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Technical design and economic evaluation of a PEM fuel cell system

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Abstract

The main objectives of this study are to develop the economic models and their characterization trends for the common unit processes and utilities in the fuel cell system. In this study, a proton electrolyte membrane fuel cell (PEMFC) system is taken as a case study. The overall system consists of five major units, namely auto-thermal reformer (ATR), water gas shift reactor (WGS), membrane, pressure swing adsorber (PSA) and fuel cell stack. Besides that, the process utilities like compressor, heat exchanger, water adsorber are also included in the system. From the result, it is determined that the specific cost of a PEM fuel cell stack is about US$ 500 per kW, while the specific manufacturing and capital investment costs are in the range of US$ 1200 per kW and US$ 2900 per kW, respectively. Besides that the electricity cost is calculated as US$ 0.04 kWh. The results also prove that the cost of PEM fuel cell system is comparable with other conventional internal engine.

Keywords: Economic analysis; Fuel cell; PEM fuel cell

1. Introduction

A classic way of harnessing energy is through fossil fuel (coal, oil and natural gas) but this method is not environmental friendly. This type of fuel is also becoming increasingly unavailable and the current demands have moved on to other energy resources, such as solar, wind power and fuel cell. Solar energy is produced in limited quantity [1] and control issues surface when there are variations in the photovoltaic (PV) output power at different isolation levels [2]. This results in low energy effectiveness. For nuclear energy, the radioactive waste it generates is a threat to life.

Currently, fuel cell is the best-known solution to the problems of energy effectiveness and environmental pollution caused by the temperature increase due to CO_2 production. The world population is predicted to experience an annual growth of 1.2–2% and is expected to reach 12 billion in the year 2050 [3]. Economic development will therefore expand along with the energy demands, predicted to be 1.5–3.0 times higher in the future. In the meantime, energy resources from oil discovery are dwindling, causing the development of new energy generation technology to increase in importance. Concurrently, issues pertaining to the environment also play a prominent role. Furthermore, clean and environmentally friendly energy technology that can replace fossil fuel is the all-important issue heatedly discussed at present. However, cost issues are the main challenge and indeed critical as far as commercialisation of fuel cell is concerned.

Hydrogen is the lightest, the simplest and one of the most abundant elements in nature. It always comes combined with other elements and has a variety of good properties. Both production and utilization of hydrogen can be emission-free. It can be obtained from a variety of feedstocks (fossil, renewable energy, nuclear). However, besides the unquestionable advantages of hydrogen, several problems occur in developing the required technologies. Among others are diffusion of hydrogen as an energy carrier, which is due to the lack of safe, efficient and cost effective storage; and the separation and sequestration of the CO_2 produced during H_2 production, by storing it in safe locations. Consequently, the fuel source considered in this system is a methanol since it is the most promising organic fuels as compared to hydrogen: high solubility in aqueous, electrolytes, liquid fuel available at low cost, easily handled as well

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Table 1
Shortcut design method for unit process of PEM fuel cell system

Components	Models
ATR and WGS [13]	Plug flow reactor: (1) adiabatic and (2) isothermal
TCM [14]	The membrane length is simplified to number of unit (NTU) and height of transfer unit (HTU)
PSA [15]	The PSA is simplified by using the Klinkenberg solution and introducing the Daud bed utilization factor
Fuel cell stack [16]	Mass balance and the polarization parametric

as transported and stored, high theoretical density of energy (6 kWh kg^{-1}), and an ideal hydrogen carrier as claimed by many experts.

Table 1 shows a percentage growth in fuel cell vehicles and vehicle costs from the year 2000 to 2010 and from 2010 to 2020 at a rate of 104 and 58%, respectively. The growth estimation was based on the number of vehicles in the years 2000, 2010 and 2020 using a learning curve technique or industrial curve that employed a macro model adapted from human activities surveyed in the industry [4]. According to the macro model, the fuel cell cost can be lowered down to the conventional combustion engine level.

2. Cost analysis

Most publications and researches, notables are [4–9], only concentrated on the cost of manufacturing a PEM fuel cell unit by considering hydrogen as a direct feed. Meanwhile, others like [10,11] concentrated on the costs of solid oxide and phosphoric acid fuel cells [12] estimate the fuel cell cost by considering only the fuel processing unit without involving the separation system. There are not many published literatures on the subject of PEM fuel cell cost analysis and economic model development as a system that reckons in the fuel processing system, separation system, system utilities and fuel cell stack. Therefore, this paper attempts to develop the economic models and presents the economic characterisation trends of a PEM fuel cell system. Besides that, this study will also show a detailed cost analysis for capital cost, manufacturing cost and investment cost by taking into account the process units and utilities in the system. On a whole, this section will be divided into two parts (refer to Fig. 1). The first part will discuss about the cost estimation for the hydrogen generation system referring to fuel processing units, separation unit and process utilities while the second part will look into the cost of a fuel cell stack.

2.1. Fuel processing units, separation unit and process utilities

In this study, the hydrogen generation system consists of a fuel processing unit and a hydrogen purification unit. The process units involved are an auto-thermal reformer (ATR), a water gas shift (WGS) reactor, a tubular ceramic membrane module (TCM) and a pressure swing adsorber (PSA) system.

Fig. 1 shows the schematic diagram of a PEMFC system currently developed for this study. The ATR involves in producing

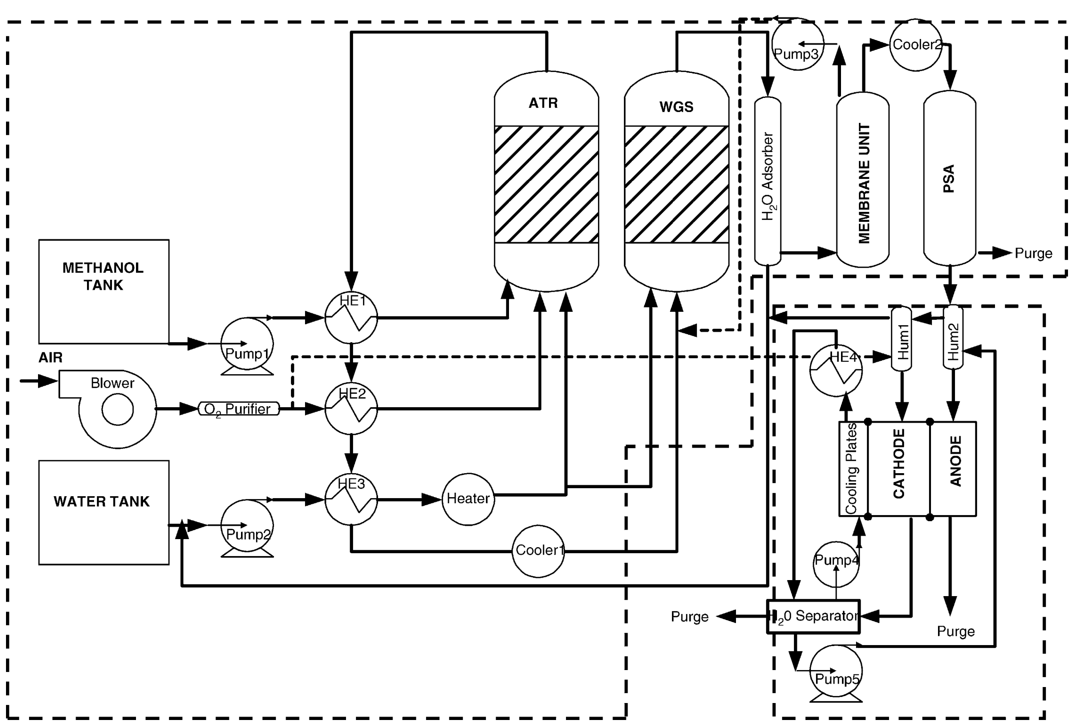

Fig. 1. Schematic diagram of PEM fuel cell system.

H_2 from methanol and steam while co-feeding with oxygen. The auto-thermal reaction combines two reactions, namely the highly endothermic steam reforming (SR),

$$CH_3OH + H_2O \rightarrow CO_2 + 3H_2 \quad (1)$$

and the exothermic partial oxidation (POX).

$$CH_3OH + 0.5O_2 \rightarrow CO_2 + 2H_2 + (CO) \quad (2)$$

Both reactions produce hydrogen at different selectivity, carbon dioxide and carbon monoxide. Hence, the selection of the feed ratio is very important in order to produce high purity hydrogen with the heat of reaction for the endothermic SR process supplied by the heat of reaction of the exothermic POX. The next step in fuel processing is WGS reaction. The production of H_2 from the CO is given by:

$$CO + H_2O \Leftrightarrow CO_2 + H_2 \quad (3)$$

Two separation units used are the TCM and PSA operated in parallel to gain a hydrogen purity of 99.9%. The last unit in the system is the fuel cell stack. Generally, the PEMFC consists of three major components, i.e. an anode, typically featuring a platinum or platinum-containing catalyst, a thin, solid polymeric sheet that acts as an electrolyte, and a cathode that is, also catalysed with platinum. The reactions in a hydrogen/oxygen fuel cell can be written as:

$$\text{Anode}: \quad 2H_2 \rightarrow 4H^+ + 4e^- \quad (4)$$

$$\text{Cathode}: \quad 4H^+ + 4e^- + O_2 \rightarrow 2H_2O \quad (5)$$

$$\text{Overall}: \quad 2H_2 + O_2 \rightarrow 2H_2O \quad (6)$$

The components of the PEMFC system were conceptually designed using the short cut design methods given in Table 1, while the cost estimation was based on the economic modeling shown in Table 2. The cost estimation was also done for the main process utilities involved in the system, such as a compressor, heat exchanger, feed pump, feedback pump and process pump. Other costs that include insulation, control, electricity and piping, taken as fixed values that are independent of the design, are estimated at US$ 450 [10].

The Guthrie–Ulrich base cost method was chosen for the equipment cost calculation because it took into account direct costs, such as construction materials, design conditions and labour, and indirect costs, such as transport costs, overheads and engineering through sums of simple multiplication factors. In general, [15] claims that the equipment purchasing cost changes with time due to inflation:

$$C_{P_2} = C_{P_1}\left(\frac{I_2}{I_1}\right) \quad (7)$$

with C_{P_2} as the equipment purchasing cost at time 2, C_{P_1} as the equipment purchasing cost at time 1, and I_n as the cost index at time n. The cost index in this study will follow the Chemical Engineering Plant Cost Index (CEPCI).

The equipment purchasing cost also depends on the size generally summed up as:

$$C_{P_2} = C_{P_1}\left(\frac{S_2}{S_1}\right)^{\alpha_n} \quad (8)$$

with C_{P_2} as the equipment cost for equipment size 2, C_{P_1} as the equipment cost for equipment size 1, S_2 as the equipment size 2, S_1 as the equipment size 1 and α_n as the cost index. The total equipment installation cost for the processing unit and process utilities is given as the manufacturing cost [18].

Non-manufacturing cost, C_{NM} consists of contingency cost, α_{cont} and fee cost, α_{fee}. The total cost of the complete module for the whole plant is given by:

$$C_{NM} = \sum_{i=1}^{n}(1 + \alpha_{cont} + \alpha_{fee})C_{M,i} \quad (9)$$

with α_{cont} and α_{fee} estimated at 15 and 3%, respectively [15].

The cost of purchasing raw materials, catalysts, and other operating supplies including a part of the product in the pipes, equipments, and plant containers is given as the working capital, C_{WC} and it is at 15% of the total investment cost, C_I, which consists of the sums of module cost and working capital:

$$C_I = C_M + C_{WC} \quad (10)$$

Apart from that, the total fixed capital cost, C_C is 80% of the investment cost [18] 1988:

$$C_{FC} = 0.8C_I \quad (11)$$

2.2. PEM fuel cell stack

The fuel cell stack cost can be estimated as follows [4]:

$$C = \frac{(C_m + C_c + C_b + C_{pt} + C_o)}{P + C_a} \quad (12)$$

$$C_{pt} = C_{wpt} \times Y_{pt} \quad (13)$$

Table 2
Economic models for unit and utilities process of PEM fuel cell system [17–19]

Components	Cost (US$)	α, β	Base cost, C_0 (10^3) (US$)
ATR	$C_{ATR} = C_0(V_1/V_0)^\alpha$, V_1 = reactor volume	0.6	1
WGS	$C_{WGS} = C_0(V_2/V_0)^\alpha$, V_2 = reactor volume	0.6	1
TCM	$C_{TCM} = C_0(n/n_0)^\alpha$, n = pore diameter/thickness of membrane	0.73	1.8
PSA	$C_{PSA} = C_0(L/L_0)^\alpha(D/D_0)^\beta$, L = bed length, D = bed diameter	0.81, 1.05	1.0
Air purifier	$C_{purifier} = C_0(L/L_0)^\alpha(D/D_0)^\beta$, L = bed length, D = bed diameter	0.78, 0.98	0.69
Compressor	$C_{compressor} = C_0(P/P_0)^\alpha$, P = output power	0.77	23
Heat exchanger	$C_{HE} = C_0(A/A_0)^\alpha$, A = surface area	0.024	0.3

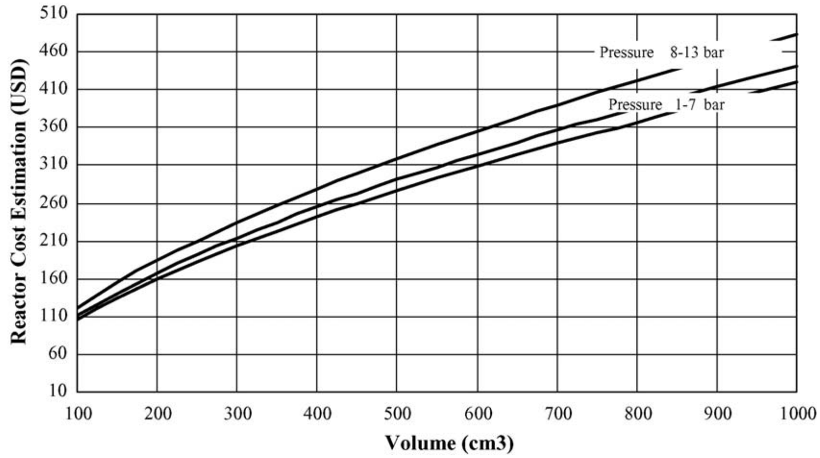

Fig. 2. Cost prediction for reactor fuel processing unit in fuel cell.

$$P = 10 \times V \times i_n \quad (14)$$

with C as the stack cost per kW (US$ per kW), C_m as the membrane cost, C_c as the electrode cost, C_b as the bipolar plate cost, C_{pt} as the platinum catalyst cost, C_{wpt} as the dead weight of platinum, C_a as the installation cost, V as the cell voltage, P as the output power density and i_n as the current density.

The fuel cell electricity cost, EC, is given as follows [6]:

$$\mathrm{EC} = \left[\frac{\left(\frac{C_F \mathrm{AEP}}{\bar{\eta}}\right) + \left\{ C_{\mathrm{fix}} + C_{\mathrm{cell}} \left(\frac{\dot{W}}{V_C A_C A_{\mathrm{cell}}} \right) \right\} \left(\frac{i_r (1+i_r)^{n_y}}{(1+i_r)^{n_y - 1}} \right)}{\mathrm{AEP}} \right] \quad (15)$$

with C_F as the fuel cell cost, AEP as the annual fuel cost, $\bar{\eta}$ as the fuel cell effectiveness average, C_{fix} as the fuel stack cost, C_{cell} as the fuel cell cost, A_{cell} as the active surface area of the cell, i_r as the annual interest and n_y as the life span of the fuel cell.

3. Result and discussion

Figs. 2–6 estimate the equipment cost for the reactor systems, membrane unit, adsorber unit, compressor and heat exchanger based on Table 2 and Eqs. (7) and (8). The cost index used was based on the year 2003 as 401. The reactor cost estimation in Fig. 2 was done on a stainless steel reactor for a 100–1000 cm^3 volume range and at an operating pressure in the range of 1–13 bars. Fig. 6 can be used to estimate the cost for the fuel cell processing unit like ATR, WGS and preferential oxidation reactor (PROX).

In Fig. 3, the membrane cost was plotted based on the membrane pore sizes in the range of 1–5 nm. It shows that the membrane cost decreases with the increase in membrane pore diameter. This agrees with [19] who find that the membrane charge density does not affect the membrane cost but the membrane cost is very much affected by the membrane pore diameter.

Fig. 4 gives the empty module cost for the adsorber system based on the length and diameter of the adsorption bed layer. The range of length chosen was within 10–30 cm, whereas the range of layer diameter was within 10–20 cm. As with the cost of reactor, the adsorbent system increases with the bed length and diameter. The effect or factor of pressure is also shown because the adsorbent system is normally operated at high pressure.

Figs. 5 and 6 give the characteristic curve for the compressor and heat exchanger. The cost estimation for the compressor system was based on five compressor types as in Fig. 5 at a range of

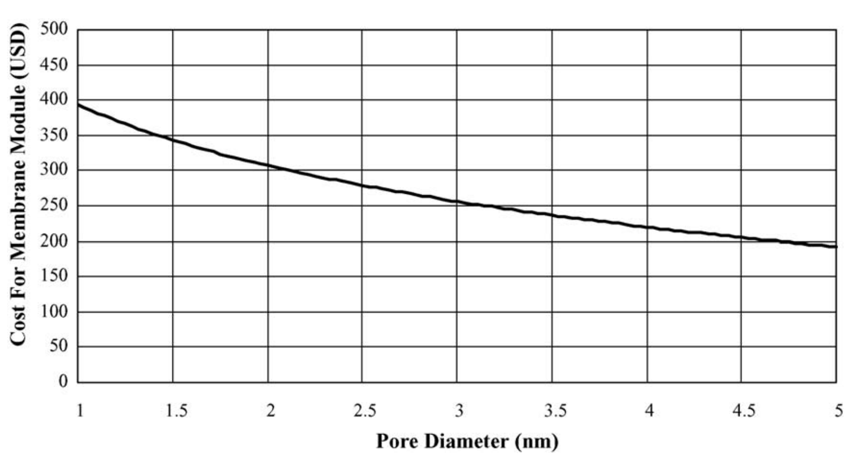

Fig. 3. Cost prediction for tubular ceramic membrane module.

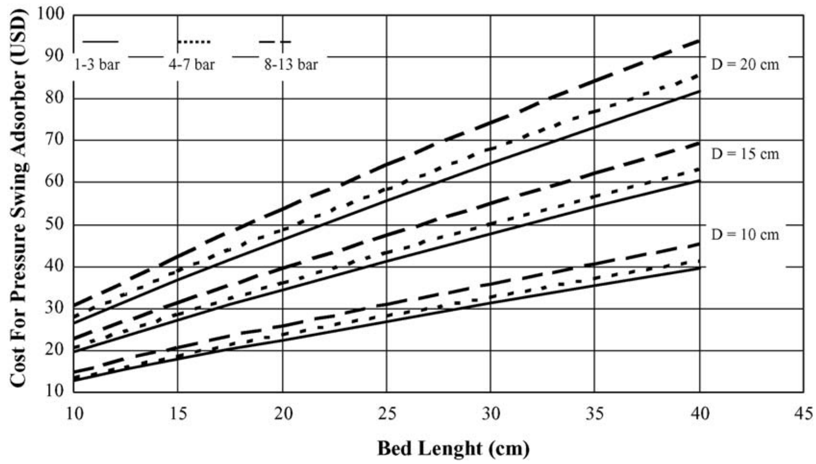

Fig. 4. Cost prediction for pressure swing adsorber.

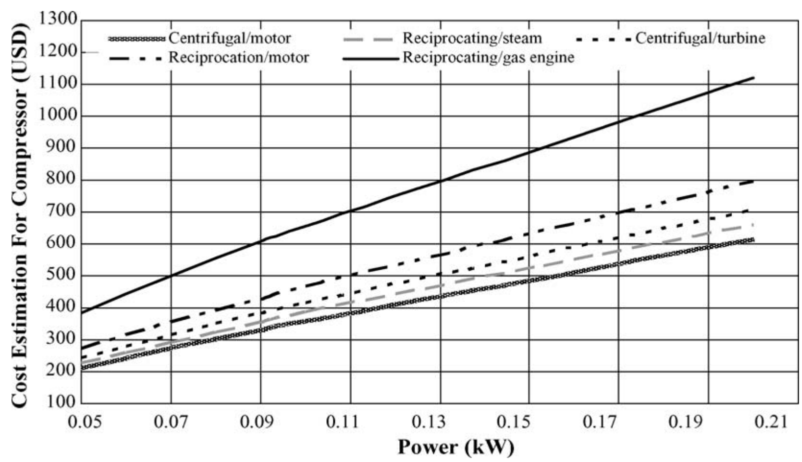

Fig. 5. Cost prediction for compressor unit.

power, 50–200 W. The cost for a reciprocal compressor type/gas engine was found to be the highest. For the heat exchanger design, the overall heat transfer coefficient and cost correction factor for the heat exchanger were taken as 37.5 W m^{-2} K^{-1} [10] and 1.3, respectively, after taking into account the heat exchanger type, column pressure and construction materials [17]. In Fig. 6, the heat exchanger price is almost constant at US$ 400 per unit for heat surface area in the range of 0.05–0.3 m^2.

Fig. 7 gives the cost estimation percentage of the components in the PEM fuel cell stack based on Tables 3 and 4.

Fig. 7 shows that the highest cost is incurred by the bipolar plate, i.e. 38%, followed by the cost for the electrode, membrane, and catalyst (platinum), i.e. 32, 12 and 11%, respectively. The results agree with the findings from previous studies by [4,5] as shown in Table 5. Meanwhile, Fig. 8 shows the specific cost estimation for each component per kW in PEM fuel cell stack.

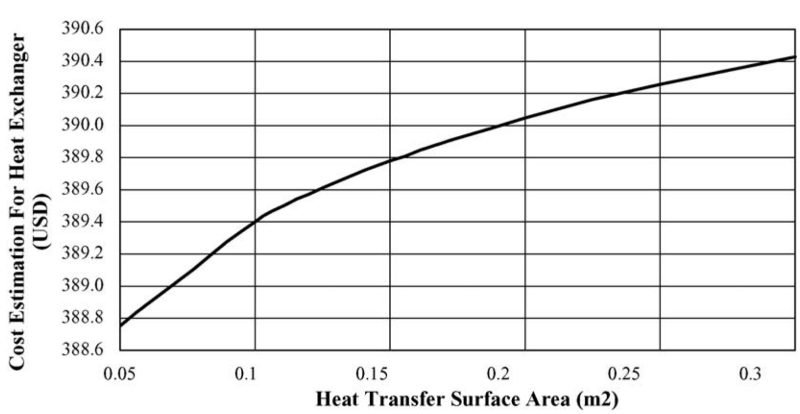

Fig. 6. Cost prediction for heat exchanger unit.

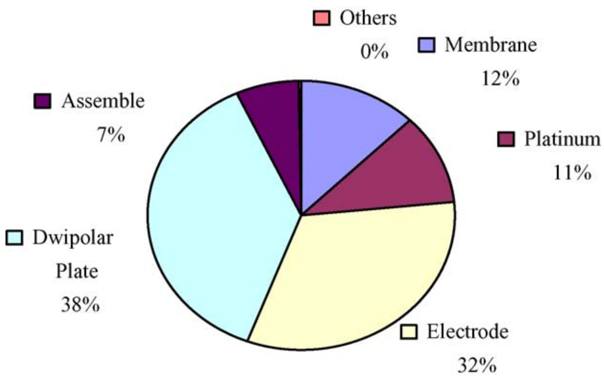

Fig. 7. Percentage of components costs in fuel cell stack.

Apart from that, the cost of a single cell is very much influenced by the amount of current and active cell area as shown in Fig. 9, which gives the cost estimation of a single cell at voltage, $V = 0.7$ V and current density, 0.9 A cm^{-2}. The stack cost was found to change with the active surface area. For this study, the price of a plate with an active area of 50 cm^2 was estimated to be within US$ 20–30.

Table 3
Specific cost for components in PEM fuel cell stack [4]

Components	Cost (US$)
Nafion membrane	550 m^{-2}
Platinum (2–4 g m^{-2})	32–64 m^{-2}
Electrode (maximum 0.8 mm for single cell)	1423 m^{-2}
Bipolar plate (maximum 4 mm)	1650 m^{-2}
End plate, bolt, plastic frame	15.4 m^{-2}
Assemble	7.7 kW

Table 6 gives the design parameters for the process units and utilities calculated based on the short cut design method (refer to Table 1). The manufacturing cost and installation for the equipment in the system are listed in Table 7.

Fig. 10 summarises the major cost estimation for a 5 kW PEM fuel cell system by taking into consideration the hydrogen generation system and stack. From the table, the specific cost for stack is at a rate of 500 per kW and the result agrees with other studies listed in Table 8.

However, it is observed that the model given by [5] estimates the cost for stack as low as US$ 200–300 per kW. This is because

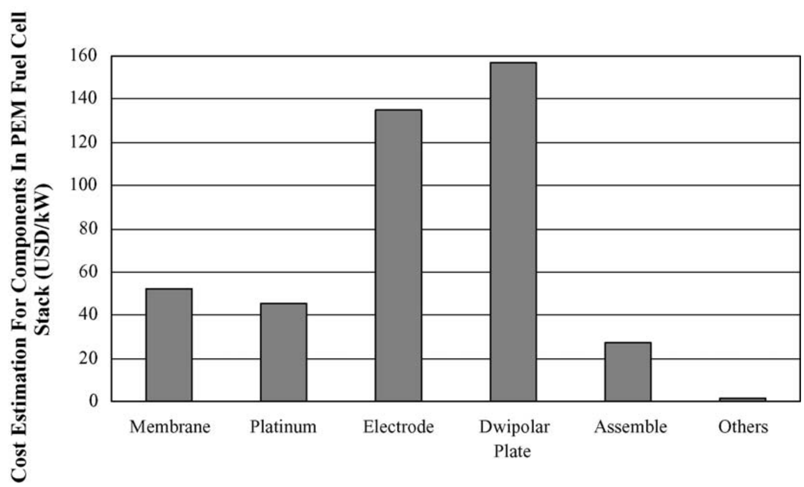

Fig. 8. Cost estimation for components in fuel cell stack.

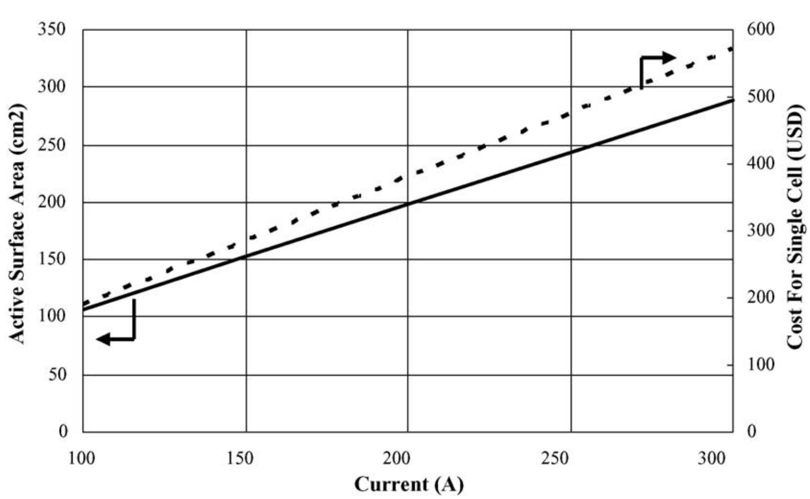

Fig. 9. Cost estimation for single cell.

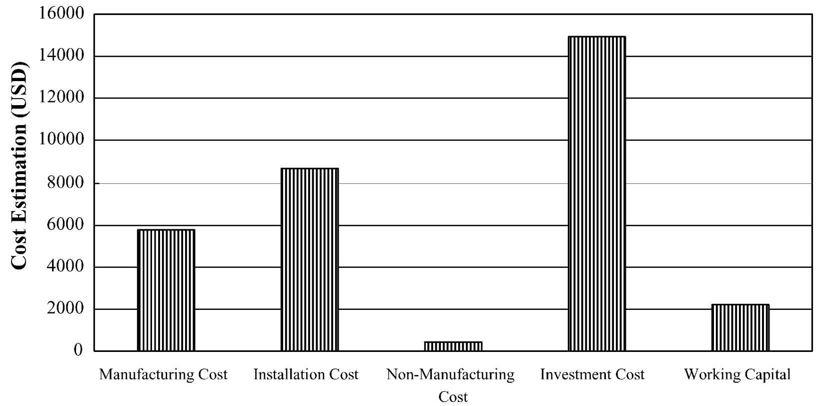

Fig. 10. Major cost estimation for 5 kW PEM fuel cell system.

the cost is referred to as high output capacity of up to 500,000 vehicle units as predicted by [4]. Meanwhile, the specific manufacturing and investment costs were estimated as US$ 1200 and US$ 2900 per kW, respectively. These results were also comparable to other studies as given in Tables 9 and 10.

Fig. 11 presents the cost percentage for process units and utilities. From the figure, it is observed that the stack is found to be the most expensive component in a fuel cell system, i.e. 42%, followed by the heat exchanger unit, i.e. 28%. This cost factor is the main reason why the stack design and heat recovery system are very much emphasised in a fuel cell system design because both exert a significant influence on the cost of the overall system, apart from the fuel resource cost.

An electricity cost comparison between this study and the previous ones are shown in Table 11 based on the information given in Table 12 The electricity cost in this study is estimated at US$ 0.04 kWh based on Eq. (15). The cost value was found to be almost the same as the values found by other studies.

Lastly, the fuel cell cost per kW has also been compared with the conventional combustion engine as shown in Table 13 and the fuel cell cost is found to be almost the same as the current conventional engine cost, ICE. The increased factor in the ICE cost from US$ 500–1000 to 1000–1500 was proven by [4] in their study. Therefore, the advantage is on the fuel cell usage rather than ICE. Furthermore, fuel cell usage is able to reduce

Table 4
Design parameter for fuel cell stack in this study

Power output (kW)	5
Voltage for single cell (V)	0.7
Current (A)	225
Power density ($mW\,cm^{-2}$)	660
Current density ($mA\,cm^{-2}$)	900
Membrane resistance ($\Omega\,cm^{-1}$)	0.05
Type of membrane	ETEK MEA Nafion 117
Membrane thickness (μm)	200
Electrode thickness (μm)	260
Active surface area ($cm^2\,cell^{-1}$)	250
Length × width	15.7 cm × 15.7 cm
Number of cell	30

Table 5
Comparion of the percentage cost of components in PEM fuel cell stack with other studies

Component (%)	[4]	[5]	This study
Electrode	38.3	52	32
Bipolar plate	45	15	41
PEM and catalysts	15.3	18	25
Others	1.4	15	2

Table 6
Design parameters

No.	Number of units	Name	Parameter
R-1	1	ATR	$V = 250\,cm^3$, $P = 3$ bar, $T = 200\,°C$
R-2	1	WGS reactor	$V = 400\,cm^3$, $P = 5$ bar, $T = 250\,°C$
M-1	1	TCM	$n = 1.5$ nm, $P_1 = 5$ bar, $P_2 = 1$ bar
UP-1	1	Air purifier	$L = 15$ cm, $D = 10$ cm
UP-2	1	Water separator	$L = 15$ cm, $D = 10$ cm
UP-3	1	PSA	$L = 25$ cm, $D = 20$ cm, $P = 6$ bar
C-1	1	Compressor	$K = 0.09$ kW
H-1	1	Heat exchanger	$0.02\,m^2$
H-2	1	Heat exchanger	$0.01\,m^2$
H-3	1	Heat exchanger	$0.08\,m^2$
H-4	1	Heat exchanger	$0.04\,m^2$
P-1	5	Feeding pump	–
S-1	30	Fuel cell stack	$A = 250\,m^2$, $P = 1$ bar, $T = 70\,°C$

Table 7
Manufacturing cost estimation for equipment in 5 kW PEM fuel cell system (cost index = 401 year 2003)

Equipment	Cost (US$)
R-1	170
R-2	230
M-1	350
UP-1	20
UP-2	20
UP-3	55
C-1	320
H-1	400
H-2	400
H-3	400
H-4	400
P-1	106 × 5
Stack	2500
Manufacturing cost	5795

Table 8
Comparison of specific cost of fuel cell stack with other studies

References	System	Cost per kW (US$)
[20]	PEMFC	500–1000
[21]	PEMFC	500–1000
[22]	PEMFC	500–1000
[23]	PEMFC	500–1000
[24]	PEMFC	400–1000
[25]	PEMFC	750–1000
[5]	PEMFC	200–300
[4]	PEMFC	400–700
This study	PEMFC	500

Table 9
Comparison of specific cost of manufacturing with other studies

References	System	Cost per kW (US$)
[26]	PEMFC (light industry)	1000–2000
[23]	PEMFC (automotive industry)	1000–2000
This study	PEMFC (automotive industry)	1200

Table 10
Comparison of specific cost of investment with other studies

References	System	Cost per kW (US$)
[12]	PEMFC	2600–3000
[22]	PEMFC	2500–3000
[11]	PAFC	3000
[7]	PEMFC	2500
[10]	SOFC	2500–3000
[27]	PEMFC	2000–3000
This study	PEMFC	2900

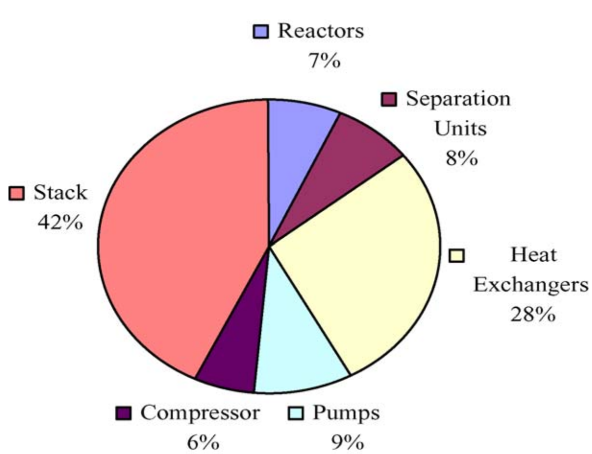

Fig. 11. Percentage cost for unit and utilities in PEM fuel cell system.

Table 11
Comparison of electricity cost with other studies

References	kWh (US$)
[26]	0.04–0.24
[22]	0.070
[7]	0.040
[11]	0.040
This study	0.040

Table 12
Data for electricity cost estimation

Parameter	Value
Power output (kW)	5
Hydrogen cost (US$ per GJ)	10
Capacity factor of fuel	0.9
Life time (years)	5
Annual rate (%)	7

Table 13
Cost comparison Of PEM fuel cell system with ICE

References	System	US$
[20]	ICE	500–1000
[23]	ICE	500–1000
[21]	ICE	1300–1500
[27]	ICE	1000–1200
This study	PEMFC	1200

the environmental pollution as well as the world demand of fossil fuels.

4. Conclusion

As a conclusion, this study proves that The PEM fuel cell system using methanol as the fuel source predicts the following:

- The highest cost in the stack is for the bipolar plate, i.e. 41%, followed by the cost for the electrode, membrane and catalyst, i.e. 34, 13 and 12%, respectively.
- The stack is the most expensive component in a fuel cell system, i.e. around 42% followed by the heat exchanger unit, i.e. 28% from the total cost.
- The specific stack cost was found at a rate of US$ 500 per kW.
- The specific manufacturing cost was found at a rate of US$ 1200 per kW.
- The specific investment cost for one fuel cell unit was found at a rate of US$ 2900 per kW.
- The electricity cost was estimated at a rate of US$ 0.04 kWh.
- The fuel cell cost estimated in this study is as competitive as the conventional combustion engine cost.

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