Chapter 5

PEM Fuel cell special Features

5.1 Comparison between batteries and fuel cells for photovoltaic system backups

The energy storage devices, batteries continue to be applied to electric power utilities for drawing benefits of peak shaving and load leveling. Battery energy storage facilities provide the utilities additional dynamic benefits such as voltage and frequency regulation, load following, spinning reserve, and power factor correction [25] [26]. Applications of the storage batteries to power systems are predicted to grow in the future due to those benefits coupled with the ability to provide peak power.

Fuel cell power generation is another attractive option for providing power for electric utilities and commercial buildings because of its high efficiency and environmentally benign feature. This type of power production is especially economical (i) where potential users are faced with high cost in electric power generation from coal or oil, (ii) where environmental constraints are stringent, or (iii) where load constraints of transmission and distribution systems are so tight that their new installations are not possible.

Photovoltaic power outputs vary depending mainly upon solar insulation and cell temperature. Since control of the ambient weather conditions is beyond human beings' capability, it is almost impossible for human operators to control the PV power itself. Thus, a PV power generator may sometimes experience sharp output power fluctuations owing to intermittent weather conditions, which causes control problems such as load frequency control, generator voltage control and even system stability analysis. There is, therefore, a need for backup power facilities in the PV power generation. Batteries and fuel cells are the most likely technologies to provide the PV system with backup power because these two backup power sources contain some distinct features in common. Those characteristics are listed below.

A. Fast Load-Response Capability
B. Modularity in Production
C. Highly Reliable Sources
D. Flexibility in Site Selection (Environmental Acceptability)

Comparison between battery backup and fuel cell backup for PV power supplement is made in the following sections.

1. Efficiency

Power generation in fuel cells directly convert available chemical free energy to electrical energy rather than going through heat exchange processes. Thus, it can be said that fuel cells are a more efficient power conversion technology than the conventional steam-applying power generations. Electricity, the conventional power generator has several steps for electricity generation and each step requires a certain amount of energy loss. Fuel cell power systems have around 40-60% efficiencies depending on the type of electrolytes and independent of size. Battery power systems themselves have high energy efficiencies, but their overall system efficiencies from raw fuel (mostly coal or nuclear) through the batteries to converted ac power are reduced to below 30%. This is because energy losses take place whenever one energy form is converted to another.

2. Capacity Variation

As the battery discharges, its terminal voltage gradually decreases. The fall of the terminal voltage on discharge is due to its internal resistance. However, the internal resistance of a battery varies with its cell temperature and state of discharge. Fuel cell systems have a greater efficiency at full load and this high efficiency is retained as load diminishes, so inefficient peaking generators may not be needed.

3. Flexibility in Operation

Fuel cells have an advantage over storage batteries in the respect of operational flexibility. Batteries need several hours to be taken for recharging after they are fully discharged. During discharge the batteries' electrode materials are lost to the electrolyte, and the electrode materials can be recovered during the recharging process. Fuel cells, on the other hand, do not undergo such material changes. The fuel stored outside the cells can quickly be replenished, so they do not run down as long as the fuel can be supplied.

4. Cost

The history of fuel cell equipment costs has shown that the price of fuel cells has dropped significantly as the commercial market grows and the manufacturing technology becomes mature.

5.2 Efficiency and hydrogen consumption Efficiency

The efficiency of a fuel cell system is defined as the percentage of the fuel that is converted to electric energy. This is made by comparing the output electric energy with the consumed chemical energy. The common value of chemical energy is the lower heating value (LHV) of the fuel. High efficiency means low hydrogen consumption. A fuel cell system that delivers 1000 W net power will consume hydrogen according to the table

$$Eficiency = \frac{Electricity}{Fuel} \tag{5.1}$$

Table 5.1 - Efficiency and hydrogen consumption

Efficiency-%	Hydrogen(nl/min)	Hydrogen (g/h)
35	17.1	86.0
40	14.9	75.3
45	13.3	66.9
50	11.9	60.2

Previously shown that it was the 'Gibbs free energy' that is converted into electrical energy. This energy would be converted into electrical energy, and the efficiency could be said to be 100%. However, this is the result of choosing one among several types of 'chemical energy' and can be indicated the following that it also changes with pressure and other factors. All in all, to define efficiency as

$$\text{Effiency} = \frac{\text{Electrical energy produced}}{\text{Gibbs free energy change}} \tag{5.2}$$

This is not very useful, and is rarely done, as whatever conditions are used the efficiency limit is always 100%. Since a fuel cell uses materials that are usually burnt to release their energy, it would make sense to compare the electrical energy produced with the heat that would be produced by burning the fuel. This is sometimes called the *calorific value*, though a more precise description is the change in 'enthalpy of formation'. Its symbol is $\Delta\bar{h}_f$. As with the Gibbs free energy, the convention is that $\Delta\bar{h}_f$ is negative when energy is released. So to get a good comparison with other fuel-using technologies, the efficiency of the fuel cell is usually defined as 2.3

$$\text{Effiency} = \frac{\text{Electrical energy produced per mole of fuel}}{-\Delta\bar{h}_f} \qquad (5.3)$$

However, even this is not without its ambiguities, as there are two different values that we can use for $\Delta\bar{h}_f$. For the 'burning' of hydrogen

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O\ (\text{steam})$$

$$-\Delta\bar{h}_f = -241.83\ \text{kJmol}^{-1}$$

Whereas if the product water is condensed back to liquid, the reaction is

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O\ (\text{liquid})$$

$$\Delta\bar{h}_f = -285.84\ \text{kJmol}^{-1}$$

The difference between these two values for $\Delta\bar{h}_f$ (44.01 kJ mol−1) is the molar enthalpy of vaporization of water. The higher figure is called the *higher heating value* (HHV), and the lower, quite logically, the 'lower heating value' (LHV). Any statement of efficiency should say whether it relates to the higher or lower heating value. If this information is not given, the LHV has probably been used, since this will give a higher efficiency figure. It is clear that there is a limit to the efficiency as defined it as in equation 2.3.The maximum electrical energy available is equal to the change in Gibbs free energy, so

$$\text{Maximum Effiency possible} = \frac{\Delta\bar{g}_f}{\Delta\bar{h}_f} \times 100\% \qquad (5.4)$$

This maximum efficiency limit is sometimes known as the 'thermodynamic efficiency'. Table 5.2 gives the values of the efficiency limit, relative to the HHV, for a hydrogen fuel cell.

Table-5.2 Efficiency Limits for PEMFC

Form of water product	**Temperature C**	$\Delta\bar{g}_f$ **kJmol^{-1}**	**Max EMF – V**	**Efficiency limit %**
Liquid	25	-237.2	1.23	83
Liquid	80	-228.2	1.18	80
Gas	100	-225.2	1.17	79
Gas	200	-220.3	1.14	77
Gas	400	-210.3	1.09	74
Gas	600	-199.6	1.04	70
Gas	800	-188.6	0.98	66
Gas	1000	-177.4	0.92	62

$\Delta\bar{g}_f$, maximum EMF (or reversible open circuit voltage),and efficiency limit(HHV basic) for hydrogen fuel cells

5.3 Efficiency and the Fuel Cell Voltage

It is clear from Table 2.2 that there is a connection between the maximum EMF of a cell and its maximum efficiency. The operating voltage of a fuel cell can also be very easily related to its efficiency. This can be shown by adapting equation 5.5.

$$E = \frac{-\Delta\bar{g}_f}{2F} \qquad (5.5)$$

If all the energy from the hydrogen fuel, its 'calorific value', heating value, or enthalpy of formation, were transformed into electrical energy, then the EMF would be given by

$$E = \frac{-\Delta\bar{h}_f}{2F} = 1.48\ \text{V if using the HHV or 1.25 if using the LHV} \qquad (5.6)$$

These are the voltages that would be obtained from a 100% efficient system, with reference to the HHV or LHV. The actual efficiency of the cell is then the actual voltage divided by these values, or

$$\text{Cell Effciency} = \frac{V_c}{1.48}\ 100\%\ (\text{ with reference to HHV}) \qquad (5.7)$$

However, in practice it is found that not all the fuel that is fed to a fuel cell can be used, for reasons discussed later. Some fuel usually has to pass through un-reacted. A fuel utilization coefficient can be defined as

$$\mu_f = \frac{\text{mass of fuel reacted in cell}}{\text{mass of fuel input to cell}} \qquad (5.8)$$

This is equivalent to the ratio of fuel cell current and the current that would be obtained if all the fuel were reacted. The fuel cell efficiency is therefore given by

$$\text{Effciency}, \eta = \mu_f \frac{V_c}{1.48}\ 100\% \qquad (5.9)$$

5.4 Why is the efficiency not 100%

All energy conversions will lead to a certain amount of degradation of energy quality. All input energy will not come out as output. Some of the energy will be lost as heat. Fuel cell development work aims to maximize the output by minimizing the losses. The losses could be traced to either the stack or the components of system. The fuel cell stack converts the chemical energy to electric energy. The electrochemical process and the conductance of current will however lead to losses and heat generation. These losses always increase at high current outtake. Stack design and operating conditions could be optimized to reduce the losses. There are two kinds of losses at system level: Fuel losses and electric losses. The fed hydrogen will be converted to electricity in the stack. Small amounts of hydrogen will however be purged out of the system. This fuel will represent a minor loss that must be considered when establishing the efficiency. The last thing to consider is the internal components of the system. They will consume some of the power delivered from the stack. Components like the air blower, cooling pump, cooling fans, valves and control circuits will support the stack and consume electric power. The net power delivered from the system will be slightly lower than the gross power from the stack, because of the internal consumption. The overall efficiency of the system takes all these losses into account.

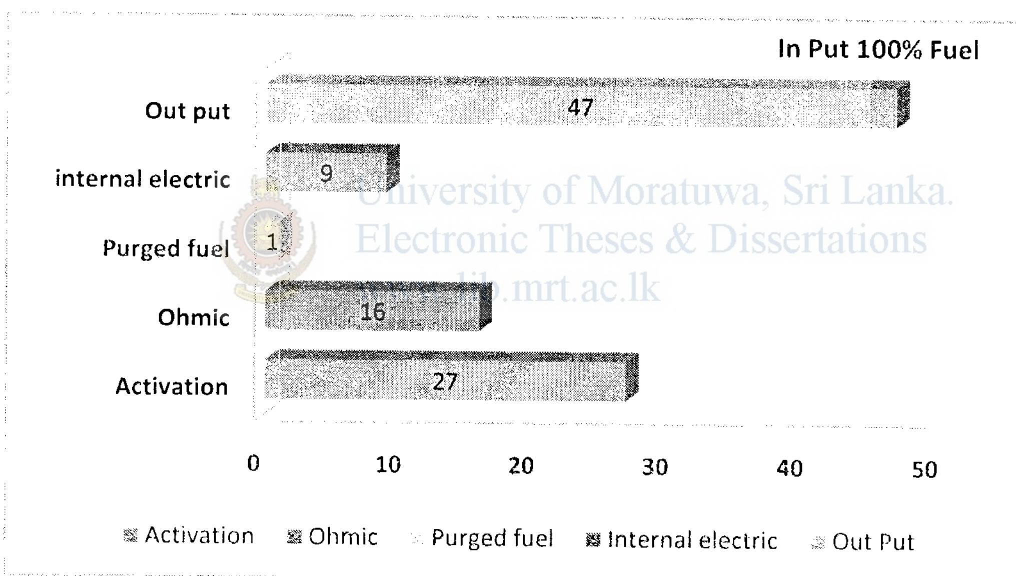

Figure-5.1 The overall losses in PEMFC system

5.6 Implementation of PEMFC system

5.6.1 Solar Hydrogen PEM Fuel cell system for a home

The development of a hydrogen economy can have many benefits for the environment. It could play a role in reducing global warming and air quality problems in and around major cities. A large percentage of the pollution that contributes to these issues is easily traced to the power demands of buildings and the emissions of vehicles. Provided hydrogen can be produced from renewable resources at reasonable costs, the use of hydrogen fuel cell technology in buildings and vehicles would effectively eliminate a major contribution to air pollution problems and global warming.

Table-5.3 The Properties of Fuel cells

Fuel Cell	Electrolyte	Operating Temperature	Electrical Efficiency	Fuel Oxidant
Alkaline FC AFC	Potassium hydroxide(KOH) solution	Room temperature to 90C	60-70%	H_2 ,O_2
Proton Exchange Membrane FC PEMFC	Proton Exchange membrane	Room temperature to 80C	40-60%	H_2,O_2,Air
Direct Methanol FC DMFC	Proton exchange membrane	Room temperature to 130C	20-30%	CH_3OH,O_2, Air
Phosphoric acid FC PAFC	Phosphoric acid	160-220C	55%	Natural gas, biogas, H_2,O_2,Air
Molten Carbonate FC MCFC	Molten mixture of alkali metal carbonates	620-660	65%	Natural gas, biogas, Coal Gas, H_2,O_2,Air
Solid Oxide FC SOFC	Oxide ion conducting ceramic	800-1000C	60-65%	Natural gas, biogas, Coal Gas, H_2,O_2,Air

The cost of solar hydrogen production needs to be competitive with similar hydrogen production processes for it to be successful in the hydrogen market. As a prototype, constructing a system today is relatively expensive. However, efficient and cost effective design and mass production can significantly reduce future production costs. The projected cost for such a system will be evaluated and compared to similar hydrogen production systems. Table 5.4 shows the cost analysis of solar hydrogen PEM fuel cell system for a single home.

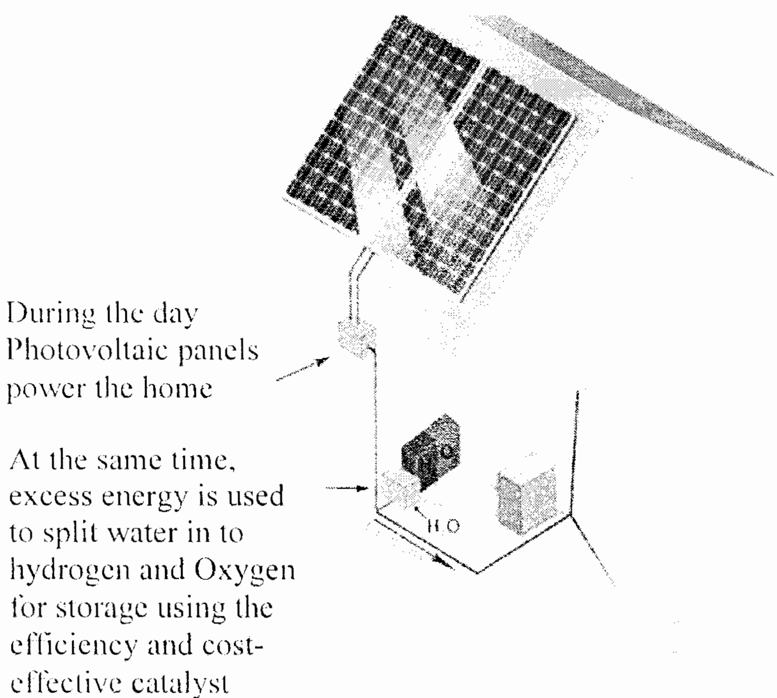

Figure 5.2- Solar hydrogen Fuel cell system for a Home

Table 5.4- Cost analysis of a solar hydrogen Fuel cell system for a Home

Power needed	1200	kwh/yr
Fraction coverage	98	%
AC output needed	0.75	kw
Module area	15.00	sqft
Area needed	183	sqft
Modules	12	
Power per module	65	watts
DC power	793	watts
Inverter efficiency	94	%
AC power	746	watts
Module cost rate	$2.10	watt
Module Cost	$1,666	
Inverter cost rate	$0.50	watts
Inverter cost	$397	
Installation cost rate	$1.00	per watt
Installation cost	$793	
Fuel backup days	2	day
Fuel storage needed	7	kwh
Fuel cell cost rate	$125	kwh
Fuel cell cost + Gas St'ge + relifef valves+ tubings	$3,500	
FC replacement time	15	yr
Total cost	**$6,356**	
Capacity factor	18	%
CA equiv array	1576.8	kwh/year/kw
Output per year	1176	kwh
Degradation rate	-0.10	%/yr
Maintenance cost per year per kw	$10.00	
Maintenance cost per year FC	$233.33	
Maintenance cost per year	$7	yr
Maintenance cost per year w/ FC	$241	yr

Output after year:	25	50	75	100
%	97.5	95.1	92.8	90.5
Total power delivered - kwh	29037	57356	84977	111914
Cost w/ maint w/out FC	$6,543	$6,729	$6,916	$7,102
Cost per kwh amortized w/out FC	**$0.23**	**$0.12**	**$0.08**	**$0.06**
Cost including maintenance w/ FC	$12,376	$18,396	$24,416	$30,435
Cost per kwh amortized w/ FC	**$0.43**	**$0.32**	**$0.29**	**$0.27**
Typical CO2 emission from oil	583	kg/MWh		
Power per lifetime per MW of PV (MWh)	39420	78840	118260	157680
Emissions saved (kg)	16928	33439	49541	65246
Typical gas consumption per MWh	125	gal		
Gas saved (gal)	3630	7170	10622	13989

5.6.2 Solar Hydrogen PEM Fuel cell Basic model

The solar hydrogen FC set contains two fuel storage cylinders, reversible PEMFC unit and the load(motor).Reversible PEMFC can act as both electrolyzer mode and Fuel cell mode. The solar module converts radiant energy into electrical energy to power the electrolyser. The electrolyser breaks water into its basic constituents of hydrogen and oxygen. These gases are stored in the graduated cylinders. When electrical power is required, the PEM fuel cell recombines the stored gases to form water, and release heat and electricity. The systematic fuel cell unit is shown in figure 5.3.

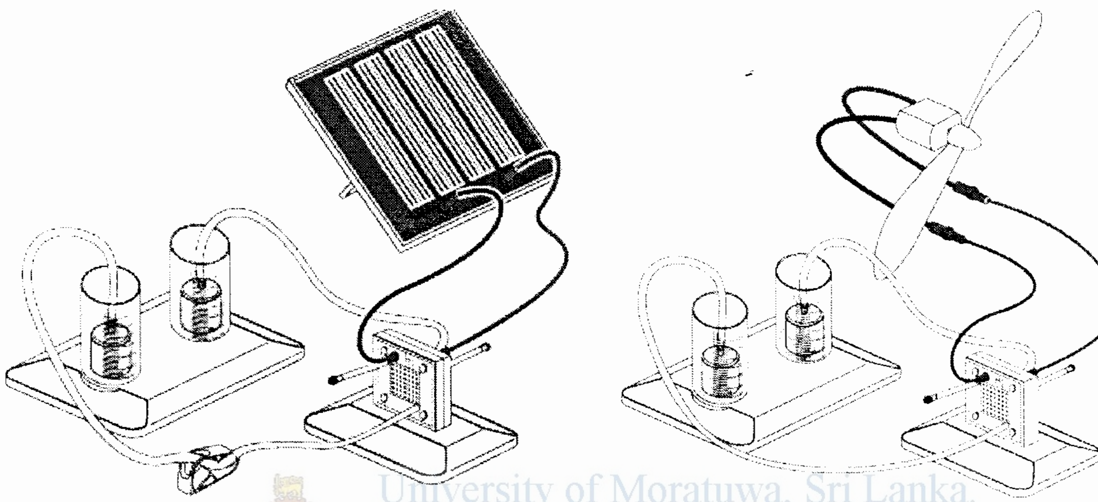

Figure 5.3- Fuel cell basic model; Electrolyzer mode -Left and FC mode-right

5.6.2 PEMFC Stack principle

Table 5.5- PEMFC Experimental data

Length	*Height*	*Area cm2*	*Current*		*No of Stacks*	*Voltage*		*Power=VI*	
1	1	1	0.5	Amp	1	0.03	Volts	0.015	Watt
1	2	2	1	Amp	1	0.06	Volts	0.06	Watt
2	2	4	2	Amp	1	0.12	Volts	0.24	Watt
4	4	16	8	Amp	1	0.48	Volts	3.84	Watt
5	5	25	12.5	Amp	1	0.75	Volts	9.375	Watt
6	6	36	18	Amp	1	1.08	Volts	19.44	Watt
5	6	30	15	Amp	1	0.9	Volts	13.5	Watt
4	6	24	12	Amp	1	0.72	Volts	8.64	Watt
3	3	9	4.5	Amp	1	0.27	Volts	1.215	Watt

According to the table 5.5, the fuel cell dimensions and its corresponding power output is given. In the third column it shows the fuel cell stack area depending on its length and height. According to the stack principle the data is calculated. The standard stack principle is given as "Once cell (anode +membrane cathode) can deliver 0.6 voltages. To get enough power out of the fuel cell, several calls are pilled in a stack. Gas plates are placed between the cells to distribute the hydrogen and oxygen gas to the membranes. The area of the membrane gives the current.1 cm2 delivers 0.5 Amp".

Table 5.6 shows the experimental data of PEM electrolyzer outputs. Table shows the Hydrogen and oxygen production due to the water electrolyzing. Also it shows the comparison between reversible actions of PEMFC.

Table 5.6- Electrolyzer Output Data

Elec 'zer Pow er-W	*Char geing Time Mins*	*No of cells in Elzr*	*Produ ced O2- cm3*	*Prod uced H2 - cm3*	*FC out put*		*Wor king time- min*	*Ele'zer I/P- Wmin*	*FC O/P Wmin*
1	2	1	7.5	15	500	mW	8	2	4
1	1	1	3.75	7.5	500	mW	8	1	4
1	4	1	15	30	500	mW	8	4	4
3	1	3	11.25	22.5	1500	mW	24	3	36
2	2	2	15	30	1000	mW	16	4	16
50	10	50	1875	3750	25000	mW	400	500	10000

5.6.3 Fuel cell Concept model Vehicle

The Model of a hydrogen car with a regenerative fuel cell shows in figure 5.12. The Fuel Cell Car works with a regenerative fuel cell. The cell can both be a Fuel Cell and electrolyser cell. This system contains following components as shown in figure 5.12.

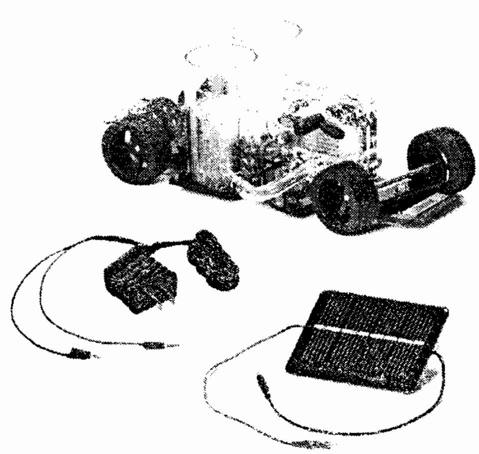

Figure 5.4-Fuel cell Concept car

1) Two cylinders with fuel storing containers
2) Reversible fuel cell
3) Controlling system with motor
4) Solar module
5) Connecting tubes and connectors

Once the solar module converts radiant energy into electrical energy to power the electrolyzer, it starts to produce hydrogen and oxygen in the storages. Reversing of the electrolyzer is a Fuel cell which converts both fuels in to electricity.

Technical data:
Power 1 W (electrolyzer mode), 500 mW (fuel cell mode), Gas storage 15 cm3 H_2; 15 cm3 O_2, HxWxD 75x90x200 mm (3"x31/2"x75/6"), Weight: 260 g, This system has Approximately 2 minutes charging time and 8 minutes running time.