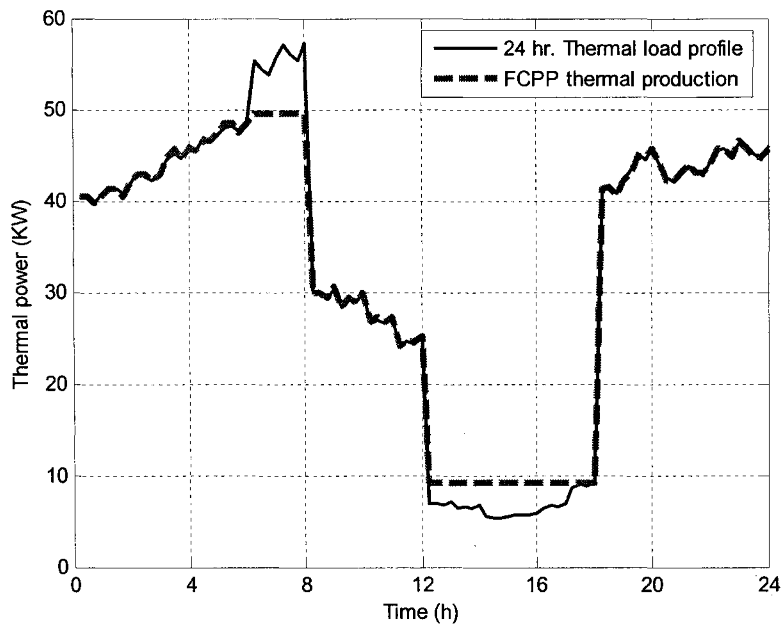

Figure 5.29 Thermal output power of the FCPP.

Figure 5.30 shows the total FCPP output power compared to the thermal load power.

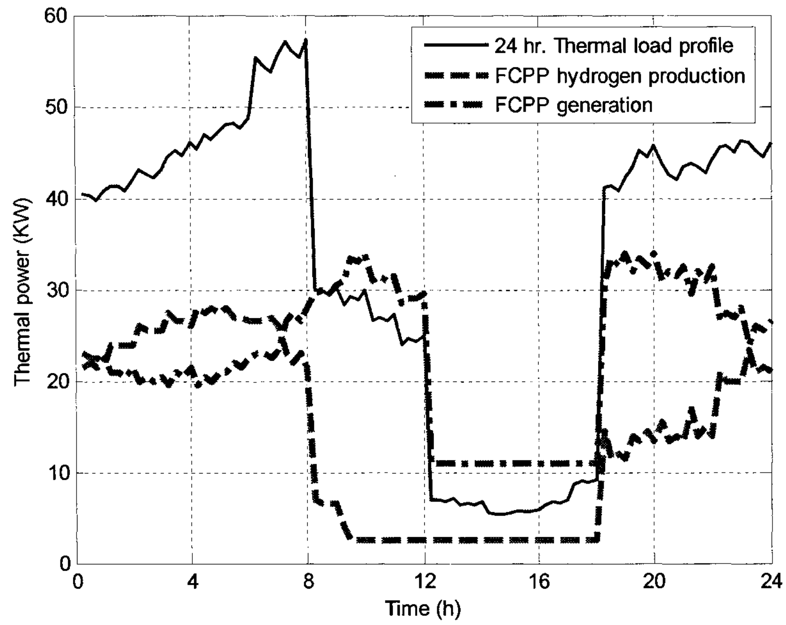

Figure 5.30 Electrical and hydrogen output powers.

Figure 5.31 shows the optimal operating cost for the FCPP while using the first strategy.

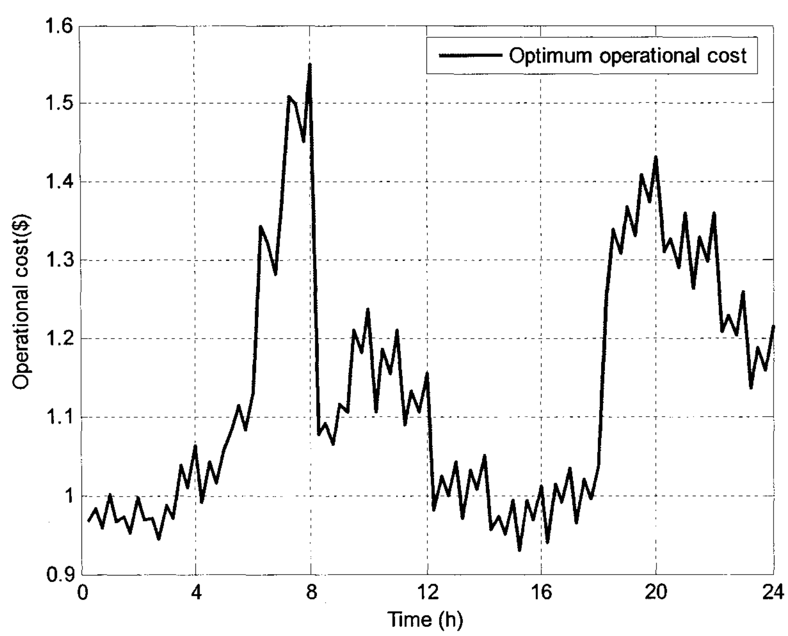

Figure 5.31 Optimum operational cost.

5.2.3.1.2 Cost Sensitivity Analysis and Evaluation. Table 5.16 includes the corresponding of the daily FCOC compared to the daily fuel usage, and the daily cost of purchasing electricity based on $0.13/kWh electricity purchasing tariff.

Table 5.16 FCOC based on electricity and hydrogen tariffs.

Selling Electricity Tariff [$]	Selling Hydrogen Tariff [$]	Daily Fuel Cost [$]	Daily Cost of Electricity [$]	Daily Profit of Hydrogen [$]	Daily Total Cost (include maintenance) [$]	[$/kWh]
0.07	1.7	127.94	17.94	35.08	112.78	7.72
	1.9	128.03	18.07	39.43	108.64	7.42
	2.1	129.63	81.27	109.83	103.04	7.05
0.10	1.7	127.95	17.59	34.75	112.75	7.72
	1.9	128.03	17.98	39.34	108.03	7.39
	2.1	129.63	81.27	109.83	103.04	7.05
0.13	1.7	128.17	-16.94	6.43	106.77	7.31
	1.9	128.17	-16.94	7.18	106.01	7.26
	2.1	129.63	81.27	109.83	103.04	7.05

As a result of the hydrogen production, the FCOC dropped more than $10/day compared to the base model.

5.2.3.2 Strategy 2 (selling excess thermal energy).

5.2.3.2.1 Test and Results. The optimal daily cost components of the FCPP system while selling excess thermal energy are summarized in Table 5.17.

Table 5.17 Component costs for 50 kW FCPP.

Component costs for 50 kW FCPP	[$]
Daily fuel cost	184.93
Daily profit of selling electricity	26.81
Daily profit of selling hydrogen	62.29
Operation and maintenance cost	1.97
Total hourly cost per (kWh)	6.69
Total daily cost	**97.80**

Figures 5.32 and 5.33 show the FCPP electrical and thermal outputs power compared to the load power.

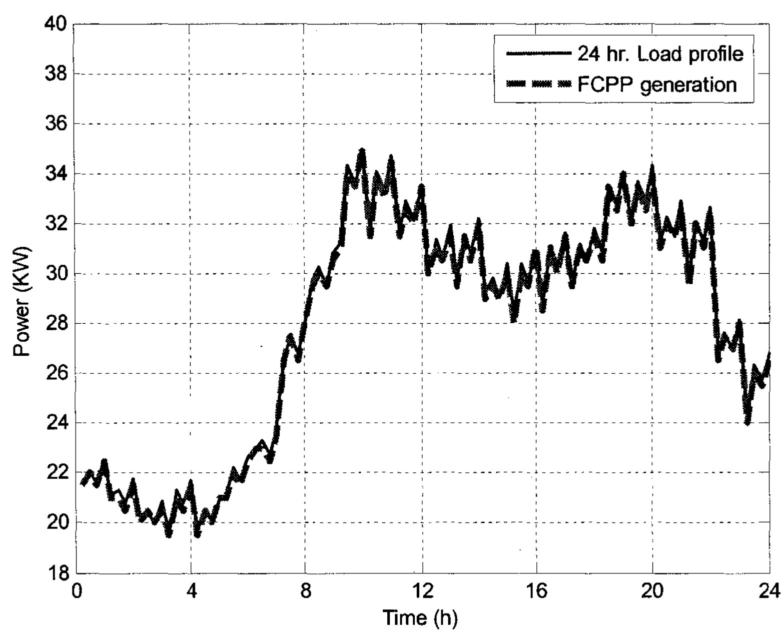

Figure 5.32 Electrical output power of the FCPP.

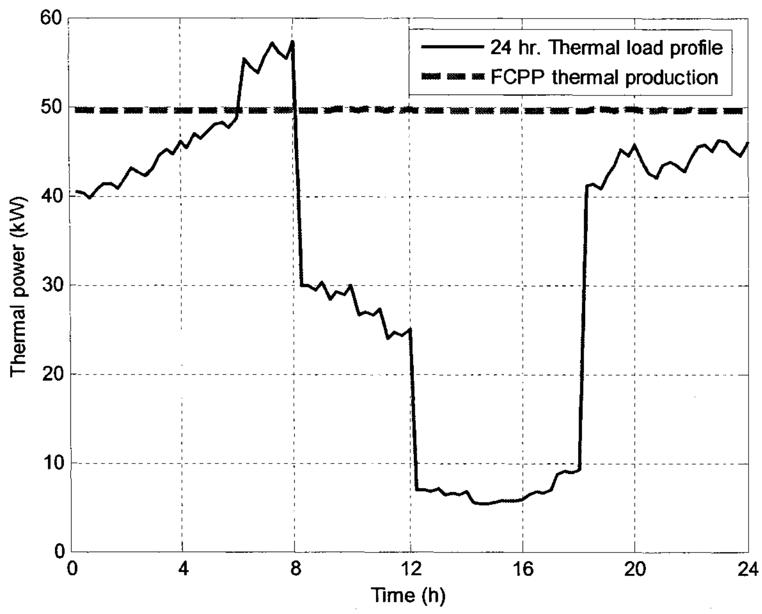

Figure 5.33 Thermal output power of the FCPP.

Figure 5.34 shows the total fuel cell output power (electrical and hydrogen) compared to the thermal load power.

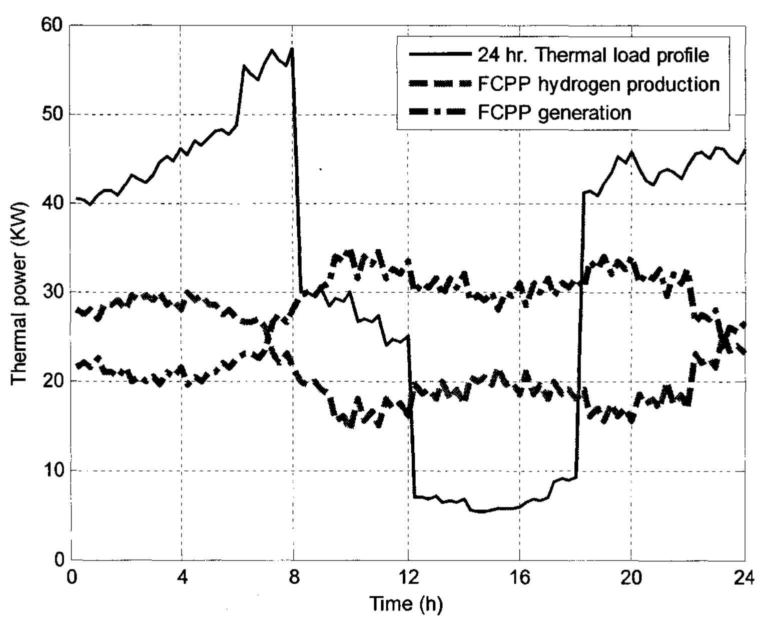

Figure 5.34 Electrical and hydrogen output powers.

Figure 5.35 shows the optimal FCOC for model II while selling excess thermal energy.

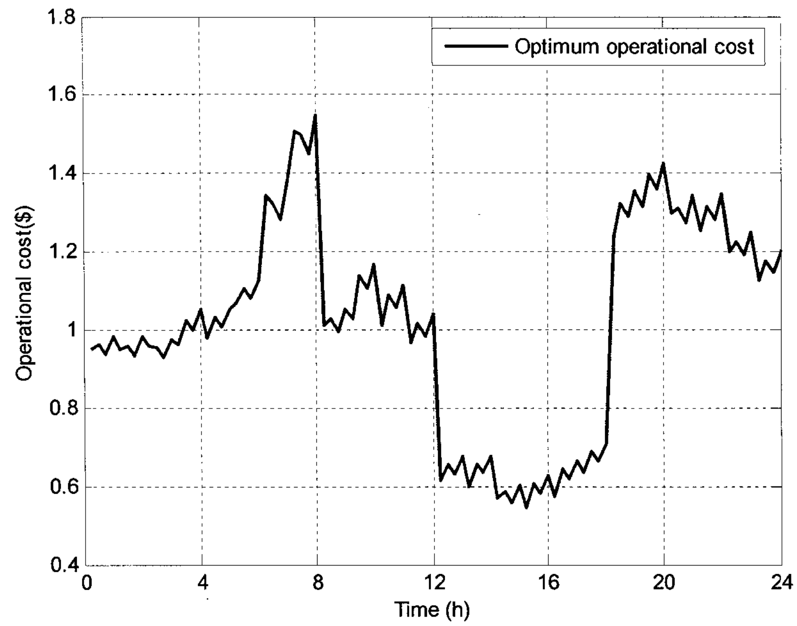

Figure 5.35 Optimum operational cost.

__5.2.3.2.2 Cost Sensitivity Analysis and Evaluation__. Table 5.18 includes the daily FCOC, the daily fuel cost, the daily profit of selling electricity, and the daily cost of purchasing gas based on \$0.13/kWh electricity purchasing tariff.

Table 5.18 FCOC based on electricity and hydrogen tariffs.

Selling Electricity Tariff [$/kWh]	Selling Hydrogen Tariff [$/kWh]	Daily Fuel Cost [$]	Daily Cost of Electricity [$]	Daily Profit of Hydrogen [$]	Daily Total Cost (include maintenance) [$]	[$/kWh]
0.07	1.7	170.88	-19.35	49.25	104.25	7.13
	1.9	184.93	-26.81	62.29	97.80	6.69
	2.1	184.16	52.64	149.23	89.53	6.13
0.10	1.7	184.94	-40.05	54.97	91.89	6.29
	1.9	184.93	-39.38	62.12	85.40	5.84
	2.1	184.16	40.42	149.23	77.31	5.29
0.13	1.7	184.94	-112.08	6.43	68.98	4.72
	1.9	184.93	-112.08	7.18	68.22	4.67
	2.1	184.16	28.20	149.23	65.09	4.45

Table 5.18 shows that the daily profit of hydrogen increases rapidly at hydrogen selling tariff of $2.10. At the same time, the daily profit of electricity drops in order to maintain the maximum total output power for FCPP at 50 kW.

5.2.4 Model III (gas compensation and hydrogen production)

Model III discusses the operational costs in terms of using gas for thermal energy compensation. The excess thermal energy produced reduce the operational cost of FCPP by either selling it to other neighborhoods or storing and reusing it when there is a shortage of thermal production. In addition, the hydrogen production power is considered in this model, which helps to decrease the FCOC. There are three strategies in terms of dealing with the excess thermal energy produced.

5.2.4.1 Strategy 1 (wasting excess thermal energy).

5.2.4.1.1 Test and Results. The optimal daily cost components of the FCPP system while wasting excess thermal energy are summarized in Table 5.19.

Table 5.19 Components cost for 50 kW FCPP.

Cost components for 50 kW FCPP	[$]
Daily fuel cost	121.46
Daily cost of purchased electricity	15.90
Daily profit of selling electricity	0
Daily cost of residential natural gas	3.88
Daily profit of selling hydrogen	36.06
Operation and maintenance cost	1.97
Total hourly cost per (kWh)	7.33
Total daily cost	**107.15**

Figures 5.36 and 5.37 show the FCPP electrical and thermal outputs power compared to the load power.

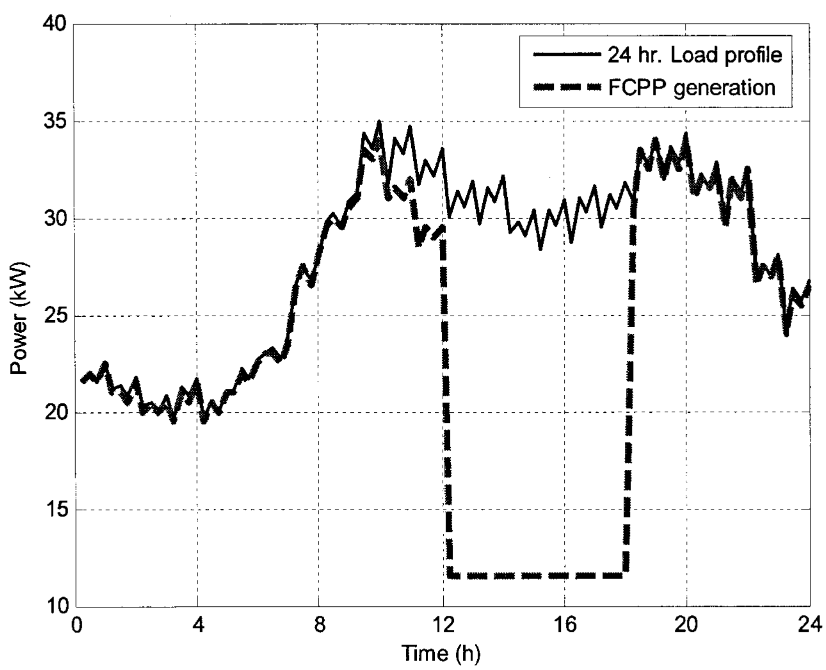

Figure 5.36 Electrical output power of the FCPP.

In this model, the thermal production is based on gas usage instead of electricity, which makes the fuel cell generated power in Figure 5.35 independent from the thermal production in Figure 5.36. The fuel cell generated power almost satisfies the load. At some intervals, there is a shortage of electricity that needs to be satisfied by buying electricity from the grid. There is almost no excess electricity that can be sold back to the grid. Natural gas is purchased to satisfy the lack of thermal energy.

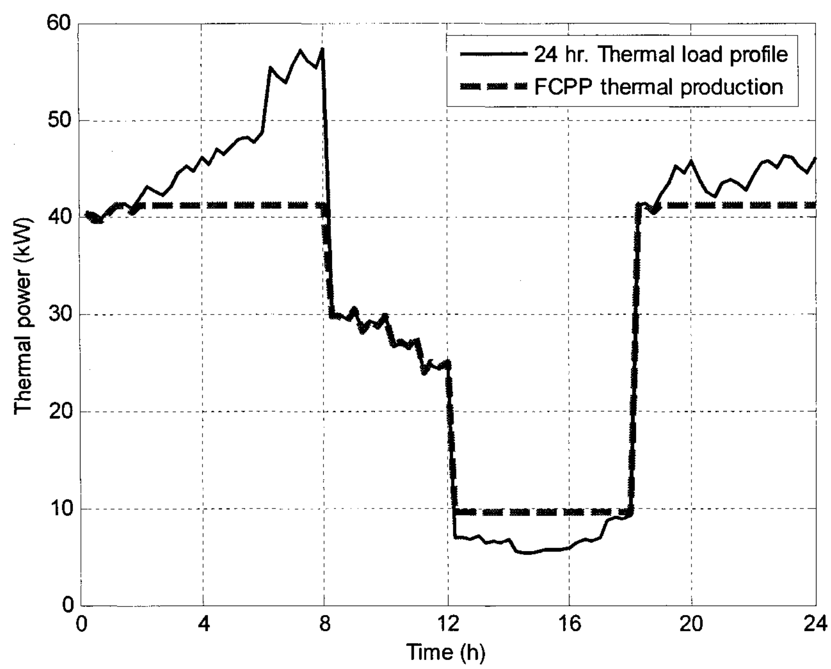

Figure 5.37 Thermal output power of the FCPP.

Figure 5.38 shows the total fuel cell output power (electrical and hydrogen) compared to the thermal load power.

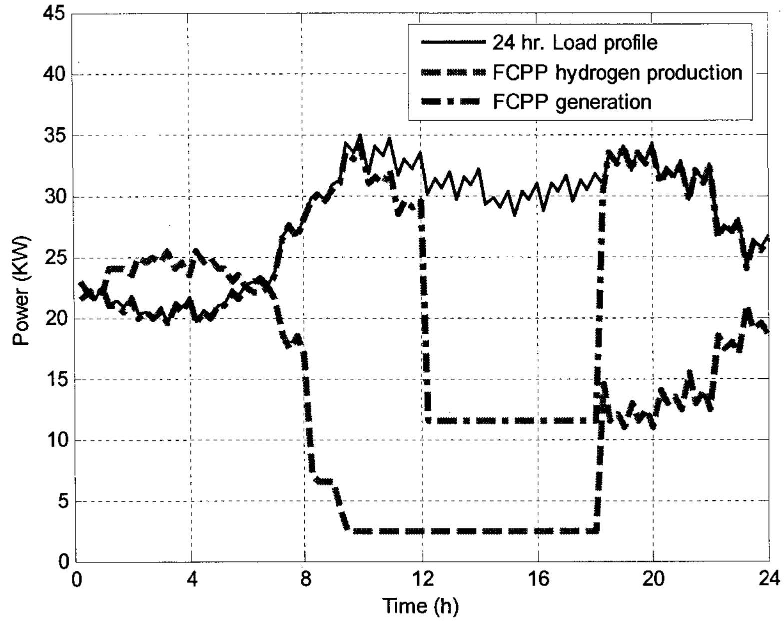

Figure 5.38 Electrical and hydrogen output powers.

Figure 5.39 shows the optimal FCOC for model III while wasting excess thermal energy.

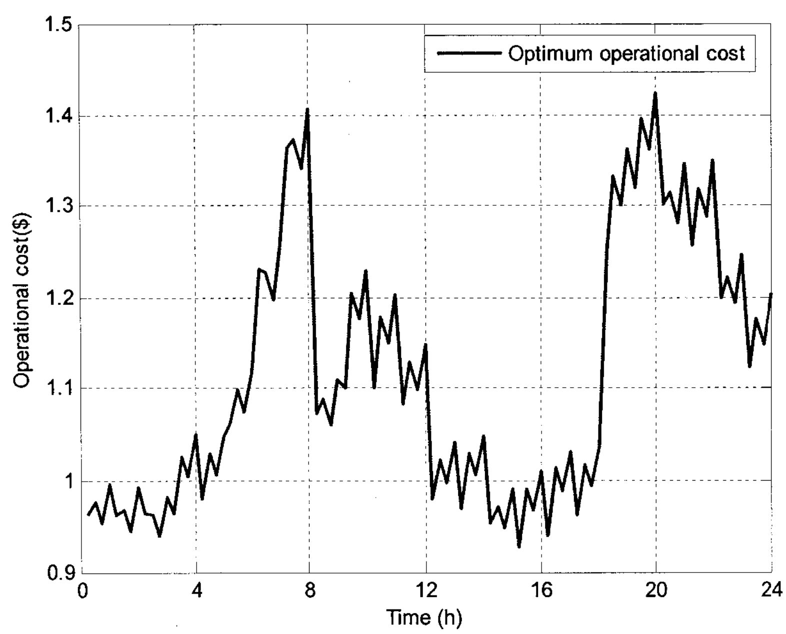

Figure 5.39 Optimal operational cost.

5.2.4.1.2 Cost Sensitivity Analysis and Evaluation. Table 5.20 shows FCOC based on electricity, gas, and hydrogen tariffs.

Table 5.20 Component costs for 50 kW FCPP.

Purchasing Electricity Tariff [$/kWh]	Selling Electricity Tariff [$/kWh]	Selling Hydrogen Tariff [$/kWh]	Purchasing Gas Tariff [$]	Total Daily Cost (include maintenance) [$]	Total Daily Cost (include maintenance) [$/kWh]
0.13	0.07	1.9	0.05	106.00	7.25
			0.06	107.15	7.33
			0.07	107.44	7.35
		2.1	0.05	101.54	6.95
			0.06	101.98	6.98
			0.07	102.15	6.99
	0.10	1.9	0.05	106.00	7.25
			0.06	107.15	7.33
			0.07	107.44	7.35
		2.1	0.05	101.54	6.95
			0.06	101.98	6.98
			0.07	102.15	6.99

5.2.4.2 Strategy 2 (selling excess thermal energy).

5.2.4.2.1 Test and Results. The optimal daily cost components of the FCPP system while selling excess thermal energy are summarized in Table 5.21.

Table 5.21 Components cost for 50 kW FCPP.

Cost components for 50 kW FCPP	[$]
Daily fuel cost	141.18
Daily cost of purchased electricity	0.57
Daily profit of residential natural gas	1.72
Daily profit of selling hydrogen	37.69
Operation and maintenance cost	1.97
Total hourly cost per (kWh)	7.14
Total daily cost	**104.29**

Figures 5.40 and 5.41 show the FCPP electrical and thermal outputs power compared to load power.

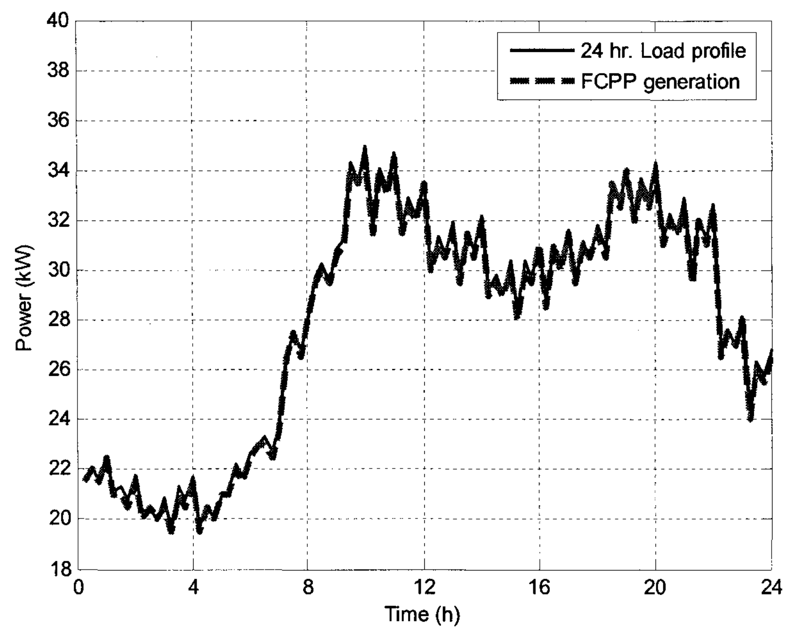

Figure 5.40 Electrical output power of the FCPP.

Figure 5.40 shows that the electrical output power for FCPP almost satisfies the load power.

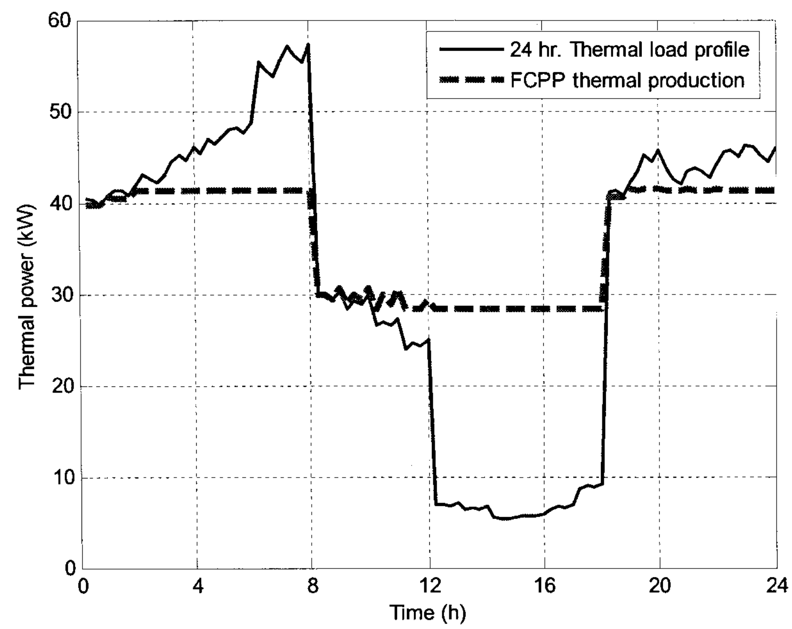

Figure 5.41 Thermal output power of the FCPP.

Figure 5.42 shows the FCPP output power compared to thermal load power.

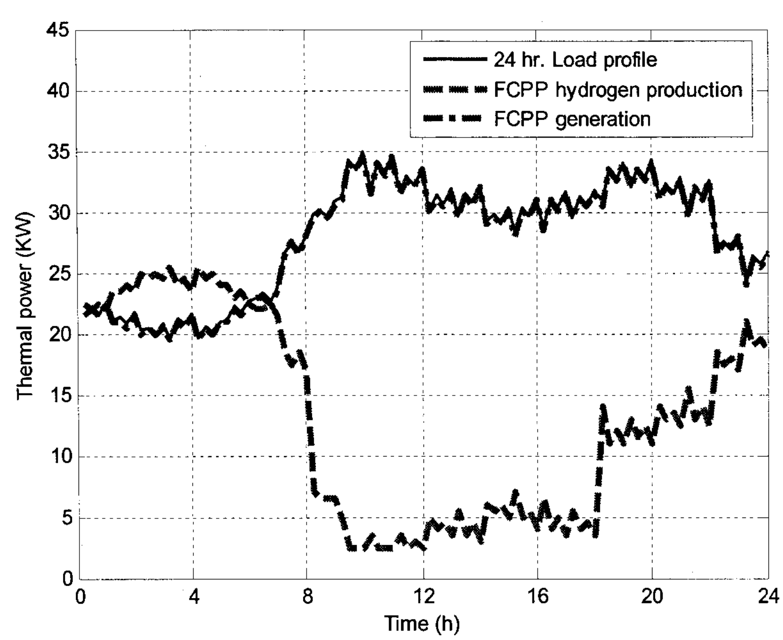

Figure 5.42 Electrical and hydrogen output powers.

Figure 5.43 shows the optimal FCOC for model III while selling excess thermal energy.

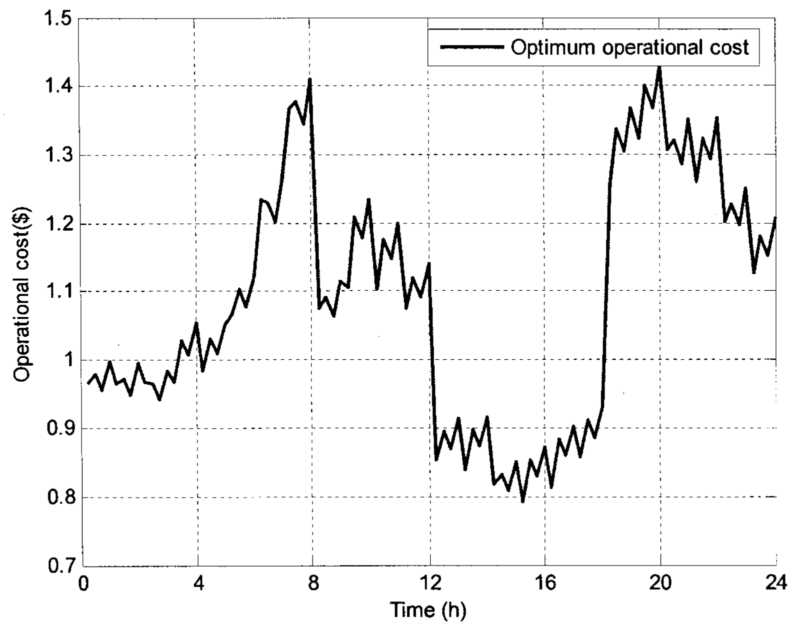

Figure 5.43 Optimum operational cost.

5.2.4.2.2 Cost Sensitivity Analysis and Evaluation. Table 5.22 shows FCOC based on electricity and hydrogen tariffs.

Table 5.22 FCOC based on electricity, gas, and hydrogen tariffs.

Purchasing Electricity Tariff [$/kWh]	Selling Electricity Tariff [$/kWh]	Selling Hydrogen Tariff [$/kWh]	Purchasing Gas Tariff [$/kWh]	Daily Total Cost (include maintenance) [$]	[$/kWh]
0.13	0.07	1.9	0.05	103.14	7.06
			0.06	104.29	7.14
			0.07	104.57	7.16
		2.1	0.05	97.56	6.68
			0.06	98.00	6.71
			0.07	98.14	6.72
	0.10	1.9	0.05	103.14	7.06
			0.06	104.29	7.14
			0.07	104.57	7.16
		2.1	0.05	97.56	6.68
			0.06	98.00	6.71
			0.07	98.14	6.72

5.2.4.3 Strategy 3 (storing excess thermal energy).

5.2.4.3.1 Test and Results. The optimal daily cost components of the FCPP system while storing excess thermal energy are summarized in Table 5.23.

Table 5.23 Component costs for 50 kW FCPP.

Component costs for 50 kW FCPP	**[$]**
Daily fuel cost	102.97
Daily cost of purchased electricity	23.18
Daily profit of selling electricity	0
Daily cost of residential natural gas	0.04
Daily profit of selling hydrogen	28.76
Operation and maintenance cost	1.97
Total hourly cost per (kWh)	6.80
Total daily cost	**99.40**

Figures 5.44 and 5.45 show the FCPP electrical and thermal outputs power compared to the load power.

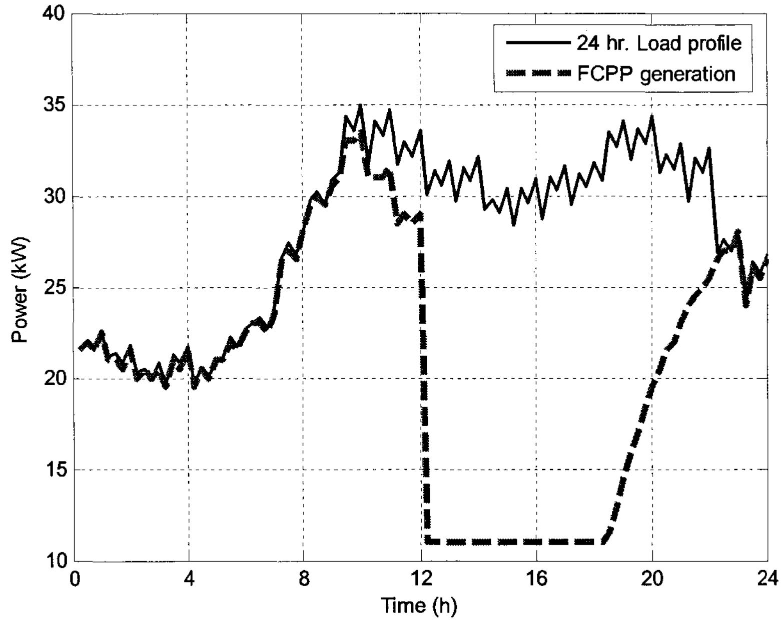

Figure 5.44 Electrical output power of the FCPP.

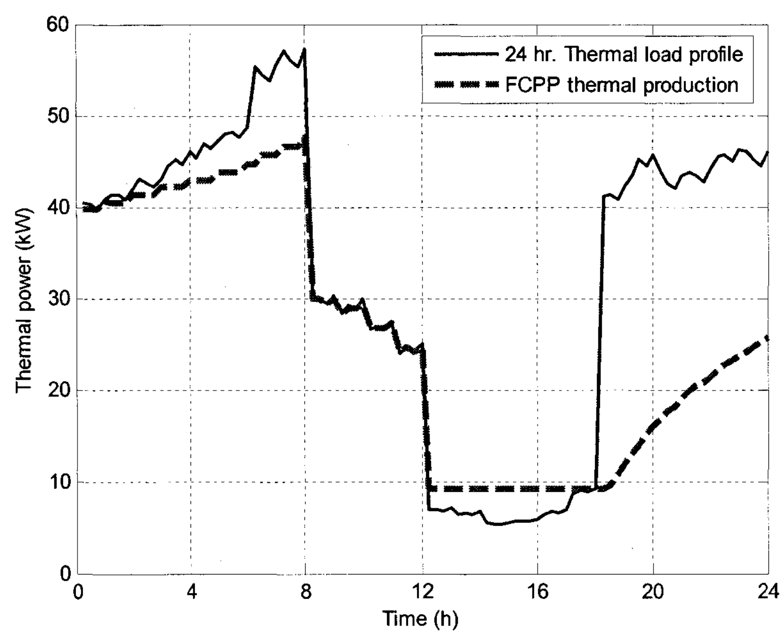

Figure 5.45 Thermal output power of the FCPP.

Figure 5.46 shows the fuel cell hydrogen and electrical outputs power compared to thermal load power.

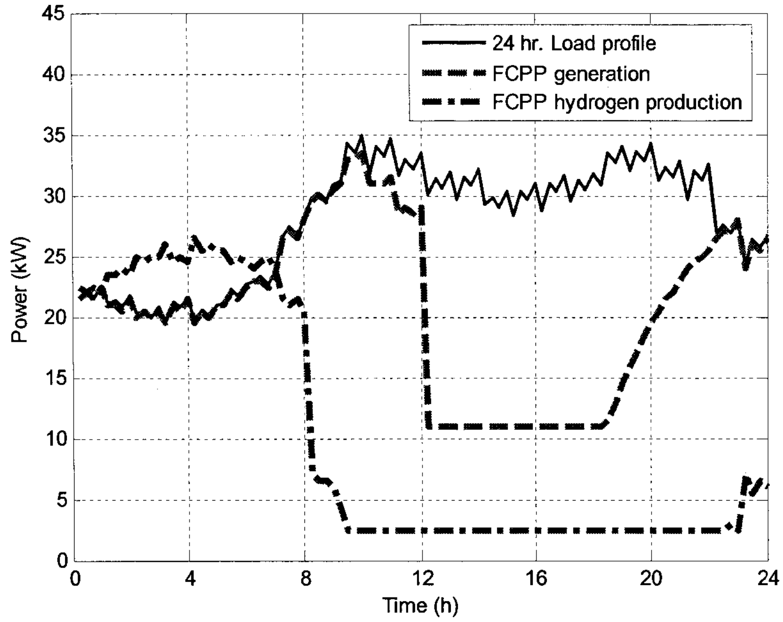

Figure 5.46 Electrical and hydrogen output powers.

Figure 5.47 shows the optimal FCOC for model III while selling excess thermal energy.

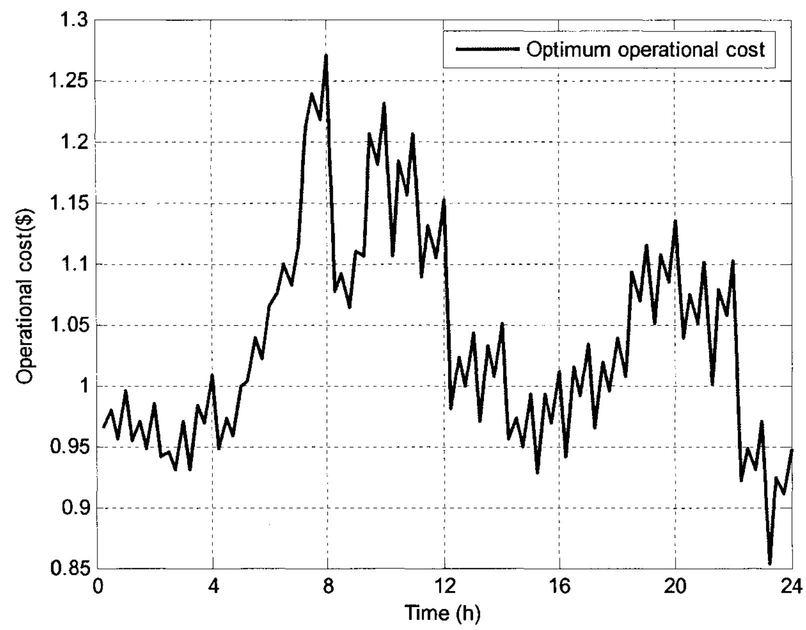

Figure 5.47 Optimum operational cost.

<u>**5.2.4.3.2 Cost Sensitivity Analysis and Evaluation**</u>. Table 5.24 shows FCOC based on electricity, gas, and hydrogen tariffs.

Table 5.24 FCOC based on electricity, gas and hydrogen tariffs.

Purchasing Electricity Tariff [$/kWh]	Selling Electricity Tariff [$/kWh]	Selling Hydrogen Tariff [$/kWh]	Purchasing Gas Tariff [$/kWh]	Total Daily Cost (include maintenance)	
				[$]	[$/kWh]
0.13	0.07	1.9	0.05	99.35	6.80
			0.06	99.40	6.80
			0.07	99.41	6.80
		2.1	0.05	95.07	6.51
			0.06	95.08	6.51
			0.07	95.08	6.51
	0.10	1.9	0.05	99.35	6.80
			0.06	99.40	6.80
			0.07	99.41	6.80
		2.1	0.05	95.07	6.51
			0.06	95.08	6.51
			0.07	95.08	6.51

5.3 FCOC using Generic Load Profile

This study has been performed for a given load profile. However, except for the change in tariffs; site-specific load profile is also a factor that can affect electricity, thermal and hydrogen production. Thus, in order to assist the power system engineers to decide on the size of fuel cell and the cost effective operating policies, a generalized technique is needed and a generic load profile is developed for this task.

rte_{l-side} is determined according to different class of load demands. Based on this approach, the fuel cell generated power is calculated for any load power. The fuel cell hydrogen generated power is calculated as well. The values of rte_{l-side} are obtained by dividing the thermal load power by the electrical load power. The values of rte_{l-side} are updated based on the strategy that has been used. Equation 5.45 calculates the rte_{l-side} values for wasting and selling excess thermal energy.

$$rte_{l-side} = \frac{P_j^{th}}{P_j^{el}} \tag{5.45}$$

If the third strategy is considered, the excess thermal energy stored can be used to reduce the thermal load power. The following equation explains the new rte_{l-side} values updated based on the third strategy:

$$rte_{l-side} = \frac{P_j^{th} - P_{j,st}^{th,usage}}{P_j^{el}} \tag{5.46}$$

The results for two models are shown in the following sections. The first model considers thermal gas usage and the second model considers thermal gas and hydrogen production usages.

5.3.1 Thermal Gas Compensation (include hydrogen production)

Three results are shown for this model regarding the excess thermal energy.

5.3.1.1 Strategy 1 (wasting excess thermal energy). Table 5.25 summarizes the fuel cell generation powers for the first strategy (wasting excess thermal energy) based on several load powers and rte_{l-side} values.

Table 5.25 Fuel cell generated power.

rte	Pj (kW)						
	LD=5kW	LD=10kW	LD=15kW	LD=20kW	LD=30kW	LD=40kW	LD=50kW
0.1	5	8	8	8	8	8	8
0.2	5	8	8	8	8	9.5	12
0.3	5	8	8	8	11	14.5	18.5
0.4	5	8	8	9.5	14.5	19.5	24
0.5	5	8	9	12	18.5	24	29.5
0.6	5	8	11	14.5	22	28.5	34
0.7	5	8	13	17	25	32	38
0.8	5	9.5	14.5	19.5	28.5	35.5	41.5
0.9	5	10	15	20	30	38.5	42.5
1	5	10	15	20	30	40	42.5
1.1	5	10	15	20	30	40	42.5
1.2	5	10	15	20	30	40	42.5
1.3	5	10	15	20	30	40	42.5
1.4	5	10	15	20	30	40	42.5
1.5	5	10	15	20	30	40	42.5
1.6	5	10	15	20	30	40	42.5
1.7	5	10	15	20	30	40	42.5
1.8	5	10	15	20	30	40	42.5
1.9	5	10	15	20	30	40	42.5
2	5	10	15	20	30	40	42.5
2.1	5	10	15	20	30	40	42.5
2.2	5	10	15	20	30	40	42.5
2.3	5	10	15	20	30	40	42.5
2.4	5	10	15	20	30	40	42.5
2.5	5	10	15	20	30	40	42.5

Table 5.26 summarizes the fuel cell hydrogen generation powers while wasting excess thermal energy based on several load powers and $r_{TE}^{l\_side}$ values.

Table 5.26 Fuel cell hydrogen generated power.

rte	Ph (kW)						
	LD=5kW	LD=10kW	LD=15kW	LD=20kW	LD=30kW	LD=40kW	LD=50kW
0.1	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.7	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.9	2.5	3.5	4	4.5	4	2.5	2.5
1	2.5	4.5	6	6.5	6.5	4	2.5
1.1	3.5	6	7.5	9	9	4	2.5
1.2	4	7	9.5	11	11	4	2.5
1.3	5	8.5	11	13	13.5	4	2.5
1.4	5.5	9.5	12.5	14.5	14	4	2.5
1.5	6.5	11	14.5	16.5	14	4	2.5
1.6	7	12	16	18	14	4	2.5
1.7	7.5	13.5	17.5	20	14	4	2.5
1.8	8.5	14.5	19	21.5	14	4	2.5
1.9	9	15.5	20	22.5	14	4	2.5
2	9.5	16.5	21.5	24	14	4	2.5
2.1	10.5	18	23	24.5	14	4	2.5
2.2	11	19	24	24.5	14	4	2.5
2.3	11.5	20	25	24.5	14	4	2.5
2.4	12	21	26.5	24.5	14	4	2.5
2.5	13	22	27.5	24.5	14	4	2.5

Figure 5.48 shows fuel cell electrical and hydrogen generation powers versus $r_{TE}^{l\_side}$ values based on 40 kW load power.

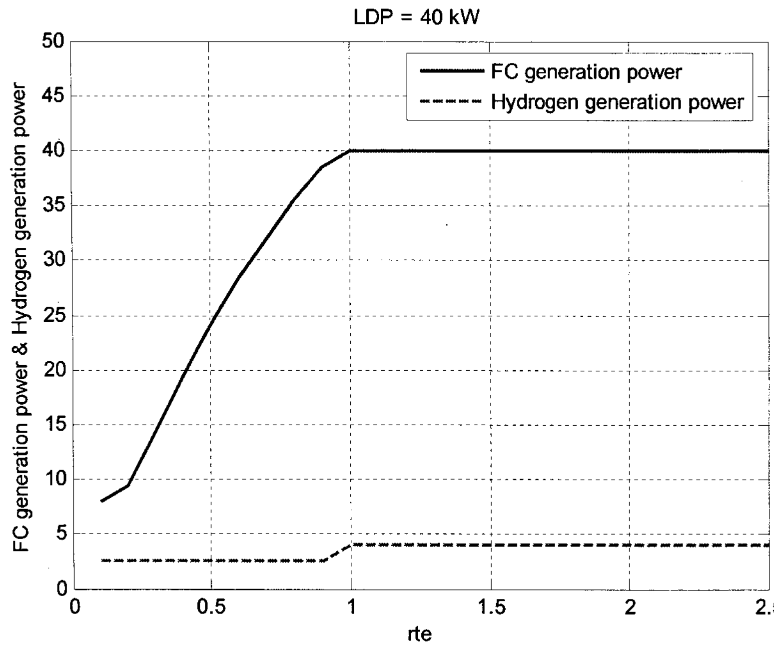

Figure 5.48 FC electrical and hydrogen generation powers versus rte_{l-side} values.

Figure 5.48 indicates that the fuel cell generated power increases gradually until it reaches a maximum load power of 40 kW. In addition, Figure 5.48 shows that the fuel cell hydrogen generation power is 2.5 kW for the first part of rte_{l-side}. Afterward, the fuel cell hydrogen generation power increases to 4.5 kW for higher rte_{l-side} values.

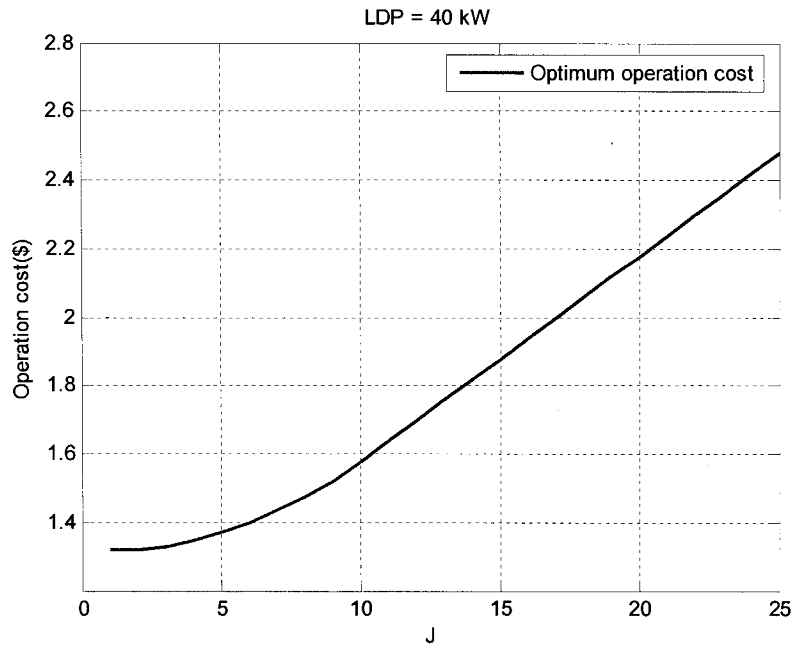

Figure 5.49 FCOC versus rte_{l-side} values.

Figure 5.49 shows that the FCOC increases gradually when rte_{l-side} increases. This figure shows almost a linear relation between the FCOC and rte_{l-side}.

5.3.1.2 Strategy 2 (selling excess thermal energy). Table 5.27 summarizes the fuel cell generation powers for the second strategy (selling excess thermal energy) based on load powers and rte_{l-side} values.

Table 5.27 Fuel cell generated power.

Rte	Pj (kW)						
	LD=5kW	LD=10kW	LD=20kW	LD=30kW	LD=35kW	LD=40kW	LD=50kW
0.1	5	10	20	30	34	34	34
0.2	5	10	20	30	34	34	34
0.3	5	10	20	30	34	34	34
0.4	5	10	20	30	34	34	34
0.5	5	10	20	30	34	34	34
0.6	5	10	20	30	34	34	34.5
0.7	5	10	20	30	34	34	38
0.8	5	10	20	30	34	36	41.5
0.9	5	10	20	30	35	39	42.5
1	5	10	20	30	35	40	42.5
1.1	5	10	20	30	35	40	42.5
1.2	5	10	20	30	35	40	42.5
1.3	5	10	20	30	35	40	42.5
1.4	5	10	20	30	35	40	42.5
1.5	5	10	20	30	35	40	42.5
1.6	5	10	20	30	35	40	42.5
1.7	5	10	20	30	35	40	42.5
1.8	5	10	20	30	35	40	42.5
1.9	5	10	20	30	35	40	42.5
2	5	10	20	30	35	40	42.5
2.1	5	10	20	30	35	40	42.5
2.2	5	10	20	30	35	40	42.5
2.3	5	10	20	30	35	40	42.5
2.4	5	10	20	30	35	40	42.5
2.5	5	10	20	30	35	40	42.5

Table 5.28 summarizes the fuel cell hydrogen generation powers for the second strategy (selling excess thermal energy) based on load powers and rte_{l-side} values.

Table 5.28 Fuel cell hydrogen generated power.

Rte	Ph (kW)						
	LD=5kW	LD=10kW	LD=20kW	LD=30kW	LD=35kW	LD=40kW	LD=50kW
0.1	30	25	15	5	2.5	2.5	2.5
0.2	30	25	15	5	2.5	2.5	2.5
0.3	30	25	15	5	2.5	2.5	2.5
0.4	30	25	15	5	2.5	2.5	2.5
0.5	30	25	15	5	2.5	2.5	2.5
0.7	30	25	15	5	2.5	2.5	2.5
0.8	30	25	15	5	2.5	2.5	2.5
0.9	30	25	15	5	3	2.5	2.5
1	30	25	15	6.5	5.5	4	2.5
1.1	30	25	15	9	8	4	2.5
1.2	30	25	15	11.5	9	4	2.5
1.3	30	25	15	13.5	9	4	2.5
1.4	30	25	15	14	9	4	2.5
1.5	30	25	17	14	9	4	2.5
1.6	30	25	18.5	14	9	4	2.5
1.8	30	25	21.5	14	9	4	2.5
1.9	30	25	22.5	14	9	4	2.5
2	30	25	24	14	9	4	2.5
2.1	30	25	24.5	14	9	4	2.5
2.2	30	25	24.5	14	9	4	2.5
2.3	30	25	24.5	14	9	4	2.5
2.4	30	25	24.5	14	9	4	2.5
2.5	30	25	24.5	14	9	4	2.5

Figure 5.50 shows fuel cell electrical and hydrogen generation powers versus $r_{TE}^{l\_side}$ values based on 35 kW load power.

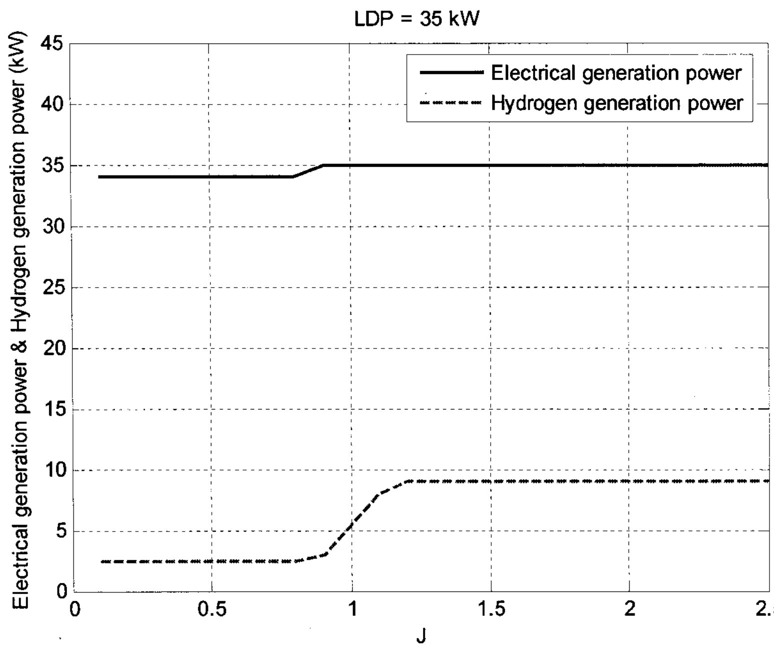

Figure 5.50 FC electrical and hydrogen generation powers versus rte_{l-side} values.

Figure 5.50 shows that the fuel cell generation power increases gradually until it reaches a maximum load power at 35 kW. In addition, Figure 5.51 shows that the fuel cell hydrogen generation power starts at 2.5 kW until it reaches 9 kW for higher $r_{TE}^{l\_side}$ values. Figure 5.51 shows that the FCOC increases gradually with increasing $r_{TE}^{l\_side}$. It also shows almost a linear relation between the FCOC and rte_{l-side}.

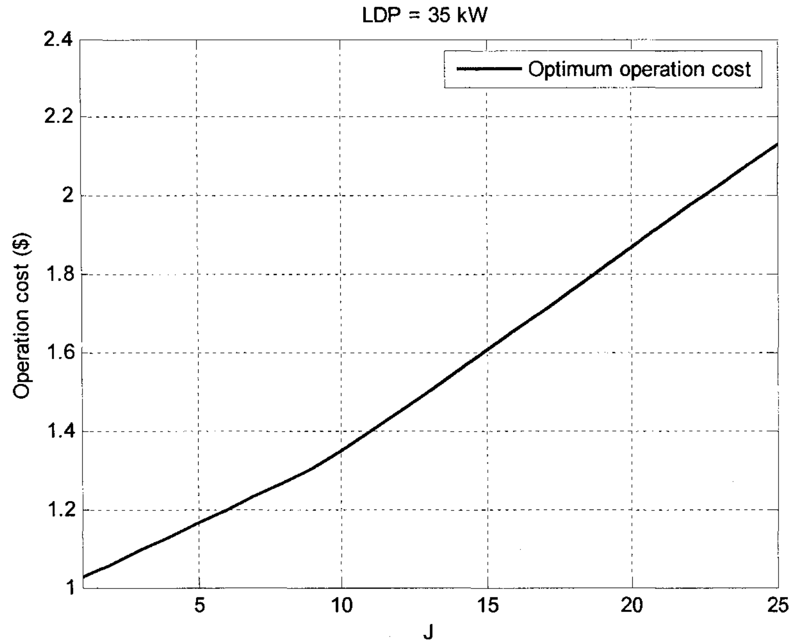

Figure 5.51 FCOC versus rte_{l-side} values.

5.3.1.3 Strategy 3 (storing excess thermal energy). Table 5.29 summarizes the fuel cell generation powers for the third strategy (storing excess thermal energy) based on several load powers and $r_{TE}^{l\_side}$ values.

Table 5.29 Fuel cell generated power.

Rte	Pj (kW)						
	LD=5kW	LD=10kW	LD=20kW	LD=30kW	LD=35kW	LD=40kW	LD=50kW
0.1	7.5	10.5	10.5	10.5	10.5	10.5	10.5
0.2	7.5	10.5	10.5	10.5	10.5	10.5	11.5
0.3	7.5	10.5	10.5	10.5	10.5	12	14.5
0.4	7.5	10.5	10.5	11.5	13	14.5	18
0.5	7.5	10.5	10.5	13.5	15.5	17.5	21
0.6	7.5	10.5	10.5	15.5	17.5	20	24
0.7	7.5	10.5	12	17.5	20	22.5	27
0.8	7.5	10.5	13.5	19	22	24.5	29.5
0.9	7.5	10.5	14.5	21	24	27	32
1	7.5	10.5	16	23	26	29	34.5
1.1	7.5	10.5	17.5	24.5	28	31	37
1.2	7.5	10.5	18.5	26.5	30	33	39
1.3	7.5	10.5	20	28	31.5	35	41
1.4	7.5	11.5	21	29.5	33.5	37	42.5
1.5	7.5	12	22.5	31	35	38.5	44.5
1.6	7.5	12.5	23.5	32.5	36.5	40	46
1.7	7.5	13.5	24.5	34	38	41.5	47.5
1.8	7.5	14	26	35.5	39.5	43	48.5
1.9	7.5	14.5	27	37	41	44.5	50
2	8	15.5	28	38	42	45.5	50
2.1	8.5	16	29	39.5	43.5	47	45
2.2	9	16.5	30	40.5	44.5	48	45
2.3	9	17.5	31	41.5	45.5	49	45
2.4	9.5	18	32	42.5	46.5	50	45
2.5	10	18.5	33	44	47.5	50	45

Table 5.30 summarizes the fuel cell hydrogen generation powers for the third strategy (storing excess thermal energy) based on several load powers and $r_{TE}^{l\_side}$ values.

Table 5.30 Fuel cell hydrogen generated power.

Rte	Ph (kW)						
	LD=5kW	LD=10kW	LD=20kW	LD=30kW	LD=35kW	LD=40kW	LD=50kW
0.1	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.6	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.7	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.8	2.5	2.5	2.5	2.5	2.5	2.5	2.5
0.9	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1.1	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1.2	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1.3	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1.4	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
1.6	2.5	2.5	3.5	2.5	2.5	2.5	2.5
1.7	2.5	3.5	4.5	4	3	2.5	2.5
1.8	2.5	4	6	5.5	4.5	3	2.5
1.9	2.5	4.5	7	7	6	4.5	2.5
2	3	5.5	8	8	7	5.5	2.5
2.1	3.5	6	9	9.5	8.5	7	2.5
2.2	4	6.5	10	10.5	9.5	8	2.5
2.3	4	7.5	11	11.5	10.5	9	2.5
2.4	4.5	8	12	12.5	11.5	10	2.5
2.5	5	8.5	13	14	12.5	10	2.5

Figure 5.52 shows fuel cell generation and hydrogen generation powers versus $r_{TE}^{l\_side}$ values based on 40 kW load power.

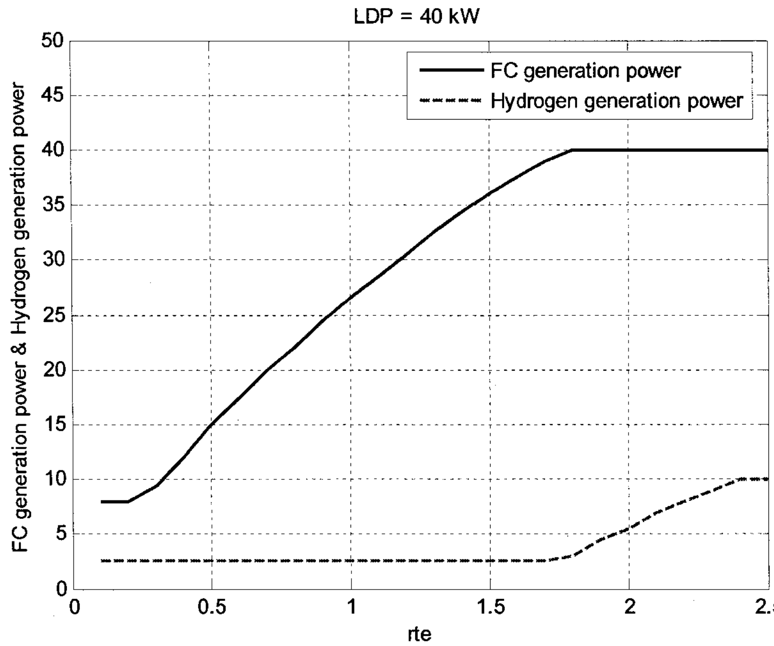

Figure 5.52 FC electrical and hydrogen generation powers versus rte_{l-side} values.

Figure 5.52 indicates the fuel cell generation power increases gradually until it reaches a maximum load power at 40 kW. In addition, Figure 5.52 shows that the fuel cell hydrogen generation power is 2.5 kW for the first part of rte_{l-side}. Afterward, the fuel cell hydrogen generation power increases until 10 kW for higher rte_{l-side} values. Figure 5.53 shows the FCOC increases gradually along with rte_{l-side} increases.

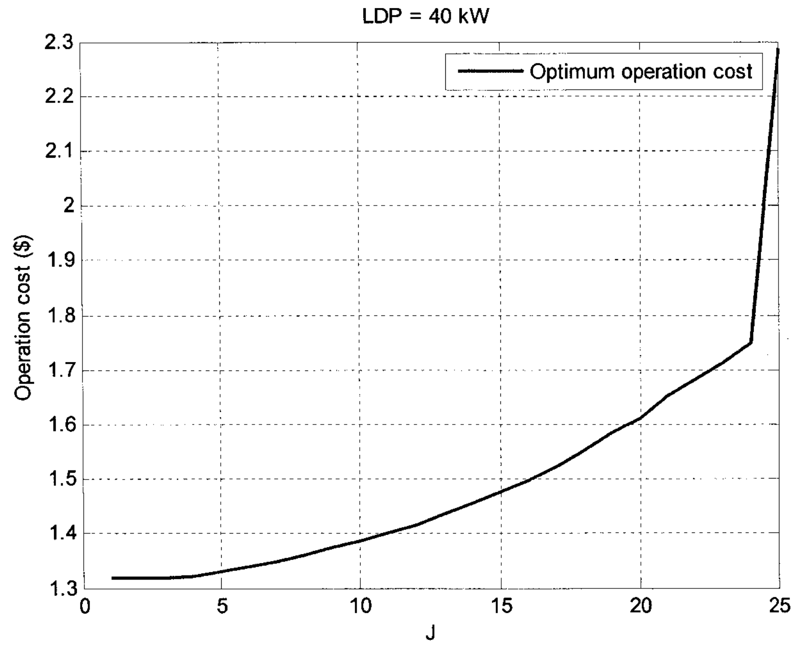

Figure 5.53 FCOC versus rte_{l-side} values.

5.4 Economic Analysis

In this section, an economical analysis is completed. Pay back period, net profit, and net cost based on operating strategy and load profile variation are calculated. Payback period is the amount of time required for the profit or other benefits of an investment to equal the cost of the investment [21]. Using fuel cell management techniques to satisfy the electrical and thermal load instead of buying the electricity and thermal energy from the grid reduces the cost.

As shown in Table 5.2, the daily FCOC for the base model regarding the first strategy is $128.90/day, which comes to $47,063 per year. Using the MATLAB algorithm, the cost of buying electricity from the grid to satisfy the electrical and thermal load is $189.94/day. The daily amount saved (net profit) using the fuel cell management technique instead of buying electricity from the grid is $61.04/day, which gives $22,280 as an annual benefit. Since the annual benefits are uniform, the payback period is $47,063/$22,280 per year = 2.11 year.

The lifetime assumed for the fuel cell is assumed to be 10 years. If the interest rate is 6%, the present worth of profit is calculated as follows:

$$PW_{profit} = A_{profit}(P/A, i\%, l) \tag{5.47}$$

where, PW_{profit} is the present worth of profit ($), A_{profit} is the annual profit, P/A is the present worth based on the annual benefit, $i\%$ is the interest rate, and l is the lifetime assumed for the FCPP.

$$PW_{profit} = 22{,}280 * (4.212) = \$93{,}843 \tag{5.48}$$

The present worth of FCOC cost is $47,063.

$$PW_{cost} = \$47{,}063 \tag{5.49}$$

The net present worth is calculated as follows.

$$PW_{net} = PW_{profit} - PW_{cost} \tag{5.50}$$

$$PW_{net} = 93{,}841.7 - 47{,}063 = \$46{,}778.7 \tag{5.51}$$

Table 5.31 lists the daily operational cost for FCPP and the daily costs of buying electricity and thermal energy from the grid.

Table 5.31 Daily FCPP operational cost comparison.

	Strategy 1 [$]	Strategy 2 [$]	Strategy 3 [$]	Daily Cost of Buying Electricity and Thermal Energy from the Grid[$]
Base Model	128.90	124.00	-	189.94
Model I	116.00	113.84	108.40	134.69
Model II	108.64	97.80	-	189.94
Model III	107.15	104.29	99.40	134.69

Table 5.32 summarizes the net profit of the daily FCOC using different strategies compared to the daily cost of buying electrical and thermal energy from the grid based on 10,000 production units.

Table 5.32 Daily saving amount (DSA) for the fuel cell operation strategies.

Daily Saving Amount	Strategy 1 [$]	Strategy 2 [$]	Strategy 3 [$]
Base Model	61.04	65.94	-
Model I	73.94	76.1	81.54
Model II	81.30	92.14	-
Model III	82.79	85.65	90.54

Table 5.33 summarizes the payback period for fuel cell operational strategies based on 10,000 production units.

Table 5.33 Pay back period for the fuel cell operational strategies.

Pay Back Period	Strategy 1 [years]	Strategy 2 [years]	Strategy 3 [years]
Base Model	2.11	1.88	-
Model I	1.56	1.50	1.33
Model II	1.34	1.06	-
Model III	1.29	1.22	1.10

Table 5.34 shows the net present worth values for FCPP operational strategies.

Table 5.34 Net present worth (NPW) for the fuel cell operational strategies.

Net Present Worth	Strategy 1 [$]	Strategy 2 [$]	Strategy 3 [$]
Base Model	57,968	65,501	-
Model I	77,710	81,121	89,484
Model II	84,022	99,057	-
Model III	85,713	89,372	98,721

Table 5.32 shows the great saving amounts that can be achieved relying on FCPP instead of buying the electricity and thermal energy from the grid. In addition, the payback periods show great motivations for FCPP industry regarding the fuel cell cost. A comparison between FCOC strategies is completed in Chapter 6 in order to choose the best model based on the cost.

CHAPTER 6

COMPARISON AND CONCLUSION

6.1 FCOC Comparisons

This section compares FCOC for all models and their strategies based on the FCPP system tariffs explained in Table 6.1. In addition, the saving for each strategy for a certain model, and the saving for each model for a certain strategy are shown in Table 6.2. The results help to choose the best model and strategy as far as FCOC is concerned.

Table 6.1 FCPP system parameter tariffs.

Parameter	Tariff
Electricity purchased tariff	0.13
Selling electricity tariff	0.07
Gas purchased tariff	0.06
Selling gas tariff	0.04
Selling hydrogen tariff	1.9

The FCOC based on the parameters mentioned in Table 6.1 are summarized below.

Table 6.2 Daily FCOC comparisons.

	Strategy (1) Waste [$]	Strategy (2) Sell [$]	Strategy (3) Store [$]	Strategy (1 – 2)	Strategy (1 – 3)	Strategy (2 – 3)
Base Model	128.90	124.00	-	4.9	-	-
Model I	116.00	113.84	108.40	2.16	7.6	5.44
Model II	108.64	97.80	-	10.84	-	-
Model III	107.15	104.29	99.40	2.86	7.75	4.89
Model (B – I)	12.90	10.16	-			
Model (B– II)	16.95	21.83	-			
Model (B – III)	18.50	15.53	-			

Table 6.2 indicates that the third strategy is superior compared to other strategies considered in this study. In addition, selling the hydrogen produced from the FCPP reduces FCOC as proven in Model II and Model III. The third strategy is neglected in the Base Model and the Model II due to the fact that the electrical power can not be stored. The result in Model II (2^{nd} strategy) yields the lowest FCOC due to the high profit made from selling hydrogen produced and selling the excess amount of thermal energy based on electricity usage. Table 6.2 summarizes the FCOC savings obtained from using the same strategy for the three models compared to the Base Model. Furthermore, it shows the FCOC savings for the same model when using different strategies.

6.2 Conclusion

The capital cost of FCPP can be reduced by increasing the fuel cell production units. In addition, the fuel cell cost increases as the fuel cell output power increases. Therefore, the results discussed in Chapter 3 clearly indicate that the 50kW FCPP has the highest cost compared to other fuel cells considered in this research.

From Table 6.2 is evident that the overall FCOC results for the third strategy (storing excess thermal energy) are the most efficient. In addition, the results show that Model II (2^{nd} strategy) yields the lowest FCOC.

Sensitivity test analysis indicates that FCOC can vary based on different tariffs such as electricity, gas, and hydrogen. Assuming higher selling tariffs and lower purchasing tariffs within a certain range reduces the FCOC for any strategy.

Reducing the operation cost of the fuel cell encourages factories, companies, government sectors, and residential areas to switch to fuel cell power from fossil fuel based power. This provides a better economic solution by cutting the cost and helping to make our environment much cleaner and pollution free. In the long run, it will also help the global economy by making the environment cleaner and pollution free.

6.3 Future Work

More research toward the development of materials and components used to build fuel cell systems is expected to lead to better performance and reduce the fuel cell capital cost. New strategies that provide less fuel consumption, higher hydrogen production, and more fuel cell efficiency can be developed to minimize the FCOC. By incorporating adaptive techniques, such as artificial intelligence techniques, to determine the FCPP outputs, more accurate and automated results can be obtained for any type load profile and FCPP size.

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APPENDICES

Appendix A: MATLAB Code

```
%%%%%%%%%%%%%%%%Read the load power%%%%%%%%%%%%%%%
clear all;close all
%Read the electrical load profile as a text file for an interval J
A=fopen('C:\Load Profiles\50eeLdSep.txt','r');
try; [a]=textread('C:\Load Profiles\50eeLdSep.txt','%f');end;b=(reshape(a,1,96));

%Read the thermal load profile as a text file for an interval J
A1=fopen('C:\Load Profiles\50thLdSep.txt','r');
try; [a1]=textread('C:\Load Profiles\50thLdSep.txt','%f');end;b1=(reshape(a1,1,96));

% Different tariff parameters
Tel_purchased=input ('Electricity purchased tariff : ');
Tel_selling=input ('Electricity selling tariff : ');
Tgas_purchased=input ('Gas purchased tariff : ');
Tgas_selling=input ('Gas selling tariff : ');Thy_selling=input('Hydrogen selling tariff : ');
%Time duration 15 minutes 0.25(h)
t_el=0.25; t_gas=0.25;t_f=0.25;

%%%%%%%%%%%%%%%%%%%Check constrains%%%%%%%%%%%%.
for j=1:96; Upper_rr(j)=25; Lower_rr(j)=30;end
for j=1:96
   for i=1:95
      Pel_diff (1) = 0;  Pel_diff (i+1) = Pel_fc (i+1)-Pel_fc (i);
      if (Pel_diff(i+1)<=Upper_rr(j))
         Purr_cost (j,i+1)=0;
      else
          if (Pel_fc(i+1)>L_el(j+1))
               Purr_cost (j,i+1)=-1*(Pel_diff(i+1)-Upper_rr(j))*Tel_selling;
         else
               Purr_cost(j,i+1)=(Pel_diff(i+1)-Upper_rr(j))*Tel_purchased;
         end
      end
      P_uprr (j,i+1) = Purr_cost (j,i+1);
      P_uprr (j,1) = 0;
   end
end

%Cheack constrains (lower ramp rates).
for j=1:96
   for i=1:95
      Pel_diff(1)=0; Pel_diff(i+1)=-1*(Pel_fc(i+1)-Pel_fc(i));
      if (Pel_diff(i+1)<=Lower_rr(j))
```

```
        Plrr_cost(j,i+1)=0;
      else
         if (Pel_fc(i+1)>L_el(j+1))
            Plrr_cost(j,i+1)=-1*(Pel_diff(i+1)-Lower_rr(j))*Tel_selling;
         else
            Plrr_cost(j,i+1)=(Pel_diff(i+1)-Lower_rr(j))*Tel_purchased;
         end
      end
      P_lwrr(j,i+1)=Plrr_cost(j,i+1);
      P_lwrr(j,1)=0;
   end
end

% Start the "for loops"
for j=1:96
    for i=1:96
        for i1=1:96
%Calculating FC total production level
            k=2.5:0.5:50;Pel_fc(i)=k(i);Ph_fc(i1)=k(i1); Pel_max(i)=50;
            Pel_fc(i)=Pel_fc(i)-P_lwrr/uprr;
            if (Pel_fc(i)+Ph_fc(i1)<=50)
              Pel_tot(j,i,i1)=Pel_fc(i)+Ph_fc(i1);
            else
             Pel_tot(j,i,i1)=0;
            end

%% %%%Determine the FC electrical output power at different production levels%%%
            k=2.5:0.5:50; L_el(j) = b(j); Pel_fc(i)=k(i);
           if ( Pel_fc(i) <= L_el(j))
 %Grid power needed to satisfy load profile if fuel cell power is less than load power
              Ele_from_grid (j,i,i1)=L_el(j) - Pel_fc(i);
              Pel_purORsel (j,i,i1) = Ele_from_grid(j,i,i1)* Tel_purchased * t_el;
 %Amount of fuel cell power saved if exceeds the power needed for the load profile
           else
              Ele_to_grid (j,i,i1)=Pel_fc(i) - L_el(j);
              Pel_purORsel (j,i,i1) = -1*(Ele_to_grid(j,i,i1) * Tel_selling * t_el);
           end

%%%%%%%Part 3: Calculating the thermal energy produced from the FC%%%%%%
          if (Pel_tot(j,i,i1)>0)
          rTE(j,i,i1)= (1.0785*(Pel_tot(j,i,i1)/50)^4-1.9739*(Pel_tot(j,i,i1)/50)^3
          +1.5005*(Pel_tot(j,i,i1)/50)^2-0.2817*(Pel_tot(j,i,i1)/50)+0.6838);
          P_auxillary(j,i,i1)=0; P_loss(j,i,i1) = (0.5/100)*Pel_fc(i);
          Pth_tot(j,i,i1)=rTE(j,i,i1)*(Pel_tot(j,i,i1)+P_auxillary(j,i,i1)+P_loss(j,i,i1));
          else
```

```
        Pth_tot(j,i,i1)=0;
        End


%%%%%%%%%%%%%%%%%%%%Model III%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%MIIIS1.m                                                          %
% This program calculates the optimum FCOC based on gas compensation and    %
%hydrogen production for strategy 1(wasting excess thermal energy)          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Compare thermal heat recovery from the fuel cell and theraml load energy
        L_th(j) = b1(j);
        if ( (Pth_tot(j,i,i1) <= L_th(j))& (Pth_tot(j,i,i1) > 0) )
%Grid power needed if fuel cell heat recovery amount doesn't satisfy the thermal load
        amount_of_HR_needed(j,i,i1)=L_th(j)-Pth_tot(j,i,i1);
        Pth_purORsel(j,i,i1) = amount_of_HR_needed(j,i,i1)* Tgas_purchased * t_gas;
        else
%Amount of thermal energy saved if FC produced power exceeds thermal load energy
        Pth_purORsel(j,i,i1)=0;
        end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%MIIIS2.m                                                          %
% This program calculates the optimum FCOC based on gas compensation and    %
%hydrogen production for strategy 2(selling excess thermal energy)          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Compare thermal heat recovery from the fuel cell and theraml load energy
        L_th(j) = b1(j);
        if ( (Pth_tot(j,i,i1) <= L_th(j))& (Pth_tot(j,i,i1) > 0) )
%Grid power needed if fuel cell heat recovery amount doesn't satisfy the thermal load
        amount_of_HR_needed(j,i,i1)=L_th(j)-Pth_tot(j,i,i1);
        Pth_purORsel(j,i,i1) = amount_of_HR_needed(j,i,i1)* Tgas_purchased * t_gas;
        else
%Amount of thermal energy saved if FC produced power exceeds thermal load energy
        amount_of_HR_saved(j,i,i1)=Pth_tot(j,i,i1)-L_th(j);
        Pth_purORsel(j,i,i1)= -1 * (amount_of_HR_saved(j,i,i1)) * Tgas_selling * t_gas;
        end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%MIIIS3.m                                                          %
% This program calculates the optimum FCOC based on gas compensation and    %
%hydrogen production for strategy 3(storing excess thermal energy)          %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
L_th(j) = b1(j);
%Compare thermal heat recovery from the fuel cell and theraml load energy
            if (Pth_tot(j,i,i1) > L_th(j))
%Grid power needed if fuel cell heat recovery amount doesn't satisfy thermal load profile
             storage(j,i,i1)= (Pth_tot(j,i,i1)-L_th(j));
            else
             storage(j,i,i1)= 0;
            end

            if ( (Pth_tot(j,i,i1) < L_th(j))& (Pth_tot(j,i,i1) > 0) )
             comp(j,i,i1)=(L_th(j)-Pth_tot(j,i,i1));
            else
             comp(j,i,i1)=0;
            end
 for j=1:95
    for i=1:96
       for i1=1:96
          new_comp(1,i,i1)=comp(1,i,i1);
          if (comp(j+1,i,i1)> storage(j,i,i1))
            new_comp(j+1,i,i1)=comp(j+1,i,i1)-storage(j,i,i1); new_storage(j+1,i,i1)=0;
          else
            new_storage(j+1,i,i1)=storage(j,i,i1)-comp(j+1,i,i1);
            storage(j+1,i,i1)=new_storage(j+1,i,i1)+storage(j+1,i,i1);
            new_comp(j+1,i,i1)=0;
          end
       end
   end
end

          if (new_comp(j,i,i1) > 0)
            Pth_purchased(j,i,i1)=new_comp(j,i,i1) * Tgas_purchased * t_gas;
          else
            Pth_purchased(j,i,i1)=0;
          end
%%%%%%%%%%%%%%%%%% Hydrogen production%%%%%%%%%%%%%%
       t_h=0.25*3600;
       F=1.05*1000*(10^-8)/0.6;
       Phy_selling(j,i,i1)=Ph_fc(i1)*F*Thy_selling*t_h;

%%%%%%%%%%%%%%%%%%Input fuel usage cost%%%%%%%%%%%%%%%
       if (Pel_tot(j,i,i1)>0)
        FC_eff(j,i,i1)=0.90*(Pel_tot(j,i,i1)/50)^5-3.01*(Pel_tot(j,i,i1)/50)^4+3.65*
        (Pel_tot(j,i,i1)/50)^3-2.07*(Pel_tot(j,i,i1)/50)^2+0.46*(Pel_tot(j,i,i1)/50)+0.37;
        P_auxillary(j,i,i1) = 0; P_loss(j,i,i1) = (5/100)*Pel_fc(i);  T_f=0.05;
        fuel_usage(j,i,i1)=(Pel_tot(j,i,i1) + P_auxillary(j,i,i1) +P_loss(j,i,i1))/
```

```
          FC_eff(j,i,i1)*T_f*t_f;
          else
          fuel_usage(j,i,i1)=0;end
% %%%%%%%%%%%%Maintenance & Operation cost ($)%%%% %%%%%%%%%
          MO_cost (j,i,i1)=0.0205;
          if (Pel_tot(j,i,i1) > 0)
          OP_cost(j,i,i1) = fuel_usage(j,i,i1) +Pel_purORsel(j,i,i1)+Pth_purORsel(j,i,i1)
          + MO_cost (j,i,i1) - Phy_selling(j,i,i1) + P_uprr(j) + P_lwrr(j);
          else
          OP_cost(j,i,i1)=500;
          end
        end
    end
end


%%%%%%%%%%%%%%Finding the optimum operation cost%%%%%%%%%%%%
for j=1:96 ;   min_OP_cost(j) = min(min(OP_cost(j,:,:)));end
for j=1:96
      TTT(:,:)=OP_cost(j,:,:); [X Y]=find(TTT == min(min(TTT(:,:))));
      coordinate(j,:,1)=X'; coordinate(j,:,2)=Y';end
for j=1:96; Pfc_productivity(j)=Pel_tot(coordinate(j,:,1),coordinate(j,:,2));end

%%%%%%%%%%%%%%Calculation and Figures%%%%%%%%%%%%%%
for j=1:96
%Calculating Daily cost of selling Hydrogen ($)
      sel_H(j)=Phy_selling(j,coordinate(j,:,1),coordinate(j,:,2));

%Calculating Daily cost of purchased or selling electricity ($)
       sel_el(j)=Pel_purORsel(j,coordinate(j,:,1),coordinate(j,:,2));

%Calculating Daily cost of purchased or selling gas ($)
       sel_gas(j)=Pth_purORsel(j,coordinate(j,:,1),coordinate(j,:,2));

%Calculating Daily fuel cost ($)
      optimum_fuel_usage(j)=fuel_usage(j,coordinate(j,:,1),coordinate(j,:,2));end

%find the cumulative FC cost parameters
cum_sel_H=-1*cumsum(sel_H);disp(cum_sel_H)
cum_sel_el=cumsum(sel_el); disp(cum_sel_el)
cum_sel_gas=cumsum(sel_gas); disp(cum_sel_gas)
cum_fuel_usage=cumsum(optimum_fuel_usage);disp(cum_fuel_usage)
cum_min_OP_cost=cumsum(min_OP_cost);disp(cum_min_OP_cost)

%plot electrical FC production level versus electrical load power
```

```
j=[1:96]; figure;plot(j,L_el,j,Pel_fc(coordinate(j,:,1)),'--');grid;
h = legend('Load','FC generation'); xlabel('J');ylabel('Power (KW)');

%Plot Hydrogen FC productivity level($)
j=[1:96];figure;plot(j,L_th,j,Ph_fc(coordinate(j,:,2)),'--',j,Pel_fc(coordinate(j,:,1)),'-.');
grid; h = legend('Thermal Load','FC hydrogen production','FC generation');
xlabel('J');ylabel('Thermal power (KW)');

%Plot thermal FC productivity level($)
for j=1:96;th_tot(j)=Pth_tot(j,coordinate(j,:,1),coordinate(j,:,2));end
j=[1:96];figure;plot(j,th_tot,j,L_th,'--');grid;
h = legend('Total FC thermal production','Thermal Load');
xlabel('J');ylabel('Thermal power (KW)');
title('Fuel cell thermal production level & Thermal load profile comparison (KW)');

%Plot selling and buying electricity amount
j=[1:96]; el_amount=L_el-Pel_fc(coordinate(j,:,1));figure;plot(j,el_amount);
grid;h = legend('(+) Purchased, (-) Sold');xlabel('J');ylabel('Power trade(kw)');

%Plot selling and buying Thermal compensation amount
j=[1:96];th_amount=L_th(j)-th_tot(j);figure;plot(j,th_amount);grid;
h = legend('(+) Purchased, (-) Unused');
xlabel('J');ylabel('Thermal power to compansate thermal production shortage (kW)');

%Plot min_OP_cost($)
j=[1:96];figure;plot(j,min_OP_cost);grid;
h = legend('Optimum operation cost');xlabel('J');ylabel('Operation cost($)');
```

Appendix B: Load Profiles

JAN	MAR	MAY	JUN	JUL	AGT	SEP	OCT	NOV	DEC
[kW]									
27.468	21.542	25.778	26.364	24.234	22.494	21.564	23.024	30.148	28.478
28.844	22.614	26.06	28.946	26.37	23.052	22.098	24.902	31.45	30.484
28.158	22.076	25.416	28.286	25.764	22.49	21.56	24.328	30.696	29.772
29.394	23.044	26.576	29.472	26.854	23.502	22.53	25.364	32.054	31.054
25.714	21.136	24.22	24.778	22.84	22.076	21.146	22.476	28.186	26.654
26.514	22.792	25.944	25.996	24.956	22.272	21.334	24.278	28.36	28.97
25.872	22.264	25.338	25.376	24.386	21.72	20.806	23.716	27.656	28.304
27.028	23.216	26.428	26.492	25.412	22.714	21.756	24.728	28.924	29.504
24.44	20.322	23.272	23.786	21.93	21.242	20.314	21.59	26.776	25.334
24.608	21.152	23.604	25.898	23.538	21.398	20.462	22.662	28.324	25.776
23.996	20.644	23.022	25.304	22.99	20.866	19.955	22.122	27.654	25.144
25.096	21.558	24.07	26.374	23.976	21.822	20.87	23.092	28.858	26.284
23.96	19.588	22.576	23.094	21.292	20.482	19.572	20.86	26.224	24.832
26.02	21.368	22.766	25.146	21.96	22.3	21.308	22.52	26.48	25.864
25.422	20.878	22.2	24.568	21.428	21.788	20.82	22	25.824	25.244
26.5	21.76	23.216	25.608	22.386	22.71	21.7	22.938	27.004	26.36
23.79	19.754	22.492	22.994	21.224	20.676	19.712	21.02	25.984	24.648
25.962	20.62	24.18	23.03	22.95	21.546	20.542	21.558	27.692	24.804
25.368	20.126	23.618	22.456	22.42	21.03	20.05	21.032	27.042	24.188
26.438	21.016	24.63	23.49	23.374	21.96	20.936	21.978	28.212	25.298
24.186	21.232	22.934	23.388	21.682	22.288	21.11	22.462	26.414	25.058
25.688	22.802	23.416	24.916	21.724	23.48	22.24	23.872	26.728	26.584
25.084	22.27	22.842	24.33	21.182	22.924	21.712	23.312	26.068	25.958
26.172	23.226	23.874	25.384	22.158	23.926	22.662	24.322	27.256	27.086
28.622	23.198	24.764	25.17	23.354	24.392	23.016	24.898	30.872	29.608
30.238	24.84	25.902	26.034	23.872	24.72	23.326	26.298	30.964	31.326
29.522	24.26	25.284	25.404	23.288	24.11	22.75	25.674	30.192	30.586
30.81	25.304	26.398	26.536	24.34	25.208	23.786	26.796	31.582	31.918
32.692	26.882	28.764	29.13	27.034	28.33	26.594	28.874	35.07	33.796
33.296	29.416	31.276	30.094	28.668	29.212	27.422	31.652	37.116	35.086
32.48	28.744	30.558	29.366	27.992	28.504	26.758	30.93	36.238	34.242
33.95	29.954	31.852	30.676	29.208	29.78	27.954	32.23	37.816	35.762
36.342	30.068	33.388	33.888	31.386	31.684	29.748	32.246	39.062	37.576
37.12	31.264	33.59	36.028	33.698	32.192	30.226	34.702	39.596	40.87
36.212	30.512	32.756	35.18	32.914	31.4	29.482	33.896	38.618	39.93
37.846	31.866	34.258	36.706	34.326	32.826	30.82	35.348	40.376	41.622
37.334	31.536	36.252	36.76	33.944	33.204	31.232	33.666	40.336	38.628
39.002	32.798	38.6	39.12	35.89	36.484	34.318	34.114	42.772	42.142
38.07	32.01	37.694	38.202	35.042	35.654	33.536	33.272	41.764	41.178
39.75	33.43	39.326	39.856	36.568	37.148	34.942	34.786	43.58	42.916
37.504	32.022	37.894	38.446	35.428	33.696	31.74	34.12	40.576	38.81
38.082	32.478	39.464	42.272	38.682	36.136	34.04	36.246	43.362	41.676
37.146	31.676	38.516	41.312	37.796	35.294	33.246	35.392	42.348	40.706

JAN	MAR	MAY	JUN	JUL	AGT	SEP	OCT	NOV	DEC
[kW]									
38.832	33.118	40.222	43.042	39.392	36.81	34.674	36.928	44.174	42.452
37.278	31.936	38.368	38.942	35.838	33.576	31.692	33.994	40.388	38.584
40.706	34.014	39.992	39.408	36.24	34.86	32.904	35.05	43.79	39.158
39.774	33.216	39.032	38.436	35.344	34.022	32.112	34.2	42.782	38.194
41.45	34.654	40.76	40.188	36.956	35.532	33.538	35.73	44.598	39.93
37.192	30.218	38.062	38.644	35.45	31.74	30.02	32.37	40.266	38.492
38.004	33.036	39.652	42.446	37.756	33.11	31.316	35.238	43.804	39.322
37.074	32.28	38.7	41.48	36.87	32.316	30.564	34.43	42.798	38.36
38.748	33.64	40.412	43.22	38.466	33.744	31.916	35.886	44.61	40.092
37.022	29.892	38.284	38.842	35.59	31.398	29.694	32.062	40.026	38.31
38.436	32.628	38.354	42.356	38.052	33.374	31.564	34.34	41.266	39.268
37.51	31.88	37.396	41.386	37.162	32.59	30.822	33.538	40.266	38.31
39.176	33.226	39.118	43.134	38.764	34.002	32.158	34.982	42.066	40.034
36.316	29.398	38.198	38.742	35.454	30.86	29.228	31.512	39.286	37.58
39.086	29.978	38.492	41.56	36.296	31.442	29.78	33.104	42.646	40.144
38.178	29.244	37.536	40.592	35.41	30.672	29.05	32.316	41.662	39.206
39.812	30.566	39.256	42.336	37.004	32.06	30.364	33.734	43.43	40.896
36.626	28.584	37.284	37.852	34.654	30.026	28.396	30.792	39.596	37.9
36.834	29.674	37.716	40.048	37.088	32.098	30.356	31.656	41.914	40.33
35.92	28.96	36.784	39.1	36.22	31.348	29.646	30.886	40.924	39.382
37.568	30.246	38.46	40.804	37.78	32.698	30.924	32.272	42.706	41.088
38.522	28.996	37.062	37.654	34.536	30.49	28.77	31.392	41.626	39.858
39.888	30.696	40.248	40.16	35.464	32.896	31.04	33.23	41.654	40.164
38.926	29.97	39.32	39.218	34.6	32.134	30.32	32.444	40.614	39.166
40.658	31.276	40.988	40.914	36.154	33.506	31.616	33.858	42.488	40.96
39.598	29.73	37.232	37.854	34.762	31.25	29.51	32.122	43.02	41
40.268	31.808	40.736	40.358	35.44	33.026	31.186	34.688	46.78	43.506
39.278	31.064	39.806	39.41	34.572	32.244	30.448	33.884	45.706	42.48
41.06	32.402	41.482	41.114	36.136	33.65	31.776	35.33	47.642	44.326
39.514	31.036	36.4	37.062	34.184	32.622	30.81	33.352	42.9	40.908
39.92	32.098	36.51	38.208	37.338	35.414	33.448	35.186	44.326	42.472
38.932	31.322	35.6	37.282	36.484	34.598	32.676	34.352	43.254	41.448
40.71	32.72	37.238	38.95	38.022	36.066	34.064	35.852	45.184	43.29
38.1	32.172	36.096	36.766	33.976	33.752	32.01	34.244	41.42	39.452
41.668	34.246	36.89	40.274	34.51	35.514	33.682	37.662	43.88	39.462
40.716	33.442	35.986	39.354	33.66	34.67	32.882	36.806	42.844	38.474
36.29	31.438	36.518	37.264	34.382	32.992	31.27	33.348	39.51	37.586
38.39	33.334	36.744	37.818	36.124	34.046	32.268	36.454	39.674	38.926
37.484	32.548	35.832	36.886	35.264	33.22	31.486	35.62	38.688	37.986
33.634	29.8	36.232	36.864	33.87	31.232	29.688	31.468	36.79	34.854
35.412	31.972	36.672	40.116	35.018	33.688	32.024	31.952	38.6	37.472
34.572	31.226	35.766	39.194	34.17	32.908	31.282	31.164	37.68	36.6
36.084	32.568	37.398	40.852	35.694	34.314	32.616	32.58	39.336	38.168
30.1	26.934	33.978	34.584	31.68	28.174	26.9	28.35	33.09	31.212
30.496	27.954	35.448	35.162	32.858	28.922	27.614	30.686	33.294	32.602

JAN	MAR	MAY	JUN	JUL	AGT	SEP	OCT	NOV	DEC
[kW]									
29.744	27.28	34.6	34.298	32.066	28.216	26.94	29.978	32.466	31.822
31.098	28.492	36.128	35.854	33.492	29.484	28.152	31.254	33.956	33.226
26.48	24.07	28.726	29.336	26.95	25.116	24.114	25.232	29.27	27.478
26.742	25.174	30.644	31.844	27.532	27.444	26.35	27.168	30.626	30.058
26.08	24.572	29.926	31.11	26.858	26.816	25.748	26.538	29.894	29.372
27.27	25.654	31.218	32.43	28.072	27.948	26.832	27.674	31.212	30.608

Thermal Load Profile

JAN_th	MAR_th	MAY_th	JUN_th	JUL_th	AGT_th	SEP_th	NOV_th	DEC_th
[kW]								
53.724	53.628	1.6	1.504	1.344	1.41	40.41	53.672	53.614
53.704	53.53	1.5855	1.6137	1.4221	1.3885	40.316	53.63	53.622
53.04	52.868	1.5475	1.5779	1.3902	1.3551	39.814	52.966	52.96
54.236	54.06	1.6159	1.6422	1.4477	1.4153	40.716	54.162	54.152
54.956	54.906	0.89	0.832	0.744	0.782	41.282	54.928	54.898
54.902	54.886	0.9088	0.8687	0.8092	0.785	41.25	54.878	54.902
54.23	54.216	0.8877	0.849	0.7915	0.7665	40.746	54.208	54.234
55.956	55.94	0.9257	0.8845	0.8233	0.7999	42.042	55.932	55.956
57.336	57.322	0.314	0.292	0.262	0.278	43.028	57.328	57.314
56.81	56.806	0.3075	0.3062	0.272	0.2661	42.624	56.822	56.794
56.118	56.116	0.3	0.2993	0.2658	0.2595	42.106	56.13	56.102
57.364	57.36	0.3135	0.3118	0.277	0.2714	43.04	57.376	57.348
59.336	59.322	0.314	0.292	0.262	0.278	44.528	59.328	59.314
60.18	60.162	0.3104	0.315	0.2637	0.2957	45.164	60.15	60.146
59.464	59.446	0.3029	0.3081	0.2574	0.2891	44.626	59.434	59.43
61.318	61.3	0.3163	0.3206	0.2686	0.301	46.02	61.288	61.284
60.388	60.366	0.358	0.336	0.3	0.314	45.314	60.372	60.358
62.538	62.496	0.3687	0.3214	0.3109	0.3194	46.908	62.506	62.466
61.808	61.768	0.3602	0.3134	0.3038	0.3119	46.36	61.776	61.738
63.12	63.08	0.3755	0.3278	0.3166	0.3253	47.346	63.088	63.048
63.798	63.644	2.592	2.44	2.176	2.278	48.028	63.716	63.622
64.058	63.848	2.5946	2.4774	2.1258	2.3544	48.2	63.822	63.858
63.26	63.054	2.5332	2.4194	2.0742	2.3002	47.598	63.026	63.062
64.696	64.484	2.644	2.5238	2.1672	2.3976	48.682	64.46	64.492
72.926	72.32	10.122	9.508	8.5	8.902	55.402	72.604	72.238
72.252	71.624	10.182	9.4538	8.4336	8.71	54.488	71.196	71.51
71.248	70.634	9.942	9.228	8.2318	8.4986	53.718	70.2	70.524
73.65	73.01	10.375	9.6344	8.5952	8.8792	55.55	72.588	72.896
74.956	74.124	13.846	13.014	11.634	12.182	57.182	74.512	74.014
73.196	74.096	14.709	13.38	12.104	12.074	56.106	73.416	73.19
72.12	73.04	14.381	13.071	11.828	11.785	55.278	72.35	72.136
74.632	75.516	14.972	13.627	12.325	12.306	57.202	74.844	74.608
75.802	62.636	12.78	12.014	10.736	11.246	29.846	75.394	74.934
76.79	63.428	12.538	12.172	11.312	11.089	29.938	76.006	76.512
75.718	62.524	12.234	11.886	11.057	10.822	29.448	74.944	75.46
77.648	64.152	12.781	12.4	11.516	11.303	30.33	76.856	77.352
72.656	59.948	11.714	11.012	9.844	10.312	28.312	72.276	71.86
74.084	61.002	12.121	11.279	10.359	10.918	29.29	73.952	73.588
73.064	60.142	11.843	11.017	10.125	10.673	28.83	72.942	72.586
75.476	62.15	12.344	11.488	10.546	11.114	29.832	75.338	74.966
68.886	56.758	10.546	9.91	8.858	9.282	26.532	68.55	68.17
68.802	56.508	10.719	10.847	9.2732	9.7688	27.008	68.834	68.712
67.84	55.7	10.469	10.611	9.0628	9.5482	26.582	67.882	67.768

JAN_th	MAR_th	MAY_th	JUN_th	JUL_th	AGT_th	SEP_th	NOV_th	DEC_th
[kW]								
69.57	57.154	10.92	11.035	9.4414	9.945	27.35	69.596	69.466
63.508	52.182	8.808	8.274	7.398	7.748	23.948	63.232	62.91
65.964	53.832	9.1368	8.0422	7.148	8.0056	24.724	65.596	64.544
65.09	53.1	8.9276	7.8458	6.9724	7.8216	24.344	64.728	63.684
66.664	54.418	9.3042	8.1994	7.2886	8.1528	25.026	66.29	65.232
61.934	50.768	7.814	7.34	6.558	6.872	6.872	61.686	61.402
63.028	51.994	7.8668	7.8422	6.8206	6.928	6.928	63.072	62.21
62.186	51.292	7.6812	7.6678	6.665	6.7648	6.7648	62.236	61.38
63.702	52.556	8.0152	7.9816	6.9452	7.0586	7.0586	63.74	62.874
57.786	47.354	7.208	6.778	6.054	6.34	6.34	57.552	57.296
59.278	48.892	7.0048	7.1202	6.4424	6.5806	6.5806	58.718	58.68
58.492	48.236	6.8336	6.9592	6.2986	6.4302	6.4302	57.94	57.906
59.904	49.416	7.1418	7.249	6.5574	6.7012	6.7012	59.342	59.298
54.828	44.848	6.318	5.938	5.31	5.564	5.564	54.624	54.398
54.67	44.388	6.1454	6.2512	5.1706	5.4188	5.4188	54.654	54.144
53.932	43.774	5.9954	6.1102	5.0444	5.2866	5.2866	53.92	53.416
55.722	45.248	6.2654	6.364	5.2714	5.5244	5.5244	55.7	55.186
52.902	43.322	6.39	6.01	5.368	5.624	5.624	52.696	52.47
51.892	42.572	6.2722	6.3284	5.6912	5.759	5.759	52.08	52.012
51.176	41.974	6.1204	6.1858	5.5638	5.6256	5.6256	51.368	51.306
52.908	43.402	6.3936	6.4426	5.7932	5.866	5.866	53.09	53.018
51.938	42.7	7.346	6.908	6.172	6.47	6.47	51.704	51.434
53.564	44.022	7.6834	7.2642	6.0292	6.7216	6.7216	52.786	52.578
52.848	43.422	7.509	7.1	5.8826	6.568	6.568	52.074	51.874
54.138	44.502	7.823	7.3954	6.1466	6.8446	6.8446	53.354	53.142
52.736	52.136	9.94	9.348	8.354	8.75	8.75	52.422	52.064
53.406	53.284	10.528	9.7792	8.3082	9.0284	9.0284	53.354	52.768
52.646	52.54	10.292	9.5572	8.1098	8.8206	8.8206	52.602	52.026
54.012	53.88	10.717	9.9568	8.467	9.1946	9.1946	53.956	53.362
53.846	53.13	11.896	11.18	9.99	10.466	41.216	53.466	53.036
53.03	52.922	11.634	11.023	10.462	11.048	41.376	53.254	52.692
52.232	52.142	11.352	10.757	10.225	10.799	40.758	52.466	51.914
54.06	53.94	11.86	11.235	10.652	11.247	42.164	54.28	53.708
56.766	56.058	11.824	11.116	9.932	10.406	43.406	56.394	55.962
59.49	58.01	11.907	11.621	9.9388	10.897	45.14	58.29	57.024
58.66	57.196	11.626	11.357	9.703	10.65	44.496	57.468	56.212
60.156	58.66	12.131	11.832	10.128	11.095	45.654	58.948	57.672
57.312	56.684	10.472	9.844	8.8	9.216	43.716	56.976	56.596
56.016	55.462	10.17	9.4982	8.894	9.1416	42.602	55.198	55.218
55.196	54.656	9.9218	9.2644	8.685	8.9226	41.97	54.386	54.414
57.114	56.548	10.369	9.6852	9.0612	9.3166	43.44	56.29	56.302
57.588	57.056	8.874	8.34	7.456	7.814	43.814	57.304	56.982
56.648	56.514	8.5826	8.742	7.6712	8.1942	43.362	56.186	56.186
55.846	55.724	8.3718	8.5438	7.4942	8.0086	42.744	55.39	55.398
59.938	59.5	7.346	6.908	6.172	6.47	45.47	59.704	59.434

JAN_th	MAR_th	MAY_th	JUN_th	JUL_th	AGT_th	SEP_th	NOV_th	DEC_th
[kW]								
59.42	58.95	7.2692	6.7904	5.9772	6.3262	45.06	59.06	58.862
60.882	60.394	7.5832	7.0858	6.241	6.6028	46.178	60.512	60.302
60.988	60.71	4.616	4.338	3.878	4.06	46.06	60.834	60.674
59.1	59.144	4.7856	4.6872	3.865	4.3756	45.11	59.25	59.192
58.31	58.36	4.676	4.5842	3.7728	4.2792	44.51	58.462	58.408
60.27	60.308	4.8734	4.7696	3.9386	4.4526	45.994	60.416	60.356

BIOGRAPHICAL SKETCH

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Khaled Al-Saadi was born in Damascus, Syria on May 29, 1978. He graduated from the University of South Alabama, Mobile, Alabama, with a B.S in electrical engineering in May, 2003. His research interests include fuel cell powered applications.