Chapter 7 Fuel Cell Technology

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7.1 Introduction

A fuel cell (FC) is an electrochemical reactor that converts the chemical energy of a fuel and an oxidant directly to electricity.

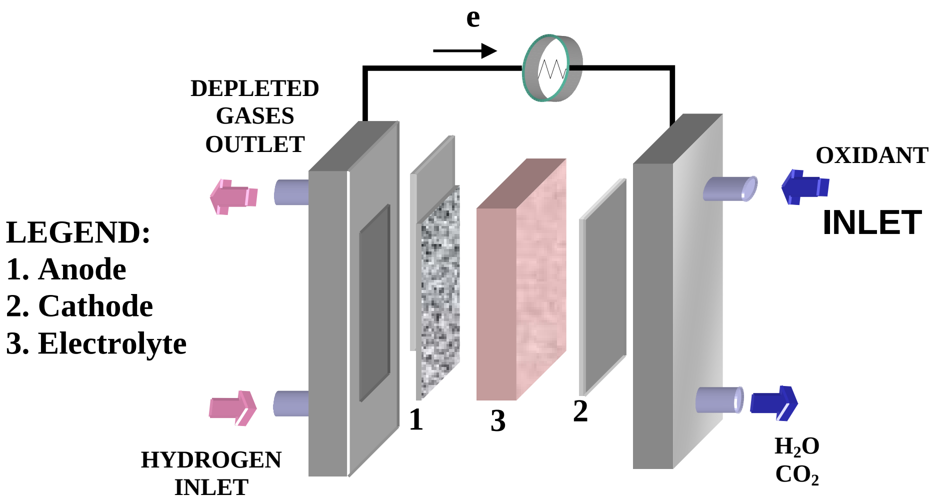

Figure 7-1. Typical components of a fuel cell for a H2/O2 system

The principal components of a fuel cell are the catalytically activated electrodes for both fuel (anode side, part 1 in the figure) and oxidant (cathode side, part 2), and an electrolyte (solid or liquid, part 3) to transport ions between the two electrodes. In addition, it has graphite bipolar plates that serve as current collectors and fuel-oxidant distributors at the same time. This is shown in the figure for the single cell hydrogen-oxygen system. The operation of a fuel cell is in the reverse direction of the water electrolysis. Gaseous hydrogen and oxygen are used to electrocatalytically produce water and electricity.

The chemical reactions that describe those systems are the following:

Acidic electrolyte*

Anode:	$2H_2 \rightarrow 4H^+ + 4e^-$	E° = 0.0 Volts
Cathode:	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	E° = 1.229 Volts
Overall reaction:	$2H_2 + O_2 \rightarrow 2H_2O$	E° = 1.229 Volts

Basic electrolyte*

Anode:	$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$	E° = -0.828 Volts
Cathode:	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$	E° = 0.401 Volts
Overall reaction:	$2H_2 + O_2 \rightarrow 2H_2O$	E° = 1.229 Volts

Two exceptions are the Molten Carbonate Fuel Cell (MCFC) and the Direct Methanol Fuel Cell (DMFC). These systems are discussed below.

Fuel cells are classified according to the type of fuel and electrolyte used. Both the operating temperature and the composition of the electrode are determined by these parameters. The five most advanced fuel cells are; Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC), and Polymer Electrolyte Membrane Fuel Cell (PEMFC). The PEMFCs are also known as Proton Exchange Fuel Cells (PEFC), Solid Polymer Fuel Cells (SPFC), or Solid Electrolyte Fuel Cells (SEFC). Another classification criterion is the way the fuel is supplied. It can be direct or indirectly fed depending if the hydrogen is supplied as a pure gas (direct) or if it is generated from a reformed carbonaceous source (indirect). The Direct Methanol Fuel Cell (DMFC) which uses methanol directly as the reducing agent at the anode is one of the most developed fuel cells of the direct fuel configuration systems. These names and abbreviations are the ones commonly used in publications. Key parameters describing these systems are given in the next table.

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*All voltages are given versus the standard hydrogen electrode (*she*).

Table 7-1. Fuel cells types and their characteristics

Fuel Cell System	Temperature Range (°C)	Efficiency[1] (%)	Electrolyte
AFC	60 – 90	50 – 60	Aqueous KOH solution (35 – 50% wt)
PAFC	160 – 220	55 – 80	Concentrated phosphoric acid
MCFC	620 – 660	60 – 65	Molten carbonate melts (Li_2CO_3/$NaCO_3$)
SOFC	800 – 1000	55 – 65	Ceramic solid (ZrO_2/Y_2O_3)
PEMFC	50 – 80	50 – 60	Perfluorosulfonic acid polymer membrane

7.2 Availability of the Resource (and markets)

Contrary to other areas in this study, fuel cells are not resources but in turn are technologies that utilize either primary resources such as carbonaceous fuels (i.e., methane from natural gas and or landfills) or secondary fuels such as hydrogen. This section will then focus on potential markets/applications and their fuel requirements.

In section 6.3.1, on chapter 6, Availability of the Solid Waste Biomass Resource, it was mentioned that several landfills in Puerto Rico have potential for landfill gas collection and conversion. A top ten list was generated. Fuel cells, especially Molten Carbonate Fuel Cells, are commercially available for this application. Notice that all of the top 10 identified landfills have over 1 MW peak capacity which is an ideal technological match with this technology that is available in 250 kW modules. It is important to mention that microturbines are also excellent for this application. Their capital costs are lower than fuel cells. However, fuel cells are better regarding the emissions and noise level profile and operating costs (no moving parts). In section 7.4, Available commercial and prototype conversion technology to produce electricity using the resource, more information will be given regarding commercially available fuel cells in general.

[1] These values of efficiency do not include the "waste" heat contribution.

Regarding potential fuel cells markets in general, the following table and figure provide a summary of the Puerto Rico Electric Power Authority clients divided by sectors and typical consumptions by specific clients. Also, an average consumption by client was estimated. For example in the residential sector, an average consumption of 900 watt per household was estimated. In this market the only fuel cell commercially available are proton exchange membrane based back up systems in stackable 1kW modules. They use very expensive hydrogen cylinders as fuel. The same units are also marketed for the commercial sector. These units would need to compete with an existing and low investment gasoline/diesel generator market (see generator table) for both the residential and low load (< 10 kW) commercial markets. Notice that the investment for generators (<< $0.5/Watt) is much less than for fuel cell systems ($4 - $6/W). Also, as mentioned earlier, the hydrogen is also expensive.

Table 7-2. Rico Electric Power Authority clients divided by sectors

	# of Clients	# of Clients	% of consume	Average consume per sector in MW	Average consume per cuenta in KV
Residential	1,315,345	90.70%	46%	1150	0.874
Commercial	130,082	8.97%	42%	1050	8.072
Industrial	1,618	0.11%	11%	275	169.963
Others	3,182	0.22%	1%	25	7.857
Total	1,450,227			2,500	

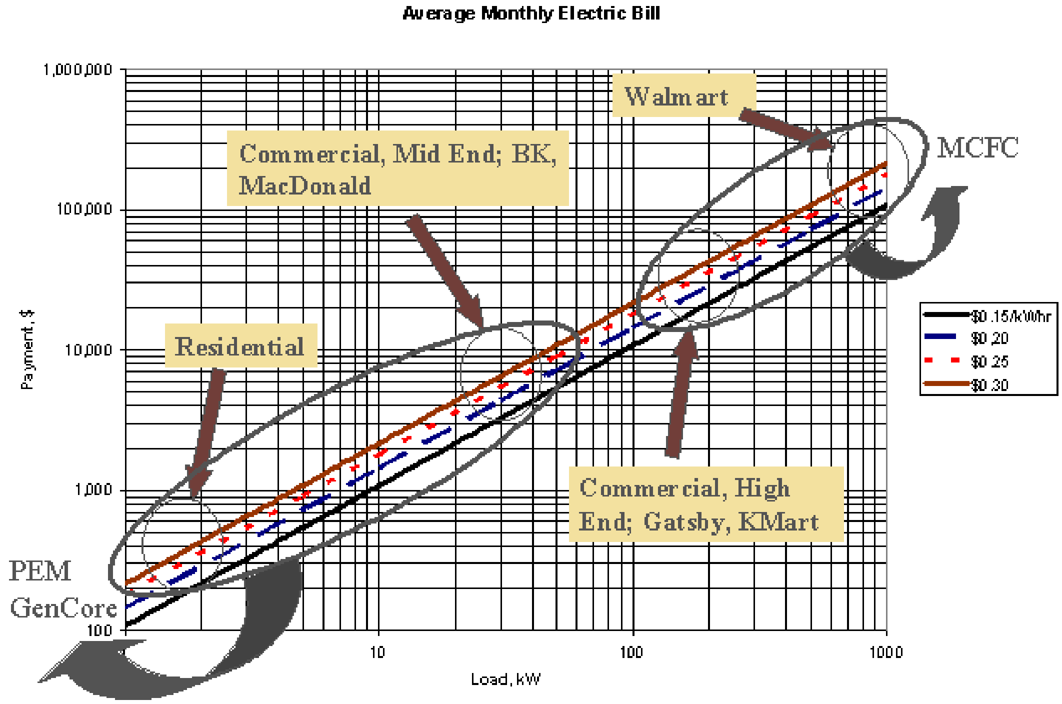

Figure 7-2. Puerto Rico Electric Power Authority typical consumptions by specific clients

Table 7-3. Energy Generators Imported to Puerto Rico

Table 1 – Energy Generators Imported to Puerto Rico

Type of Generator	1998 Quantity	1998 Value $	1998 $/Unit	1999 Quantity	1999 Value $	1999 $/Unit	2000 Quantity	2000 Value $	2000 $/Unit	Total for the last 3 years Quantity	Total for the last 3 years Value $	Total for the last 3 years $/Unit
Generating Sets, ELC, Diesel =< 75 KVA Output												
United States	148	1,043,010	7,048	926	4,723,505	5,101	1,228	6,252,071	5,091	2,302	12,018,646	5,221
Dominican Republic							1	4,000	4,000	1	4,000	4,000
Italy				9	54,717	6,080	17	129,372	7,610	26	184,089	7,080
Japan				101	253,669	2,511	154	419,499	2,724	255	679,168	2,663
Mexico				1	11,109	11,109				1	11,109	11,109
Brazil							2	7,630	3,815	2	7,630	3,815
China (Mainland)	47	50,269	1,070				12	17,822	1,485	59	68,091	1,154
China (Taiwan)				1	3,276	3,276				1	3,276	3,276
Germany				22	174,933	7,952				22	174,933	7,952
Ireland				1	15,484	15,484				1	15,484	15,484
France				86	469,045	5,454	12	70,557	5,880	98	539,602	5,506
Republic of Korea	6	49,990	8,332	20	108,400	5,420	41	201,792	4,922	67	360,182	5,376
Spain							101	304,883	3,019	101	304,883	3,019
United Kingdom				511	3,945,268	7,721	1,249	9,192,794	7,841	1,760	13,138,062	7,806
Sub-Total	201	1143329	5,688	1678	9765406	5,820	2817	17200420	6,106	4,696	28,109,155	5,986
Generating Sets, ELC, Diesel > 1000KVA												
United States	80	4,597,785	57,472	213	7,981,681	37,473	322	13,621,923	42,304	615	26,201,389	42,604
United Kingdom				5	55,650	11,130	1	43,452	43,452	6	99,102	16,517
Germany				1	33,385	33,385				1	33,385	33,385
Spain							9	299,521	33,280	9	299,521	33,280
Sub-Total	80	4,597,785	57,472	219	8,070,716	36,853	332	13,964,896	42,063	631	26,633,397	42,208
Total	5,174	11,507,051	2,224	3,779	30,569,776	8,089	5,281	48,165,305	9,120	14,234	90,242,132	6,340
Generating Sets, ELC, Gasoline => 1.5 KW BUT =< 5 KW												
Japan	135	192,380	1,425	115	141,586	1,231	460	706,617	1,536	710	1,040,583	1,466
Canada				141	145,601	1,033				141	145,601	
Sub-Total	135	192,380	1,425	256	287,187	1,122	460	706,617	1,536	851	1,186,184	1,394
Generating Sets, ELC, Gasoline > 5 KW												
United States	274	354,413	1,294	1,276	3,327,581	2,608	58,241	4,182,582	72	59,791	7,864,636	132
United Kingdom	1	38,286	38,286	20	234,363	11,720				21	272,649	12,985
Canada				11	60,595	5,509				11	60,595	5,509
China (Mainland)				1	2,420	2,420	20	29,192	1,460	21	31,612	1,505
Japan				5	20,565	4,113				5	20,565	4,113
Generating Sets, ELC, Diesel >75KVA BUT =< 375 KVA												
United States	4,667	3,384,955	725	1,305	8,457,751	6,481	993	5,108,389	5,149	6,965	17,551,095	2,520
Canada							2	3,450	1,725	2	3,450	1,725
China (Mainland)	18	56,928	3,163							18	56,928	3,163
United Kingdom	6	127,451	21,242	190	2,671,156	14,059	586	6,132,287	10,465	782	8,930,894	11,421
France				2	31,973	15,987	1	10,182	10,182	3	42,155	14,052
Italy							80	116,680	1,459	80	116,680	1,459
Mexico							2	38,099	19,050	2	38,099	19,050
Republic of Korea	4	79,835	19,959				3	35,492	11,831	7	115,327	16,475
Spain							46	369,020	8,022	46	369,020	8,022
Sub-Total	4,695	3,649,169	777	1,497	11,160,880	7,455	1,713	12,413,599	7,247	7,905	27,223,648	3,444
Generating Sets, ELC, Diesel > 375KVA BUT =< 1000 KVA												
United States	196	1,983,280	10,119	381	1,331,036	3,494	385	3,940,358	10,235	962	7,254,674	7,541
Republic of Korea	1	39,988	39,988				1	28,400	28,400	2	68,388	34,194
United Kingdom	1	93,500	93,500	4	241,738	60,435	10	415,388	41,539	15	750,626	50,042
Spain							23	202,244	8,793	23	202,244	8,793
Sub-Total	198	2116768	10,691	385	1572774	4,085	419	4586390	10,946	1,002	8,275,932	8,259

In the commercial sector, a key target for fuel cell technology could be fast food establishments. There are approximately 1,000 establishments as shown in the table below. In addition, for completeness another table is provided with all the establishments (~28,000) licensed by the Puerto Rico Health Department. This information was provided by Rita Gotilla from that agency. An advantage of the fast food market is that they maintain homogeneity in their establishments. In other words, all the facilities would convert if the corporation justifies the investment of a new technology. It should be mentioned that most if these establishments have existing generator systems. One advantage of fuel cells versus generators in these establishments is the integration of the excess heat into their heating water requirements. These would increase the efficiency of these units to 70-80%.

Table 7-4. Fast food establishments

Compañías de Fast Food	Franquicia	Sucursales
Caribbean Restaurants LLC	Burger King	167
Encanto Restaurants Inc.	Kentucky Fried Chicken Pizza Hut Taco Bell	85 52 31
Enigma Investment Inc.	Dominos Pizza	39
McDonald's Caribbean Region	McDonald's	112
South American Restaurants Corp.	Church's Chicken Pollo Tropical	91 19
Subway Island Development	Subway Restaurants	200
The Taco Maker Caribbean Operations	The Taco Maker	100
Wendco of Puerto Rico, Inc.	Wendy's	57
Intenational Restaurant Services, Inc	Chilli's Grill & Bar Romano's Macaroni Grill	 14 3
BMJ Food P.R., Inc.	Ponderoza Bonanza	29 4
The Caribbean Investment Group, Corp.	Fuddruckers Uno Chicago Grill	4 7
Wometco de Puerto Rico, Inc.	Basking-Robbins Dunkin'Donuts B-R/DD Combo stores	37 3 13
MultiSystems Restaurants, Inc.	Sizzler	11
	Total de sucursales	1078

Table 7-5. Establishments licensed by the Puerto Rico Health.

Establecimientos Departamento de Salud	
Restaurantes	5,194
Delicatesing	244
Cafeterías	5,044
Cafés	170
Freiduras	788
Puestos para la venta de carne cocida o asada	214
Refresquería	61
Puestos ambulantes	4,975
Barras	1,673
Establecimientos Mixtos	1,335
Establecimientos Temporeros	82
Escuelas	2,393
Hospitales	98
Centros de cuidado diurno	3,033
Organizaciones cívicas	97
Clubes privados	62
Iglesias	80
Casas de Hospedaje	196
Cárceles	55
Otros establecimientos en general	2,049
Total de Establecimientos	27,843

Another key component of the commercial sector are the commercial centers and malls. As can be seen from the next figure there are over 100 of those establishments around the island. The main issue in the implementation of fuel cells in these applications are the lack of raw materials such as a natural gas pipeline. These application probably would require systems in the order of 100 kWs consistent with existent and commercially available Molten Carbonate Fuel Cell systems. Notice that in some of these centers, hot water is also required. The integration of the fuel cell excess heat to this requirement will increase the efficiency of the system. On a related application, Puerto Rico Industrial Development has approximately 27 million square feet of foot print. This translates into approximately 1,280 buildings at 21,000 ft^2 per building, This is PRIDCO's building standard size. These are also potential fuel cell applications.

Figure 7-3. Commercial centers and malls in Puerto Rico

Another application that was considered was plug in fuel cell electric vehicles. See table. Specifically, estimates were performed regarding water requirements at the residential level for producing hydrogen in water electrolysis systems. The main conclusion was that on average there would be an increase of approximately 13% per household in water utilization. This was based on an average gasoline consumption of 23 gallons of gasoline per week per household.

Table 7-6. Flug in fuel cell electric vehicles.

Plug In Fuel Cell Electric Vehicles, Residential Water Requirements in Puerto Rico			
Water Requirements		**Comentarios**	
Residencias	1,000,000		
Gasolina anual, galones	1,200,000,000		
Galones gasolina por semana por residencia	23		
Libras de Gasolina por semana por residencia	172	0.9	densidad de gasolina
Libras de Hidrogeno por semana por residencia	86	2	Hidrogeno tiene 2X el contenido energetico de la gasolina
Libras de aguas por semana por residencia	776		
Galones de agua energeticos por semana por residencia	93		
Galones de agua tipicos por dia por residencia, 50 galones per capita diario	100		En PR esta aproximadamete entre 100-150 galones/dia
Galones de agua tipicos por semana por residencia, 50 galones per capita diario	700		
Galones Energeticos/Galones tipicos	*13.4%*		Usaremos un 13% adicional de agua en cada residencia
Energy($) Requirements		**Comentarios**	
Hidrogeno requerido, lb/semana	86		
Hidrogeno requerido, lb/segundo	0.000142514		
Hidrogeno requerido, g/segundo	0.064701236		
Hidrogeno requerido, gmol/segundo	0.032350618		
Corriente	6,243		I = nFmoles/segundos
Voltaje	1.5	V	
Power	9,364	W	P = IV
Energia para una semana	1,573	kWhr	E = P*tiempo
Costo semanal del hidrogeno @ $0.25/kwhr	*$393*	0.25	$/kWhr
Costo semanal de la gasolina @ $3/galon	$69	3	$/galon
Costo electricidad equivalente a $3/galon	*$0.044*		
Techo para recoger agua			
Aguas semanal necesaria por residencia	776	galones	
Agua anual necesaria por residencia, galones	40,338	galones	
Agua anual necesaria por residencia, pies cubico	5,365	pies cubicos	
Area necesaria de techo @ 50 pulgadas anuales de lluvia, ft2	1,288	50	pulgadas de lluvia anual
Largo necesario del techo, ft	*36*	*pies*	
Ancho necesario del techo, ft	*36*	*pies*	

The second part of the analysis estimated the electricity cost for producing the hydrogen at Puerto Rico's present residential electricity rates ($0.25 kwhr). This resulted in hydrogen production costs of approximately $400 per week versus $70 for gasoline. The latter utilized $3/gallon for the price of gasoline. Another interesting finding was that electricity must drop to approximately 5 cents per kwhr in order to be equivalent to $3/gallon gasoline prices.

The last part of the analysis estimated the residential area requirements in order to collect rainwater for this application. An annual rainfall of 50 inches was assumed. This resulted in a required area of 1,288 ft^2 which is equivalent to 36' x 36'.

The last sector considered in this section is the industrial market. The PREPA clients table shown above is misleading for this sector since it estimates an average of 170 kW per client. It is suspected that this sector has multiple consumption distributions with several top consumers. For example, in the following table the diesel consumption of several companies is given. Notice that 180,000 gallons per year is equivalent to approximately 200 kW thus pointing to the energy intensive nature of these companies.

Table 7-7. PREPA clients

Company	Annual Supply (Gallons)		Company	Annual Supply (Gallons)
Abbot Laboratories	9,000,000		Cyanamid	260,000
Johnson & Johnson	2,500,000		Indulac	260,000
Amgen Pharmaceutical	1,500,000		Ferrero	250,000
Upjohn	1,500,000		Cardinal Health	240,000
Baxter Laboratories	1,000,000		Hershey's	200,000
Hanes	1,000,000		Edwars Life Science	182,000
Pfizer Laboratories	3,000,000		Hewlett Packard	180,000
To-Ricos	832,000		Caribbean Refrescos	180,000
Shering Plough	800,000		Procter & Gamble	144,000
MOVA	624,000		Prod. La Aguadillana	130,000
Bristol Pharmaceuticals	500,000		Shell Foam	120,000
Locktail	360,000		Nypro	120,000
Lilly	312,000		Foulding	60,000
Mc Gaw	310,000		Serralles Distillers	50,000
IPR	300,000		Cervecería India	40,000
El Morro Corrugate	300,000		Jostra	36,000
Olay	300,000		General Electric	20,000
			Total	26,610,000

7.3 Variability of the Resource

As mentioned in the previous section fuel cells are not resources but in turn are technologies that utilize either primary resources such as carbonaceous fuels (i.e., methane from natural gas and or landfills) or secondary fuels such as hydrogen. Regarding the variability (pricing and capacity) of these resources, they are tied to market fluctuations when pipeline natural gas, propane and/or hydrogen are considered. Regarding landfill gas, it would be tied to the lifetime generating cycle of the landfill shown in the previous section.

7.4 Available commercial and prototype conversion technology to produce electricity using the resource

Commercial fuel cells are very limited. They are presently in the development and market penetration stage. The following table provides a list of some of the available systems and respective applications. In general there are three applications. As mentioned earlier the residential fuel cell market focuses on back ups. The next level is heavy commercial/light industrial with approximate loads in the 250 kW range. The next level is industrial in the 1 to 2 MW range. These, however, are modular and integrated expansions of the 250 kW units.

Some of the commercially available units are shown below.

Table 7-8. Commercial fuel cells

Manufacture	Product	Scale	Marketing	Applications
Plug Power	GenSys	5 kW	Residencial	Base Load
(PEM)	GenCor	5 kW	Lt. Comercial	Standby
UTC Power	PureCell 200	200 kW	Comercial	Base Load
(PAFC)				Reliable Power
				Premium Power
Fuel Cell	DFC300	250 kW	Comercial	Base Load
(MCFC)	DFC1500	1000 kW	Industrial	Sub station
	DFC3000	2000 kW	Industrial	Grid Enhancement

- Plug Power 120 VDC GenCore fuel cell.
- 1 Hydrogen Storage Module (HSM)
- 6 high pressure hydrogen storage bottles

Figure 7-4. GenCore PEM fuel cell system

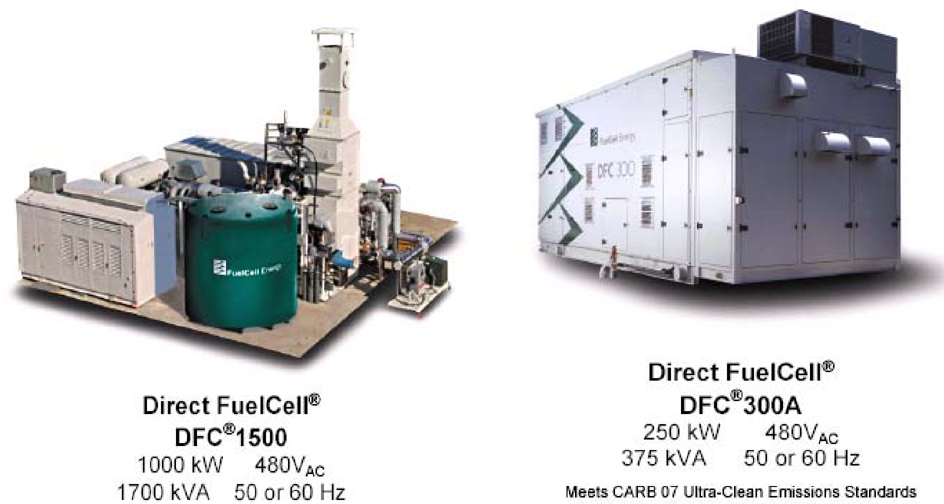

Figure 7-5. Commercial Fuel Cells

7.5 Conversion Technology footprint

The footprint of existing commercial fuel cell systems are the following:

Plug Power 120 VDC GenCore fuel cell

Physical Dimensions 44” x 26”W x 24”D

Weight 500Lbs

Does not include hydrogen cylinders rack foot print.

DFC® 300A

Height - 14.6 feet; Width - 8.0; Length -19.8 feet

Weight - 27,000 lbs

DFC® 1500A

Overall Plot Plan Dimensions 50’ x 70’

7.6 Estimate of capital cost

The following capital cost estimates are based on quotations that were obtained for a couple of projects in Puerto Rico that involved fuel cell systems. First, the company LOGAN Energy submitted a proposal on September 30, 2007 to the municipality of Caguas for a turn key 5 kW GenCore fuel cell system. They quoted $39,911. This translates into $8/W. It should be mentioned that a local company also submitted a quotation for the same project but were $3,000 higher.

The second quotation is also from Logan Engineering but for a 450 kW Molten Carbonate System operating on propane using two integrated DFC® 300A units from Fuel Cell Energy. The system was “downgraded” to 450 kW versus 500 kW. The latter is for natural gas operation. Hewlett Packard was interested in this system. A ten year lease was suggested at an approximate $6-7/W capital investment that included financing.

7.7 Estimate of potential electric energy contribution

From the previous discussion it is apparent that the potential electric energy contribution of fuel cells could include all the sectors. However, both high capital investment and raw material availability must be addressed. There are a couple of commercial systems available but their implementation in Puerto Rico will be limited to either technology transfer demonstration projects or to a highly subsidized strategy.

7.8 References for Fuel Energy Resource and Technologies

- LOGAN Energy Caguas Proposal September 30, 2007
- Caribbean Business – 2006 Business Directory – Public by Casiano Communications Inc.
- J.A. Colucci, R.A. Pérez and M. Ospinal, “Fuel Cells Applications in Puerto Rico, an Environmentally Friendly Technology,” Proceedings AIDIS 04, August 2004.