

Performance review of phosphoric acid fuel cells

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Abstract

The current technological status of phosphoric acid fuel cells (PAFC) was reviewed, focusing on large stationary CHP units. Performance figures were found that represent the real-world capabilities of the state of the art technology. Both commercial and research systems were considered, so long as they could be suitable for a consumer product.

Information was sourced from open literature where possible, for example from: journal publications, commercial data sheets and reports from field trials. This information was reviewed and modified where necessary to give a standardised view of the technology and avoid biased comparisons. Six categories were investigated: power density, efficiency, lifetime, degradation, cost, and fuel tolerance. All of the consulted information is listed and referenced, and the average for each is given.

This review is part of a series of four that focus on different fuel cell technologies for domestic CHP, available from [1]. The reviews are ongoing, and it is expected the tables of information and final values given will be updated as more information is reviewed. The aim is to keep updated with new technological advances, and to continue broadening the overview of the technology. Please contact the author at the above email address with any citable information that would help to extend this work.

Methodology

The scope of this review was to consider fuel cells for use within a small domestic CHP system; defined as the complete package required to convert natural gas into AC electricity and heat at the point of use. Fuel cells for large stationary and transport applications were also considered with discretion, as some overlap exists between these applications and domestic CHP. While the fuel cells reviewed represent modern or state of the art technology, any novel features have been demonstrated to some extent. They must also have been produced with real-world usage in mind, and not preclude the possibility of making a commercially viable product – e.g. being prohibitively expensive to manufacture or having undemonstrated durability.

A summary of the typical performance of PAFC technology is presented in the next section; represented by the mean \pm 1 standard deviation for each category of information ($\mu \pm 1\sigma$). The subsequent sections focus on each of the categories of data, and give a listing of all the consulted information. These tables follow the same format; listing the value found, the year the information came from, and some notes about the data source and the fuel cell in question. For each data source, a reference is given along with an identifying label, stating which of the following types of source the information came from:

- [field] A field trial of fuel cells, giving their performance in a real world situation
- [expt] An independently conducted experiment, typically published in a peer reviewed journal
- [theory] A theoretical calculation, typically for mass production costs
- [lit] A literature review of other data sources
- [market] Marketing information from the purveyors of the fuel cell
- [note] A ‘typical value’ that was mentioned.

Overview

All of the consulted information is summarised in Table 1, which gives the mean and standard deviation of each set of values. The range covered by 1 standard deviation is also given for convenience; it should be expected that two thirds of current systems fall within these ranges. For a definition of each parameter, please consult the introductions to the following sections.

	Mean	Std Dev	Range	# of refs.
Operating Voltage (V)	0.68	0.04	0.64-0.72	
Operating Current (Acm^{-2})	0.24	0.07	0.16-0.31	9
Power Density (Wcm^{-2})	0.16	0.05	0.11-0.21	
Stack Efficiency (HHV)	47.5%	7%	40.5-54.5%	
Net Electrical Efficiency (HHV)	30.5%	4.5%	26-35%	8
Net Total Efficiency (HHV)	72%	N/A	N/A	
Lifetime (kh)	42	11	30-53	4
(years)	4.8	1.3	3.5-6.1	
Degradation (μVh^{-1})	3.1	1.4	1.7-4.5	6
(voltage loss per year)	4%	2%	2-6%	
Complete Retail Cost ($\text{€}/kW$)	3700	1300	2500-5000	4

Table 1: Overview of performance of PAFC systems.

PAFC Electrochemical Performance

The operating voltage, current density and power density of PAFC are given in Table 2. Typically, pressurised systems were excluded, as they demonstrate significantly higher performance, but require significantly more costly auxiliary systems – and thus are generally not considered suitable for domestic CHP.

Operating Point (V/cell x Acm ⁻²)	Power Density (Wcm ⁻²)	Year	Description
0.75 x 0.19-0.21	0.14-0.16	1991	Performance of 11MW power plant assembled by Toshiba using UTC PC-23 cells, operated at 7.3 bar with 0.1 + 0.5mgcm ⁻² Pt loading. ^{[2,3][field]}
0.65 x 0.22	0.14	c. 1992	Performance of ‘advanced atmospheric water cooled’ short stack (<i>top</i>) and individual cells (<i>bottom</i>) from UTC. ^{[2][expt]}
0.75 x 0.24	0.18		
0.65 x 0.3	0.20	c. 1992	Performance of Mitsubishi atmospheric single cells. ^{[2][expt]}
0.7 x 0.3	0.21	1999	Performance of single cells made by LG-Caltex using Pt anode and Pt-Fe-Co cathode (<i>top</i>). The performance of a 50kW stack of these cells operating on hydrogen is also given (<i>middle</i>), and the subsequent performance of a 10kW stack operating on natural gas (<i>bottom</i>). ^{[4][expt]}
0.65 x 0.4	0.26		
0.66 x 0.22	0.15		
0.7 x 0.22	0.15		
0.68 x 0.13	0.09	1998	Average cell performance in a 1kW stack built at the ERI, South Africa. ^{[5][expt]}
0.62 x 0.16	0.10		
0.65 x 0.21	0.14	1993	Performance of a representative single cell from a UTC PC25A at Darmstadt, Germany. ^{[6][expt]}
? x 0.25		2001	The operating current density of UTC PC25C plants. ^{[7][field]}

Table 2: Electrochemical performance of PAFC systems.

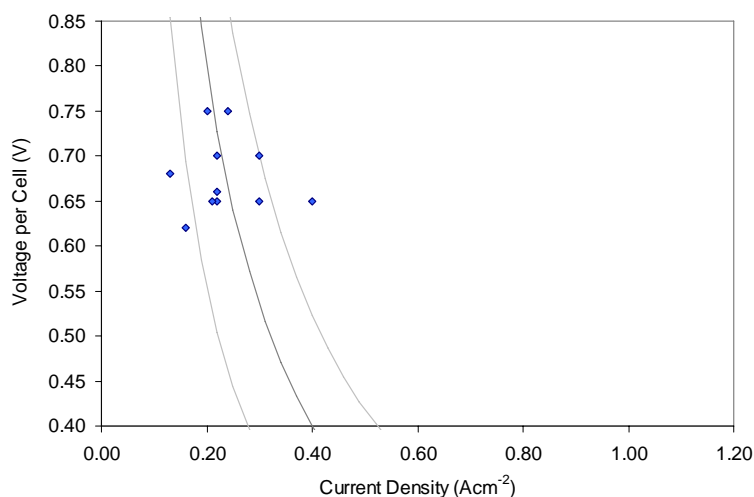


Fig 1: Plot of the operating points of listed PAFC systems, with isobars of constant power density at the mean \pm 1 standard deviation.

PAFC Efficiency

A number of definitions of efficiency are used relating to fuel cells, giving rise to some confusion and difficulty in comparing systems. A simple, yet strict physical and economic definition was used in this review:

$$\text{Efficiency} = \text{what you get out} / \text{what you put in.}$$

On this basis, the electrical efficiency includes parasitic losses from electrical components (fans, pumps, control circuits), and the power conditioning unit (transformer, inverter). Thermal efficiency is similarly based on the heat delivered to the hot water tank or heating system, net of losses in heat exchangers. The fuel input is natural gas, and so the efficiency of the reforming unit is included.

All efficiencies are quoted relative to the fuel's higher heating value (HHV). In Europe and the USA, the lower heating value (LHV) is typically used, which gives efficiencies 11% higher with natural gas, and 18% higher with hydrogen. The reasons for using HHV were threefold:

- In the UK, domestic customers pay for natural gas based on the HHV energy content
- Domestic CHP units can conveniently condense the flue gasses, making the latent heat of the water content available for extraction
- A rudimentary understanding of thermodynamics suggests that reported efficiencies over 100% (which are typically achieved by condensing boilers) are simply implausible.

The original efficiency quoted from each source is given, with a set of notes to explain what the measurement relates to:

- LHV, HHV: The heating value used
- NG, P-NG, H, P-H: The fuel used: natural gas, pressurised natural-gas, hydrogen, pressurised hydrogen
- AC, DC: Whether inversion of the stack electrical output is included.
- G, N: Whether the value is gross (exclusive) or net (inclusive) of parasitic losses.

For each quoted value, estimates for the stack and system efficiency (η_{stack} and η_{system}) are given, based on the following definitions:

- Stack efficiency is for an ambient pressure hydrogen fuelled system, excluding all ancillary losses, but including the fuel utilisation
- System efficiency is for a natural gas fuelled system, including all reforming and electrical losses

The efficiencies of the mentioned ancillary components were reviewed in a similar manner to the fuel cell technology itself, resulting in the following estimates that have been used:

- Power conditioning: $88 \pm 4\%$ (4 references)
(*inverter and transformer*)
- Other equipment: $94 \pm 2\%$ (4 references)
(*i.e. 6% parasitic losses from pumps, etc.*)
- Steam Reformer: $77.5 \pm 4\%$ (3 references)
(*steam reformation was assumed due to its higher efficiency*)^[8]

The quoted values, with estimates for stack and system efficiency are given in Table 3 to a precision of 0.5%. The variation in efficiency over the range of power output (the part load performance) was also given in some sources, and is plotted relative to the efficiency at full power in Figure 2.

η_{elec} (quoted)	η_{total} (quoted)	η_{system} (HHV)	η_{stack} (HHV)	Year	Description
36.7%		27.5%	43%	1983-1985	Performance of 4.5MW power plant made for Tokyo Electric, operated at 2.5 bar. ^{[3][field]}
41.8%	74.4%	32.5%	50.5%	1991	Table 2, Row 1. 11MW Toshiba plant. ^{[2, 3, 9][field]}
38-40%	83-87%	34-36%	53.5-56.5%	c. 1996-2004	Widely verified performance of UTC PC25 units. Efficiency was 40% at the start of life, dropping to 38% after infancy. 37% is the average efficiency over a 40kh lifetime, with approximately 35% at the end of life ¹ . ^{[2, 10-13][field trial & marketing]}
40%		22.5%	35%	1999	Table 2, Row 4 (middle). 50kW stack of LG-Caltex cells. ^{[4][expt]}
40% ²	75%	36%	56.5%	1999	Modification of a 200kW PC25C for heat recovery via coolant loop and outlet gas. Seasonal thermal efficiency was 26-38%, with an average of 35%. ^[14]
36-37.5%		27.5%	43%	1998	Table 2, Row 5. Performance of an ERI 1kW stack, corrected for the varied cell construction ³ . Efficiency was lowered by poor fuel utilisation temperature control. ^{[5][expt]}
52%		28-34%	44-54.5%	1993	Table 2, Row 6. Performance of a UTC PC25A stack (top), and the overall system (bottom). ^{[6][expt]}
38%					
31.6 ± 1.2%		31.5%	49.5%	1994-1997	Efficiency of 30 PC25B and C systems installed in military bases between 1994-1997 and operated until 2000-2003. ^{[15][field]}

Table 3: Efficiency of PAFC systems.

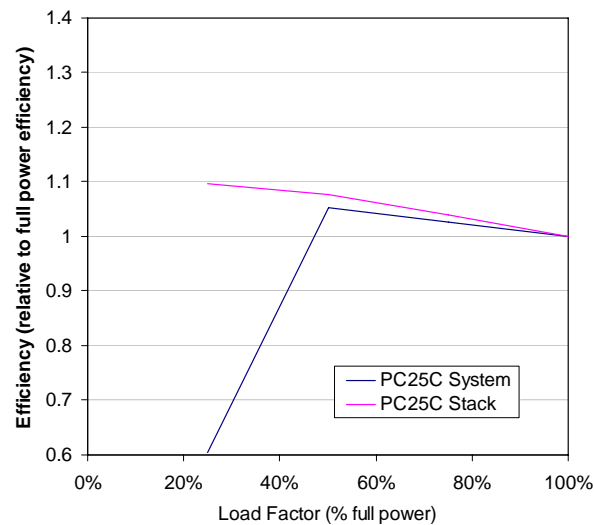


Fig 2: Part load efficiency of PAFC systems

¹ All values are w.r.t. the LHV of methane.

² This is assumed to be net AC performance vs. LHV for consistency with other results for the PC25.

³ 4 of the 30 cells in the stack contained less catalyst and electrode, and were found to have 11% lower OCV and 21% lower voltage on load. It is estimated the average voltage of the 26 standard cells would have been 2.7% higher than for all 30 cells. The uncorrected efficiencies were given as 35.0% and 36.5% vs LHV.

PAFC Lifetime

The demonstrated lifetime and rate of voltage degradation of PAFC are given in Table 4. The lifetime and failure rates of system peripherals and stacking mechanisms are equally as important as for the individual cells, and so assessments of entire CHP systems were preferred. However, the majority of published information focuses on single cells in laboratory conditions, which are expected to display higher durability due to the more amenable operating conditions.

Note: $1\mu\text{Vh}^{-1} = 1\text{mV per } 1000 \text{ hours} = 1.3\% \text{ loss of voltage per year}$.

Lifetime (kh)	Degradation ($\mu\text{V/h}$)	Year	Description
30-40		< 2002	Achieved by a fleet of 25 PC25 plants, some of which undergo extensive cycling. ^{[2][field]}
	1-2	< 2002	The efficiency of PC25 plants decreases by 8-12% over their lifetime, which gives $1-2\mu\text{Vh}^{-1}$ assuming 0.65V starting voltage and 40kh lifetime. ^{[2, 7, 13][field]}
	2	c. 1992	Test on Mitsubishi single cell at 0.2-0.25A. ^{[2][expt]}
	4	c. 1992	Test of UTCs 'advanced atmospheric water cooled' short stack over 4500h at 0.2A. ^{[2][expt]}
	3	1992	Degradation of 'previous state of the art' systems from CNR/TAE (Italy), Westinghouse/DOE, & Electric Utilities (Japan). ^{[2][note]}
46.5+		1998-2004	A PC25C operating in Halle (Germany) had passed 46500h as of 2004, with another unit having passed 40000h, both still operating. ^{[12][field]}
	5	1999	Table 2, Row 4. Test on a stack over 6000h. ^{[4][expt]}
55.5+		2001	Longest operating time for a UTC PC25A, which was still running as of 2001. Four other units had achieved over 40kh without failure. ^{[7][field]}
30 \pm 6		1994-1997	Table 3, Row 8. PC25B and C at 30 military bases. ^{[15][field]}

Table 4: Lifetime and degradation of PAFC.

PAFC Cost

Cost estimates for mass produced PAFC systems were sought, to give an approximation of the retail price if the technology were to reach commercialisation and widespread use. These costs are intended to reflect a state of the art system manufactured with present day materials and technologies at high volume. However, no cost estimates for domestic CHP units were available, and so the current and past retail price of industrial CHP systems are given instead.

All costs have been converted to 2007 Euros for consistency, based on a global inflation of 2.5% per annum (0% for Japan), and exchange rates of 160¥ = \$1.30 = £0.70 = €1. The costs are split into the following categories:

- The fuel cell stack, which are typically quoted per kW of electrical capacity
- The balance of plant (BOP), which consists of all ancillary equipment
- Operation and maintenance, which are the costs that occur during the operating lifetime

Stack Cost	BOP Cost	O & M Cost (MWh ⁻¹)	Year	Description
€3000-3900/kW (retail)	<i>Included</i>	€25	< 2002	The retail and maintenance price of an ONSI 200kW system during production. ^{[10][note]}
€2700/kW (retail)	<i>Included</i>	€51	2002	The retail and maintenance price of a UTC PC25 system. ^{[13][note]}
€5700/kW (retail)	<i>Included</i>		2002	The retail price of £694k for a 200kW system as of Jan 2002, with government subsidies excluded (£570k when included). ^{[3][note]}
€1600/kW	€48000 (for 200kW)	€13	2006	Unsubstantiated estimates for a 200kW system. ^{4 [16]}
€2500-3750/kW (retail)	<i>Included</i>		2001	The retail price of a 2 nd generation Fuji 100kW system. ^[17]

⁴ Estimates were: €1600/kW for 200kW of PAFC stack, €11750 for a fuel reformer, €10250 for heat exchangers, €26000 for electrical transformer, and €205000/yr for maintenance. Constant operation at full power was assumed with 90% availability (1578MWh/yr). To compare with other estimates, the total capital cost is €1850/kW.

PAFC Tolerance

The tolerance of PAFC to the impurities found in reformed natural gas is shown in Table 6.

Substance	Quantity	Effect	Description
CO	0.5-1%	Reversible	Performance loss reversible at 190°C _[2, 18]
CO	0.7%	Reversible	Performance loss due to increased cell resistance above 0.7%. _[19]
CO	1%	Poison	Catalyst poisoning. _[2, 3]
CO ₂	10%	Diluent	No effect other than to dilute the fuel. _[2, 3]
NH ₃	4%	Poison	Molecular nitrogen content of 4% reduces the electrolyte. _[2, 12]
S	-	Poison	Tolerance is greater than that of the reformers. _[12]
S	50ppm	Reversible	Acceptable as <20ppm H ₂ S and <30ppm COS. Performance loss is reversible by polarisation at high potential. _[2, 18]

Table 6: Tolerance of PAFC systems to fuel impurities.

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