Review of solid oxide fuel cell performance

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Abstract

The current technological status of solid oxide fuel cells (SOFC) 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 SOFC 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.

As several types of SOFC are under development with different geometries and operating temperatures, the following categories are used to distinguish the fuel cells cited in each table:

Planar	Planar geometry, typically with 120mm diameter cells
Tubular	Simple cylindrical tube cells
Semi	One of many semi-tubular, flattened-tubular or ribbed designs
IT	Intermediate temperature, defined as 600-800°C – where metal components are viable
HT	High temperature, defined as >800°C
IR	Internally reforming, using a simple pre-reformer with methane passed to the anode
ER	Externally reforming, with a separate reformer to pass hydrogen to the anode

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)*	0.69	0.06	0.63-0.75	11
Operating Current *(Acm^{-2})*	0.49	0.17	0.32-0.67	
Power Density *(Wcm^{-2})*	0.34	0.12	0.22-0.46	
Stack Efficiency *(HHV)*	53.5%	11.5%	42-64.5%	7
Net Electrical Efficiency *(HHV)*	34%	7%	27-41.5%	
Net Total Efficiency *(HHV)*	69%	2%	67-71%	
Lifetime *(kh)*	37	22	15-59	5
(years)	4.2	2.5	1.7-6.7	
Degradation (μVh^{-1})	3.2	5.1	0-8.4	6
(voltage loss per year)	4%	6%	0-10%	
Degradation $(\mu V\cdot cycle^{-1})$	n/a	n/a	0-3500	2
Stack Cost	€390	€190	€200-575	5

Table 1: Overview of performance of SOFC systems.

SOFC Electrochemical Performance

The operating voltage, current density and power density of SOFC 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})	**Cell Type**	**Year**	**Description**
0.7 x 0.5	0.35	Planar, 750°C	2006	In-house tests of Fuel Cells Scotland prototype 1.3kW stack.[2][expt]
0.7 x 0.39	0.27	Tubular, 800°C	2006	Performance of single cells from Acumentrics *(top)*, and a short-stack operating on natural gas reformed with CPOX *(bottom)*.[3][market]
0.65 x 0.24	0.16			
0.7 x 0.6 0.62 x 0.8	0.42 0.50	Planar, 800°C	2002	Average performance of anode supported FZJ cells operating on hydrogen in a short stack.[4][expt]
0.7-0.79 x 0.7	0.49-0.55	Planar, 850°C	2002	Average performance of anode supported FZJ cells operating on hydrogen in internally manifolded short stacks produced by ALSTROM.[4][expt]
0.61-0.77 x 0.55	0.34-0.42	Planar, 800°C		
0.65 x 0.46 0.6 x 0.58	0.30 0.35	Semi	2007	Performance of modified tubular cells from Siemens; Delta9 *(top)* and HPD-5 *(bottom)* operating on hydrogen, at an unknown temperature.[5][note]
0.68 x 0.35 0.63 x 0.45	0.24 0.28	Semi		
	0.5	Semi, 750°C, IR	2007	*Table 3, Row 2.* Reported by Osaka Gas.[5][note]
0.77 x 0.21	0.16	Planar, 750°C	2007	Performance of a 10kW module from KEPCO / Mitsubishi *(top)* and a 1kW system in a separate long term test.[6][expt]
0.73 x 0.3	0.22			

Table 2: Electrochemical performance of SOFC systems.

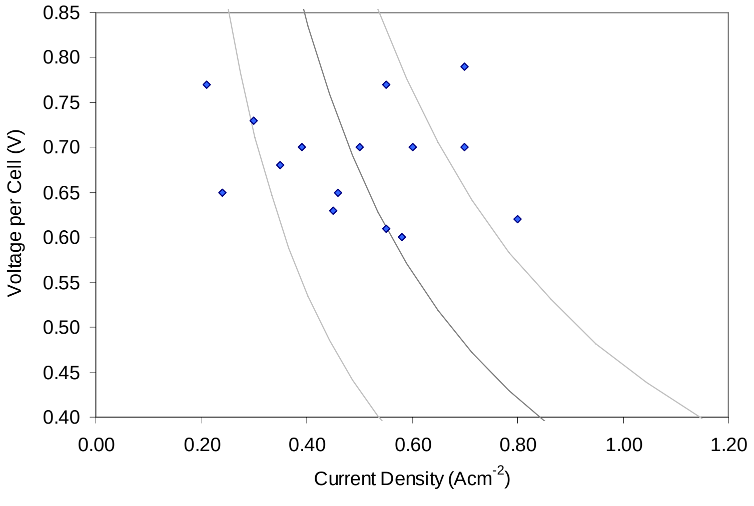

Fig 1: Plot of the operating points of listed SOFC systems, with isobars of constant power density at the mean ± 1 standard deviation.

SOFC 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: 77.5 ± 4% *(3 references)*
  (steam reformation was assumed due to its higher efficiency)[7]

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)	**Cell Type**	**Year**	**Description**
28.5% HHV, H, AC, N		*22%*	*34.5%*	Planar, 750°C	2006	*Table 2, Row 1.* Fuel Cells Scotland 1.3kW stack.[2][expt]
44% LHV, NG, AC, N	78%	*39.5%*	*62%*	Flat tube, 750°C, IR	2003-2006	Results from 1kW domestic units from Osaka Gas & Kyocera.[8-10][field, market]
54% LHV, DC, G		*40%*	*63%*			
56% LHV, NG, DC, G		*41.5%*	*65%*	Flat tube	2006	Results from 2.5kW domestic units from Tokyo Gas, Kyocera, Rinnai & Gastar.[11][market]
29% HHV, NG, DC, N		*25.5%*	*40%*	Tubular, 800°C	2006	*Table 2, Row 2.* Estimated full-power efficiency of a 6kW Acumentrics stack, based on a measured peak efficiency of 36% at 33% power.[12][market, theory]
55% LHV, H, DC, G		*30%*	*46.5%*	*?*	2005	Performance of a prototype stack *(top)* and system *(bottom)*.[13][note]
45% LHV, NG, AC, N	75%	*40.5%*	*63.5%*			
35.5-41% LHV, NG		*29-33.5%*	*45.5-52.5%*	*Multiple*	2007	Given as the aggregate performance of 6 recent small SOFC systems from American companies.[5][lit]
41% HHV, NG, AC	82%	*40%*	*62%*	Planar, 750°C	2007	*Table 2, Row 7.* 10kW module from KEPCO / Mitsubishi.[6][expt]

Table 3: Efficiency of SOFC systems.

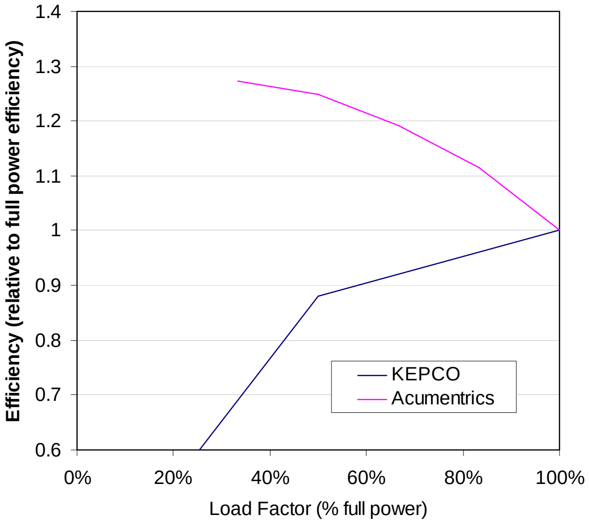

Fig 2: Part load efficiency of SOFC systems

SOFC Lifetime

The demonstrated lifetime and rate of voltage degradation of AFC 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.

The ability to cycle the fuel cell stack between ambient and operating temperature is a particular concern for SOFC, as it is known to possibly cause failure if not performed sufficiently slowly. In these cases, heating and cooling must be over extremely long times (2-10 hours), or avoided altogether by keeping the stack heated when not in use (hot idling). In other cases, particularly with tubular systems, the heating and cooling process is benign and causes no damage. Where possible, the degradation rate is reported per hour of operating time, and per thermal cycle.

Degradation rates that are marked with an asterisk were quoted as a percentage power loss, and have been converted to μVh^{-1} using an operating voltage of 0.7V. Note: $1\mu Vh^{-1}$ = 1mV per 1000 hours = 1.25% loss of voltage per year.

Lifetime (kh)	**Degradation** (μV)	**Cell Type**	**Year**	**Description**
69	0.7-3.5 / h* 0 / cycle	Tubular	2000-2007	The best results from laboratory tests on Siemens-Westinghouse cells *(top)* and air-electrode supported (AES) cells *(middle)*.[14, 15][note]
44	1.4 / h*			
16, 17, 37	~0 / h			The real-world test of a 100kW stacks in the Netherlands and USA *(bottom)*.[5, 15, 16][field]
	0 / h	Tubular, 800°C	2006	*Table 2, Row 2.* Degradation of an Acumentrics short stack over 1000h.[12][market]
	14 / h*	*Multiple Planar*	2007	*Table 3, Row 7.* The aggregate degradation of 6 recent small SOFC systems.[5] [lit]
	1.8 / h* 3500 / cycle*	IT Planar, 750°C	2005-2007	Degradation of a KEPCO / Mitsubishi 10kW module, with heating and cooling times of 7 and 10 hours during over 20 daily thermal cycles.[6] [expt]

Table 4: Lifetime and degradation of SOFC.

SOFC Cost

Cost estimates for mass produced SOFC 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)	**Cell Type**	**Year**	**Description**
€575/kW			Tubular, 800°C	2006	*Table 2, Row 2.* Cost estimate for a 6kW Acumentrics system.[3][market]
€4250-5750/kW	Incl.		Flat tubular 750°C	2006	*Table 3, Row 2.* Expected retail price of a 0.7kW domestic unit (incl. tank) from Osaka Gas & Kyocera.[17][market]
€350/kW	€625 (1.3kW)		Planar, 850°C	2006	*Table 2, Row 1.* Cost estimate for a 1.3kW stack from Fuel Cells Scotland.[18][market]
€150-450/kW			Planar	2004	Taken from a central estimate of $90/kW for 5kW residential units from Tiax. This value was modified using the sensitivity analyses provided in the original report.[1] [19][theory]
€550-600/kW			*Multiple Planar*	2007	*Table 3, Row 7.* The aggregate cost of 6 recent small SOFC systems.[5] [lit]
€50-225/kW					Estimate cost of cells, based on assumptions for high volume production.[20][theory]

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

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[1] Assumptions used in the cost estimate:

- Power density was reduced by 29% to the average presented here of $340 mWcm^{-2}$, with the relationship between cost and power density fit to $C = 33.13 / PD^{1.3566}$.
- The portion of defective cells from the firing process was chosen to be 0-1%.
- A production rate of 100MW annually.

SOFC Fuel Tolerance

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

Substance	**Quantity**	**Effect**	**Cell Type**	**Description**
CO	-	Fuel	*?*	[14]
CO_2	-	Diluent	*?*	[14]
H_2S	1ppm	Poison	*?*	[13, 14]
NH_3	0.5%	Diluent	*?*	Described as "Relatively harmless".[13, 14]
HCl	0.1ppm	Poison	*?*	[13, 14]
Si	*?*	Poison	*?*	[14]

Table 6: Tolerance of SOFC systems to fuel impurities.

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