Title

Analysis of Fuel Cell Markets in Japan and the US: Experience Curve Development and Cost Reduction Disaggregation:

Permalink

https://escholarship.org/uc/item/76v216d1

Authors

Wei, Max
Smith, Sarah J.
Sohn, Michael D.

Publication Date

2016-07-15

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

Analysis of Fuel Cell Markets in Japan and the US: Experience Curve Development and Cost Reduction Disaggregation

Max Wei, Sarah J. Smith, Michael D. Sohn

Energy Technologies Area

July, 2016

This work was funded by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, and conducted at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231.

DISCLAIMER

Analysis of Fuel Cell Markets in Japan and the US: Experience Curve Development and Cost Reduction Disaggregation

Max Wei, Sarah. J. Smith, Michael D.Sohn
Lawrence Berkeley National Laboratory
July 15, 2016

Abstract: Fuel cells are both a longstanding and emerging technology for stationary and transportation applications, and their future use will likely be critical for the deep decarbonization of global energy systems. As we look into future applications, a key challenge for policy-makers and technology market forecasters who seek to track and/or accelerate their market adoption is the ability to forecast market costs of the fuel cells as technology innovations are incorporated into market products. Specifically, there is a need to estimate technology learning rates, which are rates of cost reduction versus production volume. Unfortunately, no literature exists for forecasting future learning rates for fuel cells. In this paper, we look retrospectively to estimate learning rates for two fuel cell deployment programs: (1) the micro-combined heat and power (CHP) program in Japan, and (2) the Self-Generation Incentive Program (SGIP) in California. These two examples have a relatively broad set of historical market data and thus provide an informative and international comparison of distinct fuel cell technologies and government deployment programs. We develop a generalized procedure for disaggregating experience-curve cost-reductions in order to disaggregate the Japanese fuel cell micro-CHP market into its constituent components, and we derive and present a range of learning rates that may explain observed market trends. Finally, we explore the differences in the technology development ecosystem and market conditions that may have contributed to the observed differences in cost reduction and draw policy observations for the market adoption of future fuel cell technologies. The scientific and policy contributions of this paper are the first comparative experience curve analysis of past fuel cell technologies in two distinct markets, and the first quantitative comparison of a detailed cost model of fuel cell systems with actual market data. The resulting approach is applicable to analyzing other fuel cell markets and other energy-related technologies, and highlights the data needed for cost modeling and quantitative assessment of key cost reduction components.

Keywords: PEM fuel cells, solid oxide fuel cells, combined heat and power systems, technology learning rates, experience curves, technology deployment programs

1. Introduction to Fuel Cells in Stationary Applications

Fuel cell (FC) systems are being considered for a range of stationary and specialty transport applications due to their ability to provide reliable power with cleaner direct emissions profiles than fossil fuel combustion-based systems. Existing and emerging applications include primary and backup power, combined heat and power (CHP), materials handling equipment (MHE) such as forklifts and airport handling equipment, and auxiliary power applications such as auxiliary power units in diesel truck cabins. As a chemical energy conversion process, fuel cells have intrinsically higher efficiency and much lower criteria pollutant emissions than coal or gas combustion-based plants [1]. Stationary applications are also less constrained to the weight and size limitations of vehicles. In addition, fuel cells can serve as a reliable source of base load power in comparison to intermittent wind or solar photovoltaic supply sources. If fuel cells become widely available they could help to displace coal plants and improve public health outcomes due to the elimination of coal-fired air pollutants such as fine particulate matter, and they might also displace nuclear plants and avert the disposal issues associated with nuclear waste. Fuel cell systems also can qualify as distributed generation systems and as power supply sources close to load, they may not trigger transmission line construction or line losses.

Stationary fuel cell systems are not deployed in high volumes today due to a number of reasons that limit the market adoption of new technologies. In particular, market adoption of FC systems is constrained by their high initial capital costs and durability issues[1]. If FC lifetime is not proven in demonstration programs, for example, potential owners such as commercial building operators are not likely to invest. Similarly, if FC equipment is demonstrated to have equivalent to better lifetime than incumbent technology, but with much higher capital cost, market adoption will be low in the absence of other incentive programs.

The ultimate vision of a hydrogen economy -- where H_2 is produced renewably and fed into a fuel cell which produces no emissions -- is constrained by the above fuel cell system cost and reliability constraints, the cost and efficiency issues of generating renewable hydrogen, and the cost and infrastructure of storing and transporting hydrogen with the equivalent availability and convenience of existing fuel or energy carrier types. Currently, H_2 is predominantly produced from converting natural gas to H_2 using steam methane reforming, a process which results in greenhouse gas emissions.

The U.S. Department of Energy (DOE) has historically invested in fuel cell technology development and deployment of FC systems (e.g. roughly $95 million in fiscal year 2015), with recent reported success in the material handling and backup power segments, and there continues to be support from the federal government in terms of federal tax credits for stationary FC power systems.[2] At the state level, there are various state incentive programs such as the Self-Generation Incentive Program in California (SGIP) which provides performance-based incentives for facilities that install qualifying distributed power and heating technologies such as fuel cells.[3] Internationally, fuel cell development is progressing in many countries including Japan, Europe, and Australia. International deployment programs include renewable portfolio standards in South Korea that include fuel cells with renewable biogas and

---

[1] See for example, the U.S. Department of Energy's (DOE) Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, Section 3.4.4 at **http://energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf** accessed 1 June, 2015.

[2] http://energy.gov/savings/business-energy-investment-tax-credit-itc, accessed 10 March 2015.

[3] http://www.cpuc.ca.gov/PUC/energy/DistGen/sgip/, accessed 10 March 2015.

CHP targets in Germany that include fuel cell CHP systems.[4] The nuclear accident at Fukushima in Japan has increased concerns about nuclear power plant safety and long term viability and is another driving force for the greater deployment of non-nuclear low carbon energy sources and low-carbon distributed generation.

Globally, fuel cell shipments have grown at 15% by MW and 37% by unit per year from 2009-2014, led by the stationary sector which shipped over 80% of the units in 2014 [2]. About two-thirds of MW shipped in 2014 were in Asia, led by Japan, with about 30% of total MW shipped to North America. Solid oxide fuel cell (SOFC) MW shipments have increased from 1.1 MW in 2009 to 32.3 MW in 2014 with molten-carbonate fuel cells (MCFC) growing from 18 MW to 70 MW. Currently, the transportation market is a very small fraction of the overall fuel cell market, but that may shift if fuel cell vehicles continue to be introduced and are more widely adopted. Toyota introduced a fuel cell passenger vehicle in November 2014 and Honda in March 2016.

1.1 Technology Learning

Technology learning is widely recognized as a mechanism through which technology costs reductions can occur, a concept originating from observations that manufacturing processes improve as production increases [3]. This has important implications for understanding past technology developments and program benefits, as well as forecasting technology growth for policy planning and scenario modeling. Thus as federal and state governments make investment and policy decision in energy technology research, development, and deployment[5], the learning rate of FC systems and technologies are important as a factor for projecting future technology costs and technology adoption. For example, assuming a certain learning rate for the future defines the market adoption that is needed to meet a certain cost target and an appropriate incentive structure. Making an erroneous learning rate assumption that is too

---

[4] See for example, http://www.fuelcellenergy.com/applications/financial-incentives/international-incentives/, accessed 1 June 2015.

[5] Deployment programs here refer to a broad range of programs, from education and awareness programs, to financial incentive programs, to design competitions, to federal testing and performance standards.

conservative (or too aggressive) could lead to an inefficient policy that is too generous (or insufficient) to meet the policy target.

Experience curves are the most common framework for assessing technology learning and cost reduction with increasing production volume [4]. These curves are found, empirically, to follow a power law as shown in Equation 1, with the rate of cost reduction a power law function of cumulative production volume.

Equation 1. $C(t_2)/C(t_1) = (V(t_2)/V(t_1))^{-b}$

Where:

$C(t_2)$ = cost at time t_2

$C(t_1)$ = cost at time t_1

$V(t_2)$ = cumulative production volume at time t_2

$V(t_1)$ = cumulative production volume at time t_1

b = empirically observed parameter

The percent by which cost decreases for every doubling of production is referred to as the learning rate ($LR = 1-2^{-b}$), while the fraction of initial cost remaining after every doubling of production is defined as the progress ratio (PR=1-LR).

Market prices are often utilized as a proxy for a product's manufactured costs since market prices are more directly observable than manufacturing costs. However, prices can mask the cost structure of a product and introduce uncertainties in the product's technology learning due to pricing and market effects. Despite these caveats, market prices are often used for experience curve analyses.

1.2 Fuel Cell Experience Curves

Historic examples of fuel cell experience curves have limited production volume and time series data. Rivera-Tinoco et al. [5] find early commercial learning rate for solid oxide fuel cells (SOFC) slowing down to a learning rate of 5% in the early commercial phase from an apparent 44% learning rate in the pilot phase. Schoots et al. [6] find that proton exchange membrane fuel cells (PEM) in transportation have a learning rate of 21% for a global cumulative capacity of 100 MW, but this only represents on the order of a few thousand vehicles (e.g., 100 kW * 1000 units = 100 MW for Toyota Mirai fuel cell vehicle at 114 kW peak power).

Staffell and Green [7] examine the learning rate of the Japan micro-CHP market from initial introduction to early commercialization with a learning rate of about 19% in the pilot phase of development and market introduction. Neij [8] notes that many earlier studies utilize experience curves for cost analysis of fuel cells, but most assume a learning rate rather than presenting a historical time series of price data (e.g., [9] and [10]). Thus an updated look at experience curves would be helpful for the latest assessment of fuel cell cost trends using the most recent data for commercialized fuel cell systems.

Earlier work has highlighted the piecewise linear learning rate observed in many energy-related technologies ([11] , [12]) and noted the correlation of deployment programs to downward bends or changes in the learning rate from an initial learning rate prior to the deployment program to a faster learning rate after the deployment program for several energy-related technologies.

In this work, we study learning rates which are observed for early commercial or commercial fuel cell systems for Japanese micro-CHP and in California under the state's Self-Generation Incentive Program. We describe the empiricall- observed learning rates and compare the policy and external environments for both cases. An approach for disaggregating the observed cost reduction in the micro-CHP case is described and analysis results presented. Finally, we discuss general observations and pertinent policy lessons from the two case studies along with how the cost reduction disaggregation analysis can be generalized to other technologies.

2. Japan's Micro-CHP program and the California SGIP Program

In this section we highlight some of the key similarities and differences in the two regions' fuel cell programs. We discuss the implications of these findings together with the empirically derived cost reduction results in the Discussion section below.

Table 1. Japan's Micro-CHP program and the California SGIP

Case	**Japan Ene-farm**	**California SGIP**
Companies	Toshiba, Panasonic, AISIN	Bloom Energy, Fuel Cell Energy, Doosan (formerly ClearEdge Power/UTC Power)
Company Type	Large diverse	Dedicated FC (BE and FCE), Large diverse (Doosan)
System Application	Residential micro-CHP	Commercial power
System Size	0.7-1 kW	200-500 kW
Incumbent Energy Source Costs	\$0.26/kWh, Japan residential \$1.08/therm LNG import price	\$0.11/ kWh, U.S. commercial \$0.447/therm NG city gate price
Incentive Structure	Decreasing over time (\$12000 per system to \$3300 from 2009-2014)	Decreasing by 10% annually (currently \$1830/kW), plus 30% Federal tax credit
Long Term Target	\$5000/unit[a] and 5.3M units in 2030; 1.4M units in 2020 (Japan Government) [13]	\$1300/kW in 2020 (U.S. DOE)

NG = natural gas; LNG = liquefied natural gas; DOE = Department of Energy

[a] Total price to consumer, including delivery and installation

Both case studys produce systems with fuel cells as an energy provider and in both cases there were initially generous subsidies from the government, which are now declining. Comparison of the two programs shows marked differences in many areas: markets, energy prices, development models, and environmental and exogenous factors. The role and stated goals of the government are more directed and specified in Japan with a target annual volume in 2020 and 2030; whereas the U.S. policy is to provide incentives to offset higher capital costs without a policy mandate to install a specified target number of units nationwide by a certain date.

Joint development in Japan is organized by several organizations such as the New Energy and Industrial Technology Development Organization (NEDO), the Fuel Cell Commercialization Conference in Japan (FCCJ), and governmental organizations. Additionally, the Advanced Co-generation and Energy Utilization Center Japan (ACEJ) works to advance Ene-farm sales and maintenance activities through publications and training programs. Under this arrangement, joint development is conducted by city gas companies, LPG companies, and industrial partners including Toshiba Fuel Cell Power Systems, Aisin Seiki, and Panasonic [14]. In contrast, U.S. development is more confined within single companies such as Bloom Energy and Fuel Cell Energy. For a given market, there are more players and a more competitive environment in Japan whereas there are fewer players in stationary power market segments in the U.S. For example, Bloom Energy is virtually the only supplier for medium sized commercial markets from 100 to 350 kW, with the Doosan phosphoric-acid fuel cell (PAFC) system starting at 400 kW.

Both U.S. and Japan develop multiple fuel cell technologies. The Ene-farm program has both PEM (Toshiba, Panasonic) and SOFC (Aisin Seiki) market entrants with PEM capturing most of the market share at present. In the U.S., the mid-sized commercial market is represented by SOFC (Bloom Energy), phosphoric acid fuel cells (Doosan), and molten-carbonate fuel cell systems at the MW-sizes.

The Japan Ene-farm product features a much smaller fuel cell power level than the fuel cell systems in the California SGIP – almost two orders of magnitude smaller at the nominal 0.7-1 kW power level. The Japan Ene-farm project is based on PEM fuel cell technology for the largest players (Toshiba and Panasonic) and SOFC technology for other vendors including Aisin Seiki. The California SGIP is also open to different fuel cell technologies, but current technology entrants are dominated by SOFC technology, followed by molten-carbonate (MCFC) and PAFC technology.[6]

Distributed generation systems are more economically favorable in regions with high prices for electricity purchased from the grid and relatively low natural gas prices. The cost difference between the price of electricity and the cost of natural gas, or spark spread,[7] is about twice as high in Japan for both sectors as it is in the U.S. as Japan has a much higher cost of electricity compared to the U.S. for both residential and commercial sectors.

There is also a significant difference in the types of companies producing fuel cells in the two regions. In Japan, large, diverse and presumably more stable companies such as Toshiba and Panasonic only receive a tiny fraction of annual total revenue from annual sales from micro-CHP, whereas U.S.

---

[6] The following website has a map of California fuel-cell installations: http://www.nfcrc.uci.edu/3/FUEL_CELL_INFORMATION/CALIFORNIA_INSTALLATIONS/index.aspx

[7] More exactly, the spark spread is defined by the following equation: Spark spread ($/MWh) = power price ($/MWh) – [natural gas price ($/mmBtu) * heat rate (mmBtu/MWh)], where the heat rate for a natural gas combined cycle gas plants is typically at 7000Btu/kWh, or a conversion efficiency of about 50%.

companies such as Bloom Energy and Fuel Cell Energy are dedicated fuel cell companies. UTC Power in the U.S. was a part of a large conglomerate United Technologies, but was sold to ClearEdge in 2013 (which subsequently filed for bankruptcy in 2014 and was purchased by Korean conglomerate Doosan).

3. Data Collection and Cost Reduction Disaggregation Approach

Data from California's SGIP program is drawn from a publically available database of information managed by the California Center for Sustainable Energy.[8] Cost data from this database represents total eligible system costs and thus includes non-fuel cell "balance of plant" or "balance of system" costs such as power electronics and air handling subsystems as well as installation costs. SGIP installed costs included systems that have been approved and/or constructed and are split into technology type (SOFC, PEM, PAFC, or MCFC). Data for fuel cell micro-CHP in Japan is drawn from market sources and publicly reported cost data from fuel cell-related websites and from technical conferences and trade shows.

In disaggregating experience curves and cost reduction, contributions from economies of scale, product design improvements, learning by doing, and competition are expected. The approach for disaggregating cost reductions is as follows and is depicted in Figure 1:

1. Determine learning rate from experience curve constructed with annual sales and price data.
2. Develop a manufacturing cost model or adopt an adjacent technology cost model, describing
   a. Manufacturing cost versus annual production volume
   b. Manufacturing cost dependence on critical materials
   c. Product performance specifications and/or parametric relationships with cost
3. Obtain knowledge of number of manufacturers and manufacturing volumes over time. From this, estimate the increase in production volume as an input to manufacturing cost model.
4. Obtain information on product design. From this estimate changes in product materials, configuration, and/or layout as inputs to the manufacturing cost model.

Key steps are thus determining the increase in manufacturing volume from year 1 to year N and translating product design, performance, and integration information into cost reductions through material savings, assembly savings, or process impacts on cost model.

---

[8] http://energycenter.org/self-generation-incentive-program/business/document-library, accessed 15 February 2014.

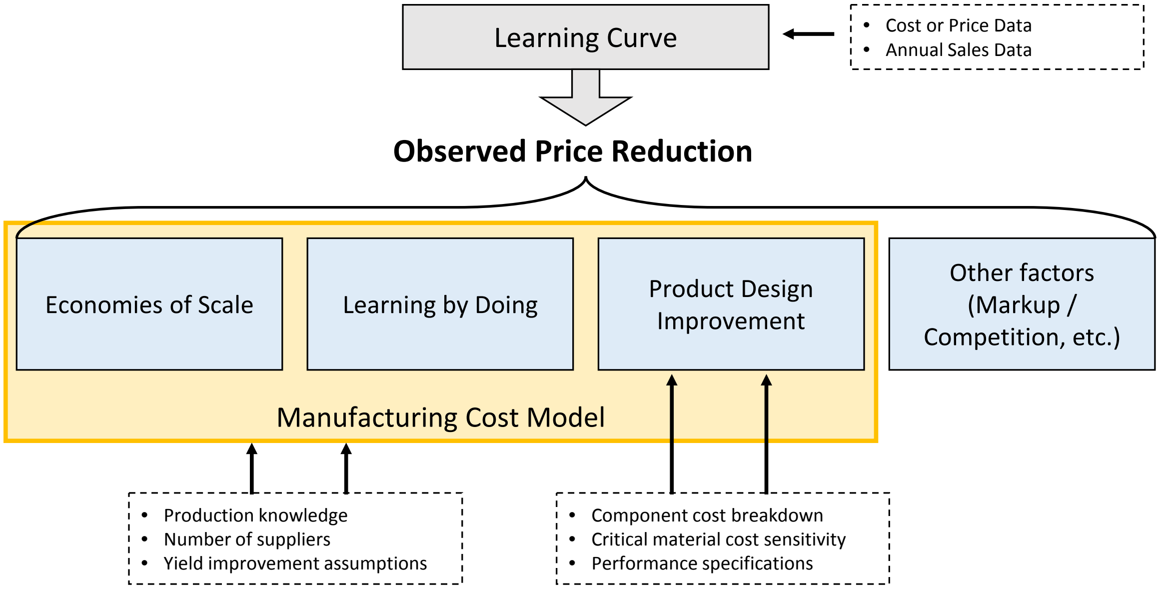


Figure 1. Disaggregating a technology's experience curve price reduction

Figure 1 shows the observed cost reduction disaggregated into economies of scale, learning by doing, and product design improvement. In this case, the remaining cost reduction residual is lumped into "other factors" such as product mark-up and marketplace competition. In practice, "learning-by-doing" -- interpreted here as manufacturing process learning or improvements in factory productivity or factory yield (i.e. the ratio of saleable output to material inputs) over time -- will not be directly observable. One way for accounting for this is as an adjustable parameter in the manufacturing cost model that has the general functional behavior of monotonically improving yield with increased volume of production whose functional dependence may be drawn from other manufacturing technologies.

This approach is predicated on the availability of a manufacturing cost model. The U.S. Department of Energy has sponsored several cost models in the past for a number of technologies (e.g., batteries, LEDs, fuel cells). Disaggregating cost reduction in this way is a bottom-up manufacturing cost modeling approach; an alternative "top-down" approach might focus more on market structure, pricing strategy and pricing power on the supply side. The bottom-up approach is analytically tractable in the sense that it can utilize publically available data such as the cost or cost trends of components installation costs, while other cost factors can be obtained from publically available market reports.

In addition to a suitable manufacturing cost model, this approach assumes the availability of the data sets in Figure 1 that are inside of the dashed boxes. These may include:

- Economies of scale: Production knowledge and number of suppliers are either drawn from publically available data or inferred from market reports.
- Product design improvement: Performance specifications such as product design improvement or performance changes over time are assumed to be publically available. Information about component integration or component cost reductions (e.g., the cost of a power inverter from a third-party supplier) is assumed to be known.

3.1 Annual Production Volume

We model the Japanese market as being served by two primary vendors in the 2009-2013 time frame, Panasonic and Toshiba, who both produce PEM FC systems. These two primary vendors produced about 1,300 units in 2009, increasing to about 15,000 units in 2013. These assumptions are consistent with sources obtained through the U.S. Department of Energy and market reports in the general media.[9]

3.2 Fuel Cell System Cost Modeling Example

The U.S. DOE has supported fuel cell system cost modeling for many years for both stationary [15] and automotive systems [16]. We choose the cost model of Wei et al. for 1 kW systems as a representative cost model for this analysis. This is a bottom-up cost model for CHP fuel cell systems assuming a vertically integrated fuel cell stack manufacturer and largely purchased balance of plant components. Each stack component is modeled starting from equipment costs, and factoring in material, operating costs, and labor costs. Figure 2 shows the output of the modeled direct manufacturing costs of a 1 kW CHP PEM fuel cell system for a fuel cell stack vendor as a function of annual production volume

---

[9] Source for Panasonic production: Communication with DOE, 6 February 2014. Source for Toshiba production: http://fuelcellsworks.com/news/2012/01/24/toshiba-revamps-ene-farm-residential-fuel-cell, accessed 13 November 2014.

and broken down by stack costs, fuel processor costs, and non-fuel processor balance of plant costs (e.g., power inverter, supporting pumps, and auxiliary boiler). The fuel processor is the subsystem that provides hydrogen fuel to the fuel cell stack assuming a natural gas input line. In this case the fuel processor consists of two primary parts: (1) a natural gas purification system and (2) a steam reforming unit to decompose the natural gas into hydrogen fuel.

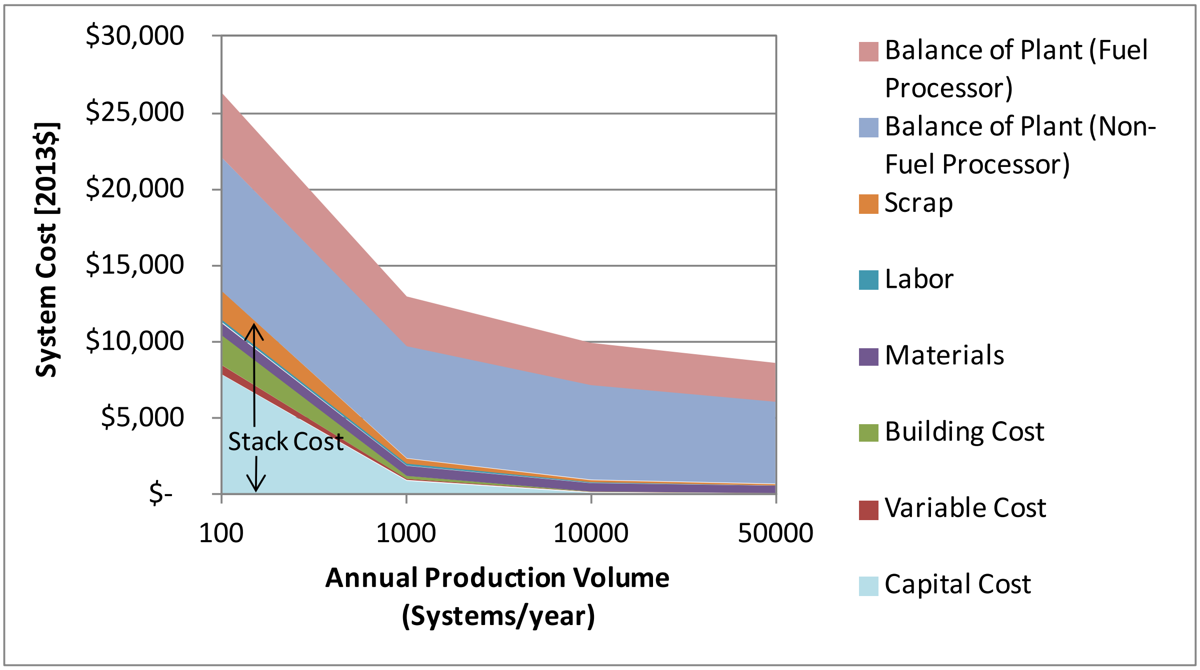


Figure 2. LBNL Direct Cost Model, 1kW CHP system (Wei et al., 2014). Overall system cost is dominated by balance of plant costs above an annual production volume of several hundred units per year. Note that this cost does not include corporate markups (e.g., sales and marketing and profit margin) and installation costs.

This depiction allows the delineation of fuel cell stack manufacturing costs (“Stack Cost” in Figure 2) and non-fuel cell components such as fuel processor and other balance of plant components. At higher production volumes, overall costs shifts from the fuel cell stack to the non-fuel cell stack components. As volume increases, the stack becomes a much smaller component of costs with the assumption that normalized fuel cell stack costs (cost per kW) drop rapidly at higher volumes due to greater tool utilization and learning-by-doing manufacturing improvements such as defect inspection and real-time process control. One reason BOP costs are higher is because they are largely purchased off-theshelf components and a system vendor would pay equipment markups. Over time, BOP integration of components, in-house production, or supplier contract negotiations is expected to reduce these costs.

The largest cost reduction component with increasing annual production volume is the reduction in capital costs. This “economies of scale” is observed due to tool sets achieving a higher rate of utilization, and therefore capital (equipment) costs are amortized over a larger number of annual units. Material costs dominate at higher volume. The largest cost reduction is achieve from increasing annual production from 100 to 1,000 units, but thereafter about 20% cost reduction is achieved for every ten-times increase in annual production volume.

We take as a proxy the Lawrence Berkeley National Laboratory (LBNL) cost model [15]. Actual market price in 2009 was about $34,700 in 2013 U.S dollars (2013$) corresponding to vendor production of about 1,300 units per year, and dropped to $20,000 in 2013 at 15,000 units per year. The cost model estimates a cost of $25,100 per unit at 1,300 units per year. Increasing volume to 15,000 in 2013 reduces the modeled cost by 23% to $19,400 per system. A corporate markup of 100% is assumed to cover general and administrative costs (G&A), sales and marketing costs (S&M) and other costs. Earlier financial analysis of publically-traded fuel cell companies in North America financial statements indicate a corporate markup of 40-50% just for G&A and S&M. Here a larger markup is assumed to account for additional costs such as non-recurring R&D expenses and any product startup costs not accounted for in Figure 2. Both the experience curve data reported and the LBNL cost estimates do not include installation and taxes.

There are several possible reasons the LBNL cost model is lower than the observed market price. The LBNL cost model assumes a high degree of automation at 1,000 units per year and process yield for each stack module of approximately 80%.[10] At lower production volumes, costs may still be high if their

---

[10] An exception to this statement is that the fuel cell stack assembly module yield is assumed to be much higher than 80% since any loss at this step would necessitate scrapping all the value-added steps from other process modules. Overall Process yield is held fixed at the two annual production volumes of 1000 and 10,000 units per year. Actual “learning-by-doing” yield improvements from process learning, improved defect metrology, and real-time process control are expected but not known. However, since the fuel cell stack is in general a much smaller fraction of

production facilities still rely on manual processing and assembly which may drive up cycle times and labor costs and lower process yield. The LBNL cost model was developed assuming a domestic manufacturer and some manufacturing costs are higher in Japan, such as energy costs, although recent costs of labor are reasonably well matched[11] and costs of components may not differ significantly. The fuel cell stack process yield may be lower than that assumed in the LBNL model due to the lack of fully developed and characterized process modules and immature or insensitive defect metrology.

Despite these uncertainties, the shape of the curve is still believed to be representative of economies of scale for a more automated production facility. For example, another cost model for PEM CHP systems funded by the DOE reports 18% cost reduction from 1,000 to 10,000 units [17], similar to the dependence depicted here. The cost modeling approach offers a model of the economies of scale associated with scaling up of production and improved capital utilization, i.e., it isolates the economy of scale factor. Note that the economy of scale cost reduction factor in this case is independent of the corporate markup factor since we are assuming the markup is a constant scaling factor across the range of annual manufacturing volumes.

3.3 Cost reduction from reported product design improvements

Information on product design is used to estimate changes in product materials, configuration, and/or layout as an input to the cost model. Through published reports and conferences, material costs and design integration have been reported from both Toshiba and Panasonic.

For material costs both Toshiba and Panasonic report a 10-15% reduction in number of cells and 20% reduction in platinum (Pt) used.[12] A reduction in the number of cells corresponds to lower Pt content by a proportional amount, so most of the Pt reduction is assumed be achieved from cell count reduction

---

overall system costs than the balance of plant, this yield improvement factor is a not a major contribution to overall costs under these assumptions.

[11] Labor costs are well matched (see http://www.bls.gov/news.release/pdf/ichcc.pdf, accessed 20 March 2015.

[12] http://fuelcellsworks.com/news/2012/01/24/toshiba-revamps-ene-farm-residential-fuel-cell/, accessed 2 December 2014. 12/2/14; and Shimuzu (2015)

rather than reduction in Pt area loading. From the LBNL cost model sensitivity analysis, this translates into about 10% lower stack costs from lower material and assembly costs.

Toshiba reports 40% fewer components through improved design integration, for example the transition from discrete inverter and control board to an integrated inverter and multilayer printed circuit board.[13] We estimate this design integration translates to between 15-25% lower balance of plant costs from process consolidation and lower material costs.

The total cost reduction from cell count reduction and greater balance of plant integration can then be inferred based on the relative mix of costs from the fuel cell stack and balance plant shown in Figure 2. At 15,000 units per year, the fuel cell stack is estimated to be 10% of the total system cost. Total unsubsidized price reduction from 2009-2013 thus is estimated to be 19% from product performance, design improvement, and other factors such as component cost reduction through new or negotiated supplier contracts.

4. Summary of Results

Table 2 has a summary of experience curve learning rates. A learning rate of 12% is observed in Japan for fuel cell micro-CHP versus a fairly flat learning rate for fuel cells systems in California. A learning rate in the range of 0-5% is quoted in Table 2 for three different fuel cell technologies. The average learning rate for the three technologies in Figure 4 is 4.8%, but two of the three technologies (SOFC and PAFC) have a very poor fit and thus a flat learning rate. The relatively flat learning rate in California is consistent with the very low learning rate for early commercial SOFC systems in Europe reported in [5].

The Japan micro-CHP fuel cell system was commercialized in 2009. Since then, over 100,000 units have been delivered with a learning rate of 12%. The experience curve presented in Figure 3 shows the cost reduction from 2009 to 2014 is estimated to be 42%. The main data set is from the FC Expo 2015 technical conference [13].

---

[13] Ibid.

Table 2. Summary of experience curve learning rates for stationary fuel cells considered in this work

Product	Years	Learning Rate from this Work
Stationary Fuel Cells	2001-2014	LR (avg.) ~ 0-5% (California) LR ~12% Japan Micro-CHP 2009-2014

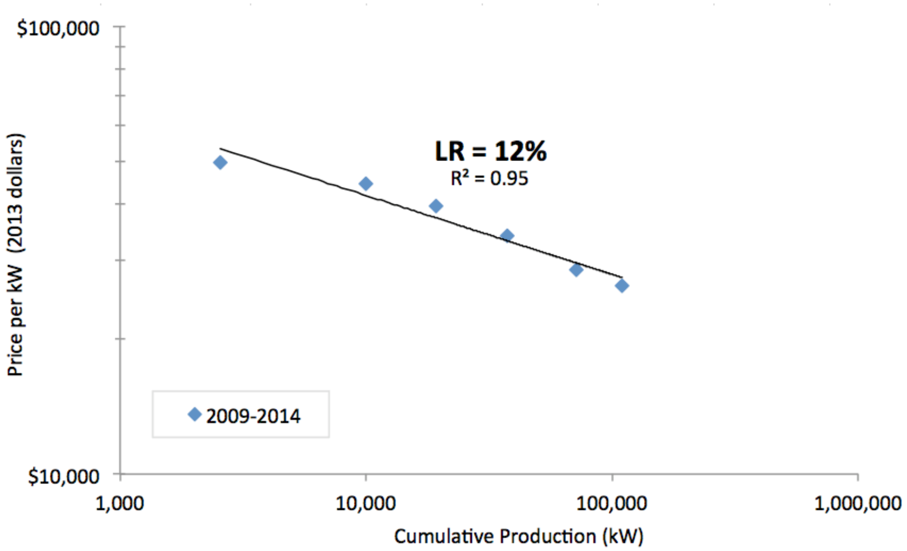


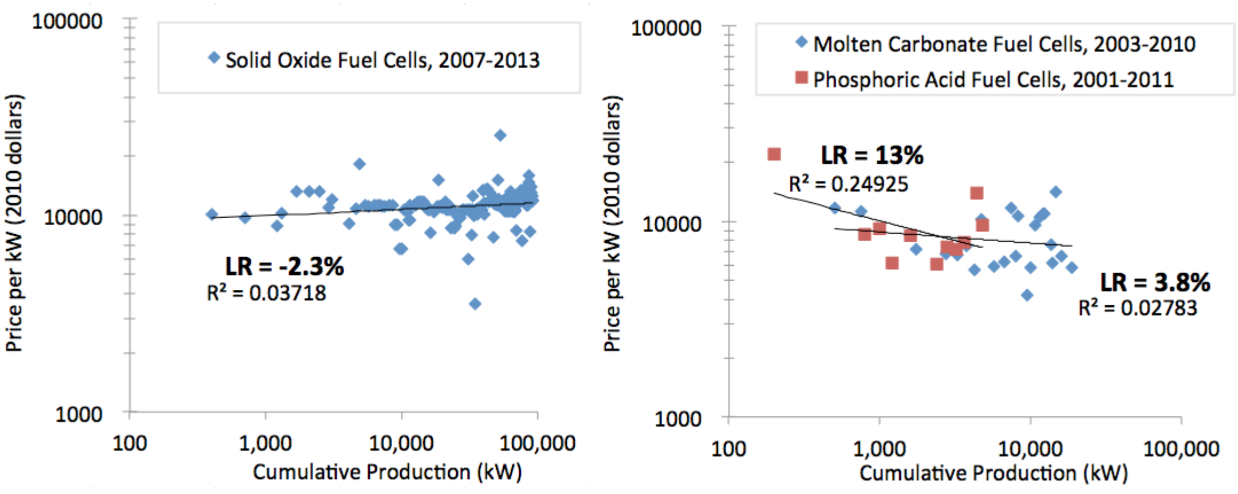
Figure 3. Observed cost reduction for Japan micro-CHP system cost from 2009-2014 ("commercialized product phase). A learning rate of 12% is observed with 42% reduction in cost from 2009 to 2013.

A table of cost reduction disaggregation elements is shown in Table 3. Overall cost reduction from 2009 to 2013 is 42%. System vendor production volume increased by an order of magnitude from approximately 1,300 units per year to about 15,000 units per year and is estimated to give 23% cost reduction from economies of scale. Design improvements in fuel cell stack and balance of system components are estimated to contribute about 19% cost reduction as described above. This leaves a residual of 7% for cost reduction of other factors. In other words, most of the observed cost reduction can be explained by economies of scale and product design improvements. Note the savings in Table 3 are not additive but rather represent the relative savings percentage for each element, i.e., the total 42% savings is given by the expression [1 - (1-23%)*(1-19%)*(1-7%)].

Table 3. Summary of cost reduction disaggregation in fuel cell micro-CHP in Japan from 2009-2013.

Years	LR	Cost Reduction (observed)	Manufacturing Cost Model	Est. CR from Economies of Scale	Est. CR from Technology/ Design	Est. CR from Other factors (Margin, competition, etc.)
2009-2014	12%	42%	Low Temperature PEM CHP Direct Manufacturing Cost Model (Wei et al., 2014)	23%	19%	7%

LR = learning rate; CR = cost reduction



(a) (b)

Figure 4. Reported costs of fuel cell total system cost per kW for the California SGIP program for (a) SOFC, and (b) PAFC, and MCFC systems.

The reported costs of fuel cell systems installed in California as reported in the SGIP database[14] is shown in Figure 4. Although the total installed power is comparable to the Japan CHP case (e.g. 100 MW for SOFC), the number of installed units is much lower than the Japanese case because the size per system is much higher (typically 400-700 kW). There is a very low or near zero cost reduction observed in California. (The face-value power-law learning rates for SOFC, PAFC, and MCFC in California, are -2.3%, 12.9%, and 3.8%, respectively, but in all cases the R^2-fit is very low.) Note also that over time, greater performance monitoring and reporting requirements for the SGIP program may have contributed to higher system prices.

---

[14] http://energycenter.org/self-generation-incentive-program/business/document-library, accessed 15 February 2014.

The California SGIP costs represent total system costs that are eligible for the state SGIP incentive and thus includes installation costs in addition to capital costs. These system costs include balance of plant costs such as fuel processor costs, air handling equipment, installation costs permitting costs, and other soft costs. Since there are a range of possible installation sites and installation scenarios, especially for the case of combined heat and power installations, there is an additional source of variation in costs that has not been explored in this work. For example, some sites may have enclosures or pre-poured concrete landing areas, some may have electrical connections in place already, some may be linked to biogas systems, and so on. Normalizing across the range of heterogeneous installation and site-specific factors would require detailed study of each site and was beyond the scope of this work.

The SOFC fuel cell system does not show any cost reduction. The SOFC vendor, Bloom Energy has stated that the fuel cell module is 40 kW[15] and base system size is 200 kW. The cumulative volume of approximately 100 MW thus represents about 500 systems units cumulative production or on the order of hundreds of systems (~20 MW) per year. Bloom currently quotes capital costs of $7000-8000 per kW, so the observed $10,000 per kW installed costs implies that installation costs and other soft costs are 20-30% of the overall cost.

Similarly the PAFC and MCFC reported system costs do not show a discernible cost reduction, with average system costs between $8,000-9,000 per kW. This data set represents a small number of units and both of these technologies are more mature technologies compared to the SOFC case, so it is possible that this data set represents a flat portion of the experience curve. For reference, the near term 2015 DOE target for installed cost with natural gas is $3,000-4,000 per kW.

Both of these plots are segregated by geography, but limiting the micro-CHP data to Japan is warranted because there is miniscule production of fuel cell micro-CHP systems outside of Japan.

---

[15] See for example http://iosrjournals.org/iosr-jece/papers/sicete-volume6/66.pdf, accessed 10 March 2015, and http://www.raabassociates.org/Articles/Fox%20Presentation%20for%20Posting%20after10.26.12%20Roundtable.pdf, accessed 10 March 2015.

California represents over 50% of the fuel cell market in the U.S., so the California SGIP database is a reasonable representation of fuel cell system costs across the U.S.

5. Discussion

Some key considerations and differences in the Japan and California case are described in this section including development, market, technology, and policy factors.

The target annual volume in 2020 and 2030 for Japan's micro CHP provides more "market certainty" in the Japan case, where both fuel cell providers and supply chain vendors can count on a certain overall market volume trend and associated total revenue projection. Additionally, the market for distributed power and CHP systems is more favorable in Japan due to the higher spark spread, which is much larger in Japan as quantified above for residential and commercial markets.

Japan's joint development model may also provide more resources and R&D efficiency, as coordination among participants and perhaps the existence of a national mandate for the number of units would make it more appealing for companies to participate. A deeper understanding of the workings of the joint development model and its benefits and tradeoffs may be needed in future analyses of similar technologies.

The Japan Ene-farm product features a much smaller fuel cell power level than the California case and therefore the relative mix of non-fuel cell balance of plant and fuel-cell stack or fuel cell "hot box" costs differ. Fuel cell stack costs are expected to be a higher component of overall system costs at higher fuel cell power levels, as balance of plant costs are more "amortized" with larger system sizes [14]. If fuel cell stack cost reduction is very difficult, this may allow more nominal cost reduction for smaller fuel cells systems through balance of plant costs reductions such as more integrated design of balance of system components. Other possible differences in cost versus system size are safety measures such as leak detection equipment, but this was not extensively studied in this report. (Both the Japan and U.S. FC systems are currently configured to be outdoors.)

Japanese FC system suppliers are dominated by large, diverse companies such as Panasonic and Toshiba in concert with large utility companies such as Tokyo Gas and Electric Company. An argument could be made that this provides greater resources for more sustained development in Japan, compared to dedicated fuel cell system companies more common in the U.S. The exception to this in the U.S. is UTC Power, a subsidiary of a large, multinational corporation, United Technologies. However, the eventual sale of UTC Power was potentially driven in part is because cost reduction is harder to achieve for larger FC systems as noted above and perhaps UTC Power did not foresee a growing market with no national mandate for sales volume in place as there is in Japan.

Exogenous factors should not be underestimated. The Fukushima nuclear accident in 2011 led to a huge shift in primary energy consumption in Japan away from nuclear power, and fuel cell systems figure prominently in Japan's most recent national energy plan. Before the Great East Japan Earthquake and Tsunami March 2011, nuclear power constituted 28.6% of primary energy in Japan [13]. After the nuclear shutdowns stemming from the nuclear accidents at the Fukushima Nuclear Power Plant complex, nuclear power plunged to only 1.7% of primary energy in Japan in 2012. During this time, the fraction of primary energy from fossil fuels (oil, natural gas, and coal) increased from 62% prior to the tsunami to 88% in 2012. Thus there has been a greater impetus in Japan to develop greater energy efficiency and install more distributed energy systems since this cataclysmic event.

Both the micro-CHP and California FC costs, as system costs, do not necessarily reflect the underlying cost of the fuel cell stack. Therefore, it is possible in the California case that the fuel cell stack has achieved a level of cost reduction that is hidden within the overall system cost. More likely is that U.S. fuel cell manufacturers are seeking to recoup their investment costs and may not have the resources to invest heavily in R&D. Also, there is less competition in the U.S. medium sized commercial power and CHP markets: systems at 100-700 kW can be served by Bloom Energy SOFC (power only) systems; the UTC/Doosan PAFC system is in multiples of 400 kW; and Fuel Cell Energy's MCFC systems are in the MW range, with virtually no other competitors. This marketplace of limited competition provides less of a downward force on pricing and also limits the development of a diverse supply chain. Understanding of the extent to which existing incentives may support prices in a less than competitive environment could benefit from further investigation in the context of designing responsive deployment and incentive programs.

The cost modeling approach is applicable to other technologies, but subject to the availability of a suitable cost model showing cost dependency with production volume, data availability in production volumes over time, and product design and performance information. A rough performance model, either as part of the cost model or as an accompanying model element, is also needed in order to translate reported performance and design improvements to material and manufacturing cost reductions. In the case of the Japan micro-CHP market, all three elements of analysis are available: a readily available cost model, vendor production data, and publically reported system performance and design improvements. In the case of SOFC technology in California, very little information has been available about system design and performance changes over time.

Finally, “learning-by-doing” in terms of process yield and process control is difficult to assess without detailed industry process knowledge and information such as critical defect densities, but follow up research can perhaps gain insights from historical data or modeling from other adjacent industries.

6. Conclusions

The Japan micro-CHP program benefits from several factors such as more favorable market conditions (e.g. higher spark spread), while the recent exogenous shock of the 2011 tsunami has also accelerated the policy and market acceptance of distributed generation and fuel cell systems. The U.S. market is harder to enter due to much less expensive grid electricity and lower gas prices, which make it harder for fuel cell distributed electricity systems to compete with grid electricity.

Japan has a different technology development model than the U.S., with more joint development as well as a long-term national mandate for the market adoption of FC CHP systems. The U.S. has not supported joint development as widely. The Japan micro-CHP has had much greater cost reductions than the California stationary fuel cell system market under the SGIP program with the micro-CHP case having much higher unit volumes (number of systems per year) than FC systems in California.

To the extent that price data can be used as a rough proxy to infer technology learning and cost, deployment programs in and of themselves may not lead to significant cost reduction, as seen in the California fuel cell market. These programs may further require a strong development environment, government mandates for market adoption, and in the case of fuel cell distributed generation, more favorable market conditions and the presence of exogenous factors.

We demonstrate a bottom-up cost modeling approach that can been applied to disaggregate observed experience curve cost reduction and use the approach to estimate the cost reduction components in the Japan micro-CHP program into three components: economies of scale, product design improvements, and other residual effects. This approach provides insight into the technology dependencies and economies of scale of product and system manufacturing and can be applied to other technologies. The approach requires a cost model framework and information about industry participants, vendor production volumes, and evolving product performance and design information.

Acknowledgements

This work was funded by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy, and conducted at Lawrence Berkeley National Laboratory under Contract No. DE-AC02-05CH11231.

References

[1] Darrow, Ken, Rick Tidball, James Wang, and Anne Hampson. Catalog of CHP Technologies. (U.S. Environmental Protection Agency Combined Heat and Power Partnership, March 2015). https://doe.icfwebservices.com/chpdb/

[2] E4tech, The Fuel Cell Industry Review 2014, November 2014. Available at http://www.e4tech.com/fuelcellindustryreview/, accessed on 10 December 2015.

[3] Wright, T.P. (1936), "Factors Affecting the Cost of Airplanes", Journal of the Aeronautical Sciences, Vol. 3, No. 4, pp. 122-128.

[4] Weiss, M., M.K. Patel, H.M. Junginger, K. Blok (2009), A review of experience curve analyses for energy demand technologies , Technological Forecasting and Social Change, volume 77, issue 3, pp. 411 – 428.

[5] Rivera-Tinoco, Rodrigo, Koen Schoots, Bob van der Zwaan (2012), Learning curves for solid oxide fuel cells Energy Conversion and Management, Vol. 57, pp. 86-96, doi:10.1016/j.enconman.2011.11.018.

[6] Schoots, K., G.J. Krame, B.C.C. van der Zwaan (2010), Technology learning for fuel cells: An assessment of past and potential cost reductions, Energy Policy 38, 2887–2897.

[7] Staffell, I., R. Green (2013), The cost of domestic fuel cell micro-CHP systems, International Journal of Hydrogen Energy 38 (2), 1088-1102.

[8] Neij, Lena (2008), Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments, Energy Policy, 36, 2200-2211, ISSN 0301-4215, http://dx.doi.org/10.1016/j.enpol.2008.02.029.

[9] Lipman, T., D. Sperling (1999), Forecasting the cost of automotive PME fuel cell systems—using bounded manufacturing progress functions, Proceedings for the IEA International workshop “Experience curves for policy making-the case of energy technologies”. May 10–11, 1999, Stuttgart, Germany.

[10] H. Tsuchiya, O. Kobayashi (2004), Mass production cost of PEM fuel cell by learning curve, Hydrogen Energy, 29, pp. 985–990.

[11] Van Buskirk, R.D., C. L. S. Katner, B. F. Gerke, and S. Chu (2014), “A retrospective investigation of energy efficiency standards: policies may have accelerated long term declines in appliance costs”. Environmental Research Letters, Vol. 9, pp. 114010-114021.

[12] Wei, M., S. Smith, M. Sohn, (2015), “Non-Constant Learning Rates in Retrospective Experience Curve Analyses and their Correlation to Deployment Programs,” Lawrence Berkeley National Lab Report, April 2015

[13] Shimuzu, Toshiki, “Evolution of “Ene-Farm” and the Activities for the Market Expansion,” Panasonic Corporation, Fuel Cell Expo Technical Conference Session FC-1, Tokyo Japan, Feb 25, 2015.

[14] Kasuh, Takahiro (2015), Why does Japan believe in domestic fuel cell? Adaptation to European market?, Osaka Gas Co. Ltd., EGATEC2013, European Gas Technology Conference, Paris, 30-31 May 2013. Available at: http://www.marcogaz.org/downloads/EGATEC2013/Day2-May31/PS5/PS5f_6_Kasuh.pdf, accessed on 15 October 2015.

[15] Wei, M., T. Lipman, et al. (2014), “A Total Cost of Ownership Model for Low Temperature PEM Fuel Cells in Combined Heat and Power and Backup Power Applications,” Lawrence Berkeley National Laboratory Report, November 2014. Available at http://ses.lbl.gov/publications/total-cost-ownership-model-low, accessed 1 December 2014.

[16] Marcinkoski, Jason, Brian D. James, Jeff A. Kalinoski, Walt Podolski, Thomas Benjamin, John Kopasz, Manufacturing process assumptions used in fuel cell system cost analyses, Journal of Power Sources, Volume 196, Issue 12, 15 June 2011, Pages 5282-5292, ISSN 0378-7753, http://dx.doi.org/10.1016/j.jpowsour.2011.02.035.

[17] James, B.D., A.B. Spisak, W.G. Colella, “Manufacturing Cost Analysis of Stationary Fuel Cell Systems.” Strategic Analysis, September 7, 2012.