Fuel Cells – Turn up the Heat

Abstract

The concept of the fuel cell was first published in 1938 by Christian Friedrich Schonbein [1]. Based on this publication Sir William Grove invented the precursor of the fuel cell in 1839. The Grove Cell created current by applying two acids to zinc and platinum electrodes separated by a porous ceramic pot. In 1842 Grove developed the first actual fuel cell which produced electricity with hydrogen and oxygen, much like many fuel cells in use today. Fuel cells remained an intellectual curiosity until the 1960's when the US space program identified a requirement for extended life batteries for which fuel cells seem to offer a promising solution. The current focus on green technologies has caused an increased interest in consumer uses of fuel cells for transportation, residential and commercial power supply, emergency backup power and portable power supplies for consumer and battlefield applications. Increased usage of any technology begs the question of how to address the costs associated with that technology. This article describes a research effort using publically available data to develop cost estimating relationships for various types of power systems that utilize fuel cell technology.

Introduction

A fuel cell is an electrochemical cell which converts some fuel, usually hydrogen, into electric current. It does this through a reaction between the fuel and an oxidant in the presence of an electrolyte. The waste product of this chemical process is water and heat. Fuel cells, unlike conventional batteries, consume reactant from an external source rather than one stored in the battery. They do require a continuous supply of fuel, but given that this supply is available, they will not run out of charge like a conventional battery.

Because fuel cells require neither flame nor combustion to convert fuel to electricity, there is much hope that they will become a viable power source of the future as we try to reduce our carbon footprint. Fuel cells are very reliable and not as likely to be effected by the environment as some more conventional power delivery systems are. Because of this they are being adopted in industries such as the telecommunications industry where outages are particularly problematic. They are also often considered for power generation in remote areas where energy from the grid is expensive and outages are frequent. Because heat is a waste product of the fuel cell electricity generation process, micro combined heat and power systems are gaining popularity for residential and small business needs. Other interesting uses of fuel cell power include material handling, backup power systems and uninterruptable power supplies.

Despite increases in the use of fuel cells, they continue to evade wide spread use because they are expensive. Certainly significant progress has been made through increases in efficiency and improvements in manufacturing processes but it is still more expensive, in most domains, to get electricity from fuel cells than from more conventional methods. According to a report from the Department of Energy in May 2010, high volume automotive fuel cell stack cost has been reduced from

$275/KW in 2002 to $61/KW in 2009 and appear to be on track to reach the $30/KW goal by 2015. [2]. The same report indicates a 24% increase in system power density for stationary fuel cells making it possible to reduce the fuel stack volume, weight and cost.

Fuel Cells

In general, fuel cells are made up of three primary parts – the anode, the electrolyte and the cathode. Chemical reactions occur at the interfaces of the three different segments. The result of these reactions is that the fuel (usually hydrogen) Is used to create electric current and water and/or carbon dioxide is created.

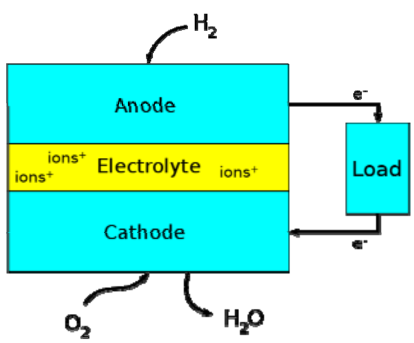


Figure 1 Fuel cell Configuration

The anode, electrolyte and cathode are layered as shown in Figure 1[3]. A catalyst, generally a fine platinum powder, is used at the anode to oxidize the fuel, creating positively charged ions and negatively charged electrons. The electrolyte allows the ions to pass through but prevents the electrons from passing through – forcing them to travel through the wire creating current. The ions travel through the electrolyte to the cathode and rejoin the electrons where a second chemical reaction, usually with oxygen, creates water and/or carbon dioxide. The cathode catalyst is usually nickel. Fuel cells are generally classified based on the electrolyte substance.

This research focused on the following types of fuel cells.

- Proton exchange membrane fuel cells (PEMFC) – a proton exchange membrane is the electrolyte substance. Hydrogen fuels the reaction at the anode catalyst and oxygen reacts with the electrons on the cathode catalyst to form water, which is the only waste product. Platinum is generally used as the anode catalyst. PEMFC are used in both stationary and portable fuel cell applications and their lower temperature ranges and power-to-weight ratio makes them suitable targets for transportation applications. These seem to be the most widely used type of fuel cell for the types of power systems studied.

- Phosphoric Acid Fuel Cells (PAFC) - Liquid phosphorous acid acts as the electrolyte substance. Hydrogen fuels the reaction at the anode catalyst and electrons react with oxygen at the cathode to form both water and heat. PAFCs tend to be less powerful than many other fuel cells, making stacks larger and heavier. Like PEMFCs, they require expensive platinum catalysts.

Typical uses of PAFCs include stationary power with some uses in larger transportation vehicles such as buses.

- Molten Carbonate Fuel Cells (MCFC) – a molten carbonate salt mixture creates the electrolyte substance. MCFCs are able to operate at very high temperatures, making it unnecessary to use precious metals as a catalyst. They tend to be more efficient and less expensive than PEMFC or PAFCs. High operating temperatures limit their uses to primarily large stationary power systems.

- Solid Oxide Fuel Cells (SOFC) – solid oxide materials act as the electrolytic substance. These cells conduct negative oxygen ions from the cathode to the anode. Like MCFCs, this type of fuel cell operates at very high temperatures, thus there is no requirement for expensive platinum catalysts and they do not require pure hydrogen for operation. There uses include commercial and residential power supply and auxiliary power for vehicles.

- Reformed Methanol Fuel Cells (RMFC) – this is a subset of the PEMFC that uses methanol reformed to hydrogen as the fuel. These fuel cells operate at high temperatures and produce carbon dioxide as waste products. Their small size makes them a good option for portable power delivery systems.

Cost Research Methodology

The goal of this study was to develop credible, defendable cost estimating relationships (CERs) using publically available cost data and to make these relationships available to the cost estimating community through publication in the PRICE TruePlanning® framework. Admittedly, the use of only publically available data is often problematic and can result in a less 'accurate' estimate. But often the most 'accurate' estimate is unusable because the use of proprietary data enforces a 'code of silence' around the genesis of the model, making it unusable to those who need to defend estimates with actual projects. A model built with publically available data, with well documented ground rules and assumptions, creates an environment of full disclosure.

Fuel cell power systems presented an appealing target for this research because power systems costs are likely to trend well regardless of operating platform making it possible to extend the results beyond the commercial platform from which most of the data was collected. The study focused on the following type of fuel cell power systems:

- Backup power systems – used for emergency backup and uninterruptable power supplies

- Stationary power systems – used to provide electricity (and sometimes heat) to residential and small business consumers

- Material handling power system – used to provide power for forklifts and other equipment used to move materials and products in large warehouse settings

- Portable power systems – used to provide power to laptops, other small electronics, battlefield equipment

Not surprisingly, actual cost data was not available for most of the systems studied. Even finding price data was challenging since many manufacturers will not publish these but prefer for potential buyers to call and speak to a sales person. This research relied on on-line catalogs (where they existed), research papers, magazine articles and press releases to discover and confirm prices for the systems studied. Table 1 contains a summary of the data points upon which this research is based.

Initial observations indicated that the primary cost drivers for fuel cell systems include

- Type of power system (portable, backup, etc)
- Type of fuel cell (PEMFC, RMFC, etc.)
- Power rating of the system

Weight also appeared to be a cost driver but very closely correlated to power rating, with power rating appearing slightly more significant.

Manufacturer	Unit	Selling price	First Piece Cost (2010$)	Use	Power	Fuel Cell Type	Length	Width	Height	Weight	Max temp	Min temp	Current	Efficiency	References
ReliOn	t-1000	4500	3388.54411	Backup power	600-1200w	PEMFC	14	21.5	26	98-164	115	335	50@24VDC 25@48VDC		
reliOn	T-2000	9000	6775.111239	backup power	600-2kw	PEMFC	21	21.5	26	134-244	115	335	80@24VDC 40@48VDC		
Horizon	H-1000	4000	5790.283935	backup power	1kw	PEMFC				15			17-84		http://www.fuelcellstore.com/en/pc/viewCategories.asp?idCategory=53
Horizon	h-3000	10500	15199.49533	Backup power	3kw	pemfc				38					http://www.fuelcellstore.com/en/pc/viewCategories.asp?idCategory=53
Horizon	H-5000	15000	21713.56475	backup power	5kw	pemfc				60					http://www.fuelcellstore.com/en/pc/viewCategories.asp?idCategory=53
PlugPower Gendrive	GD-240	22-33k	40959.07635	Material Handling	10.5kw	PEMFC	38	31	20	2600	104	-22	36VDC		http://www.hydrogenassociation.org/general/products/browse_fuelCells6to250.asp
PlugPower Gendrive	gd-160	32k	47661.03932	Material Handling	8.7kw	PEMFC	38.5	22.62	27.12	2260-3350	104	25	36-48VDC		http://www.hydrogenassociation.org/general/products/browse_fuelCells6to250.asp
PlugPower Gendrive	GD-170	35k	50533.59159	Material Handling	10.1kw	PEMFC	38.6	22.87	32.7	3000-400	104	25	36-48VDC		http://www.hydrogenassociation.org/general/products/browse_fuelCells6to250.asp
Ballard	FCVelocity 9ssl	20000	24712.25284	Material Handling	4.4kw	PEMFC	31	6	76	17					http://www.ballard.com/files/pdf/Case_Studies/Material_Handling_Economic_Benefits_041510.pdf
Ballard	FCVelocity 9ssl	40000	49424.50568	Material Handling	19.3kw	PEMFC									http://www.fuelcellstore.com/en/pc/viewCategories.asp?idCategory=53
Ultracell	xx25	5000	3983.206311	Micro/portable	25W	RMFC	5.9	9.1	1.7	2.5	122	-4	16.8	na	http://www.investorvillage.com/smbd.asp?mb=6597&mid=2854530&pt=msg
Ultracell	xx55	10000	10393.87781	Mobile power - militar	50W	RMFC	10.7	8.2	3.2	3.5	122	-4	12v-30v		
Jadoo Power	Ngen	2050	1828.393504	portable - fuel storage	100w	PEMFC	4.3	4.3	7.5	5					http://www.ncbi.nlm.nih.gov/pmc/articles/PMC1797861/
Trulite	KH4	2000	2229.259315	portable - military ref	150-250w	PEMFC	8.5	13.7	16.2	23	104	34		na	http://www.trulitetech.com/news/HoustonBusinessJournal-Trulite7.27.07.pdf
Medis technology	Power pack	20-30	50.17422753	Portable power	1w	PEMFC	677mm	95	37	12.3 oz				na	http://news.cnet.com/8301-11128_3-10039102-54.html
PlugPower Gensys	5c,4c	25350	32576.68019	Stationary	5kw	PEMFC	51.2	35.5	74	1212					http://www.communicationstoday.co.in/oct2007/plug-power-brings-fuel-solutions-to-remote-india-2225-41.html
FCE	DFC300	4600/kw	1295910.539	Stationary	300kw	MCFC	20 ft	15	14.5	77K			480vac	up to 75%	http://www.powergenworldwide.com/index/display/articledisplay/303179/articles/cogeneration-and-on-site-power-production/volume-8/issue-4/features/gearing-up-for-the-market-commercialization-of-stationary-fuel-cells-on-the-horizon.html
FCE	DFC1.5M	4300/kw	6199260.393	Stationary	1.5M	MCFC	50	70		242k			480VAC	up to 75%	http://www.powergenworldwide.com/index/display/articledisplay/303179/articles/cogeneration-and-on-site-power-production/volume-8/issue-4/features/gearing-up-for-the-market-commercialization-of-stationary-fuel-cells-on-the-horizon.html
FCE	DFC 3MW	3250/KW	9370481.195	Stationary	2M	MCFC	60	55		252k			13.8K	up to 75%	http://www.powergenworldwide.com/index/display/articledisplay/303179/articles/cogeneration-and-on-site-power-production/volume-8/issue-4/features/gearing-up-for-the-market-commercialization-of-stationary-fuel-cells-on-the-horizon.html
UTC PureCell	400	4500/kw	1820897.638	Stationary	400kw	PAFC	27.5feet	8.5	10	60K			480 VAC	with cogen	http://www.powergenworldwide.com/index/display/articledisplay/303179/articles/cogeneration-and-on-site-power-production/volume-8/issue-4/features/gearing-up-for-the-market-commercialization-of-stationary-fuel-cells-on-the-horizon.html
Bloom box		700k-800k	741367.5853	Stationary	100kw	SOFC									http://news.cnet.com/8301-11128_3-10461359-54.html
Horizon Greenhub	Powerbox 1000	10450	10329.72169	Stationary UPS	1000w	PEMFC	40	60	25cm	20kg			220-230VAC	55	http://www.thehydrogencompany.com/subsiteproducts_54-906.html
Idatech	igen	5200 (gov price)	5817.008322	Stationary	250w	PEMFC - liquid f	13.3	17.25	17.5	40	50	-20		na	http://www.fs.fed.us/eng/pubs/htmlpubs/htm09732309/

Table 1 : Summary of fuel cell data collected

Data Normalization

Clearly significant effort was necessary to make price data a useful proxy for a first piece cost. The study was focused solely on understanding the production costs of the fuel cell power systems. Some assumptions and conjecture were necessary to facilitate this process. The literature studied supports the assumptions built into this analysis. The following steps were applied to the price data

1. Price was converted from its base year to 2010 using PRICE Systems published escalation rates.

2. For each unit an assumption was made for volume of production based on size and application of the unit and how widespread its use appears to be based on review of product websites.

3. A markup was determined based on the production volume and this markup was removed from the price

4. For fuel cells that were sold prior to 2010, an adjustment was made to account for the fact that there is confirmed evidence that fuel cell development is getting more cost effective every year. This fact is due primarily to government incentives focused on establishing wider spread use of fuel cells through lower costs gained with improved manufacturing processes. Values of 2% cost reduction per year for stationary and backup power systems and 15% cost reduction per year for backup and portable power systems [4],[5] were applied. This adjustment aligned the costs to what they would have been in 2010 based on improvements in technology and processes.

5. For systems where the application was military, costs were adjusted to eliminate the effects on cost of making the units military issue using the relationship used in the PRICE Models for adjusting for such costs. Since most of the data was purely commercial, the data was normalized to that platform.

6. Based on production volume and learning curve assumptions (determined by the size and type of systems), learning curve effect was backed out of the cost to come up with a first piece cost proxy.

Additional normalization required converting all weights to pounds and all power to Watts. The assumption was made that the costs applied to the entire power delivery system, not just the fuel cells that power the system.

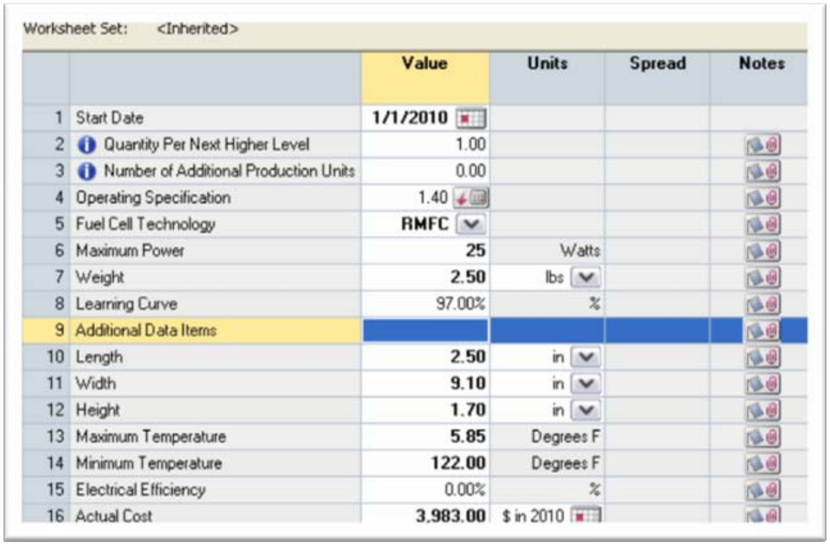
Analysis

Within the stratifications of application and fuel cell type, power was by far the most significant cost driver for these systems. Weight was considered a cost driver but was determined to be too closely correlated to power to add any value to the relationship.

Separate analysis was performed on each of the power system types. Where appropriate, analysis was performed separately for each type of fuel cell. Because not all fuel cell types were represented in all data sets, in some cases more generic algorithms were applied across the fuel cell types. Regression analysis was performed along these stratifications and cost estimating relationships were developed for production manufacturing costs. Appendix A contains the relationships along with figures of merit.

Delivering the model

Once CERS for production manufacturing were developed, the next step was to build these into a model that can plug and play in the TruePlanning ® framework. The TruePlanning model development tool was used to create four cost objects, one for each of the power delivery systems studied. These cost objects contain the cost drivers identified and the CERs developed as well as additional fields for storing other attributes of a fuel cell power system and a field for storing actual costs as shown in Figure 2. This makes it possible for the cost object to support both estimation and the collection of historical data. It also makes it possible to do estimate vs. actual comparisons right in the framework as shown in Figure 3.



Worksheet Set: <Inherited>

		Value	Units	Spread	Notes
1	Start Date	1/1/2010			
2	Quantity Per Next Higher Level	1.00			
3	Number of Additional Production Units	0.00			
4	Operating Specification	1.40			
5	Fuel Cell Technology	RMFC			
6	Maximum Power	25	Watts		
7	Weight	2.50	lbs		
8	Learning Curve	97.00%	%		
9	Additional Data Items				
10	Length	2.50	in		
11	Width	9.10	in		
12	Height	1.70	in		
13	Maximum Temperature	5.85	Degrees F		
14	Minimum Temperature	122.00	Degrees F		
15	Electrical Efficiency	0.00%	%		
16	Actual Cost	3,983.00	$ in 2010		

Figure 2: Sample cost object inputs for Portable Power Fuel Cell Systems

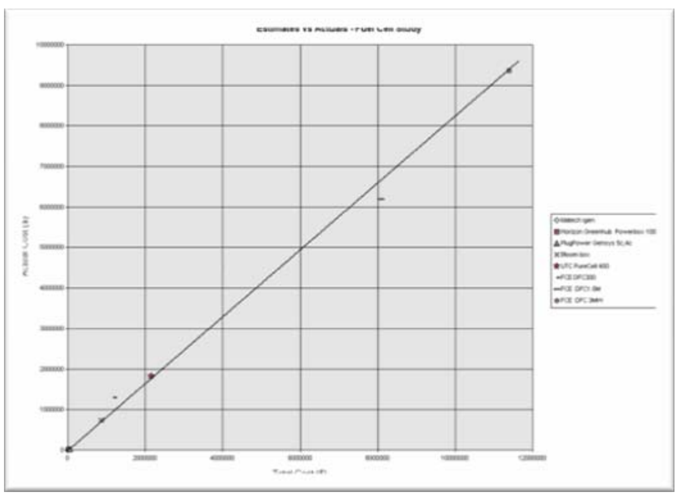


Figure 3: Estimate vs Actual Comparison for Stationary Power Systems

For completeness the activities of production engineering and production tooling and test are also calculated for the fuel cell cost objects. A study was conducted of systems of similar sizes and complexities to the systems studied in order to identify how engineering and tooling and test activities vary with respect to production manufacturing. These relationships were used to extend the production manufacturing costs in these models. The cost objects also contain features that allow them to share size and complexity with other cost objects in product breakdown structure. This shared data makes it possible to estimate not only the costs of the individual fuel cell systems but also the costs of integrating these fuel cell systems with other equipments in an assembly or sub-assembly.

Conclusions

There are many potential advantages of replacing traditional power systems with those employing fuel cells. Fuel cells are highly reliable and efficient means of delivering power. They provide a greener solution because they require no combustion. They are also a viable alternative to help reduce our country's dependence on foreign oil. Despite the many advantages, fuel cells are just starting to get mainstream attention for many applications. The primary reason for this is that they still do not present the best cost solutions. Over the past few years improvements in efficiency and manufacturing processes have brought fuel cell costs down significantly and with further investment they are on target to compete with other energy sources by 2015.

This paper describes a study of fuel cell technology and the costs of some of its applications. The intent of this paper is twofold; describing the results of this research and communicating an effective framework for delivering this research to the cost community in a fashion that they can understand it, use it effectively, defend its results and use it to support good decisions when planning projects.

References

[1] http://en.wikipedia.org/wiki/Fuel_cell#History
[2] http://www1.eere.energy.gov/hydrogenandfuelcells/accomplishments.html
[3] http://en.wikipedia.org/wiki/File:Fuel_Cell_Block_Diagram.svg
[4] http://www.fuelcellseminar.com/media/5235/dem42-3_leo.pdf
[5] http://www.itm-power.com/cmsFiles/investors/Tradition_FuelCellReport_Apr2010.pdf

Appendix A

Portable power systems

The fuel cell types used for portable power were of fuel cell types RMFC and PEMFC. The analysis resulting in the following relationships:

For RMFC

$$Cost = 32 * power ** 1.384$$

For other fuel cell types

$$Cost = 15.6 + 151 * power ** 0.5$$

What follows summarizes the statistics of these relationships with the original data set.

System	Power	Fuel Cell Type	First Piece Cost (2010$)	Estimated First Piece Cost (2010$)	GSRQ (r^2)	R^2	adj R^2	StdErr
Ultracell xx25	25	RMFC	3983	3714	0.995924498	0.987943	0.983924	506.6854
Ultracell xx55	50	RMFC	10394	9694				
Jadoo Power Ngen	100	PEMFC	1828	1674				
Trulite KH4	250	PEMFC	2229	2636				
Medis technology Power pack	1	PEMFC	50	183				

Table 2 : Portable Power Fuel Cell Results and Statistics

Stationary Power systems

Stationary fuel cell power uses the widest variety of fuel cell types of all of the power systems studied in this research. There were 3 data points each for PEMFC and MCFC with one each of SOFC and PAFC. The PEMFC and MCFC analysis are applied to estimates for those types of fuel cells. For the SOFC and PAFC a blended relationship was established while for other fuel cell types an analysis of all the fuel cells applies. SigmaPlot was used for the analysis with the following results.

For PEMFC

$$cost = 4554 + 5.61 * power$$

For MCFC

$$cost = 0.305 * power ** 1.19$$

For SOFC and PAFC

$$cost = 381500 + 3.59 * power$$

else

$$cost = 27320 + 4.47 * power$$

System	Power	Fuel Cell Type	Actual Cost	Estimated Cost	GSRQ (r^2)		R^2	adj R^2	StdErr
PlugPower Gensys 5c,4c	5000	PEMFC	32577	35820.54	0.997136348		0.982779	0.980318	455394.3
FCE DFC300	300000	MCFC	1295911	1053018.9					
FCE DFC1.5M	1500000	MCFC	6199260	7148426.5					
FCE DFC 3MW	2000000	MCFC	9370481	10066710					
UTC PureCell 400	400000	PAFC	1820898	1904743.2					
Bloom box	100000	SOFC	741368	776045.31					
Horizon Greenhub Powerbox 1000	1000	PEMFC	10330	11160.598					
Idatech igen	250	PEMFC	5817	6536.8592					

Table 3 : Stationary Power System with Stats

Material Handling Power Systems

The only types of fuel cells in the material handling fuel cell data set were of types PEMFC. SigmaPlot was used for the analysis with the following results:

$$cost = 1750 * power ** 0.347$$

System	Power	Fuel Cell Type	Actual Cost	Estimated Cost	GSRQ (r^2)	R^2	adj R^2	StdErr
PlugPower Gendrive GD-240	10500	PEMFC	40959	47707.48	0.569714892	0.290619	0.054158	10517.37
PlugPower Gendrive gd-160	8700	PEMFC	47661	44693.768				
PlugPower Gendrive GD-170	10100	PEMFC	50534	47068.82				
Ballard FCVelocity 9ssl	4400	PEMFC	28333	40448.07				
Ballard FCVelocity 9ssl	19300	PEMFC	56667	67562.874				

Table 4: Material Handling Power System Stats

Backup Power Systems

All of the data points in this data set used the PEMFC type fuel cells. SigmaPlot was used for analysis with the following results:

$$cost = 3.035 * power ** 1.045$$

System	Power	Fuel Cell	Actual Cost	Estimated Cost	GSRQ (r^2)	R^2	adj R^2	StdErr
ReliOn t-1000	1200	PEMFC	3389	5496.6596	0.942935717	0.911	0.881333	2637.08
reliOn T-2000	2000	PEMFC	6775	9374.126				
Horizon h-1000	1000	PEMFC	5790	4543.1224				
Horizon h-3000	3000	pemfc	15199	14320.103				
Horizon h-5000	5000	pemfc	21713	24421.824				

Table 5: Backup power system stats