A review of small stationary fuel cell performance

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Abstract

The current technological status of four fuel cell technologies was reviewed, focusing on small (0.5-5kW$_e$) stationary units suitable for domestic CHP. These were polymer electrolyte membrane fuel cells (PEM, PEMFC, PEFC, SPFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), and alkaline fuel cells (AFC).

Seven categories of data were investigated that would impact on the performance of micro-CHP systems:

- Power density – power output per cm^2 of cell area, which determines the number of cells (or stack area) required;
- Efficiency of the complete natural gas fuelled CHP system, at full and part load;
- Durability – the operating lifetime and rate of degradation of the fuel cell stack;
- Reliability of the system, including ancillary components;
- Current prices and estimated high-volume manufacturing costs;
- Start-up time and other dynamic constraints on power output;
- Fuel tolerance of the stack, which impacts on the required fuel processing stages.

Performance figures were sought to represent the real-world capabilities of state of the art systems. Wherever possible, data was sourced directly from the field, giving the performance actually experienced by users, rather than quoted by the manufacturers. Both commercial and research systems were considered, so long as they could be suitable for a consumer product.

Due to the vast differences in research activity for each fuel cell technology, there was a wide range in the quality and age of available sources. Much of the PEMFC data came from the extensive field trials in Japan, which were highly regarded due to their relevance to this study. For SOFC, much of the data came from academic literature as commercial demonstrations are only just beginning. As domestic micro-CHP scale AFC and PAFC systems are only beginning to be developed, data had to come from similar, but not entirely relevant industrial CHP units, and from publications that are over a decade old.

The first revision of this review was published in 2007, and is available (for legacy) from http://wogone.com/iq/fuelcells. This review is an ongoing project, and it is expected that the final values presented will be updated as more information is collected and reviewed. The aim is to stay updated with the latest technological advances, and to continue broadening the overview of fuel cell technologies.

As the progress of technology marches on, the data presented in this revision will slide out of date. If readers could contact me at the above email address with any citable information (references to articles, web pages, etc.), I would gratefully acknowledge their efforts in improving this work.

Table 1: The following tables summarise the performance of each fuel cell technology, giving the weighted mean and standard deviation for each data category. Ranges that should cover two-thirds of systems are given for each value.
* Intermittent operation was assumed for calculating lifetimes and voltage losses, with 4,000 operating hours per year.

PEMFC performance	**Mean**	**Standard deviation**	**Range (μ ± σ)**	**Number of references**
Operating cell voltage _(V)_	0.68	0.08	0.60-0.76	8
Operating cell current _(A/cm^2)_	0.51	0.30	0.20-0.81	
Power density _(W/cm^2)_	0.33	0.17	0.16-0.50	
Gross stack electrical efficiency _(HHV)_	37.1%	4.9%	32.3-42.0%	20
Net system electrical efficiency _(HHV)_	26.7%	3.5%	23.2-30.2%	
Net total efficiency _(HHV)_	66.9%	6.6%	60.3-73.6%	19
Operating lifetime _(kh)_	19.7	10.0	9.7-29.7	22
_(years)_*	4.1	2.5	2.4-7.4	
Degradation rate _(μV/h)_	8.0	7.8	0.1-15.8	17
_(power loss per year)_*	4.7%	4.6%	0.1-9.3%	
Current retail price	€20,000 to €50,000 for 1kW systems			2
Volume cost estimate	Anywhere from €100 to €10,000 per kW			4

SOFC performance	**Mean**	**Standard deviation**	**Range (μ ± σ)**	**Number of references**
Operating cell voltage _(V)_	0.71	0.05	0.66-0.76	11
Operating cell current _(A/cm^2)_	0.34	0.17	0.17-0.52	
Power density _(W/cm^2)_	0.27	0.14	0.13-0.41	
Gross stack electrical efficiency _(HHV)_	44.2%	5.7%	38.5-50.0%	10
Net system electrical efficiency _(HHV)_	34.7%	4.5%	30.2-39.2%	
Net total efficiency _(HHV)_	72.4%	4.4%	68.0-76.8%	6
Operating lifetime _(kh)_	11.3	7.1	4.2-18.4	12
_(years)_*	2.8	1.8	1.0-4.6	
Degradation rate _(μV/h)_	12	16	0-28	16
_(power loss per year)_*	6.9%	9.2%	0-16%	
Current retail price	Over €50,000 for 1kW systems			2
Volume cost estimate	Between €300 and €900 per kW			5

PAFC performance	**Mean**	**Standard deviation**	**Range (μ ± σ)**	**Number of references**
Operating cell voltage _(V)_	0.66	0.03	0.63-0.70	9
Operating cell current _(A/cm^2)_	0.24	0.04	0.20-0.28	
Power density _(W/cm^2)_	0.16	0.02	0.14-0.18	
Gross stack electrical efficiency _(HHV)_	44.3%	4.6%	39.8-48.9%	7
Net system electrical efficiency _(HHV)_	32.5%	3.3%	29.1-35.8%	
Net total efficiency _(HHV)_	76%	-	69-78%	2
Operating lifetime _(kh)_	58	15	43-72	7
_(years)_*	14.5	3.7	10.9-18.2	
Degradation rate _(μV/h)_	2.6	1.3	1.3-3.9	7
_(power loss per year)_*	1.6%	0.8%	0.8-2.4%	
Current retail price	Around €3000-5000 per kW for industrial CHP			5
Volume cost estimate	_Unknown_			-

AFC performance	**Mean**	**Standard deviation**	**Range (μ ± σ)**	**Number of references**
Operating cell voltage _(V)_	0.68	0.03	0.65-0.71	4
Operating cell current _(A/cm^2)_	0.14	0.03	0.11-0.17	
Power density _(W/cm^2)_	0.10	0.03	0.07-0.12	
Gross stack electrical efficiency _(HHV)_	41.3%	3.6%	37.7-44.8%	4
Net system electrical efficiency _(HHV)_	29.7%	2.6%	27.1-32.2%	
Net total efficiency _(HHV)_	66.6%	-	-	1
Operating lifetime _(kh)_	6.7	1.9	4.8-8.6	7
_(years)_*	1.7	0.5	1.2-2.1	
Degradation rate _(μV/h)_	19.5	9.4	9.1-28.0	8
_(power loss per year)_*	10.9%	5.5%	5.4-16.5%	
Current retail price	_Unknown_			-
Volume cost estimate	Between €150 and €600 per kW			6

Methodology

Information was mostly sourced from open literature, for example from journal publications, field trial reports and commercial data sheets. Due to the commercial nature of the industry, some information must however remain confidential.

Data was reviewed and modified where necessary to give a standardised view of each technology and to avoid biased comparisons. In compiling technology wide averages, a semi-quantitative weighting was given to each source of data based on its perceived relevance.

Tables of data are presented in the following sections, giving the original and modified information, along with the date and a brief description of the report. The weighting factor (w) is also given for each result, so that the relative contribution towards the averages presented in Table 1 can be seen.

Weighting method

Not all data sources are equal. In trying to collect a broad overview of the field, some reports are cutting edge, some are from over a decade ago. Similarly, some are from extensive field trials and report the performance experienced in people's houses, others are from promotional material. A weighting method was devised in order to reconcile these differences, and prevent the less representative (but still beneficial) sources from dominating the overall averages presented in the abstract.

A weighting factor (w) for each datum was defined as follows; from the number of measurements or units that are represented (N), the age of the data source in years (A), and two qualitative multiplication factors based on the source quality (SQ), and data quality (DQ):

$$w = \big(1 + \ln(N)\big) \cdot \exp\left(-A \cdot \left(\frac{\ln(2)}{3}\right)\right) \cdot SQ \cdot DQ$$

- The quantity term $\big(1 + \ln(N)\big)$ accounted for the greater representation offered when more units are tested. A single value arising from three units would be given approximately double the weighting, data from a group of 10 would be given a weighting of 3.3, and data from 100 would be given 5.6.
- The time constant of $(-\ln(2)/3)$ accounted for the decreasing relevance of older data due to the continual march of technological improvement. Data that is three years old was given half the weighting, six year old data was given quarter the weighting, etc.
- The source quality (SQ) reflected differences between the ideal source of information, and was given the following values:
  - 4 for data arising from field trials
  - 2 for data arising from independent (preferably peer reviewed) experiments
  - 1 for manufacturer's specifications, promotional material and other sources
- The data quality (SQ) reflected differences between the ideal domestic CHP system and what was actually tested. It was given the following values:
  - 1 for complete systems running on natural gas
  - 0.9 for the fuel cell stack only (full or short stack)
  - 0.5 for single cells only
  - 0.7 for operation on hydrogen
  - 0.5 for pressurised operation

The weighted mean and standard deviation (μ *and* σ) for each data set was calculated as follows; where each data value x_i has a weighting factor of w_i, and n is the number of non-zero weights:[1]

$$\mu = \frac{\sum(w_i \cdot x_i)}{\sum w_i} \qquad \sigma = \frac{n}{n-1} \cdot \frac{\sum(w_i \cdot (x_i - \mu)^2)}{\sum w_i}$$

Power Density

The electrochemical performance of each fuel cell type is presented: the operating voltage, current density, and resulting power density, per unit area of cell. Ideally, pressurised systems were excluded as they demonstrate significantly higher performance, but require significantly more expensive auxiliary systems which precludes them from use in commercially viable systems.

Commercial examples of every technology show similar operating voltages around 0.65-0.7V. Voltages are not significantly higher than average for AFC systems which operate with limited current density, or significantly lower than average for PAFC due to their electrolyte. Power density is one of the clear dividing lines between the technologies, as highlighted in Figure 5. The power density of PEMFC and SOFC cells continues to advance, with the highest reported values being in excess of 500mW/cm^2.

In Figures 1-4, the voltage and current density of each system are plotted together, to give industry-wide VI curves. Lines are included on each graph to indicate the average current density (plus one standard deviation), and a weighted linear fit of voltage against current density. Please note the different scales for current density in the first and second sets of figures.

Figure 1: PEMFC electrochemical performance

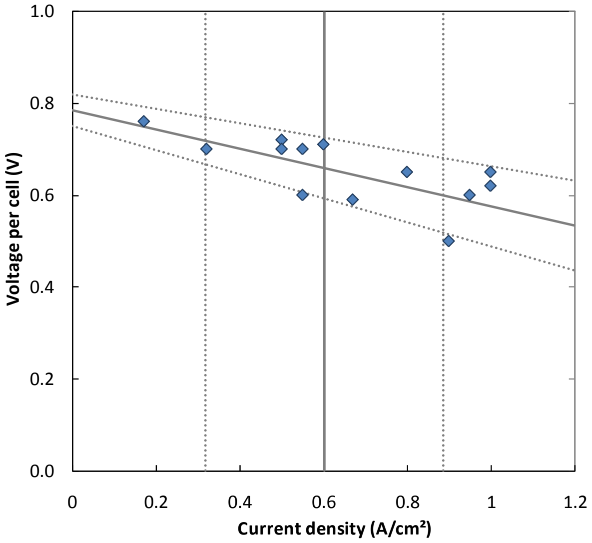

Figure 2: SOFC electrochemical performance

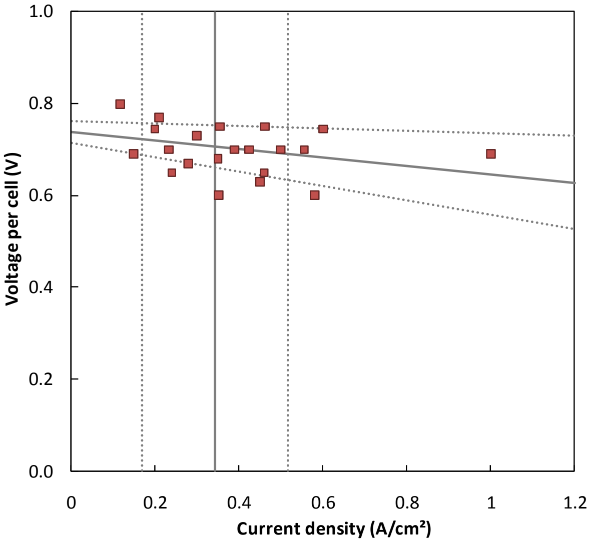

Figure 3: PAFC electrochemical performance

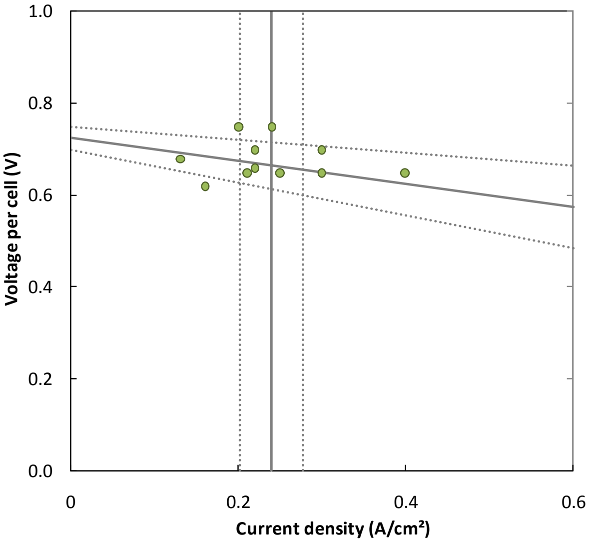

Figure 4: AFC electrochemical performance

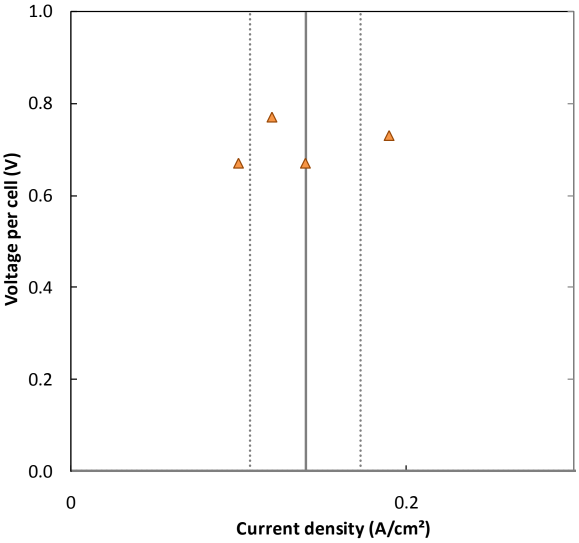

Figure 5: Average power density of each fuel cell technology.

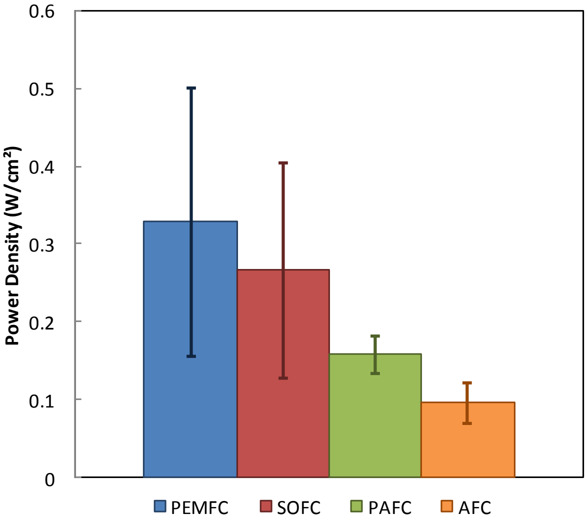

Table 2: PEMFC electrochemical performance

Operating Point (V/cell x A/cm^2)	**Power Density** (W/cm^2)	**Catalyst Loading** (mg/cm^2)	**Year**	**Description**	***w***	**Ref.**
0.72 x 0.5	0.36	?	*2007*	Results from operating a single small-scale Ballard cell.	*1.69*	[2]
0.62 x 1.0	0.62					
0.59 x 0.67	0.40	0.2 + 0.2	*2007*	Results from single cells produced by the CCM method operating on unhumidified hydrogen & air.	*1.20*	[3]
0.5 x 0.9	0.45					
0.7 x 0.5	0.35	0.45_{PtRu} + 0.6	*2006*	Results from a single Gore 56 cell at start of operating life.	*1.34*	[4]
0.65 x 0.8	0.52					
0.71 x 0.6	0.43	0.05 + 0.4	*2004*	Results from single cells optimised with a low catalyst loading. Operated on 150kPa hydrogen.	*0.30*	[5]
0.65 x 1.0	0.65					
0.7 x 0.55	0.39	?	*2003*	The performance of 55-series cells running on natural gas, as claimed by Gore.	*0.34*	[6]
0.6 x 0.95	0.57					
0.7 x 0.32	0.22	0.4 + 0.7	*2002*	Results from an in-house stack built with E-Tek catalysts.	*1.07*	[7]
0.6 x 0.55	0.33					
0.76 x 0.17	0.13	?	*2002*	Results from operating Gore 56 cells in a 36-cell stack.	*1.07*	[8]

Table 3: SOFC electrochemical performance

Operating Point (V/cell x A/cm^2)	**Power Density** (W/cm^2)	**Cell Type**	**Year**	**Description**	***w***	**Ref.**
0.77 x 0.21	0.16	Planar 750°C	*2007*	Performance of a 10kW KEPCO/Mitsubishi module *(top)*, and a 1kW system *(bottom)* in long term tests.	*2.32*	[9]
0.73 x 0.3	0.22					
	0.50	Flat Tube, 750°C	*2007*	Reported by Osaka Gas for 1kW domestic units from Kyocera, operating on internally reformed natural gas.	*1.16*	[10]
0.75 x 0.35	0.27	Planar 850°C	*2007*	Performance of 1cm^2 demonstration cells for the Hexis Galileo model, demonstrating a new cathode formulation. Using an excess of hydrogen and air.	*0.82*	[11]
0.7 x 0.43	0.30					
0.75 x 0.46	0.35	Planar 900°C				
0.7 x 0.56	0.39					
0.65 x 0.46	0.30	Flat Tube	*2007*	Performance of modified tubular cells from Siemens; Delta9 cells *(top)* and HPD-5 cells *(bottom)* were operated on hydrogen, at an unknown temperature.	*0.82*	[10]
0.6 x 0.58	0.35					
0.68 x 0.35	0.24	Flat Tube				
0.63 x 0.45	0.28					
0.7 x 0.39	0.27	Tubular 800°C	*2006*	Performance of single cells from Acumentrics *(top)*, and a short-stack operating on reformed natural gas *(bottom)*.	*0.69*	[12]
0.65 x 0.24	0.16					
0.7 x 0.5	0.35	Planar 750°C	*2006*	Testing of a prototype Fuel Cells Scotland 1.3kW stack, using InDEC cells operating on hydrogen.	*1.30*	[13]
0.80 x 0.20	0.16	Planar 800°C	*2004*	Performance of 1.2kW stacks using Topsøe cells when operated on reformed natural gas.	*1.16*	[14, 15]
0.79 x 0.2	0.12	Planar 750°C				
0.7-0.79 x 0.6	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.	*0.52*	[16]
0.61-0.77 x 1.0	0.34-0.42	Planar 800°C				
0.67 x 0.28	0.19	Planar 950°C	*2000*	Results from a single 1kW Sulzer Hexis unit in a European field trial, fed by steam reformed natural gas.	*0.92*	[17]
Confidential data collected from a short stack running on hydrogen					*1.30*	-

Table 4: PAFC electrochemical performance

Operating Point (V/cell x A/cm^2)	**Power Density** (W/cm^2)	**Year**	**Description**	***w***	**Ref.**
0.65 x 0.25	0.16	*2001*	The operating voltage and current density of UTC PC25C plants at start of life.	*5.80*	[18, 19]
0.7 x 0.3	0.21	*1999*	Performance of single cells made by LG-Caltex using Pt anode and Pt-Fe-Co cathode.	*0.32*	[20]
0.65 x 0.4	0.26				
0.66 x 0.22	0.15	*1999*	The performance of a 50kW stack of LG-Caltex cells operating on hydrogen *(top)*, and the subsequent performance of a 10kW stack operating on natural gas *(bottom)*.	*1.56*	[20]
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, in South Africa.	*0.51*	[21]
0.62 x 0.16	0.10				
0.75 x 0.2	0.15	*1991 - 1997*	Performance of 11MW power plant assembled by Toshiba using UTC PC-23 cells, operated at 7.3 bar with 0.1 + 0.5mg/cm^2 Pt loading.	*0.58*	[22, 23]
0.65 x 0.21	0.14	*1993*	Separate measurements of the performance from single cells of a UTC PC25A.	*0.16*	[22, 24]
0.75 x 0.24	0.18				
0.65 x 0.3	0.20	*1992*	Performance of Mitsubishi atmospheric single cells.	*0.06*	[22]

Table 5: AFC electrochemical performance

Operating Point (V/cell x A/cm^2)	**Power Density** (W/cm^2)	**Cell Type**	***Year***	**Description**	***w***	**Ref.**
0.67 x 0.14	0.09	Platinum	*2003*	Performance of a 0.8kW Eident stack using 0.52mg/cm^2 total Pt loading.	*2.34*	[25]
0.67 x 0.1	0.07	Platinum	*1999*	Performance of a 0.4kW Zevco Mark II module.	*0.93*	[26]
0.73 ± 0.10 0.19 ± 0.08	0.14	*Multiple*	*1998*	Average of 6 operating points from 5 different sources, which are not listed separately here.	*0.74*	[27]
0.77 x 0.12	0.09	*?*	*1960*	Tests by Karl Kordesch on a 6kW fuel cell stack used for transport.	*0.00*	[28]

Efficiency

Methods

The following four tables present the information gathered on fuel cell micro-CHP system efficiencies, split by the cell technology used. Each table gives the estimated electrical efficiencies of the fuel cell stack and the whole system, and the total CHP efficiency – all against the Higher Heating Value of the fuel input. A description of the source is given, along with the original efficiencies given in the source, and the key markers denoting what the measurement relates to. The following abbreviations for the key markers were used in the following tables:

- **Heating value of fuel input:** *(LHV, HHV)*
- **Fuel used:** natural gas *(NG)*, hydrogen *(H)*, or pressurised hydrogen *(PH)*;
- **Electricity output:** *(AC/DC)* to indicate whether losses from the inverter are included;
- **Ancillary loads:** Whether the energy output is measured gross *(G)* excluding parasitic losses, or net *(N)* and includes the electricity and heat consumed by pumps, fans, controllers, the reformer, etc.

These markers were used to estimate the three standard definitions of efficiency which are included in the following tables. The following definitions of efficiency are used to give a more standardised means of comparing the efficiencies found in each report:

$$Stack\ efficiency = \frac{DC\ electricity\ output}{HHV\ of\ hydrogen\ energy\ input}$$

$$System\ efficiency = \frac{AC\ electricity\ output - electricity\ consumption}{HHV\ of\ natural\ gas\ input}$$

$$\begin{aligned} Thermal\ efficiency &= System\ efficiency + Thermal\ efficiency \\ &= System\ efficiency + \frac{Useful\ heat\ output\ recovered\ in\ coolant\ water}{HHV\ of\ natural\ gas\ input\ to\ reformer\ \&\ aux.burners} \end{aligned}$$

In order to calculate these standardised efficiencies, the original reported values were modified to account for the four points listed above. In doing so, the following table of component efficiencies was used to estimate the losses in converting natural gas to hydrogen, DC to AC power, and in powering the auxiliary systems needed to operate a fuel cell system:

Table 6: The assumed efficiency of other system components.
The results used to produce these values are given in the following sections.

Component	Efficiency
AFC fuel processor:	81.5 ± 4%
PAFC fuel processor:	83 ± 4%
PEMFC fuel processor:	81.5 ± 4%
SOFC fuel processor:	89 ± 4%
Inverter & power conditioning:	89 ± 5%
Parasitic loads (pumps, controller):	96 ± 3%

To summarise, the following rules were applied to each source:

- If the source used lower heating values, electrical and thermal efficiency were converted to HHV:
  - × 0.9008 if using natural gas;
  - × 0.8454 if using hydrogen.[29, 30]
- If the fuel cell ran on hydrogen, the efficiency of the fuel processor was accounted for:
  - Stack efficiency was unchanged, and system electrical efficiency was multiplied by the fuel processor efficiency given in Table 6;
  - Thermal efficiency by the square root of this value, for lack of a more precise estimate;[1]
- If DC electrical output was measured, system efficiency was multiplied by the efficiency of the inverter and transformer;
- If parasitic losses were not included (gross efficiency given), the estimated system efficiency was reduced further.

In a small number of instances, the performance of a system running in realistic conditions (natural gas fuelled, AC output, net of parasitic losses) was presented alongside the laboratory results (hydrogen fuelled, gross DC output). Five examples of this are seen in the following tables, which are useful for checking the validity of the auxiliary component efficiencies given the previous sections. In all the cases where joint information is given, the estimated system efficiency deviates by less than 2% from the actual values, and the two appear to be evenly balanced. The spread in differences can be explained by some manufacturers having above or below average performance for their auxiliary systems, while the near-zero mean implies there is little bias (systematic error) in the process – even though the auxiliary efficiencies were taken from a separate set of sources, rather than tailored to fit this subset of data.

Table 7: Estimated system efficiency for models where a comparison could be made.

	Given for a natural gas fuelled system	Estimated value, based on a hydrogen system, stack or cells
Toshiba TM-1 (PEMFC) [34]	32.0%	30.2%
Plug Power (PEMFC) [35]	19.7%	21.4%
Prototype (SOFC) [36]	38.1%	36.5%
Kyocera & Osaka Gas (SOFC) [37-39]	37.3%	37.2%
UTC PC25A (PAFC) [24]	30.3%	30.1%

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[1] The logic for this was that thermal efficiency of a natural gas fuelled system will be lower than that of one running on hydrogen, as some of the useful chemical energy in the fuel is lost ($CH_4 \rightarrow H_2$ conversion rates are ~80% in steam reformers).[31, 32] However, thermal efficiency will not suffer as strongly as electrical efficiency, as some useful heat can be recovered from the fuel processor. In the case of a poorly optimised H-Power PEMFC system, this accounted for around 1/3 of the thermal energy output.[33]

Table 8: Efficiency of PEMFC systems, as reported originally (left) and when modified to give the consistent definitions of efficiency (middle). The conditions used in each measurement are given with the reported values: heating value, fuel, electricity output and inclusion of ancillary loads.

Reported Values						**Estimated HHV Efficiency**						
Elec.	**Total**	**Test conditions**				**Stack**	**System**	**Total**	***Year***	Description	*WF*	Ref
27.7%	64.8%	HHV,	NG,	AC,	N	38.5%	27.7%	64.8%	*2009*	Average performance of 1kW ENEFARM systems from all manufacturers, installed into Japanese houses. *Bottom:* 175 systems installed in 2005, operated during 2006; *Middle:* 777 installed in 2006, operated during 2007; *Top:* 930 systems installed in 2007, operated during 2008.	*3.58*	[40]
26.4%	63.2%	HHV,	NG,	AC,	N	36.7%	26.4%	63.2%	*2008*		*2.78*	[41]
26.0%	63.1%	HHV,	NG,	AC,	N	36.2%	26.0%	63.1%	*2007*		*1.84*	[42]
20%	57%	HHV,	NG,	AC,	N	27.7%	19.9%	57.0%	*2009*	Results from a 12 month field trial of a single fuel cell system. Average results from the whole trial (top), and results from a single month when the fuel cell was allowed to operate uninterrupted (bottom)	*2.71*	-
22%	62%	HHV,	NG,	AC,	N	30.0%	21.6%	61.5%				
32%	85%	LHV,	NG,	AC,	G	37.7%	27.1%	74.8%	*2009*	Rated specifications for the Baxi Gamma 1.0	*0.88*	[43]
38.0%	93.0%	LHV,	NG,	AC,	?	46.2%	33.2%	82.7%	*2008*	Rated specifications for the latest generation of Panasonic ENEFARM units at full power.	*0.54*	[44]
35.5%	84.1%	LHV,	NG,	AC,	?	43.1%	31.0%	74.8%	*2008*	Achieved during a trial of three 1kW systems from Fuji Electric.	*0.79*	[45]
27%	80%	LHV,	NG,	AC,	G	31.3%	22.5%	70.6%	*2007*	Rated specifications for the Baxi Beta 1.5 Plus.	*0.43*	[46]
	74.9%	HHV,	NG,	-,	-			74.9%	*2006*	Measured performance of Ballard 1030 v3 stacks, installed in LIFUEL systems in Japan.	*0.68*	[47, 48]
37%	87%	LHV,	NG,	AC,	G	43.6%	31.3%	76.4%	*2006*	A comparison between the manufacturers specifications and the achieved efficiencies, of LIFUEL systems.	*0.17*	[49]
30%	75%	LHV,	NG,	AC,	N	37.6%	27.0%	67.6%			*0.68*	
32%	71%	HHV,	NG,	AC,	N	44.5%	32.0%	71.0%	*2005*	Specifications of the FY2005 model Toshiba unit: the TM1-A. Top - running on natural gas (as used in the Japanese field trials). Bottom - a pure hydrogen model.	*0.36*	[34]
37%	77%	HHV,	H,	AC,	N	42.0%	30.2%	74.5%				
33%	83%	LHV,	NG,	AC,	?	40.1%	28.8%	73.9%	*2005*	Measured from 2 sets of 700W Toshiba LPG fuel cells installed in Japanese homes in 2005. The average generating efficiency to June 2008 was reported.	*1.40*	[50]
31%	76%	HHV,	NG,	AC,	?	41.8%	30.1%	75.1%	*2004*	Efficiency from a 2nd stage trial by Fuji Electric of their 1kW natural gas reforming PEMFC system.	*0.28*	[51]
34%	83%	HHV,	NG,	AC,	?	45.8%	33.0%	82.0%	*2004*	Reported as the highest achievement by a 1kWe Mitsubishi stack.	*0.21*	[52]
26.5%	63.5%	LHV,	NG,	DC,	G	27.5%	19.7%	53.1%	*2003*	Performance of a 4kW Plug Power beta unit installed in France. System efficiency *(top)* was measured, while stack efficiency *(bottom)* was calculated theoretically.	*0.34*	[35]
36%		LHV,	H,	DC,	N	30.4%	21.4%				*0.34*	
43%	80%	HHV,	PH,	DC,	N	43.0%	30.9%	71.8%	*2003*	A 5kW Ballard stack (MK5-E), operated on 3 bar H_2.	*0.34*	[53]

Reported Values			**Estimated HHV Efficiency**			***Year***	Description	*WF*	Ref
Elec.	**Total**	**Test conditions**	**Stack**	**System**	**Total**				
44%	80%	HHV, PH, DC, N	44.0%	31.6%	71.5%	*2003*	An unnamed commercial 1kW stack, operating on 2 bar H_2.	*0.34*	[54]
30%	68%	HHV, NG, AC, G	39.2%	28.2%	66.2%	*2002*	Reported for a 10kW demonstration stack.	*0.13*	[55, 56]
34%	72%	LHV, NG, AC, G	40.0%	28.8%	63.0%	*2002*	A 250kW Ballard unit during a 1 year field trial.	*0.27*	[57]
36%		LHV, NG, DC, N	39.7%	28.5%		*2001*	A prototype 1kW Proton Motor stack “suitable for reformant gas operation"	*0.21*	[58]
41%	80%	HHV, PH, DC, N	41.0%	29.5%	72.6%	*2001*	An 1kW R&D stack containing 0.9mg/cm² Pt catalyst and operated on 2 bar H_2.	*0.21*	[54]

Table 9: Efficiency of SOFC systems, as reported originally (right) and when modified to use consistent definitions (left).

Reported Values			**Estimated HHV Efficiency**						
Elec.	**Total**	**Test conditions**	**Stack**	**System**	**Total**	**Year**	**Description**	***w***	**Ref.**
36.1%	74.0%	HHV, NG, AC, N	46.0%	36.1%	74.0%	*2008*	Average performance of 0.7-1kW SOFC systems installed in Japanese houses, mostly from Kyocera. Top: 35 systems installed in 2008, measured from Aug-Nov 2008 Bottom: 27 systems installed in 2007, measured Jan-Dec 2008	*3.00*	[59]
34.1%	71.3%	HHV, NG, AC, N	43.4%	34.1%	71.3%			*2.27*	
41%	82%	HHV, NG, AC, ?	50.6%	39.8%	80.8%	*2007*	Performance of a 10kW module from KEPCO / Mitsubishi.	*0.43*	[9]
35.5% - 41%		LHV, NG, ?, ?	37.6% - 43.4%	29.1% - 33.6%		*2007*	Given as the average performance of 6 recent small SOFC systems from American companies.	*0.77*	[10]
29%		HHV, NG, DC, G	30.6%	24.0%		*2006*	Estimated full-power efficiency of a 6kW Acumentrics stack, based on a measured peak efficiency of 36% at 33% power.	*0.34*	[60]
56%		LHV, NG, DC, N	56.6%	44.4%		*2006*	Results from 2.5kW domestic units from Tokyo Gas, Kyocera, Rinnai & Gastar.	*0.34*	[61]
36%		HHV, H, AC, N	40.9%	32.1%		*2006*	Testing of a prototype Fuel Cells Scotland 1.3kW stack, using InDEC cells operating on hydrogen.	*0.69*	[13]
45%	75%	LHV, NG, AC, G	48.5%	38.1%	65.1%	*2005*	Performance of a prototype stack *(top)* and system *(bottom)*.	*0.14*	[36]
55%		LHV, H, DC, N	46.5%	36.5%				*0.14*	
44%	78%	LHV, NG, AC, G	47.5%	37.3%	67.9%	*2004*	Results from 1kW domestic units from Osaka Gas & Kyocera. Field trials of a system running on natural gas are given *(top)* and experiments on a hydrogen fuelled stack *(bottom)*.	*0.43*	[37-39]
56%		LHV, H, DC, N	47.3%	37.2%				*0.11*	
28%	70%	LHV, NG, DC, N	28.1%	22.0%	59.9%	*2000*	Mean efficiency of the best performing 1kW Sulzer Hexis field trial unit in Europe. The average over all 6 units was ~30% lower. A 20% increase in thermal efficiency was envisioned with better insulation.	*0.34*	[17]

Table 10: Efficiency of PAFC systems, as reported originally (left) and when modified to give the consistent definitions of efficiency (middle).

Reported Values			**Estimated HHV Efficiency**			***Year***	**Description**	***w***	**Ref.**
Elec.	**Total**	**Test conditions**	**Stack**	**System**	**Total**				
38.0%	83-87%	LHV, NG, AC, N	46.7%	34.2%	74.8% - 78.4%	*2004*	Widely verified performance of UTC PC25 units: Efficiency starts at 40% and drops to 38% after infancy; this falls further to 35% at the end of life, giving a lifetime average of 37% over 40,000 hours. (vs. methane LHV)	*4.49*	[22, 55, 56, 62, 63]
40.0%		LHV, H, DC, ?	32.8%	24.0%		*1999*	Measured from a 50kW LG-Caltex stack.	*0.52*	[20]
37.0 ± 0.75%		LHV, NG, DC, G	36.6% - 38.1%	26.8% - 27.9%		*1998*	Performance of an ERI 1kW stack, corrected for the varied cell construction. Efficiency was lowered by poor fuel utilisation temperature control.	*0.56*	[21]
42%	74%	HHV, PH, AC, N	47.5%	34.8%	70.5%	*1991 - 1997*	11MW Toshiba plant.	*0.22*	[64]
31.6 ± 1.2%		HHV, NG, AC, N	43.1%	31.6%		*1997*	Efficiency of 30 PC25B and C systems installed in military bases between 1994-1997 and operated until 2000-2003.	*1.10*	[65]
52%		LHV, H, DC, G	41.3%	30.3%		*1993*	The measured performance of individual cells from a UTC PC25A stack *(top)*, and the overall system *(bottom)*.	*0.09*	[24]
38%		LHV, NG, DC, N	41.1%	30.1%					
37%		HHV, H, AC, ?	40.4%	29.6%		*1985*	Performance of 4.5MW power plant made for Tokyo Electric, operated at 2.5 bar.	*0.01*	[23]

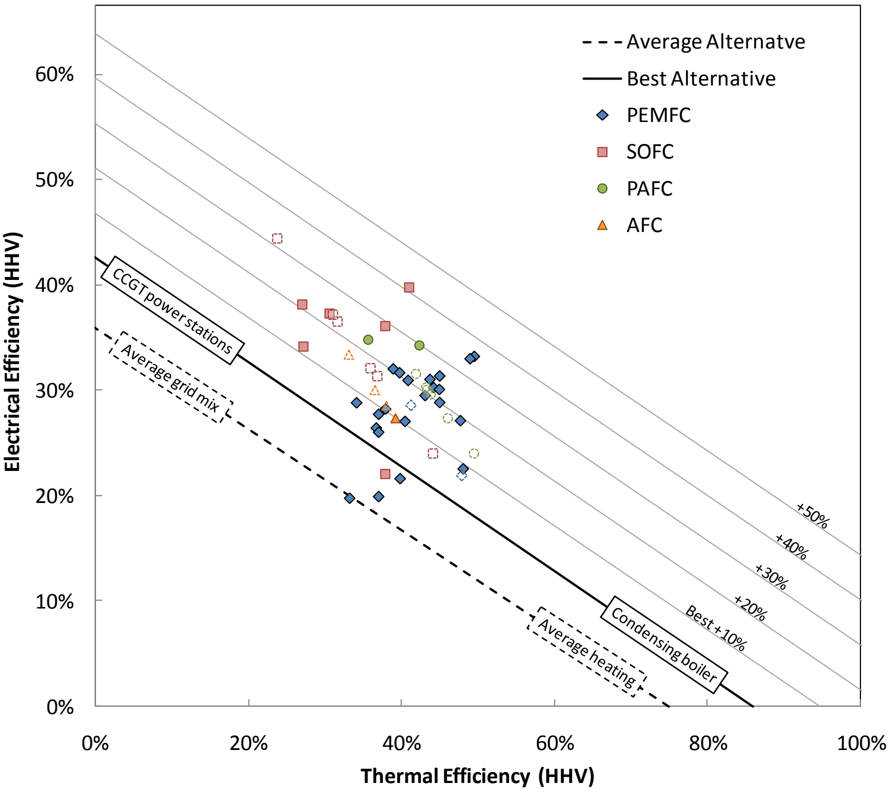
Table 11: Efficiency of AFC systems, as reported originally (left) and when modified to give the consistent definitions of efficiency (middle).

Reported Values			**Estimated HHV Efficiency**			***Year***	**Description**	***w***	**Ref.**
Elec.	**Total**	**Test conditions**	**Stack**	**System**	**Total**				
45.0%	87.0%	LHV, PH, DC, N	38.0%	27.4%	66.6%	*2006*	Independent Power's Pulsar-6, 6kW stack operating on 4-6 bar hydrogen and pressurised air.	*1.32*	[66]
55%		LHV, PH, DC, N	46.5%	33.5%		*2004*	Astris-E8 2.4kW stack, operating on 6-200 bar hydrogen and pressurised air.	*0.83*	[67]
51%		LHV, H, DC, ?	41.8%	30.1%		*2003*	Performance of a 0.8kW Eident stack using 0.52mg/cm^2 total Pt loading.	*1.32*	[25]
47%		LHV, H, DC, N	39.7%	28.6%		*1999*	Performance of a 0.4kW Zevco Mark II module.	*0.52*	[26]

Discussion

Figure 6 plots the electrical and thermal efficiency of different CHP systems. Lines connect the efficiency of competing systems in the UK, with the average being gas central heating and the UK average grid efficiency, and the best being a top-rated condensing boiler and a CCGT power station. It is seen that most fuel cell systems are 10-40% above the best available alternative in the UK; or 30-60% above the average systems currently in place.

Figure 6: Thermal and electrical efficiency of fuel cell CHP systems, plotted against lines that connect the electrical and thermal efficiency of traditional alternatives. Filled data points indicate that both thermal and electrical efficiency of the fuel cell was known. Hollow data points indicate that only electrical efficiency was recorded, and thermal efficiencies were estimated based on the average total efficiency for that type of system.



Part Load Efficiency

One of the widely reported benefits of fuel cells is their high efficiency at part load. This is an inherent characteristic of the fuel cell stack itself as individual cell voltages rise towards Open Circuit Voltage (~1V) when less current is drawn from them, giving the highest efficiency at low loads. Twelve sources were found which had measured the efficiency of complete fuel cell systems (as opposed to only the stack) at different levels of power output. The part-load efficiency of each system is plotted in Figure 7 relative to its efficiency at full power. It is clear that across nearly all products electrical efficiency falls as power output decreases, and the thermal efficiency of domestic-scale systems is either constant or falls.

The part-load efficiency can be broken down into the different components:

- Efficiency of the fuel cell stack is higher at lower load factors, as cell voltage rises at lower current densities – see Figure 8 for a comparison.
- Reformer efficiency drops slightly: at half load, the efficiency is 90-95% of full power efficiency.[33, 68]
- Fuel utilisation however falls more sharply, by 10-30% at half power.[9, 33, 35]

- Inverter and transformer efficiency stays constant over much of the power range, falling only at very low load-factors – and thus does not have a significant impact.[12, 69, 70]

Figure 7: Whole system electrical efficiency (including fuel processing, inverters and parasitic loads) from different fuel cell CHP systems, measured against power output. The efficiency of each system is presented relative to full power.

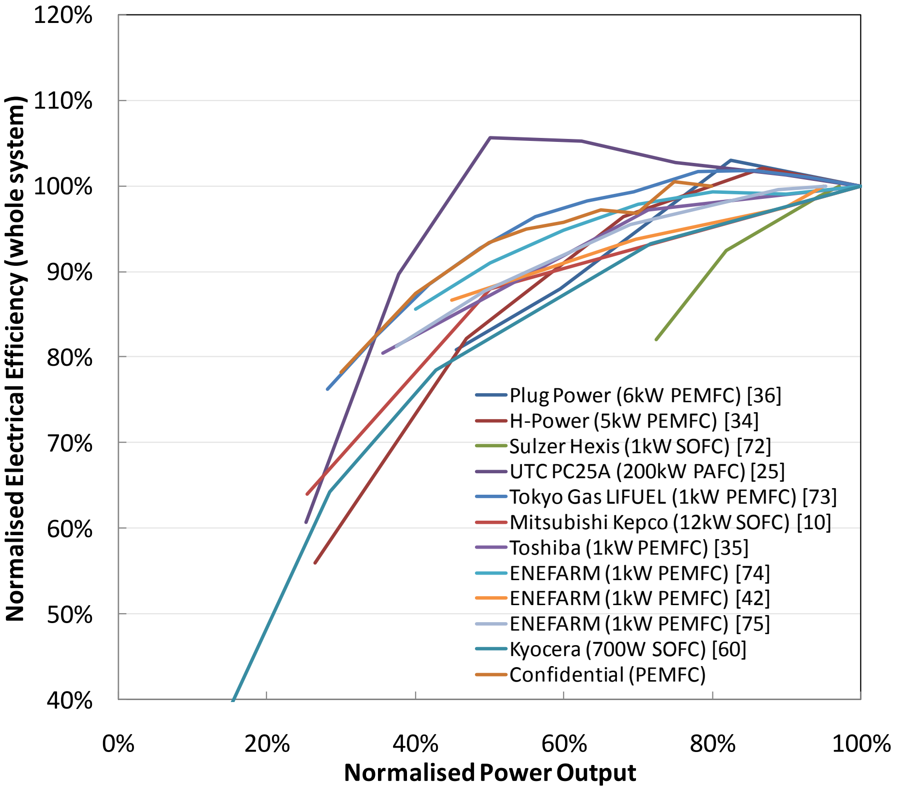


Figure 8: A comparison of the part-load electrical efficiency of the fuel cell stack and whole system for three fuel cell CHP products.

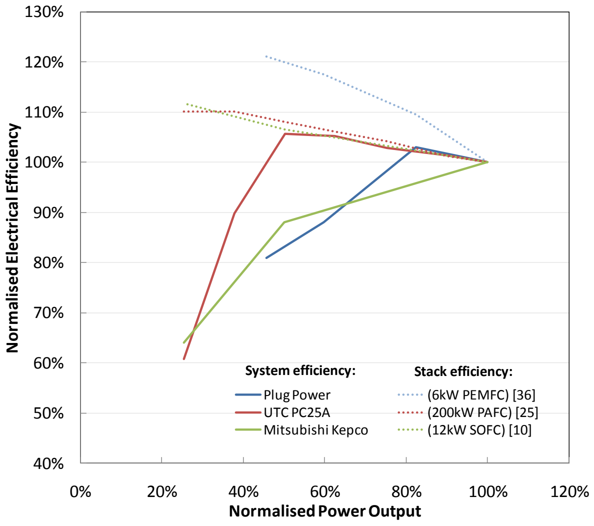
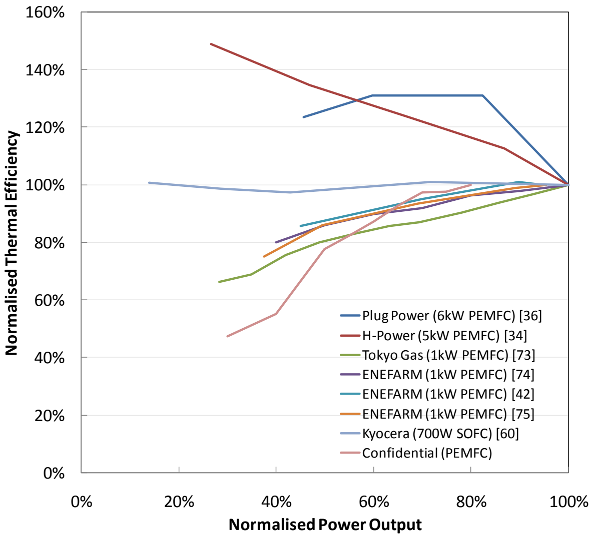


Figure 9: Thermal efficiency of different models of fuel cell CHP system measured against power output. As in Figure 7, the efficiency is given relative to full power.



Fuel Processor Efficiency

Processing natural gas into useable hydrogen is one of the major energy consuming stages in a domestic CHP system, and lowers the overall efficiency significantly. Steam reforming of natural gas was the only method considered, as it offers higher efficiency than can be achieved with Auto-Thermal Reformers (ATR) or Partial Oxidation (POX) reactors. For example, the efficiency of an H-Power ATR was 62.5% when operating at maximum power, or 60% at the rated 4kW.[33] The increased difficulty of reforming higher hydrocarbon fuels will also result in lower efficiency. As another example, auto-thermal reforming of LPG (a mixture of propane and butane) yielded 50% HHV efficiency.[71]

To remain consistent with the rest of this report, fuel conversion efficiency was considered relative to HHV energy contents. It is worth noting that most publications report LHV efficiencies for fuel processors, so the values presented here for converting natural gas to hydrogen are a factor of 1.066 higher than in most sources.[2]

Most authors gave the efficiency for the entire integrated processor that was used in their particular system, and did not separate their analysis into individual components. It was therefore difficult to give a breakdown of the efficiency of individual components. It was also notable that most of the studied fuel processors were for PEMFC systems, with notably none found for SOFC systems.

Table 12 presents data on the efficiency of different fuel processing systems, making use of the following acronyms for each stage that is included:

- DeS – Desulphuriser
- SR – Steam Reformer
- WGS – Water Gas Shift
- PROX – Preferential Oxidation
- CO – Unspecified carbon monoxide removal stage
- FP – Complete fuel processor

*Table 12: Efficiency of fuel processing systems. Efficiencies noted with * were converted from LHV.*

Component	Efficiency (HHV)	Year	Source	Ref.
SR + ?	81.4%	2008	Reported for a novel town gas reformer developed by Tokyo Gas and Mitsubishi, which produces 99.999% pure hydrogen.	[73]
FP	85-87%*	2005	Measured over 1800 stop-start cycles for a Tokyo Gas fuel processor.	[74, 75]
SR + WGS	81.5-82.1%*	2005	Measured from a steam reformer when coupled with a 1kW PEMFC stack from Proton Motor. Was tested with and without PROX stage, and with anode off-gas recycling.[3]	[58]
SR + WGS + PROX	80-80.5%*			
DeS + SR + WGS + PROX	83%	2004	Measured from a compact natural gas reformer developed by Osaka Gas. Tests used simulated off-gas recycling to mimic operation when coupled with a fuel cell..	[72]
SR + WGS + PROX	76.1-79.3%*	2003	Measured for a steam reformer operating with a 4kW Plug Power PEMFC installed in a French town hall.[4]	[35]
SR + WGS + CO	81%	2003	Reported for the fuel processor developed by Fuji Electric.	[76]
SR + ?	88.5%*	2003	Reported for a multi-fuel reformer developed by the Hiroshima Research Centre, for use with a 1kW PEMFC system. Results based on either city gas or LPG.	[76]
SR + WGS + CO	82%*	2000	Two reported values for an early version of the fuel processor developed by Tokyo Gas for use in LIFUEL PEMFC systems.	[68, 77]
	81.7%*	2001		
DeS + SR + WGS	85.3%*	1993	Measured from a 200kW industrial PAFC (PC25A). The efficiency showed little change over 18,000 operating hours.	[24]

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[2] This value is calculated from the ratio of HHV to LHV energy content for hydrogen and natural gas (1.183 / 1.110).[72]

[3] Over 100% reformer efficiency was reported with off-gas recycling, as this was assumed to increase reformer output rather than the fuel utilisation in the stack. Those results are therefore not considered here.

[4] Reformer efficiency was calculated from the fuel processing efficiency and hydrogen utilisation rates given.

Power Conversion Efficiency

Information was harder to find on power converters, so many are from larger industrial CHP systems. These may not be representative for those used in domestic CHP systems, as low voltage single-phase inverters have different characteristics to 400V three-phase systems. Table 13 gives the data, using the following acronyms:

- Inv – Inverter
- Tr – Transformer

Table 13: Efficiency of power conversion systems.

Component	Efficiency	Year	Source	Ref.
Inv + ?	92%	2009	Rated performance of the inverter in a TOTO 2kW class fuel cell (210W lost in converting 2.85kW DC output)	[59]
Inv + Tr	81.4%	2007	Measured difference between AC and DC efficiency of a 10kW KEPCO / Mitsubishi stack.	[9]
Inv	96.7-97.5%	2006	Measured from the Acumentrics power inverter developed for the SECA project, over the range of 2-5kW output.	[12]
Tr	97.0-97.4%			
Inv + Tr	86%	2006	*Confidential information from a custom 1.5kW, 3-phase inverter.*	-
Inv + Tr	92-94%	2004	Modelled efficiency of 6 products in the range of 0.5-5kW, based on product specifications.	[69]
Tr	97.5-98%	2004	Reported for a custom designed Ballard transformer.	[69]
Inv	96.5-97%	2004	Reported for a 30kW Ballard Ecostar Power Converter.	[78]
Inv + Tr	89%	2004	Measured from a H-Power RCU 4500 v2.	[33]
Inv + Tr	92%	2002	Estimated as the realistic maximum efficiency of a simplified electrical subsystem for a fuel cell CHP unit.	[79]
Inv	90%	2001	Target for the1kW PEMFC developed with Tokyo Gas, which was expected to be met by market entry.	[80]
Inv + Tr	80.5%	2001	Measured from a H-Power system tested by Gaz de France.	[70]
Inv + Tr	83-87%	1999	Reported for a 50kW PAFC stack that produced 16V at 700A.	[20]
Inv	97%	1993	Measured from a PC25A PAFC, converting 220V DC to 400V AC.	[24]

Parasitic Loads

The net power output of a fuel cell system is further degraded by parasitic loads: the electrical requirements of the system controller, pumps and blowers. These loads are often excluded from the reported efficiencies of domestic fuel cell systems, all the way up to centralised power stations. For comparison, CCGT, coal and nuclear power stations in the UK respectively consume 2.0%, 5.3% and 9.4% of the power they generate.[81] Note that the parasitic loads presented in Table 14 can be thought of as *(1 – efficiency)*.

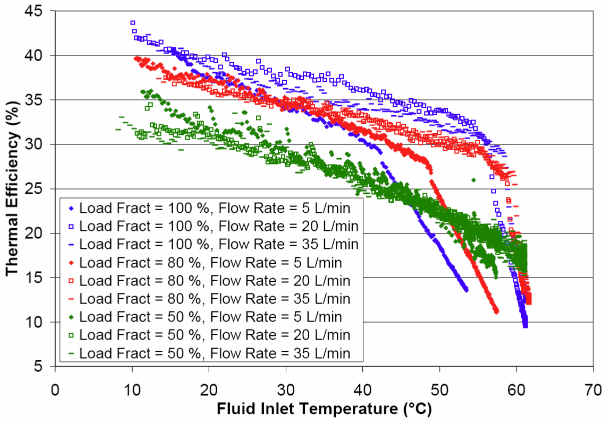
Table 14: Power drawn by fuel cell systems, relative to their power output.

Component	Parasitic Draw	Year	Source	Ref.
All	12%	2009	Supplemental equipment in a TOTO 2kW class fuel cell consumed 340W (relative to 2.85kW DC output)	[59]
All	3.9%	2004	Reported for a 2.4kW AFC system at full load.	[82]
All	4.8%	2004	Reported 300W power consumption from a 6.3kW AFC system at full load.	[83]
All	22%	2004	Measured from a H-Power RCU 4500 v2. Parasitic loads were equivalent to 6% of the gross natural gas consumed, and were magnified by the low efficiency of the stack.	[33]
All	9%	2001	Estimated power consumption of the 1kW PEMFC developed with Tokyo Gas, all full power.	[80]
Con	5.6%	2001	Measured power consumption of the system controller a 5kW Ballard stack, which was equivalent to 2.5% of the gross hydrogen consumed when operating at 45% electrical efficiency.	[53]
All	4.1%	1991	Measured difference between the gross and net AC efficiency of the 11MW PAFC power station operated in Goi.	[64]

Thermal Loop Temperature

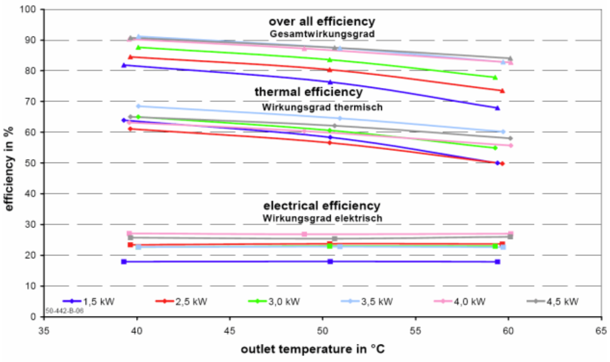
It is known that with other microgeneration systems, thermal efficiency falls as the inlet temperature of coolant water rises.[84] When this rises above the dew point of the flue gasses (50-57°C) condensation of water vapour in the heat exchangers is inhibited. This is not a particular effect for fuel cell systems, and has been observed in condensing boilers, IC engines and Stirling engines.[85-87]

Figure 10: Thermal efficiency of a PEMFC CHP system against coolant inlet temperature. Taken from [88]



An unnamed 5kW PEMFC system was installed and tested at NIST in 2005.[88] The fuel cell was used to heat 1000L of fluid at different temperatures and thermal efficiency was measured. During normal operation, efficiency decreased at 2.2-3.1% HHV per 10°C temperature rise. A sharp knee was seen in some of the tests when the outlet temperature reached the maximum rated 63°C, and efficiency fell off rapidly. Due to this, a separate real-world test for providing hot water was found to give thermal efficiencies of just 7-14% HHV.

Figure 11: Thermal efficiency of a PEMFC system against coolant outlet temperature. Taken from [89]



A prototype Vaillant "Euro 2" 4.6kW PEMFC system was tested at the Technical University of Munich, also in 2005.[89] The fuel cell was operated at steady state for between 5 and 20 hours at a series of power outputs and inlet/outlet temperatures. The electrical efficiency was seen to be constant with output temperature, and the thermal efficiency fell by 3.5-7.0% LHV per 10°C – over the range of 26-54°C inlet temperatures (30-60°C outlet).

External Temperature

There is limited evidence to suggest that the ambient temperature around the fuel cell system has an impact on its efficiency. From analysis of SOFC systems in the northern region of Japan, average electrical efficiency fell from ~36.5% at 5°C to ~35.5% at -5°C. Correlation in the data set was poor ($R^2 = 0.24$) so more evidence is needed. This would obviously only affect fuel cells that are installed outdoors – as they are in Japan at present.[59]

Start-up Energy Requirements

A substantial amount of energy is required to pre-heat microgeneration systems to operating temperature – as seen with condensing boilers and Stirling engines in field trials by the Carbon Trust.[85] Despite this, the amount of energy required to start fuel cell micro-CHP systems has not been widely studied, and only one prior experimental investigation has been found.

The Vaillant "Euro 2" (4.6kW PEMFC system) was started up from cold, with detailed monitoring of the energy consumed and produced.[89] During the 2.5 hour cold-start of the fuel cell, 29.0kWh of natural gas was consumed (LHV), producing 18.3kWh of heat and 1.4kWh of electricity. The natural gas consumption equated to 6.3kWh per kW of electrical output, however the useful energy outputs must be accounted for:[5]

- The efficiency of the system at steady state was 25.7% electrical + 65.0% thermal (LHV) - so the amount of gas that would have been consumed in producing the 1.4kWh of electricity (and some heat) could be calculated, and subtracted from the total start-up consumption.
- Similarly, the remaining heat production could be credited with avoided production from a condensing boiler (with 95% LHV efficiency). Additional production from the fuel cell could not be used, as the electricity by-product of CHP generation would not be credited.
- The following table shows these steps towards arriving at the additional gas consumption:

Data from [89]

	Electricity produced (kWh)	Heat produced (kWh)	Gas consumed (kWh LHV)
Entire start-up sequence of the fuel cell from cold:	1.4	18.3	29.0
Credit for electricity production by the fuel cell:	1.4	3.55	5.45
Subtracted amount:		14.75	23.55
Credit for heat production by a condensing boiler:		14.75	15.5
Subtracted amount:			8.05

It is therefore estimated that an additional 8.05kWh of natural gas (8.95kWh HHV) was required to heat the fuel cell from cold. If this scales linearly with capacity, a 1kW fuel cell would require 1.95kWh of gas consumption to start from cold.

It should be noted that this method of crediting avoided production is one possibility, and that without detailed thermodynamic modelling it would be impossible to separate the amount of gas used solely to raise the generator temperature from that used in producing useful energy.[90]

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[5] I wish to thank Thomas Badenhop (Vaillant) for discussing this calculation and result.

Lifetime and Degradation Rates

The functional lifetime is a crucial and contentious issue for the commercialisation and economic viability of fuel cell micro-CHP systems, and is one of the characteristics which varies most between designs. The de-facto target of 40,000 hours continuous operation has hung over the industry for nearly a decade,[91, 92] only being attained in the field by industrial PAFC systems from UTC and Fuji. Figure 12 shows that the demonstrable lifetime of PEMFC systems is gradually moving towards this target, but SOFC and AFC appear to have stagnated with stack tests not lasting for more than 10,000-20,000 hours for SOFC, or 5,000-10,000 hours for AFC.

Figure 12: The improvement in demonstrated stack and system lifetimes of different fuel cell technologies over the past 15 years. A weighted exponential fit is shown for each technology, with a label giving the rate of improvement, and estimated average lifetime as of 2009.

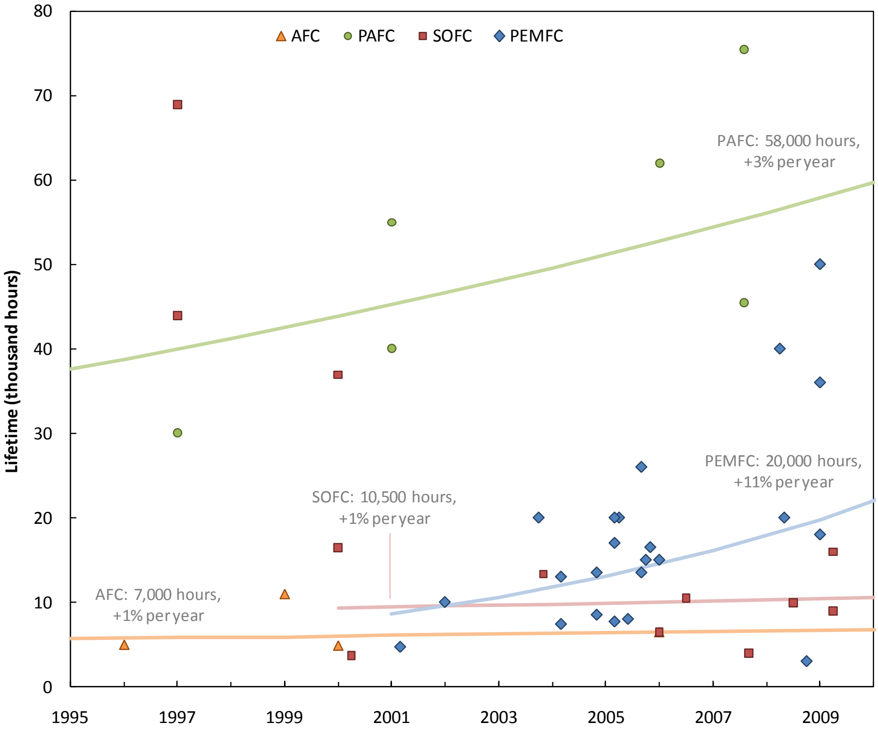

Table 15: PEMFC lifetime and degradation rates

Lifetime (kh)	**Degradation** (μV/h)	***Year***	**Description**	***w***	**Ref.**
50	3.7	*2009*	Single cell tests at Osaka Gas, ran on H_2, CO_2 (20%) and CO (10ppm). The cell was fabricated in 2001, and has not yet failed. Degradation without CO appears to be 0.6μV/hr.	*1.14*	[93, 94]
36	35				
18		*2009*	Full 0.75kW cogeneration unit operated at Osaka Gas. It is not known whether the unit failed.	*2.27*	[93]
3.0 ± 0.7	16 ± 6	*2008*	12 demonstrations of 50kW Nedstack units for chlor-alkali plants, using "type A" cells	*1.87*	[95]
20		*2008*	Achieved by two JOMO ECOCUBEs, installed in the Japanese Large Scale Fuel Cell Demonstration Project. The 700W stacks were produced by Toshiba Fuel Cells, and installed in 2005.	*4.69*	[96]
40		*2008*	The estimated lifetime of new generation Matsushita LIFUEL systems, based on accelerated aging experiments. These systems are also expected to perform 4,000 stop/start cycles before failing.	*0.90*	[44]
8	2 - 4	*2005*	Tests on a 40 cell Nuvera stack, operating on steam reformate.	*0.90*	[97]
10 - 17	0.5 - 5	*2005*	Reports of cells and stacks in a variety of tests and conditions.	*0.45*	[4]
26	6.4 (plus 40-140 temporary)	*2005*	A single cell (Gore 56) running on hydrogen. The temporary decay was observed throughout the test. Failure of the cell was due to experiment definition, rather than inability to operate.	*0.45*	[4]
13-20		*2005*	Durability of FY2005 LIFUEL units from Matsushita & Ebara	*0.90*	[74, 98]
15		*2005*	Claimed as the current durability of a Ballard 1030 v3.	*0.45*	[99]
20		*2005*	2 sets of a 700W Toshiba FC installed in Japanese homes in 2005 - fuelled by LPG. Ran continuously for 20,000 hours.	*2.34*	[50]
7.7	7.3	*2005*	Results from the FY2005 model Toshiba unit: the TM1-A. Top: field trial units (no failure reported) Middle: stack in the lab running on reformate (believed to have failed) Bottom: short-stack running in the lab on reformate (unsure)	*1.11*	[34]
17	5.6				
20	4.6				
	1.5	*2004*	Long term tests (5000 hours) for a 20 cell stack from Mitsubishi on low humidity steam reformate (25% CO2, 10ppm CO)	*0.36*	[100]
4 - 13	3.5	*2004*	Results from trials of 300 PlugPower units, which may include such radical repairs as complete stack replacement.	*2.49*	[101]
7.4		*2004*	Early 250kW Ballard trial units achieved 2.5-5kh, a later revision averaged 7.4kh without failing	*1.43*	[102]
	2 - 10	*2004*	Quoted as the commonly reported range of values.	*0.36*	[102]
13	0.5	*2004*	Lab trial of a Ballard short stack operating on natural gas.	*0.72*	[102]
15 - 25	1 - 5	*2003*	Single cells with Gore 56 membranes, running at 0.6A/cm^2.	*0.14*	[22, 103]
10		*2002*	A single cell using a 3M membrane operating on reformate.	*0.11*	[22]
	8 (plus 424 temporary)	*2002*	A 36 cell stack running at 0.2A/cm^2. The 0.4mV/hr degradation was seen during constant operation, but could be recovered by stopping power output and starting the stack again.	*0.45*	[8]
4.7 ± 2.3		*2001*	The average life-span of 4-5kW systems from Plug Power, Nuvera, ReliOn and IdaTech - installed as part of the US DoD Residential PEM Fuel Cell Demonstration Project in 2001-02.	*0.93*	[104]
			Plus 2 confidential values from anonymous sources.	*1.54*	-

Table 16: SOFC lifetime and degradation rates

Lifetime (kh)	**Degradation** (µV/h)	**Cell Type**	**Year**	**Description**	***WF***	**Ref**
10.0	7 *	Planar, 850°C	*2008*	Testing of a 30 cell (350W) Staxera stack, on hydrogen at 0.75V/cell x 0.125A/cm^2.	*1.78*	[105]
	14 *	*Multiple Planar*	*2007*	Given as the average degradation of 6 recent small SOFC systems from American companies.	*1.77*	[10]
4.0	56-126 *	Planar, 950°C	*2007*	Demonstration of Sulzer Hexis sytems, which "required replacement in as little as six months" due to leakage of fuel.	*1.00*	[106]
	9 + 13 mV/cycle	Planar, 950°C	*2006*	Degradation of a 5-cell Hexis short stack over 3500h with nickel coating on the anode side of the interconnect.	*1.58*	[11]
	2-5	Planar, 850°C	*2006*	Degradation of single Topsoe cells tested on syngas, at current densities of 0.25-1A/cm^2 over 1500h.	*0.79*	[14]
10.5		Tubular	*2006*	Demonstration of a 5kW Acumentrics SOFC system for stationary, auxiliary & backup power running in their lab.	*1.26*	[107]
6.5	37 *	Planar, 950°C	*2006*	Degradation of a 1kW Hexis Galileo 1000 N stack during 6000 hours of operation.	*1.58*	[11]
	0	Tubular 800°C	*2006*	Degradation of an Acumentrics short stack running on reformed natural gas, measured over 1000h.	*0.79*	[60]
13.4	13	Planar, 800°C	*2003*	Long term experiment with a 5-cell Topsoe short stack running on hydrogen and nitrogen, including 9 thermal cycles. Average voltage dropped from 0.77V to 0.62V during the test, predominantly because of two cells.	*0.79*	[15]
	1.8 * + 3.5 mV/cycle	Planar, 750°C	*2005*	Degradation of a KEPCO / Mitsubishi 10kW module, with heating and cooling times of 7 and 10 hours during over 20 daily thermal cycles.	*1.26*	[9]
	25 + 2-4 mV/cycle	Planar, 800°C	*2002*	Data froma 2-cell short stack of the FZJ 'E-Design', using stainless steel interconnects with a ceramic contact layer. Voltage degradation was measured over 4000h of running on hydrogen at 0.3A/cm^2 to be 2-3%/1000h. A similar stack was thermally cylced 40 times to 220°C at 2°C/min, increasing degradation rates to 5-8%/kh (140-220mV over 2900h)	*0.44*	[108]
2.1-4.8	24 *	Planar, 950°C	*2000*	Degradation of a single Sulzer Hexis stack during a 3000 of steady state operation. Additional voltage loss was caused by shutdowns. Average lifespan taken from 10 stacks that were run during the field trial.	*0.79*	[106]
37	~0	Tubular	*2000*	Lifetimes of 100kW Siemens-Westinghouse stacks demonstrated in field trials in the Netherlands and USA	*0.91*	[10, 22, 109]
16-17	~0					
69	0.7-3.5 * + 0 µV/cycle	Tubular	*1997*	The best results from laboratory tests of Siemens-Westinghouse large tubular single cells.	*0.05*	[22, 23, 110]
44	1.4 *	Tubular	*1997*	The best results from laboratory tests of Siemens-Westinghouse air-electrode supported (AES) single cells.	*0.05*	[22, 23]
Plus 3 confidential values from anonymous sources.					*4.15*	-

Table 17: PAFC lifetime and degradation rates

Lifetime (kh)	**Degradation** (μV/h)	***Year***	**Description**	***WF***	**Ref**
75.6		*1998 - 2007*	From the installed fleet of Fuji Electric FP100E and F models, 4 of 22 units have failed after 42-49,000 operating hours, and another 5 units have already exceeded this *(bottom)*. The longest lived unit was installed in 1999, and had operated for 72,500 hours as of August 2007.	*4.76*	[111]
45.4					
62		*1999 - 2006*	Longest reported lifetime for a UTC PC25C - in Central Park Police Station. At least 7 other units have operated for longer than 50,000 hours.	*2.56*	[112]
	4.9 *	*1994 - 2001*	The operating voltage of 14 UTC PC25B plants decreased by 7.6% per 10,000 hours *(top)*, and the voltage of 15 PC25Cs fell by 5.04% per 10,000 hours *(bottom)*.	*1.74*	[19]
	3.3 *				
40		*1992 - 2001*	After 40,000 of operating a fleet of UTC PC25B plants: 2 were still operating at full power, 8 at a reduced maximum power (to preserve cell voltage), and 1 stack had failed.	*1.64*	[19]
55		*1992 - 2001*	Longest reported lifetime for a UTC PC25A operated by Tokyo Gas - as of 2001.	*0.80*	[18, 63]
	1.3 - 2.0 *	*1992 - 2001*	The operating voltage of 5 UTC PC25A plants had decreased by 4-10% after 20k operating hours, and 8-12% after 40k hours *(top)*. The voltage of six late-model PC25C had fallen by 4% after 20kh, and were expected to be at 6% after 30kh *(bottom)*.	*1.43*	[18]
	1.1 - 1.5 *				
	2 - 5	*1999*	Degradation rate of Mitsubishi single cells, tested over 6000 hours at 0.2-0.25A/cm^2.	*0.13*	[20, 22]
30 ± 6		*1994 - 1997*	The lifetime of UTC PC25B and C installations at 30 US military bases, installed between 1994-1997 and operated until 2000-2003.	*0.79*	[65]
	4	*1992*	Test of UTCs 'advanced atmospheric water cooled' short stack over 4500h at 0.2A/cm^2.	*0.05*	[22]
	3	*1992*	Degradation of 'previous state of the art' systems from CNR/TAE (Italy), Westinghouse/DOE, & Electric Utilities (Japan).	*0.03*	[22]
23		*1991 - 1997*	Lifetime of the 11MW Toshiba power plant in Goi.	*0.08*	[64]

Table 18: AFC lifetime and degradation rates

Lifetime (kh)	**Degradation** (μV/h)	**Cell Type**	**Year**	**Description**	***WF***	**Ref**
5 - 8		Ni / Ag	*2006*	Internal tests at Astris Energi "consistently see 5,000 hours" with new carbon materials.	*3.93*	[113, 114]
	27 *	Pt	*2003*	An Eident Energy V1.1 module is expected to lose 10% of its initial power over 2500 hours.	*1.97*	[25]
	5 - 10	Pt	*2003*	Single Eident Energy V1.1 cells were operated at 0.67V x 0.15A/cm^2 during a 2800 hour test, with electrolyte replacement. Voltage loss at 0.1A/cm^2 *(top)* was half that at 0.2A/cm^2 *(bottom)*.	*1.97*	[25]
	20					
4.9 ± 1.1		*Multiple*	*1986 - 2000*	The average of six lifetime studies that are not repeated here.	*1.75*	[27]
	24	Ni	*2000*	Half cell test at KTH. Cell was operated at 0.1A/cm^2 over 1500 hours. Unoptimised electrode hydrophobicity was thought to cause the rapid decay.	*0.98*	[115]
11	3.4	Pt/Pd	*1999*	Half cell test at KTH. Cell was operated at 0.1A/cm^2, with intermittent polarisation at high current density and electrolyte changes.	*0.78*	[116]
5	17	Ag	*1996*	Half cell tests at DLR. Cells were operated at 0.1-0.15A/cm^2. 15,000 hour lifetime was predicted for a full module with a changeable circulating electrolyte, however this was never built.	*0.39*	[117, 118]
6		Pt	*1987*	Tests by Elenco into CO_2 poisoning.	*0.05*	[27]
5	13	Pt	*1987*	Elenco and Zevco tests showed minimum cell lifetime to be 5,000 hours.	*0.10*	[26, 27]
8		Ni / Ag	*1986*	The average lifetime achieved by approximately 20 Siemens units. 15,000 hours was mentioned as the maximum seen.	*0.09*	[22, 119]
	25	Pt	*c. 1970*	Degradation of UTC stacks running on H2/O2 during space missions.	*0.00*	[22]

Ancillary Component Lifetimes

Fuel processor

- The Osaka Gas fuel processor used in 50-100kW PAFC systems had demonstrated 40,000 hour lifetimes in 2001. The components used in it were identical (except in scale) to those used in their 1kW PEMFC fuel processor (with the additional of a further CO cleanup stage).[120]
- The Tokyo Gas fuel processing system for 1kW PEMFC systems has been demonstrated for at least 20,000 hours and 4,000 stop-start cycles with no loss of efficiency. They were confident that 10 year operation (40,000 hours) will be achieved as demonstrations continue.[77]

Power conversion

- Data on inverter lifetimes is relatively scarce, however warranties of 10-15 years are now offered by leading manufactuers.[121, 122]

Reliability

PEMFC

Only the Japanese manufacturers of ENEFARM systems have been willing to release information on the durability of their demonstration systems, which spans the past 6 years of development. From the data presented by the NEF,[40] fleet-wide values for the MTBF were estimated[6] to rise from 2,300-5,500 hours in 2005-06 to 5,100-9,800 hours in 2007. Based on the first data point for revised 2008 models, a tentative MTBF of over 30,000 hours was seen – however this will need to be confirmed once more recent data is released.

Table 19: Key results about the reliability of Japanese PEMFC systems during the research and demonstration project.

Year	Results	Ref.
2002-03	• Average of 4 failures per system experienced across a fleet of 33 in a 1 year period. • 1/2 of all failures occur during 4 months • The three least reliable components: fuel processor (30% of all failures), fuel cell stack (25%) and water treatment (24%).	[123]
2005 (1st stage)	• Average of 3 failures per system experienced across a fleet of 175 in a 1 year period. • 1/3 of systems experienced 1 or less failures, but some experienced up to 8. • The three least reliable components: water treatment (37% of all failures), fuel processing system (18%) and system controller (17%). • The fuel cell stack itself only accounted for 3% of failures.	[124]
2005 (1st)	• MTBF was reported to be over 3,300 hours for the 40 installed Toshiba systems.	[34]
	Average number of failures per system per year across the entire demonstration fleet, split by the year of installation:	[40, 125]
2005 (1st)	> 2.5, from the first 2 years of operation	
2005 (2nd)	> 2.3, from the first 2 years of operation	
2006	> 2.4, from the first 2 years of operation	
2007	> 1.2, based on the first 12 months of operation	
2008	> 0.3, based on the first 3 months of operation	

SOFC

The reliability of the SOFC systems installed in the Japanese field trials has been reported by the NEF.[59](p. 85) It is thought that 21 faults developed in the 28 systems operating in 2006; which reduced to 6 faults during 2007. The following values for MTBF were given:

2006: 1626 hours
2007: 5654 hours
2008: 7926 hours (projected)

PAFC

11 commercial PAFC systems were operated by Tokyo Gas (UTC PC25A and PC25C, Fuji Electric FP50 and FP100).[18] The MTBF over their lifetime was 4593 ± 2626 hours, and during the 2000 fiscal year was 4688 hours. Plant availability was 91.3 ± 10.3% over their lifetime, and 96.6% during 2000. The failure occurance rate over 5 years was between 0.2 and 0.8 forced shutdowns per 1,000 hours of operation.

Reliability of the US Department of Defense's fleet of UTC PAFC systems was not as good, as they were earlier models than used in Japan.[19] MTBF was 1594 hours for the fleet of 14 PC25B units, and 1766 hours for the 15 PC25C units. During 2000-01, the MTBF for PC25C models had improved to 2621 hours. The average outage time was 899 hours for the PC25Bs, and 317 hours for the PC25Cs. Plant availability was 56% (30-75% range) for PC25Bs and 77% (62-82%

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[6] These estimates were simply based on 8,760 operating hours per year. MTBF values would have been lower if the actual number of operating hours (3-6,000 hours per year) were used.

range) for PC25Cs. Availability of the PC25B series was low, as they were discontinued during the trial, and so replacement parts became hard to source.

Other mentioned values:

- 2,500 hour MTBF for the PC25.[62]
- 6,750 hour MTBF for the 400kW 'advanced PAFC'.[62]

Operating Constraints

Table 20: Turndown ratio for fuel cell micro-CHP systems.

Fuel cell system	Turndown ratio	Ref.
Ebara-Ballard & Panasonic LIFUEL models (1kW PEMFC)	30%	[74, 98, 126]
Baxi Gamma (1kW PEMFC)	30%	[43]
Viessmann Fuel Cell Energy Center (2kW PEMFC)	20%	[127]
Kyocera (0.7kW SOFC)	7-14% (50-100W minimum)	[59](p. 47)
ENEFARM (1kW PEMFC)	40% was the minimum load factor typically seen during demonstrations	[41, 98, 126]
Toshiba & Eneos ENEFARM models (1kW PEMFC)	36% (250W minimum)	[128]

Table 21: Start up time for fuel cell micro-CHP systems.

Fuel cell system	Start up time	Ref.
H-Power: 4.3kW PEMFC	'Over an hour'	[70]
Toshiba ENEFARM (PEMFC)	1 hour	[129]
Vaillant NextGenCell, based on a high temperature PEMFC membrane.	Less than one hour	[90]
Unnamed PEMFC[7]	0.75-1.25 hours until full power	-
CFCL GenNex module (1kW SOFC)	13 hours (preliminary specifications)	[130]
GS Fuel Cell, Fuel Cell Power & Hyosung (1kW PEMFC)	'About 1 hour'	[131]

Maximum ramp rate: It is thought that SOFC systems in particular will not be capable of changing power output rapidly, however the Kyocera system appears to tolerate load changes of 300W per minute (0.7% per second).[59](p. 48)

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[7] This is the mean time until full power output (± one standard deviation) taken from an analysis of 181 operation periods of a field-trial system.

Estimated High-Volume Manufacturing Cost

Literature estimating the cost of mass produced fuel cell CHP systems was sought to give a basis for estimating the retail price when the technology has is fully commercialised and in widespread use. These costs are intended to reflect the current state-of-the-art design, manufactured with present day methods at high volume (i.e. >10^5 systems per year).

The assumptions used in each cost estimate differed 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 with the other information presented in this report. Typical examples were lowering the power density of the fuel cells to the industry-wide average (thus increasing the number of cells required); or increasing the price of platinum to reflect current prices. The individual modifications are given as footnotes to each table of data.

All costs have been converted to 2007 Euros for consistency, based on a constant global inflation rate of 2.5% per annum (0% in Japan), and exchange rates of 150¥ = $1.30 = £0.70 = €1. The cost is split into the following categories:

- The fuel cell stack, which is typically quoted per kW of electrical capacity;
- The balance of plant (BoP), which consists of all ancillary equipment;
- Operation and maintenance, which includes all ongoing costs incurred during the operating lifetime.

Table 22: Current and expected retail prices for PEMFC micro-CHP systems (top); and estimates for the mass-production costs of stacks and systems (bottom).

System Price	Year	Description	Ref.
€22,000 - €24,000	2009	Initial sale price of ENE·FARM models from Toshiba and Eneos were ¥3,255,000 through Osaka Gas, and ¥3,465,000 for Panasonic models sold through Tokyo Gas.	[128, 132]
~€56,000	2008	80M Won was the expected price for Korean systems from GS Fuel Cell, Fuel Cell Power & Hyosung in 2008; down from 100M in 2007 and 130M in 2006.	[131, 133]
€20,000 - €200,000	2005-2009	An indicative range of quotes received by the University of Birmingham's Fuel Cells Group for micro-CHP systems	-

Stack Cost	BoP Cost	O & M Cost (/MWh)	Year	Description	Ref.
€600/kW (materials)	€190 + €175/kW		2005	Estimated materials cost for the stack and balance of plant, using empirical formulae to relating to capacity.[8]	[134]
€2450	€11,900		2004	Manufacturing costs for 1kW ENEFARM systems estimated by the system manufacturers in 2004, considering a production volume of 10,000 units per year.	[135, 136]
€180-5500/kW	€230		2000	Costs for a 1kW domestic system were extrapolated from a 50kW pressurised stack, with a separate assessment for the BoP.	[27]
€85 + €160/kW			1999	Estimate for a 3kW stack (3-50kW were considered) using commercial cost estimation software and information from the US Department of Energy. BoP costs were considered, but were unfeasibly high.[9]	[137]

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[8] 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%

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

Table 23: Current and expected retail prices for SOFC systems; and estimated costs for mass produced stacks and systems.

System Price	Year	Description	Ref.
€47,500	2000-2005	Mentioned as the cost of 1kW CHP systems demonstrated by Hexis. The newer Galileo model was described as "less costly", but no price was given.	[10]
~€70,000	2007	The METI technology roadmap described Japanese 1kW-class models as costing "tens of millions of yen" at the end of FY2007.	[138]

Stack Cost	BoP Cost	O & M Cost (/MWh)	Cell Type	Year	Description	Ref.
€4250-5750/kW			Flat tubular 750°C	2006	The expected retail price of a 0.7kW domestic unit (including hot water tank) from Kyocera & Osaka Gas.	*[139]*
€575/kW			Tubular, 800°C	2006	Materials costs for a 6kW Acumentrics Phase I Generator, estimated as part of the SECA project.	[12]
€350/kW	€625 (1.3kW)		Planar, 850°C	2006	Estimated materials costs for a 1.3kW system based on the Fuel Cells Scotland stack.	[140]
€150-450/kW			Planar	2004	The range of estimated costs given for a 5kW residential unit, from a sensitivity analysis performed by Tiax.[10]	[141]
€550-600/kW			*Multiple Planar*	2007	Given as the range of costs for 6 recent small SOFC systems.	[10]
€50-225/kW					Estimated cost of manufacturing individual cells, based on assumed mass-production process.	[142]

Table 24: Retail prices for PAFC based industrial CHP systems. Note, no estimates were found for domestic CHP systems.

Stack Cost	BoP Cost	O & M Cost (/MWh)	Year	Description	Ref.
€4666/kW			2008	The retail price of a 100kW Fuji system, including installation.	[143]
€1600/kW	€240/kW	€13	2006	Unsubstantiated theoretical estimates for a 200kW system.[11]	[144]
€2700/kW		€51	2002	The retail price of a UTC PC25 system.	[63]
€5700/kW			2002	The retail price of a 200kW system as of Jan 2002, which could be reduced to €4700/kW with government subsidies.	[23]
€3000-3900/kW		€25	<2002	The retail price of a 2004kW ONSI system during production.	[56]
€2500-3750/kW			2001	The retail price of a 2nd generation Fuji 100kW system.	[145]

- 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..

[10] 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 fitted 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.

[11] The breakdown of estimated cost was: €1600/kW for the 200kW 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).

Table 25: Estimated costs of mass produced AFC fuel cell systems

Stack Cost	**BOP Cost**	**O & M Cost** (/MWh)	**Year**	**Description**	**Ref.**
€220/kW			2006	Claimed materials cost for the Astris Powerstack M-250.	[146]
€600/kW			2003	The actual bill for materials required to produce an Elenco V1.1 module, approximately €220 of which would be for platinum. Assembly costs were not included.[12]	[25]
€130-560/kW	€225	€2-26	2001	Estimates for high-volume manufacture of a domestic AFC system, including the ongoing costs of soda lime consumption for a CO_2 scrubber.	[27]
€400-500/kW			1992-1994	Based on a review of reports from DLR, LBST, ZSW, Hoechst & The Royal Institute of Technology in Stockholm.	[117]
€75-240/kW			1986, 1993, 1999	Projections and estimates for stack or material costs, taken from three separate sources.	[27]
€200/kW			1998	Projected mass-production cost of a Zevco module, which was sold for €1600/kW at the time.	[27]

Fuel Tolerance

A summary of the tolerance to impurities of each fuel cell stack is given in Table 26, while more detailed information from the first revision of this report is given on the following page.

Table 26: Fuel tolerance of different systems.

	PEMFC [22, 31, 91, 147]	**SOFC** [23, 31, 36]	**PAFC** [22, 23, 31, 62, 91, 148]	**AFC** [31, 116-118, 149-152]
Sulphur (as S, H_2S)	< 0.1 ppm	< 1 ppm	< 50 ppm	?
CO	< 10-100ppm[13]	*Fuel*	< 0.5-1%	< 0.2%
CO_2	*Diluent*	*Diluent*	*Diluent*	< 100-400ppm or < 0.5-5%[14]
CH_4	*Diluent*	*Fuel / Diluent*[15]	*Diluent*	*Diluent*
NH_3	Poison	< 0.5%	< 4%	?

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[12] Calculated from a specific power of 160W per gram of platinum (as given), and an updated platinum price of €32/g.

[13] CO_2 tolerance is highly dependent on the cell design. Strongly bonded nickel and silver electrodes with a circulating electrolyte can be highly tolerant, while platinum and carbon with an immobilised electrolyte are highly sensitive.

[14] Standard Pt anode catalysts can only withstand CO concentrations up to 10 ppm, and PtRu alloys up to 30 ppm.[31] These limits can be extended by bleeding air into the anode and using alternative bi-layer catalysts.[153, 154]

[15] Internal reforming is possible with SOFC anodes, making desulphurised natural gas a viable fuel. Extended lifetimes required for domestic CHP operation have not yet been demonstrated however.

PEMFC:

Substance	Quantity	Effect	Description
CO	10ppm	Poison	Platinum catalyst poisoning.[54, 91]
CO	10ppm	Poison	Caused a reduction of 0.1-0.2V during operation, unsure if this is permanent degradation.[147]
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[22]
S, NH_3, HCl, Si	*?*	Poison	Mentioned as poisons.[23]

SOFC:

Substance	Quantity	Effect	Description
CO	1400ppm	?	Kyocera SOFC system[59]
CO	-	Fuel	[23]
CO_2	-	Diluent	[23]
H_2S	1ppm	Poison	[23, 36]
NH_3	0.5%	Diluent	Described as "Relatively harmless".[23, 36]
HCl	0.1ppm	Poison	[23, 36]
Si	*?*	Poison	[23]

PAFC:

Substance	Quantity	Effect	Description
CO	0.5-1%	Reversible	Performance loss reversible at 190°C[22, 91]
CO	0.7%	Reversible	Performance loss due to increased cell resistance above 0.7%.[148]
CO	1%	Poison	Catalyst poisoning.[22, 23]
CO_2	10%	Diluent	No effect other than to dilute the fuel.[22, 23]
NH_3	4%	Poison	Molecular nitrogen content of 4% reduces the electrolyte.[22, 62]
S	-	Poison	Tolerance is greater than that of the reformers.[62]
S	50ppm	Reversible	Acceptable as <20ppm H_2S and <30ppm COS. Performance loss is reversible by polarisation at high potential.[22, 91]

AFC:

Substance	Quantity	Effect	Cell Type	Description
CO_2	~400ppm	None		Hydrocell employs an amine based regenerative filter. Regenerated by periodic heating to release CO_2.[155]
CO_2	0.1%	50h life	Pt + fixed electrolyte	Rapid decay and cell death was seen in experiments with platinum anodes and a non-circulating electrolyte.[116]
	5%	5h life		
CO_2	<100ppm	None	Standard Pt	Experiments showed that CO_2 causes electrode pores to be blocked or mechanically damaged. Strongly bonded electrodes can support un-scrubbed air for many thousands of hours.[151]
	~400ppm	None	Strongly bonded	
CO_2	0.3-0.4%	<1% voltage loss	*?*	Reversible loss of performance seen in experiments.[150]
CO_2	1%	None	Ag	No significant effect on performance in experiments at 72°C.[152]
CO_2	4%	9% voltage loss	Ni/Ag	Reversible loss of performance seen in experiments.[152]
CO_2	5%	No degradation	DLR (Ni/Ag)	CO_2 found to have no influence in degradation rate on strongly bonded, non-noble electrodes over several thousand hours.[117, 118]
CO	0.2%	V loss	Ni/PTFE	Reversible loss of performance – 10% current – at 72°C.[149]

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