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The cost of domestic fuel cell micro-CHP systems

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Abstract

Numerous academic and industrial estimates place the cost of a future mass-produced small stationary fuel cell system at around $1,000 per kW, which compares well with targets set by agencies such as the US Department of Energy. Actual sale prices for domestic microgeneration systems do not fit so neatly with these targets, and are currently 30–50 times higher, even though mass production began three years ago.

This paper explores the void between academic projections and commercial reality. It presents a systematic review of cost data from manufacturers in Europe, Asia and the US, along with near-term projections from manufacturers and other relevant organisations. Using these data, the potential for cost reductions through industry scale-up and learning by doing are quantified. The minimum feasible price of a typical 1 kW natural gas combined heat and power system is then estimated from industry data.

Based on the findings, even a heroic effort by industry is unlikely to reduce the price of small domestic-scale systems to the $1,000/kW mark. By aligning the scope and boundaries of cost estimates with the realities of a practical system, we show that a long-term target of $3,000–5,000 for a 1–2 kW system is more realistic, and could feasibly be attained by 2020 at the current rate of progress.

1 Introduction

Forty years after the economics of fuel cells were first assessed [1], academics and government agencies are still reliant on general estimates and targets for system cost [2-4]. In itself this should not be a problem, as all emerging technologies (e.g. third generation nuclear, carbon capture and storage or energy storage) are subject to significant cost uncertainty, and it should be reasonable to assume that the targets laid out in well-informed national roadmaps and technology forecasts can be met with consistent progress from industry.

However, information on historical and current prices for fuel cells is not widely disseminated due to commercial secrecy and low production volumes. There has been no way to determine whether the projections given in literature and by manufacturers are feasible, optimistic or completely unobtainable. The prices that are likely to be obtained in the near future are of great importance, as governments and companies alike must decide how to distribute limited funding for R&D activities and subsidies for early-stage deployment.

Residential combined heat and power (CHP) is one of the most promising applications for polymer electrolyte membrane (PEMFC) and solid oxide (SOFC) fuel cells, tapping in to the worldwide market of over 15 million mains-gas connected domestic boiler and furnace replacements per year [5, 6]. These systems can be fuelled by widely available natural gas, and produce grid-synchronised AC power alongside low-grade heat for space heating and domestic hot water.

A complete packaged product typically consists of:

- The main fuel cell system:
    - A fuel cell stack (converts hydrogen to heat, electricity and water);
    - A fuel processing system (converts natural gas (or other hydrocarbons) to hydrogen + CO_2);
    - A grid-tie inverter (to convert low-voltage DC to AC with export ability);
    - Heat exchangers (to transfer waste heat from the exhaust and coolant loops to an external system);
    - Balance of plant (pumps, valves, sensors, pipework, electronic control systems, etc.)
- Additional thermal management:
    - An auxiliary boiler to supply peak heat demands (usually integrated into the fuel cell system);
    - A high-efficiency heat store (so that a low-capacity fuel cell can supply the majority of the building's heat demand);
- Control, interaction and feedback:
    - Touch-screen LCD interface;
    - Remote control system;
    - Smart-meter for consumption/production.

When considering fuel cells for domestic-scale distributed generation, academic and industrial estimates place the cost of a mass-produced fuel cell stack at around $500 per kW, with an additional $500–1,000 per kW for other components in a complete micro-CHP system. These estimates compare well with targets set by agencies such as the US Department of Energy (DOE), which had aimed (in 2007) to demonstrate fossil fuelled PEMFC CHP systems for under $750/kW by 2011 and under $450/kW by 2020 [7]. These targets were recently revised to $1,200/kW by 2015 and $1,000/kW by 2020, for a complete 2 kW natural gas fuelled PEMFC system [8, 9]. Similarly, the DOE's SECA programme established cost targets for 3–10 kW stationary SOFC systems, initially starting at $800/kW for Phase I (2005), then falling to $700/kW for Phase II (2008) and $400/kW for Phase III (2010) [10, 11]. Their cost reduction efforts now aim to demonstrate fuel cell stacks only for $175/kW and complete systems for $700/kW [12].

Actual sale prices have not fitted so neatly with these targets. They are currently 30–50 times higher, even though some manufacturers have now started volume production. The most commercially mature systems retail for around $30,000 per kW in Japan, three years after they were launched by three manufacturers (see Table 2 later). Prices have fallen by more than half in four years [13]; however, to meet the DOE's targets, the world's most advanced systems would require a cost reduction of around 92% in just three years.[1]

In an independent review conducted by NREL, "the majority of stakeholders believe that the DOE cost targets are unnecessarily aggressive for [the 1kW] power level and that the technology is capable of reaching an end product (including water tank) selling price to the utilities of $5,000–7,000/kW by 2012–2015" [14]. The targets may prove to be counterproductive if they damage the technology's reputation by leaving stakeholders unimpressed at the apparent lack of progress against unrealistic goals.

This void between academic theory and commercial reality raises some important questions for economists and policy makers alike. Three possibilities could reconcile these differences, each with very different implications for the commercial prospects of the technology:

- Current prices are highly inflated and do not represent the underlying cost of manufacturing these systems;
- As the technology matures, learning by doing will allow current prices to naturally fall to the projected levels;
- The projected targets for mass production do not reflect the reality of manufacturing complete systems.

This paper begins with an overview of the current commercial status of stationary fuel cells. In an attempt to assess these possibilities, it then reviews the available price data for fuel cell micro-CHP systems, focussing on the most commercially advanced systems from Europe, Japan and South Korea. It demonstrates how rapidly these prices are declining, showing that billions of systems would have to be produced to reach the DOE targets, based on past experience. By breaking down the costs of producing a domestic fuel cell system, we propose that these targets under-estimate the importance of the balance of plant required for system integration, and do not cover all of the major components that would be required to fulfil the needs of domestic energy demands. A more realistic target of $3,500 is proposed for a complete system, and the paper finishes by discussing the implications of these findings, and exploring ways in which this target could be reached more rapidly.

2 Current commercial status

Fuel cells have been under development for the past 50 years, but are still relatively immature in commercial markets. There are, however, three major markets where fuel cells have moved from the laboratory to the company showroom: portable units, large stationary combined heat and power (CHP), and domestic micro-CHP.

Fuel cells are often seen as lagging behind other domestic energy technologies, "forever 5 years away from commercialisation" [15, 16]. However, Japanese manufacturers began to roll the first units off automated production lines in 2009, marking the long-awaited transition towards mass production. With over 10,000 domestic micro-CHP units already operating in Japan and annual sales expected to double this in 2012, the commercialisation of domestic fuel cell CHP is already underway.

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[1] The cost of manufacturing these systems (as opposed to their prices) is not precisely known, but even if a substantial mark-up of 100% at present were to fall to zero by 2020, the underlying cost would have to fall from $15,000 to $1,200.

A survey of small stationary fuel cell developers suggests that around 20,000 CHP and backup-power systems under 10 kW had been installed worldwide as of 2011 [17]. Of these, about 85% were PEMFCs and the remainder were virtually all SOFCs.

Three countries are leading the demonstration and commercialisation of fuel cells: Japan, Germany and South Korea. The USA is a key player in the fields of industrial-scale CHP and fuel cell vehicles, but has seen relatively little development of domestic scale CHP due to an unattractive financial and regulatory landscape.

By far the greatest activity has occurred in Japan. A series of large scale demonstration programmes have been carried out since 2002, resulting in the installation of 3,352 PEMFC and 233 SOFC units into private homes [18, 19]. After the completion of the Large-scale Stationary Fuel Cell Demonstration Project in 2009, the EneFarm brand of PEMFC systems was launched collectively by Panasonic, Eneos (JX Nippon Oil & Sanyo) and Toshiba. These have been based on PEMFC stacks ranging from 0.7 to 1.0 kW electrical output (0.9–1.4 kW thermal), packaged with a fuel processor for either natural gas, LPG or kerosene and a hot water tank with integrated supplementary boiler.

Just over 25,000 EneFarm systems have been sold to homeowners and new house builders in the three years following the demonstration, with the aid of government subsidies of $9,000–11,000 per system [18]. Government spending on EneFarm subsidies has totalled $277m (¥33bn) since 2005, with a further $75m requested for 2012–13 [20].

Japan is also at the forefront of SOFC development. Companies such as Kyocera, Nippon Oil and Toto have been engaged in residential demonstrations of 0.7–1 kW systems since 2007. Commercial sales of two models from Kyocera and Eneos began in March 2012, and approximately 300 systems had been pre-ordered at this time. The government roadmap aims for fundamental materials research and residential demonstrations to continue until at least 2012 before widespread commercialisation in 2015–2020 [18].

The South Korean government has identified fuel cells as a priority technology, and is supporting a large demonstration of up to 500 Residential Power Generators (RPGs) by offering subsidies of 80% of the purchase price [21]. After an initial field test of 1 kW RPGs in 2004, four Korean companies (GS Fuel Cell, FuelCell Power, HyoSung and LS) began demonstrating fuel cells for this trial, and had installed 210 units between 2006 and 2009, at a cost of $18m in subsidies [22]. Their roadmap sees trials continuing until 2014, then commercial sales expanding rapidly from 2015 onwards.

In Germany, the Callux residential field trials began in 2008 with three manufacturers: Hexis, Vaillant (both SOFC) and Baxi Innotech (PEMFC). It was intended that 800 units would be installed by 2012; however, the project is around a year behind schedule due to technical and logistical issues so that just 200 units had been installed by 2011 [23]. Other European demonstrations include the FC-District Project which is operating in Spain, Greece and Poland; and small-scale trials with individual natural gas distributors in the UK. Commercial activity in Europe has been limited so far, however the IEA envisages “that the full commercial market in 2020 will have a volume of 72,000 units per year” [12].

3 Early estimates of future costs

Even if the present cost of manufacturing fuel cell systems was widely known, it would not give an indication of how much they would cost to build en-masse once they were fully commercialised. The transition from low volume, highly specialised assembly to automated mass-production lines will bring about enormous reductions in labour intensity and plant utilisation, and thus in manufacturing costs. The cost of producing systems at high-volume has therefore been estimated by many organisations to give an idea of where this bottom line could be expected to lie.

To do this, the fuel cell system is broken down into components, and then into individual materials and production stages. These are often parameterised; for example, the area of electrolyte required is expressed as a function of power density, so that a sensitivity analysis can be performed. The cost of each material, process and component is then estimated from interviewing relevant companies or with industrial cost estimation software, which contains a database of reviewed costs for standard manufacturing goods and processes.

Assumptions about the construction and performance of the system are critical to the results, as are expectations for the future costs of materials and of specific components such as polymer membranes. As the industry producing these was for many years close to being a monopoly, the cost to the fuel cell manufacturer could have exceeded the production cost by a significant margin. Estimated costs can therefore vary widely between studies as different assumptions are used [24].

Such discrepancies are most obvious when comparing studies of fuel cell stacks for automotive use with those for stationary purposes such as micro-CHP. The widely publicised high-volume estimates for the former of as little as $20 per kW (e.g. [7, 25]) are not valid for stationary systems as their design criteria are too different [24]. Automotive stacks are much larger, in the range of 50–100 kW, and benefit from simpler auxiliary systems as they run on pure hydrogen rather than reformed hydrocarbons. Their design has a focus on high power density and low cost, rather than long lifetime and low degradation. As seen in Table 1, the estimated costs for mass produced stationary stacks and systems are somewhat higher; however, they still compare favourably to the target costs set by the DOE and SECA. These estimated mass-production costs also suggest that fuel cells will eventually be a financially attractive investment for households without any form of subsidy, as they are much lower than estimates for the economic value generated over their lifetime (in the form of reduced energy bills) [2, 26, 27].

4 Prices for small stationary fuel cell systems

This section starts with the prices that manufacturers have been willing to sell their systems for – as opposed to the current, projected or future cost of manufacturing these systems. In a sufficiently competitive industry, prices should be close to costs, but can rise well above costs if a company is able to exploit market power. Until recently there were few, if any, published prices for fuel cell CHP systems as each machine was individually built and sold with a tight confidentiality agreement. With the exception of the newly released EneFarm systems, it is still challenging to find any manufacturers who can or will openly state how much their systems cost to produce today: the strategic value of leaving competitors uncertain about your costs is continuing to keep firms quiet [39]. The prices outlined in the next sub-section vary between $20,000 and $200,000 for a complete micro-CHP system, with specific prices depending strongly on the manufacturer and order volume. It is possible to show, however, that these very different prices are consistent with a single underlying relationship between the number of systems produced and the prices charged. Trying to estimate what these prices would be in other scenarios (e.g. when mass produced or in the future) nonetheless poses a challenge [40].

	Fuel cell stack cost (per kW)	Whole system cost (per kW)	Year of study	Details	Source
PEMFC	$1,600 $500	$7,250 $2,400	2011	Cost analysis of 1 kW (top) and 5 kW (bottom) systems based on the EneFarm design produced at 50,000 per year. Made by Strategic Analysis, Inc. (formerly Directed Technologies) using DFMA costing methodology.	[28, 29]
	$190	$325	2009	Baseline costs for a 10 kW CHP system produced at 50,000 per year. Presented by the Carbon Trust to represent current systems manufactured at high volume. The whole system excludes the fuel processor.	[30]
	$1,700	$2,900	2005	Estimated total capital investment for building a 5 kW methanol system, using the Guthrie–Ulrich base cost method. Materials, manufacturing and overheads accounted for approximately one third of the total cost each.	[31]
	$230	$560	2000	Baseline costs for a domestic system, extrapolated from separate assessments of a 50 kW pressurised stack produced at 500,000 units per year, and of the fuel processing systems and balance of plant.	[32]
	$1,250	$5,300	1999	Estimates from Directed Technologies Inc. for 3–5 kW systems produced at 10,000 per year volume, made using industrial cost estimation software and information from the US Department of Energy.	[24]
SOFC	$770–820		2007	Manufacturing costs for 3–10kW systems from six American companies, estimated at production volumes around 50,000 per year as part of the SECA Phase I project.	[33]
	$200		2006	Cost modeling for the SECA project, considering the materials and manufacturing of 5 kW stacks produced at 50,000 per year.	[34]
	$510	$1,200	2006	Estimated cost at volume production for a 1.3kW system based on the Fuel Cells Scotland planar stack.	[35]
	$150		2004	Central estimate from the TIAX cost model of a 5 kW residential planar SOFC stack produced at 20,000 systems per year.	[36, 37]

Table 1: A summary of previous bottom-up cost estimates for stationary fuel cell stacks and systems. Where possible, values were updated to reflect current material prices (notably $50/g of platinum), and some estimates were modified to be more consistent with the domestic CHP systems in use today, as detailed in [38]. All prices are given in 2010 USD, converted using PPP rates of ¥120 = €0.86 = £0.65 = ₩780 = AU$1.44 = $1 and 2.5% annual inflation.

4.1 Current and historic price data

It should be of little surprise that this data was most readily available for EneFarm systems, as their commercial development has now reached the state at which prices are openly displayed on distributors' websites, and orders can be placed by those with enough money.

Price data has also been published in two other field trials of PEMFC systems, but only anecdotal evidence is available for the other systems, as pre-commercial manufacturers remain secretive. Industrial-scale PAFC systems have been sold for decades and their prices are well known, however these do not give a valid indication of what micro-CHP systems would cost due to the non-linear economies of scale. The cost per kW for smaller scale systems is expected to be several times higher, as seen with other microgeneration technologies [27].

Table 2 collates the actual sale prices of seven models of fuel cell system. No clear trend can be seen between technologies, as the differences in price are currently dominated by production volumes and system capacity. Excluding the non-comparable PAFC systems, it is clear that EneFarm are the cheapest available systems, which is understandable as they are the most commercially mature.

	System	Electrical Capacity (kW)	Year price was set	Price (2010 USD)	Description	Source
PEMFC	Eneos	0.7	2011	$21,800	Revised price for the improved Ene-Farm models launched in 2011 and 2012.*	[41, 42]
	Panasonic	0.75	2011	$22,300		[43]
	Toshiba	0.7	2012	$21,000		[44]
	Eneos	0.7	2009	$26,600	Initial sale prices of Ene-Farm systems in Japan.*	[45]
	Panasonic	1	2009	$28,800		[46]
	Toshiba	0.7	2009	$26,600		[45]
	(1 kW class)		2010	$54,000	*Quoted prices from an anonymous European supplier for a natural-gas fuelled system.*	
			2008	$239,000		
	GS Fuel Cell, FuelCell Power, HyoSung	1	2010	$77,000	The base price for systems in 2010.	[22]
		1	2008	$106,000	The average price of systems installed in the final year of the Residential Fuel Cell Monitoring Project.	[47, 48]
	Plug Power	5	2002–06	$64,000–86,000	The average purchase price during the US Department of Defense field trials, excluding installation (which averaged $11,000).	[49, 50]
SOFC	Eneos	0.7	2011	$21,800	Initial sale price for the first SOFC-type Ene-Farm system.*	[41, 51]
	Kyocera	0.7	2012	$22,200	Initial sale price for the EneFarm “Type S”.*	[52]
			2010	$52,500	Quoted in the METI technology roadmap and by Kyocera during the demonstration project.	[53]
			2008	$82,000		
	CFCL	1.5	2011–12	$29,600	Revised sale prices with 2 year warranty, excluding installation (estimated at $1,110).	[54, 55]
			2010–11	$31,250	Initial sale price, inclusive of installation and 2 years servicing. Price rose to $48,000 for a 5-year contract.	[56]
	Sulzer Hexis	1	2000–05	$72,000	The cost of early demonstration systems. The later Galileo model was described as “less costly”, but no price was given.	[33]
PAFC	UTC and Fuji	100–400	2000–09	$4,300–8,300 per kW	The average sale price of large-scale CHP systems over the last decade.	[57-61]

*Table 2: Recent sale prices for fuel cell micro-CHP systems, excluding impact of any subsidies and installation (unless specified). Note: * All Ene Farm systems include an integrated boiler, hot water storage tank and 10-year warranty.*

As shown later, much of the discrepancy between prices can be explained by the different stages of commercial development of each product, and particularly the volumes at which they have been manufactured. What this does not reveal, however, is how SOFC prices will compare to those of PEMFC in the future. Until more data is available on the pricing and historic levels of production for these systems, it remains to be seen whether SOFC will ultimately become more economical than PEMFC as these technologies mature.

4.2 Learning and experience curves

The higher prices cited in Table 2 are from the manufacturers that have produced fewer systems, and as production volumes grow, prices tend to fall. This is an example of learning by doing, which implies that costs will fall with greater experience of production, as processes are optimised and specialised equipment is developed to reduce labour intensity. There is “overwhelming empirical support for such a price-experience relationship from all fields of industrial activities, including the production of equipment that transforms or uses energy” [62].

Past studies often find a linear relationship between the log of the cost of production and the log of cumulative output. This implies that the same percentage reduction in costs would be achieved each time cumulative output doubled, a figure known as the learning rate. The histogram in Figure 1 shows that this has been between 9% and 27% for most energy-related technologies, and similar rates have been estimated for fuel cells in the past. Strictly speaking, a learning curve uses data on costs, while information on prices is used to construct an experience curve [62].

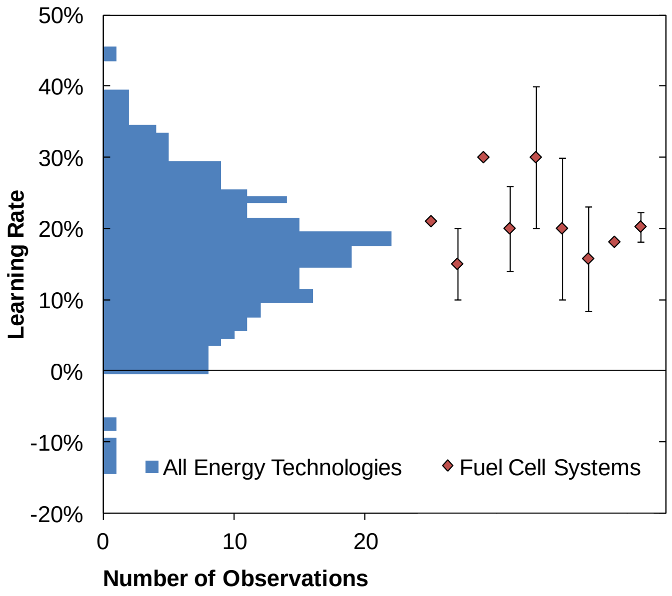

Figure 1: A comparison of the learning rates observed for energy generation technologies (histogram, left) [63-65] and estimated for PEM fuel cells (points, right) [13, 25, 66-72].

Early attempts to estimate learning rates for fuel cells were hampered by the limited information available, making formal modelling impossible [40, 66]. Most studies attempted to estimate the rate at which costs would fall in the future based on past experiences with similar technologies, typically for use in vehicles (e.g. [25, 66-72]). As argued above, their characteristics imply significantly lower costs than for domestic CHP systems; however, the learning rates for vehicle and CHP systems might still be comparable.

Figure 1 shows that there is no consensus on the appropriate learning rate, although most studies fall towards the higher end of the range observed for other technologies – averaging 14-28%. Neij argues that modular technologies such as fuel cells have experienced higher learning rates than monolithic products such as turbines, but concedes that rates as high as 30% are rarely observed [40]. Conversely, Schwoon opted for more conventional learning rates of 10–20%, arguing that several components of a fuel cell system (pumps, motors, inverters) are already well developed within other products, and would not benefit strongly from the early phase of the fuel cells' own learning curve [66].

4.2.1 Experience curves for EneFarm systems

Previous work by the authors [13] compiled historic prices for Japanese PEMFC systems installed during public field trials from 2004–09. These precursors to the EneFarm were found to have a learning rate of 19.1–21.4%, and a base cost of $33,100 (2010 USD) once 3,512 units had been produced. Put together, these suggested that sale prices should fall to the region of $5,000 once a million units have been produced. It is now possible to add a further data point to the EneFarm experience curve, as sales and price data are now available for 2010 and 2011.

Figure 2 plots the historic and new price data for EneFarm systems on log-log axes. Each point represents the range in the cumulative number of installations and prices during a year of the demonstrations, then for a generation of commercially released product. Prices are presented in 2010 USD, converted from inflation-adjusted Yen at a fixed rate of ¥120 per $ (the purchasing power parity (PPP) average during the period). Using different exchange rates for each year's sales would distort the learning rate due to the different rates of inflation in the US and Japan.

The historic data in [13] covered 3,352 cumulative sales, and assumed that the initial sale prices announced in 2009 (see Table 2) would apply to a further 5,000 sales, the manufacturers' projections for first year. These prices in fact remained in place from April 2009 to December 2011, covering 22,452 sales. The two points at the same horizontal level in Figure 2 show the final year of demonstrations and the initial commercial launch, which were at similar prices. It is not possible to forecast how long, or for how many sales the 2011–12 revised prices will remain in effect, so we make a similar assumption as in [13], that the new EneFarm models and prices will remain current during 2012 and 2013 and thus will apply to 50,000 sales, according to projections by the manufacturers and retailers plus our extrapolation from historic growth rates.

Figure 2 shows that because the initial sale price in 2009 remained in effect for longer than we had originally expected, the experience curve is flatter than before. The data for 2012 also support a lower learning rate, pulled down from 20.4% to 15.2%. The revised experience curve passes through each year's data except for 2004 when the demonstrations began, and highlights that the 2009 'shake-down' price was very low, as we had argued in [13]. We have no information on the profit margins implied by these sale prices; it may be that companies were only willing to make the sharp reduction in prices seen in 2008-09 because their costs were even lower, but we suspect that the companies were in fact willing to sell some systems below cost in an attempt to gain market share, and delayed further price reductions until costs had fallen below the 2009 prices.

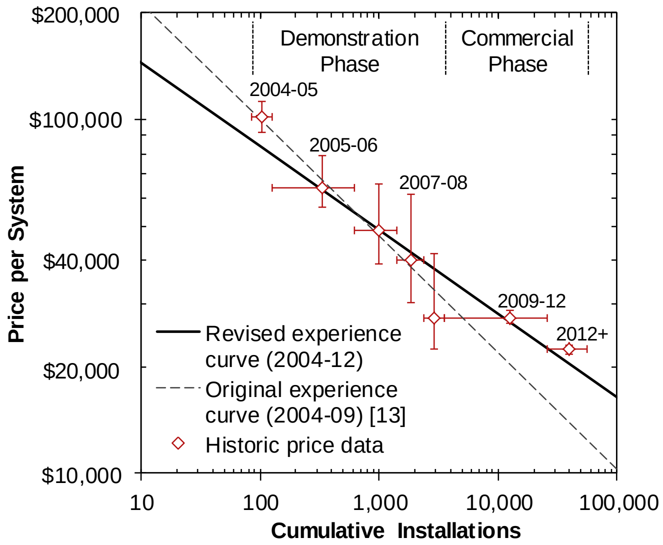

Figure 2: An experience curve for EneFarm systems from 2004 to 2012.

4.2.2 Experience curves for other PEMFC systems

In addition to the new EneFarm data, limited information is available on the price and sales volumes of two other PEMFC systems listed in Table 2, which can also be plotted to see how the experience of other manufacturers lined up.

The contracted price of 1 kW systems from GS, FCP and Hyosung were published for the three years of the South Korean demonstration project, along with the number of units to be delivered – 40, 70 and 100 respectively [48]. Due to a lack of published information prior to these trials, it was assumed that these companies collectively produced 15 systems per year for R&D purposes from 2004 onwards, mirroring the assumptions made about EneFarm systems in [13]. An anonymous manufacturer also provided price data over the course of developing their PEMFC system; however the background for this must remain confidential.

The prices and cumulative experience for these other systems are plotted against the EneFarm data in Figure 3. As different groups of companies are involved in each set of trials, it is appropriate to keep the sales in each market separate when constructing the figure. The parameters for the curves plotted in Figures 2 and 3 are given in Table 3, and can be used with the standard learning curve equation:

$$P_n = P_{base} \times \left(\frac{Q_n}{Q_{base}}\right)^{-b}$$

The price of the nth unit (P_n) is modelled as a function of a reference price (P_{base}), and the ratio of the experience gained by manufacturers at the time of producing the nth unit (Q_n) and the reference unit (Q_{base}), raised by the experience parameter (b). We use the cumulative number of systems produced (i.e. the quantity) as a proxy for experience, for the reasons outlined in [13].

Fitting a curve to all three data sets in Figure 3 produces $P_n = \$32{,}316 \times (n/10000)^{-0.251}$, giving an experience curve that is similar to the 'Lower Bound' presented in [13], with an average learning rate across all three systems of 16.0%.

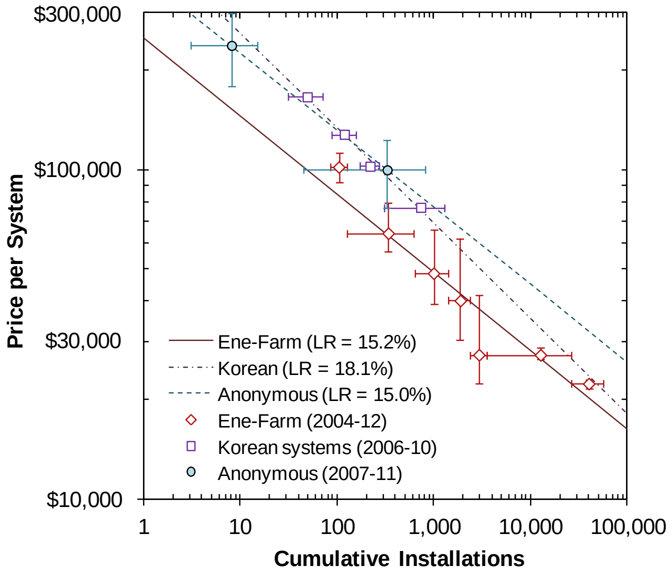

Figure 3: Experience curves fitted to price data from EneFarm and other PEMFC systems.

	Reference quantity (Q_{base})	Reference price (P_{base})	Experience parameter (b)	Learning rate ($L = 1 - 2^{b}$)
Original EneFarm (2004–09)	3,512 ± 80	$30,923 ± 206	0.328 ± 0.021	19.1–21.4%
Revised EneFarm (2004–12)	25,000	$22,693	0.237	15.2%
Korean systems (2006–10)	1,000	$68,715	0.289	18.1%
Anonymous (2007–11)	1,000	$76,965	0.235	15.0%
All PEMFC systems combined	10,000	$32,316	0.251	16.0%

Table 3: Derived parameters for the experience curves for EneFarm and other PEMFC systems.

4.3 Projected future prices

Some of the manufacturers and agencies involved in major fuel cell demonstrations have published projections of future prices. These organisations are best placed to make predictions as they currently have the most experience with commercialising micro-CHP systems. Table 4 summarises recent projections made by major organisations and companies, giving the year the prediction was made and the year and scale of production associated with the predicted price.

Technology / Region		Year for projection	Production volume	Price (2010 USD)	Description	Source
PEMFC	South Korea	2010		$15,500	Target cost stated in the 2008 Korean national action plan.	2008 [48]
		2012	10,000 cumulative	$10,500	Target price set in 2008 by the Ministry of Knowledge Economy.	2008 [47]
		2012		$20,000	Targets set out in the KOGAS roadmap for small stationary fuel cells.	2011 [22]
		2030		$3,000–5,000		
	Japan	2010	10,000 p.a.	$20,250	Estimated manufacturing cost for EneFarm systems made by the manufacturers.	2004 [73]
		2012	50,000 p.a.	$6,000–10,500	The METI technology roadmap for production cost of residential cogeneration systems.	2008 [53]
		2015	500,000 p.a.	$4,500–6,000		
		2015	100,000–200,000 p.a.	$4,250	Target prices announced by Panasonic in 2008 and ENEOS in 2011.	2008–11 [74, 75]
		2020-2030	“widespread dissemination”	$3,500	The METI technology roadmap for production cost of residential cogeneration systems.	2008 [53]
SOFC	Japan	2015	50,000 p.a.	$4,000	Target price announced by JX Nippon for the launch of EneFarm-S in Germany.	2012 [76]
		2015	“several thousand” p.a.	$8,500 / kW	The METI technology roadmap for production cost of residential cogeneration systems.	2008 [18, 53]
		2020-2030	“widespread dissemination”	$3,500 / kW		
		–	“mass production”	$5,000	Osaka Gas and Kyocera’s expectation for retail price under full dissemination.	2007 [77]
	Australia	–	“mass production”	$5,500–7,000	Statements from CFCL on the eventual price of the BlueGen when mass produced.	2009 [56, 78]

Table 4: Expectations and targets given by the manufacturers and government bodies involved with world-leading fuel cell demonstrations.

These projections suggest significant cost reductions in future, but they are substantially higher than the estimates produced from numerous academic and corporate studies (Table 1). A striking feature is that neither the Japanese government, nor the manufacturers of the world’s leading PEMFC or SOFC systems expect prices to fall below $3,500 (¥400,000), even in twenty years’ time. This is almost three times higher than the DOE’s target for 2015.

We can compare these targets with the experience curves derived above, noting that the impact of uncertainty about the speed of learning is profound. Figure 4 demonstrates how many systems would need to be produced to meet various target costs. With the historic average learning rate of 16%, we could expect the millionth system to cost around $10,000. A 3% increase in this learning rate (within the range exhibited by manufacturers so far) would reduce this price to around $8,000.

With a 16% learning rate, the METI target of $3,500 would be reached after 70 million systems had been built. With a learning rate of 19% this cumulative experience falls to 15 million, which is not unreasonable given that markets outside of Japan are now developing rapidly. The US DOE target of

$1,000/kW appears simply unfeasible; 10 billion systems would have to be produced at a learning rate of 16%, or 1 billion with a 19% rate. For the DOE's target to be reached after a more modest 10 million systems had been produced, not only would the market have to double in size every year until 2020, the learning rate must also double from current levels to 29.4%.

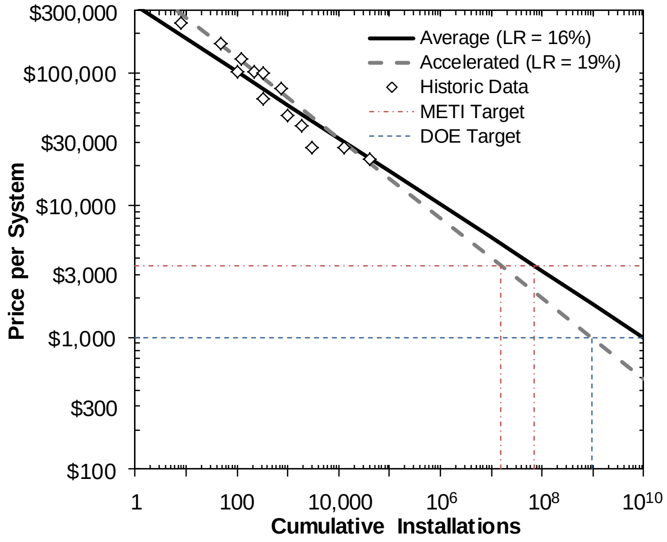

Figure 4: Learning curves projected forwards to 10 billion units, plotted against horizontal cost targets.

5 Reconciling the differences

The near-term government targets and academic estimates presented in Section 3 appear very different from the current commercial situation described in Section 4. We believe that this is because the targets and cost estimates presented in Section 3 are not representative of actual prices paid because their scope does not include all of the components required for a complete micro-CHP system.

The systems being sold in Japan have no hidden extras, for they contain everything required to operate successfully in the home, except for installation labour. In fact, all pre-commercial and retail micro-CHP systems include an auxiliary boiler, hot water tank, 'intelligent' system controller, remote feedback systems for the user, and internet based communications for the manufacturer.[2] While none of these components are essential, functionality would be seriously inhibited without them.

The DOE state that their targets are for a complete system, including "all necessary components" for fuel processing, power conditioning and thermal management [9]. Similarly, most of the bottom-up estimates in Table 1 consider these sub-systems as well as just the stack. However, by focussing only on the fuel cell stack and other major systems, these estimates do not give the total cost to the consumer. Much of the cost comes from relatively simple, but numerous mass-produced components for which substantial cost reductions are not possible.

5.1 Estimated Breakdown of Manufacturing Costs

To look at the effect of scope on target costs, we need to know how the price of today's micro-CHP systems breaks down. Very few manufacturers are willing to give a breakdown of their current prices into components, materials, manufacturing, overhead and other costs (let alone profit margin), due to obvious commercial sensitivities. Only two examples from the last decade can be inferred from

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[2] Examples of this include EneFarm [79], Baxi [80], and CFCL [81].

publicly available information, both showing that a fuel cell running on hydrogen forms only 20% of the total cost:

- Between 2002 and 2004, hydrogen-fuelled Plug Power GenSys systems sold for $15,000, whereas natural-gas fuelled CHP systems cost $65,000 ($55–75,000 range) [82].
- In 2003, Ballard sold bare OEM PEMFC stacks for ¥1M and Nexa stacks (with enough peripheral equipment to be useable) for ¥2.5M, while the Ebara-Ballard complete micro-CHP system was priced at over ¥12.5M [83].

One approximation to current manufacturing cost was found in a forward-looking cost estimate produced in 2004 by the group of EneFarm manufacturers. This was made at a time when systems retailed for $100,000, and considered the reductions that could be made by up-scaling production volume to 10,000 units per year. A more recent cost breakdown is being produced by Strategic Analysis (formerly Directed Technologies) [28, 29]. They consider the production of PEMFC and SOFC CHP systems from 1 to 100 kW, with present-day technologies and production processes scaled up to volumes of 50,000 systems per year.

Figure 5 compares these estimates of the manufacturing cost of the main generator unit, which includes the major systems integral to the fuel cell, but not the auxiliary boiler and hot water storage. In both cases, the balance of plant consisted of “the components needed to make the main systems work together”, namely pumps, valves, mass-flow meters, filters, hydrogen regulators, hydrogen sensors, ejectors, pipe-work and structural elements.

One factor stands out clearly in both sources: it is the seemingly trivial balance of plant, rather than the platinum-filled stack and major sub-systems, that contributes the majority of the cost. Other cost breakdowns for larger-scale industrial CHP systems concur that the stack, fuel processor and power conversion only account for around half of the total fuel cell system cost (excluding thermal backup and storage) [12, 84].

There are upwards of 1,000–2,000 components in a complete PEMFC system and 200–600 in an SOFC, with major elements of the balance of plant including 30+ each of valves, pumps, blowers and sensors, plus extensive pipe-work [85, 86]. The IEA remark that there is a lack of suppliers of these components, and they have little incentive for reducing costs [12].

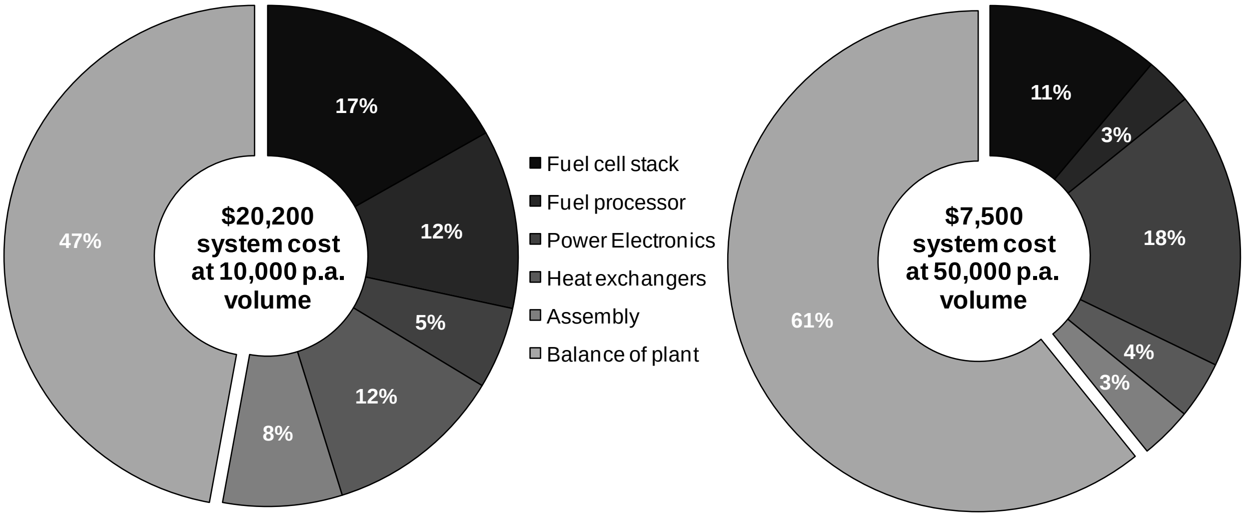

Figure 5: The breakdown of the projected manufacturing cost of EneFarm-type systems, made by the five active manufacturers in 2004 (left), and Strategic Analysis Inc. in 2011 (right). Adapted from [28, 73].

Most cost estimates do not ascribe much importance to these components, as they are thought to be reasonably generic and trivial in comparison to the major systems. However, the significant cost shares in Figure 5 given to ancillary components are “felt to reflect the significant cost contribution of multiple minor components” [24]. If there is little scope for learning in the production and use of generic, minor, components, this could adversely affect the pace of future cost reductions.

5.2 Implications for experience curves

The standard methodology for deriving an experience curve produces a line which is linear when drawn on a double-log scale. Jamasb and Köhler point out that cost reductions often come from a combination of formal Research and Development and informal learning-by-doing, and that studies should therefore attempt to capture these separate effects [87]. This would be particularly relevant for a radically new technology, subject to large amounts of R&D spending, such as the fuel cells we study here. Unfortunately, we have no suitable data on private R&D spending, and so cannot pursue this line of enquiry.

The data presented in Figure 5 do allow another alternative to be explored. While the estimates are not strictly compatible, we note that while the cost of the fuel cell stack and other major components falls by nearly three-quarters (from $10,700 to $2,925) between the two pie charts, the cost of the balance of plant falls by just over one-half (from $9,500 to $4575). This suggests that the learning rate for the fuel cell and other major components is significantly higher than for the balance of plant, which is intuitively plausible given the relative immaturity of fuel cells.

Figure 6 presents an exploratory “two-component” experience curve, based on this data. The uppermost dashed line is a linear experience curve for the overall CHP system, based on the learning rate of 16% derived above, and the assumption that a cost of $20,200 would be reached for cumulative sales of 50,000 systems (which is consistent with our Japanese data). The overall learning rate suggests that a system cost of $7,500 would be reached once just under 3 million systems had been produced. These production levels can then be compared with the paired cost estimates for the stack and major sub-systems and for the balance of plant to derive learning rates of 20.5% and 12% respectively. The resulting linear experience curves are the other two broken lines in Figure 6.

The solid line in Figure 6 shows the total system price, derived by adding the two component curves together. It is no longer linear but has a slope that falls as the total number of systems produced increases. This is because the weight placed on the fuel cell (subject to rapid learning) progressively falls as its cost is reduced by that learning. This combined learning rate falls with the log of experience from 19.5% for the first system, to 16% for the 300,000th system, down to 15% for the five-millionth system.

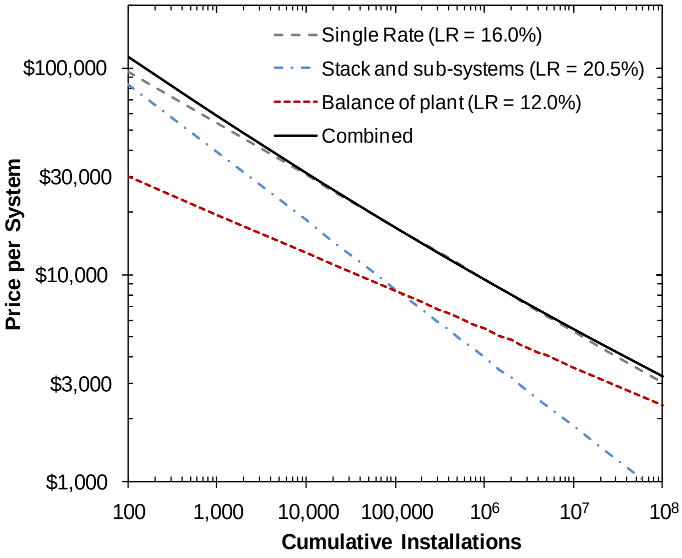

Figure 6: Influence of different learning rates for components on the progression of total system price.

This offers a straightforward explanation for the patterns observed in Section 4. The experience curve derived in Section 4.2.1 has a lower learning rate than our earlier estimate [13], reflecting the tendency for the slope of the two-component curve to fall as output rises.[3] The uppermost data point in Figure 2 lies above the revised experience curve, which is linear, but it would be possible to draw a non-linear curve that passed through all the data. The learning rate estimated for Korea in Section 4.2.2 is higher than that for Japan, but shows systems at an earlier stage of development and is close to our previous estimate for Japan. Although our anonymous data is also for systems at a relatively early stage of development, its relatively low learning rate might be sensitive to the limited amount of data we have from this source.

5.3 Estimated Bottom Line Cost for Systems

Bearing these ancillary costs in mind, it is useful to think what the minimum possible cost for a fuel cell micro-CHP system could be. The scope of different studies can be compared to help explain why such discrepancies exist between different estimates and targets. By revising the definition of "complete system" used in the studies listed in Table 1, it is possible to produce a bottom-line target cost that is more consistent with what consumers could actually expect to pay. Table 5 gives a comparison of the different groups of studies, highlighting the differences in scope and the importance of the components not included in those studies that suggest the lowest costs.

The lower end of the stack and sub-system costs presented in the literature comes to $800. The auxiliary boiler and heat storage, which are not considered in most studies, add considerably to this cost at around $1,500 together.[4] Taking the long-term METI and KOGAS targets as the minimum total cost, the balance of plant could be expected to cost $1,000–2,000 at a minimum.

The resulting ratio of costs for the main generator is 9% stack, 26% sub-systems and 65% balance of plant. This has a lower share of stack costs than the EneFarm manufacturers' prediction (18%), and the Strategic Analysis prediction (12%), as could be expected if the stack has a higher learning rate than the balance of plant.

	Potential Minimum	**Other literature sources**	**EneFarm manufacturers**	**Directed Technologies / Strategic Analysis**	**METI Target (2020–2030)**	**KOGAS Target (2020–2030)**	**DOE Target (2020)**
Fuel cell stack	$200	$200–500	$3,400	$725	$3,500	$3,000–5,000	$1,000
Major sub-systems	$600	$600–1,200	$5,700	$1,600			
Balance of plant	$1,500	–	$9,500	$3,900			
Auxiliary boiler	$1,000	–	–	–			–
Hot water tank	$500	–	–	–			–

Table 5: Potential minimum costs for manufacturing each component of a fuel cell micro-CHP system at high volume, with a comparison to other cost estimates and targets.

On reviewing Table 5 it is obvious why it is unreasonable to expect that a complete fuel cell CHP system could ever be bought for $1,000 – the boiler and hot water tank which are necessary components of this system cost more than that alone. The DOE include "other equipment for heat rejection to [water and space heating systems]", but neglect the systems themselves, assuming they will not be integrated into the fuel cell [9]. Most domestic fuel cells are packaged as 'complete home solutions' and so come integrated with a boiler and hot water tank in order to maximise efficiency and operate correctly with the fuel cell. While it should, in theory, be possible for a fuel cell system to be retrofitted into an existing heating system, this has led to major operational problems in the past [89].

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[3] Our earlier estimate was also affected by the timing of the 2009 price reduction, as argued above.

[4] Wholesale costs for gas furnaces in the US typically range from $1,000–3,000, and similarly condensing gas boilers in the UK retail for $1,000–1,500 (not including installation) [88]. Hot water cylinders holding 100–300 L (as typically used in fuel cell systems) are available from around $500 wholesale.

The DOE target, covering just the fuel cell generator can therefore be thought of as the incremental cost of buying a fuel cell system. For consumers faced in 2020 with having to replace their heating system, the choice may be between a $1,500 conventional system, and a $1,500 boiler and tank integrated with a $1,000–2,000 fuel cell system.

We believe this incremental cost is likely to be closer to $2,000 as suggested by the METI target and other cost breakdowns; however, the important point is that it is the extra cost on top of a conventional system, and not the total price that consumers could expect to pay. Consumers would also have to pay for any additional installation costs – connecting the fuel cell system to the gas supply and domestic heating pipes might not cost any more than with a condensing boiler, but there would also be some electrical work before the fuel cell could safely be connected to the house and thus the wider electricity network. Conversely, earlier fears about the limited life of fuel cells and the possibility that it might be necessary to replace the fuel cell system before the balance of plant [26] seem less pertinent in the light of recent lifetime figures [43].

6 Discussion

An open question that remains is whether the projected future prices for entire systems are consistent with commercial success. Current technologies may not be sufficient to access mass markets; however, there may be alternative approaches that could shift the development of these systems on to new experience curves at lower cost levels than those seen to date [30].

One possible answer is system simplification, which is evident from the latest round of press releases from the Japanese EneFarm manufacturers:

- Toshiba claims to have reduced costs by 30% between 2009 and 2012 by reducing the number of cells by 15%, the amount of platinum by 20%, and particularly the number of BoP components by 40% [44].
- Eneos have made their system 40% smaller due to system simplification [42].
- Panasonic reduced the size of core system components by 30–40%, the total number of system components by 30%, and the weight by 20% [43].

This demonstrates some of the incremental progress that has been made in increasing power density (and thus reducing the number, and cost, of cells), reducing platinum loadings and optimising the design of the balance of plant. These gradual improvements are captured within the historic learning rate though, and so the learning curve methodology assumes that such progress will continue to be made in the future.

Jumping on to a lower learning curve implies a step-change reduction in costs, which will require a radical overhaul of the entire system. This change may well be driven by cell-level improvements that allow entire sub-systems, such as the fuel processor or humidification, to be removed [30].

6.1 Remove the Reformer

Strategic Analysis estimate that 80% of the balance of plant cost is due to the fuel processor [29], so removing this system in particular would have the greatest impact – halving total system costs.

Much of the interest in SOFC based systems is their greater tolerance to fuels. Direct internal reforming fuel cells (DIR-SOFC) can run directly on methane, and so only require a desulphurising unit to run on natural gas with current odorants [91]. Further research into alternative odorants that are not deleterious to catalysts could eliminate even this stage.

For PEMFC systems, this would require a move away from platinum and noble catalysts entirely. Recent work has therefore focussed on supported metal catalysts, and on platinum-free liquid anodes and cathodes, which can simultaneously lower material costs, achieve reactant humidification and improve fuel tolerance [92].

A second option is to directly supply the fuel cells with hydrogen, rather than converting it on-site in an expensive and complex chemical reactor. Interest in centralised hydrogen production is growing, and thousands of kilometres of pipeline exist across Europe and the US [93, 94]. The obvious barrier to extending this 'hydrogen economy' is the cost of developing infrastructure. However, if networks of hydrogen production and distribution are developed to stimulate and then serve hydrogen vehicles, it could be possible for domestic customers to piggy-back on that development, eliminating the need for thousands of dollars of equipment per household.

A benefit of centralised production would be the opportunity to fit carbon capture and storage (CCS) equipment to large methane reforming plants. This is the most promising way for fuel cell CHP to move from being lower carbon than current heating and power systems to being a truly zero- or negative-carbon option. Decentralised hydrogen production from electrolysis at times of surplus wind generation has been discussed, but is unlikely to produce large amounts of low-cost hydrogen [95].

If the fuel processor cannot be removed, it could instead be utilised better. The Honda Home Energy Station demonstrated this concept [96], producing hydrogen for both a domestic CHP system and a Honda Clarity fuel cell vehicle (FCV). With the potential to produce hydrogen fuel at the equivalent of $0.90 per gallon with current natural gas prices ($10/GJ)[5], the additional cost of the fuel processor becomes less of an obstacle.

6.2 Collaboration

Greater cooperation between manufacturers could also accelerate the rate of price reductions. EneFarm is the culmination of over a decade of collaborative research and demonstration by Japanese fuel cell manufacturers and energy distribution companies. Extended cooperation was born from the realisation that the problems that had to be overcome were too great for any one company to achieve alone.

System manufacturers decided on, and then published specifications for standardised balance of plant (BoP), which component suppliers then openly competed to develop and sell [86]. This collaborative strategy almost attained a four-fold decrease in balance of plant costs in just two years, whilst improving durability and readying the whole supply-chain for mass production [85].

7 Conclusions

This paper collates past estimates, current data and future targets for the price of domestic fuel cell CHP systems. We analyse price data from Europe, Japan and South Korea, and demonstrate that regardless of the manufacturer, PEMFC prices tend to converge on $30,000 once 10,000 systems have been built. Over the past eight years, these prices have fallen at an average rate of 16% per doubling of capacity.

It appears as though this rate of reduction is higher during the early demonstration and commercialisation phases, then decreases as systems become more mature. This could be caused by higher levels of learning due to research and development in the early years of the product lifecycle, or because the fuel cell stack, with a higher learning rate, initially forms a high proportion of the system

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[5] Assuming 70% reformer efficiency this gives $14.29 per GJ of hydrogen, or $1.77 for the energy equivalent of one US gallon of gasoline. FCVs typically exhibit double the fuel economy of gasoline vehicles, giving half the cost per mile.

cost, which learning reduces over time. An estimated learning rate of 20.5% for the fuel cell stack and 12% for generic balance-of-plant components would be consistent with the declining learning rates seen for Japanese EneFarm systems.

In light of this information, we conclude that the US Department of Energy's targets of $1,200/kW by 2015 and $1,000/kW by 2020 are simply untenable. Economies of scale cannot be relied upon solely to reduce system prices to these extremely low levels. To reach $1,000 per system, the domestic fuel cell market must quadruple in size year-on-year so that ten billion fuel cells have been produced by 2020. If learning rates gradually decline from 16%, this number would be still higher.

These targets do not include all the elements of a complete "home-enegy" system, and thus do not reflect the design of nearly every domestic fuel cell microgeneration system sold to date. We also believe they underestimate the complexity of the balance of plant required for system integration and safe, reliable operation in the home. To quote the US Energy Information Administration: "differences in practices regarding the inclusion or exclusion of various components of costs can have a large impact on overall cost estimates" [90].

By including all the necessary components of a domestic system (including an auxiliary boiler and hot water storage tank) the DOE target more than doubles, becoming closer to the Japanese government's target of $3,500 by 2020–2030. Learning alone can more easily attain a $3,500 target, requiring fuel cells to be adopted by a more reasonable 70 million households – around 10% penetration in Europe, Japan, South Korea and the US.

Incremental learning is not the only route to cost reduction. Several promising developments in cell design and system simplification are discussed, which present the opportunity for the technology to leap-frog onto a lower learning-curve and achieve these levels of cost at an earlier date. Together, these initiatives give us confidence that the cost of future fuel cell CHP systems can be reduced to a level where they form a commercially competitive part of a lower-carbon energy system.

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