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Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US

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HIGHLIGHTS

- Learning rates developed for two fuel-cell deployment programs in Japan and the U.S.
- Develop and demonstrate a new cost-modeling approach to disaggregate observed cost reductions.
- Compares differences in the technology and market ecosystem in the two countries.
- Presents policy observations for market adoption of future fuel cell technologies.

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ABSTRACT

Technology learning rates can be dynamic quantities as a technology moves from early development to piloting and from low volume manufacturing to high volume manufacturing. This work describes a generalizable technology analysis approach for disaggregating observed technology cost reductions and presents results of this approach for one specific case study (micro-combined heat and power fuel cell systems in Japan). We build upon earlier reports that combine discussion of fuel cell experience curves and qualitative discussion of cost components by providing greater detail on the contributing mechanisms to observed cost reductions, which were not quantified in earlier reports. Greater standardization is added to the analysis approach, which can be applied to other technologies. This paper thus provides a key linkage that has been missing from earlier literature on energy-related technologies by integrating the output of earlier manufacturing cost studies with observed learning rates to quantitatively estimate the different components of cost reduction including economies of scale and cost reductions due to product performance and product design improvements. This work also provides updated fuel cell technology price versus volume trends from the California Self-Generation Incentive Program, including extensive data for solid-oxide fuel cells (SOFC) reported here for the first time. The Japanese micro-CHP market is found to have a learning rate of 18% from 2005 to 2015, while larger SOFC fuel cell systems (200 kW and above) in the California market are found to have a flat (near-zero) learning rate, and these are attributed to a combination of exogenous, market, and policy factors.

1. Introduction-fuel cells in stationary applications

Fuel cells are both a longstanding and emerging technology for stationary and transportation applications, and their future use may be critical for the deep decarbonization of global energy systems. For example 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 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

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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 [2]. If FC lifetime is not proven in demonstration programs, for example, potential owners such as commercial building operators are not likely to invest in them. 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.[1] 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.[2] 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 CHP targets in Germany that include fuel cell CHP systems.[3] 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.

Proton exchange membrane (PEM) fuel cells and solid oxide fuel cells (SOFC) have been an active area of research for material development and characterization, fuel cell stack manufacturing processes, stack and system operation and characterization, and management of reactants and heat [3–6]. Both PEM fuel cells and other types of fuel cells have been an active area of development for a wide set of diverse applications from heat and power in residential applications [7] to bus transportation [8] and waste water treatment [9].

Globally, fuel cell shipments have grown at 15% by MW and 37% by unit per year from 2009 to 2014, led by the stationary sector which shipped over 80% of the units in 2014 [10]. About two-thirds of MW shipped in 2014 was 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.

As we look into future applications, a key challenge for policymakers 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. Learning rates can dynamic quantities and should be updated on a periodic basis to understand price reduction trends and the potential impacts of deployment programs, technology development, exogenous factors, and other factors. For example, to our knowledge, a price versus cumulative volume trend for the SOFC fuel cell market in California under the state's Self-Generation Incentive Program (SGIP) has not been published.

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) for SOFC fuel cell systems in California, the latter for the first time. 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. This report thus provides a critical update on fuel cell costs from an experience curve perspective and disaggregates observed cost reduction components using a direct manufacturing cost model.

A generalized procedure for disaggregating experience-curve cost-reduction components is described and applied to the Japanese fuel cell micro-CHP market. This approach utilizes a vendor-level manufacturing cost model and known features of the Japanese fuel cell market are synthesized to estimate system cost reductions due to economies of scale, product performance improvement, and product design improvements. This approach provides an explicit decomposition of observed fuel cell system cost reduction elements for the first time.

We describe the empirically-observed learning rates as a function of production maturity and compare the policy and external environments for both cases. 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. 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.

This work highlights the critical importance of updating experience curves over time since with changes in technology, regulations, and international market conditions, changes in the slope of the experience curve can be observed. The Japanese micro-CHP market is found to have a learning rate of 18% from 2005 to 2015, while larger SOFC fuel cell systems (200 kW and above) in the California market are found to have a flat (near-zero) learning rate, and these are attributed to a combination of exogenous, market, and policy factors described below. The technical 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.

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

[2] http://www.cpuc.ca.gov/sgip/, accessed 22 December 2016.

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