Review of PEM fuel cell performance

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Abstract

The current technological status of polymer electrolyte membrane fuel cells (PEMFC, PEFC, or SPFC) was reviewed, focusing on small (0.5-5kWe) stationary units suitable for domestic CHP. 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 PEMFC technology is presented in the next section; represented by the mean ± 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)*	0.66	0.07	0.59-0.73	8
Operating Current (Acm^{-2})	0.65	0.25	0.40-0.90	
Power Density (Wcm^{-2})	0.42	0.14	0.27-0.56	
Stack Efficiency *(HHV)*	43%	6.5%	36.5-50%	10
Net Electrical Efficiency *(HHV)*	27%	4%	23-31.5%	
Net Total Efficiency *(HHV)*	72.5%	9%	63.5-81.5%	
Lifetime *(kh)*	14	7	7-21	9
(years)	1.6	0.8	0.7-2.4	
Degradation (μVh^{-1})	5	3.5	1.5-8.5	7
(voltage loss per year)	6%	5%	2-11%	
Cost	*Too little information..*			3

Table 1: Overview of performance of PEMFC systems.

PEMFC Electrochemical Performance

The operating voltage, current density and power density of PEMFC are given in Table 2, along with the catalyst loading of the cells. 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})	**Catalyst Loading** (mgcm^{-2} Pt)	**Year**	**Description**
0.7 x 0.6	0.42	1	2002	General achievement for mass-producible electrodes operating on reformed natural gas.[2][lit]
0.7 x 0.55 0.6 x 0.95	0.39 0.57	*?*	2003	Performance of Gore 55 cells on natural gas.[3][market]
0.76 x 0.17	0.13	*?*	2002	Gore 56 cells in a 36-cell stack.[4][expt]
0.7 x 0.5 0.65 x 0.8	0.35 0.52	0.45_{PtRu} + 0.6	2006	Single Gore 56 cell at start of operating life.[5][expt]
0.7 x 0.32 0.6 x 0.55	0.22 0.33	0.4 + 0.7	2002	An in-house stack built with E-Tek catalysts.[6][expt]
0.59 x 0.67 0.50 x 0.90	0.40 0.46	0.2 + 0.2	2007	Single cells produced by the CCM method operating on unhumidified hydrogen & air.[7][expt]
0.71 x 0.6 0.65 x 1.0	0.43 0.65	0.05 + 0.4	2004	Single cells optimised with a low catalyst loading, probably using a Gore membrane. Operated on 150kPa hydrogen (100kPa gas, 50kPa water vapour).[8][expt]
0.72 x 0.5 0.62x1.0	0.36 0.62	*?*	2007	From a single small-scale Ballard cell.[9][expt]

Table 2: Electrochemical performance of PEMFC systems.

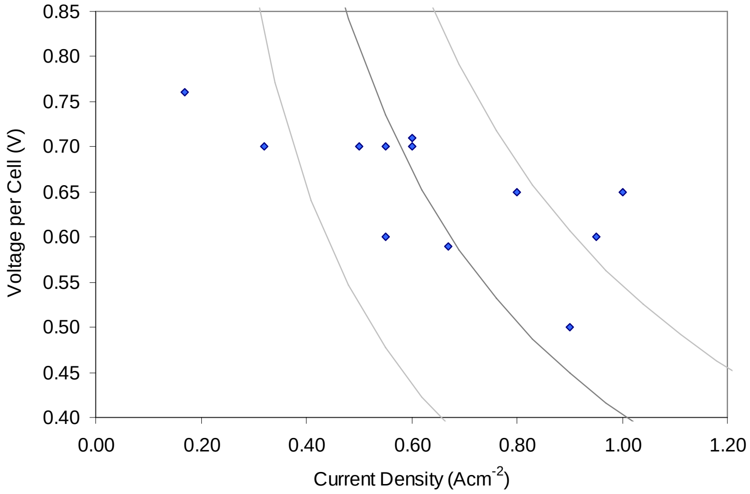

Fig 1: Plot of the operating points of listed PEMFC systems, with isobars of constant power density at the mean ± 1 standard deviation.

PEMFC 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:

Efficiency = what you get out / 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 ± 4% *(4 references)*
  (inverter and transformer)
- Other equipment: 94 ± 2% *(4 references)*
  (i.e. 6% parasitic losses from pumps, etc.)
- Steam Reformer + PROX: 76 ± 4% *(3 references)*
  (steam reformation was assumed due to its higher efficiency)[10]

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
32-36%[1] LHV, NG, AC, N	65-80%	*29-32.5%*	*46-51.5%*	2002	A 250kW Ballard unit during a 1 year field trial.[11][field]
41% HHV, P-H, DC, G	80%	*26%*	*41%*	2001-2003	An in-house 1kW stack containing 0.9mg Pt total, operating on 2 bar H_2 and 3 bar air.[12][expt]
43% HHV, P-H, DC, G	80%	*27%*	*43%*	2003	A 5kW Ballard stack (MK5-E), operating on 3 bar H_2 and 3 bar air.[13][expt]
44% HHV, P-H, DC, G	80%	*27.5%*	*44%*	2003	An unnamed commercial 1kW stack, operating on 2 bar H_2 and 3 bar air.[12][expt]
34% HHV, NG, AC	83%	*33%*	*52.5%*	2004	Highest achievement by a 1kWe Mitsubishi stack.[14][market]
30% HHV, NG, AC, N	68%	*30%*	*47.5%*	2002	Reported for a 10kW demonstration stack.[15, 16][note]
HHV	75%			2006	Performance of Ballard 1030 v3.[17][marketing] – better to use 1030 ...
31% LHV, NG, DC, G		*23%*	*36.5%*	2001	A prototype 1kW Proton Motor stack "suitable for reformant gas operation".[18][expt]
26.5% LHV, NG, DC, G	63.5%	*19.5%*	*31.5%*	2003	Performance of a 4kW Plug Power beta unit installed in a French town hall. System efficiency *(top)* was measured, while stack efficiency *(bottom)* was calculated.[10][field]
36% LHV, NG, DC, G		*20.5%*	*32.5%*		
27%[2] LHV, NG, AC	80%	*23.5%*	*37.5%*	2007	Quoted specifications for the Baxi Beta 1.5 Plus.[19][market]

Table 3: Efficiency of PEMFC systems.

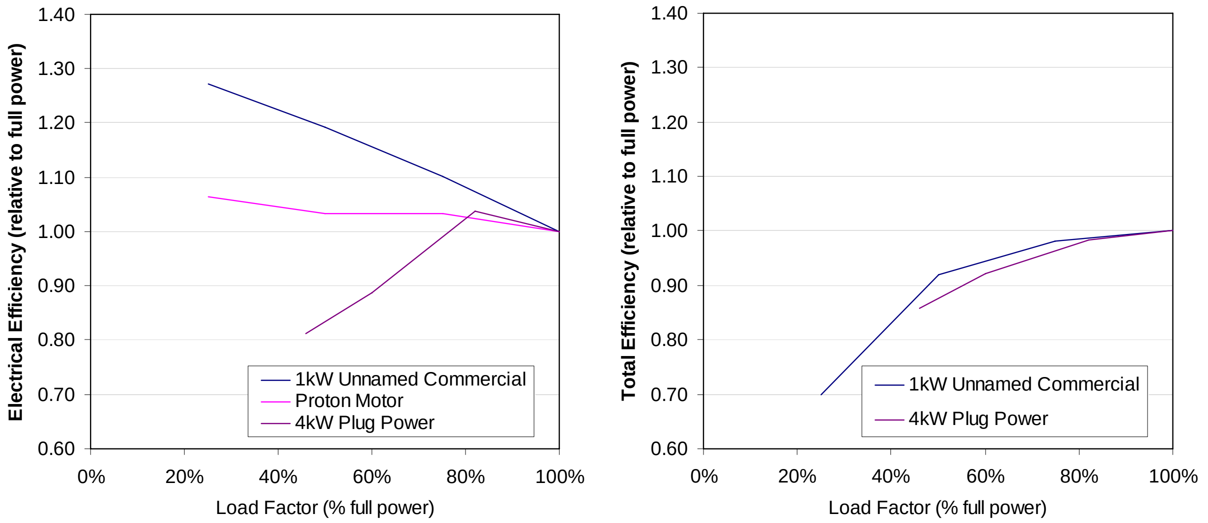

Fig 2: Part load efficiency of PEMFC systems.

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[1] Range shown is from different measurements of efficiency at full power, with averages of 34% electrical, 72% total.

[2] Based on the claims of 80% total efficiency, and 2:1 heat to power ratio.

PEMFC Lifetime

The demonstrated lifetime and rate of voltage degradation of PEMFC 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: 1μVh^{-1} = 1mV per 1000 hours = 1.3% loss of voltage per year.

Lifetime (kh)	**Degradation** (μVh^{-1})	**Year**	**Description**
<5		2005	Lifetime of 1st generation demonstration stacks.[20][lit]
4-13	>3.5	2004	Trials of 300 PlugPower units. May include such radical repairs as a stack replacement.[21][field]
7.4+		2004	Early 250kW Ballard trial units achieved 2.5-5kh, a later revision averaged 7.4kh without failing[22][field]
10-17	0.5-5	2006	Reports of cells and stacks in a variety of tests and conditions.[5][lit]
10		2002	A 3M membrane operating on reformate.[2][market]
15-25 max	1-5	2003	Gore 56 series cells at 0.6A.[2, 23][market]
	8 + 424$_{\text{(temp)}}$	2002	Gore 56 cells in a 36-cell stack had a non-recoverable decay of 8μV (25μV when poorly humidified) at 0.2A. The 424μV decay was recovered by switching the stack off.[4][expt]
26+	6.4 + 40-140$_{\text{(temp)}}$	2006	Single Gore 56 cell on pure hydrogen. The recoverable decay was 40-140μV. Failure was due to experiment definition, rather than inability to operate.[5][expt]
	2-10	2004	Commonly reported value.[22][lit]
13+	0.5	2004	Lab trial of a Ballard short stack operating on natural gas.[22][expt]
15		2005	Current durability of stack and system lifetime for Ballard 1030 v3.[24][note]
Plus 1 confidential value from an unnamed source. (2006)			

Table 4: Lifetime and degradation of PEMFC.

PEMFC Cost

Cost estimates for mass produced PEMFC 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.

Current retail prices for fuel cells are in the range of €10,000-100,000+ per kW due to the massive embedded research and development costs, and the high cost of manufacturing on an individual or low volume basis. These additional expenses would be greatly reduced if systems were sold by the thousands, making the retail price tend towards the cost of materials and energy inputs during construction.

The assumptions used in each cost estimate tend to differ widely, as they were concerned with different scenarios – e.g. current or future performance of the fuel cell; residential or industrial CHP units. When sufficient detail was given in the estimate, these assumptions were altered to conform to the other information presented in this report. Typical examples are lowering the power density of the fuel cells and thus increasing the number of cells required to achieve a given power output; or increasing the price of platinum to reflect current prices. The individual modifications are given as footnotes to Table 5.

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)	**Year**	**Description**
€180-5500/kW	€230		2000	A number of extrapolations from a 50kW pressurised system arrived at $200-6000/kW, with a separate assessment leading to $255 for the BOP.[25][theory]
€85 + €160/kW			1999	Detailed bottom-up analysis of individual component costs for a 3-50kW stationary system, using commercial cost estimation software and information from the DOE and Ford.[3][26][theory]
€600/kW (materials)	€190 + €175/kW		2005	Empirical formulae were used to model the variation with size of individual components for a pressurised methanol stack.[4][27][theory]

Table 5: Cost estimates for present day, mass produced PEMFC systems.

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[3] The analysis of BOP costs was omitted due to misgivings in component costs, which were typically 5x higher than expected.

- The number of bipolar plates was reduced by 33%, as 1 cooling channel every 3 cells was considered instead of 1 for every cell.
- The stack power density was reduced by 30%
- Platinum cost was raised by 240% to €32/g
- The area of individual cells was held at 100cm^2, rather than scaling down to 10cm^2 for a 1kW stack (giving an unrealistic 3x3x160cm dimensions). This removed the benefit of larger stacks using larger die stamps, etc..

[4] Some unexpected conclusions were drawn from this report, such as an almost constant cost of $400 for heat exchangers of any size.

- The cost of heat exchangers, pumps and misc. components were reduced by a factor of 5, to be in line with other reports.
- The compressor was replaced with a $15 blower, to remove the additional expense of pressurisation.
- Overall BOP costs were assumed to scale proportional to capacity$^{0.7}$, which was roughly the mid-point of the individual components.
- The stack power density was reduced by 33%

PEMFC Fuel Tolerance

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

Substance	Quantity	Effect	Description
CO	10ppm	Poison	Platinum catalyst poisoning.[12, 28]
CO	10ppm	Poison	Caused a reduction of 0.1-0.2V during operation, unsure if this is permanent degradation.[29]
CO	100ppm	None	100ppm CO + 2% O_2 at the anode gives the same performance as no CO, resulting in a 4% loss of fuel[2]
S, NH_3, HCl, Si	*?*	Poison	Mentioned as poisons.[30]

Table 6: Tolerance of PEMFC systems to fuel impurities.

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