**Impacts of the American Recovery and Reinvestment Act and the Investment Tax Credit
on the North American Non-Automotive PEM Fuel Cell Industry**

Girish Upreti^a, David L. Greene^{b,c}, K.G. Duleep^d, Rapinder Sawhney^a

^a Department of Industrial and Systems Engineering, The University of Tennessee, Knoxville,
TN 37996, USA

^b Howard H. Baker, Jr. Center for Public Policy, The University of Tennessee, Knoxville, TN
37996, USA

^c Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville
TN 37996, USA

^d H-D Systems, Washington, DC, VA 22016, USA

Corresponding author's current contact information:

Girish Upreti,

Department of Industrial and Systems Engineering

The University of Tennessee

525 John D. Tickle Building

851 Neyland Dr, Knoxville, TN 37996

Email: girishup7@gmail.com

Phone: (865) 974-7655

Fax: (865) 974-0588

ABSTRACT

The North American fuel cell industry has achieved major cost reductions while improving the durability and reliability of its products. Nevertheless, the costs of fuel cell systems and the cost and availability of hydrogen remain barriers to commercialization. Risk aversion to novel technology is also an issue. This paper estimates the impacts of government subsidies such as the American Recovery and Reinvestment Act (ARRA) and the Investment Tax Credit (ITC) on the sales of fuel cell Backup Power (BuP) and Material Handling Equipment (MHE) by North American firms. A fuel cell market model published in 2011 has been updated based on the data collected from interviews, annual reports, and published literature. The updated model integrates effects of learning-by-doing, scale economies and exogenous technological progress on component and system costs, estimates customers' choices between fuel cell and competing established technologies, and is used to measure the impacts of government policies. The combination of industry progress and government support led to rapid sales growth while industry consolidation reduced the number of firms enabling the remaining firms to achieve greater economies of scale. The ARRA is estimated to have reduced the cost of fuel cells for MHE and BuP via scale economies and learning by doing. This is estimated to induce additional sales of approximately 5,600 fuel cell MHE and BuP units through 2025. If the ITC expires in 2017, it is likely to cause a sharp reduction in the sales of North American fuel cells. However, if the ITC is gradually phased out by 2022, sales could remain approximately constant during the phase-out period.

1. Introduction

North American firms have been manufacturing fuel cell Backup Power (BuP) and Material Handling Equipment (MHE) for more than a decade for demonstrations and commercial sales. The most attractive market for fuel cell BuP systems appears to be telecom towers. There are about 300,000 telecom towers providing coverage to nearly all of the US and there are roughly 5 million towers worldwide [1]. The average life of Telecom BuP systems is 15–20 years, implying an average annual demand of 15,000 to 20,000 BuP systems units in the U.S. alone. Global markets, especially developing countries are potentially a much larger opportunity for North American fuel cell BuP manufacturers. The older towers require 5 to 10 kW of BuP while

newer towers need only about 2.5 kW. Less expensive air-cooled fuel cell systems can provide sufficient power for modern 4G telecom towers [1].

Electric forklifts compete in classes, I, II, and III with class I being the largest, class II intermediate and class III being the smallest size and capacity. Fuel cells have been applied to classes I to III. In general, classes I and II are powered by 8–10 kW fuel cell systems, while the smaller class III forklifts require only 2–4 kW of maximum continuous power. In 2012, sales of classes I and II forklifts amounted to approximately 50,000 units with an equal number of class III units sold [2, 3].

In 2009 the US government allowed ARRA funds to subsidize purchases of fuel cell BuP and MHE systems in order to stimulate economic growth and promote advanced, low-emission energy technologies. The U.S. fuel cell market also benefited from the ITC which provides tax credits of \$ 3,000/kW for fuel cells or 30 % of capital cost, whichever is less. In 2008, the ITC was extended through the end of 2016. After more than a decade of R&D effort, PEM fuel cell technology offers high efficiency, durability and reliability, and costs have been reduced significantly due to mass production [4, 5]. The fuel cell technology program continues to promote R&D activities to validate the fuel cell technology [6].

2. Fuel cell industry status

There have been important changes in the structure of the MHE and BuP fuel cell industries since the 2011 study [7]. Mergers and acquisitions have led to a reduction in the number of North American fuel cell firms. Ballard Power Systems acquired IdaTech in 2012, a leading producer of methanol reforming and hydrogen-fueled BuP units. Plug Power acquired Relion in 2014, another major manufacturer of fuel cell BuP equipment. This leaves four (down from six) North American manufacturers in the BuP market: Alteryx, Ballard, Hydrogenics and Plug Power (Relion). With Nuvera's decision to focus on research and development, Plug Power is the only remaining North American commercial manufacturer of fuel cell MHE systems and Ballard Power Systems is the sole supplier of Plug Power's fuel cell MHE stacks.

The distribution of fuel cell sales co-funded by the ARRA for 2009–2013 is shown in figure 1. The Department of Energy reports that the ARRA partially supported purchases of 524 MHE units and 824 BuP units [8,9]. ARRA supported sales peaked in 2010 at 308 units for MHE and

in 2011 at 421 units BuP systems. The ARRA expenditures for fuel cell MHE support was \$ 9.7 million, while the industry cost share was \$ 11.8 million. Similarly, ARRA funded BuP sales were \$ 18.5 million from DOE and \$ 30.8 million from industry [10]. In addition, the Department of Energy has subsidized 83 BuP units and 189 MHE units out of its departmental appropriations. Thus, total DOE-subsidized fuel cell sales amount to 907 BuP units and 713 MHE units. Since 2009, firms have purchased 5,568 BuP units and 8,340 MHE units without DOE support. All of these sales benefitted directly or indirectly from the ITC and ARRA deployments.

Figure 1. here

Total estimated annual sales of BuP and MHE units by North American firms are shown in Figure 2. These numbers were obtained from interviews with OEMs and from published sources such as annual reports, and the press releases. Backup power led the industry in total shipments until 2013. The shipment for forklifts peaked in 2014. We do not have a source of shipment by firms except when firm reports and in some cases orders are reported instead of shipments.

Figure 2. here

3. Data collection and assumptions

Several research papers published since the 2011 study provide detailed estimates of the costs of fuel cell MHE and BuP systems. Contini et al. [11] estimated the manufacturing costs of a 10 kW fuel cell MHE unit (Fig. 3). Although the class of the forklift is not listed, the 10 kW power rating suggests that it is most likely a class I or possibly a class II forklift. The cost plot in figure 3 provides evidence scale economies. Costs were also estimated for a 25 kW MHE systems. “Other” categories in the figure below are the humidifier, hydrogen recirculation system, and hydrogen regulator, radiator, blowers, and more. Contini et al. identified the carbon fiber composite hydrogen storage tank as a potential target for cost reduction [11]. They estimated the cost of a composite hydrogen storage tank at \$ 3,494 at a volume of 100 units/year, decreasing to

\$ 3,373 per tank at 10,000 units/year. However, the cost of a steel tank is \$ 804 at a volume of 100 units/year, decreasing to \$ 731 per tank at 10,000 units/year, a cost savings of over \$ 2,500.

Figure 3. here

Larriba et al. report fuel cell system prices of \$ 30,000 for a class I forklift, \$ 28,000 for a class II and \$ 14,000 for a class III forklift [12]. These prices do not include the forklift truck. Renquist et al. report a price tag of \$ 35,000 for a class I forklift [13]. Ramsden estimated the capital cost of \$ 33,000 for class I and II fuel cell forklifts and \$ 15,000 for class III [14]. HD systems estimated the cost of a 5 kW MHE fuel cell system at \$ 15,000–\$ 16,000, with additional costs of \$ 4,000 for controller and power conditioning, \$ 2,000 for high-power batteries and \$ 1,000 for a stainless steel hydrogen storage tanks [2]. Dominguez et al. estimated a savings for fuel cell forklifts of 20 minutes per battery recharging event [15]. Assuming two battery swaps per day, a 340 day year and a \$ 24/hr labor cost accounts to well over \$ 5,000 per year in potential labor savings. Qi states increased productivity of 15 % and up to 30 % lower operating costs for fuel cell MHE [1].

Plugpower customers have reported significant productivity advantages for fuel cell MHE. Sysco Houston, a provider of food products, reported that battery changes require an additional maintenance worker to assist the forklift operator during the 10–15 minute battery change whereas the operator alone can refuel a fuel cell forklift in approximately 3 minutes. United Natural Foods, Inc, Wegmans Food Markets, Inc., and Golden State Foods, Inc, all reported substantial labor costs saving on refueling fuel cell forklifts. The elimination of battery swapping and rapid refueling was also cited by Elgowainy et al. as important advantages of fuel cell versus battery-powered forklifts [3]. VW and BMW who are using fuel cell MHE report the environmental benefits and sustainability of fuel cells versus batteries in terms of reduced emissions and grid electricity use, and the elimination of hazardous materials such as battery acid and lead from the workplace (Plug Power, 2015). Environmental benefits and sustainability are not included in our model. They are rather interpreted as factors that increase the value of the fuel cell option for some firms. They are assumed to be components of the unmeasured, firm-specific utility of the fuel cell option.

Kurtz et al. estimated costs of BuP systems for different run times ranging from 8 to 176 hours [16]. Complete fuel cell unit costs ranged from \$ 30,700 for the 8 hour system to \$ 76,000 for

the 176 hour outage and assume only one outage per year. HD Systems assumes more frequent outages of short duration which is a much more likely scenario for the U.S. market [2]. The data for the 8 hour shortage are shown in table 2. HD Systems estimated the cost of a 5 kW BuP unit at about \$ 11,000 for the stack and balance of plant, \$ 5,000–\$ 6,000 for controller and power conditioning and \$ 5,500 to \$ 6,000 for six 49 liter (0.62 kg) hydrogen storage tanks.

Kurtz et al. and HD Systems conclude that fuel cell BuP systems can compete with battery and diesel generators today [2, 16, 17]. In comparison to battery systems, the cost advantages of fuel cells increase as the duration of an outage increases. Fuel cell BuP has advantages of longer run time, reduced maintenance, reduced noise and zero emissions [18]. Also, fuel cell BuP systems require much less frequent maintenance [16].

Data and assumptions used in this study are derived primarily from HD Systems, Kurtz et al., Contini et al. and Ramsden [2, 11, 14, 16]. HD Systems assessed costs of a hypothetical 5 kW MHE unit, the same size used in this study. Ramsden estimated costs for a larger 8–10 kW class 1 or 2 forklift and separately for an under 3 kW class 3 forklift. A 2/3 Class III, 1/3 Classes I & II weighted average of the two is shown in table 2 as a synthetic 5 kW system. In all markets, several products of differing sizes have been combined into representative 5 kW size units in this study. We characterize a single, uniform market for each product to match the representation in the 2011 model. The studies also estimated costs for an equivalent battery powered forklift. Ramsden assessed data provided by firms operating over 600 forklifts co-funded by the DOE and Defense Logistics Agency (DLA). HD Systems’ assumptions are based on interviews with MHE fuel cell manufacturers and published sources. The two studies’ detailed analyses are compared with the assumptions used in this study in tables 1 and 2 [2, 14]. Data for the costs of fuel cells and their components, their expected lifetimes, maintenance, installation, infrastructure, labor savings, and fuel costs in tables 1 and 2 under “This Study” are used to calculate an equivalent annualized cost (EAC) for each technology and their competitors.

Table 1. here

Table 2. here

A cost of capital of 10 %/year is assumed for all applications. For MHE, the number of shifts and the intensity of forklift use during a shift are key determinants of the fuel cell's economic competitiveness. HD Systems assumes 3.5 hours use of forklift per shift and two shifts per day which are assumed to enable recharging during breaks and idle time making it possible to use a single battery pack for one forklift [2]. On the other hand, Ramsden estimated an average of two battery packs per forklift based on a survey of 7 different forklift operations [14]. The rate of hydrogen consumption assumed is similar to Hosseinzadeh et al.'s estimate of 0.15 kg/hr [19].

Labor costs are a key factor in the competition between fuel cell and battery forklifts. Ramsden predicted an average of 10.5 minutes for a battery swap and 3 minutes to refuel with hydrogen [14]. Renquist et al. estimate 15 minutes and 5 minutes, respectively for the same operations [13]. Larriba et al. report 10–30 minutes for a battery change and 3–5 minutes for hydrogen refueling [12]. Assuming automated battery charging, HD Systems estimates that both battery and fuel cell forklifts require less than 3 minutes to complete the processes. An automated battery charging systems is expensive and not all firms have such facility. Thus, this study assumes 5 minutes for hydrogen refueling and 15 minutes for a battery swap as suggested by Renquist et al.

The cost estimates for BuP systems were developed by comparing cost estimates from HD Systems and Kurtz et al. The capital cost estimates of Kurtz et al. were not used for several reasons. Kurtz et al. assume a much more powerful diesel generator (25–35 kW) than is required to provide for a 4–6 kW of electrical power and so it's much more costly [20]. The capital costs of batteries and fuel cells are also much higher than HD Systems found to be the case in more recent interviews with OEMs and other published sources. BoP costs estimated by Kurtz et al. also include permitting and other site costs not included in this study. The cost of hydrogen is assumed to be \$ 10/kg estimated by Kurtz et al.

4. Learning-by-doing, scale economy and technological progress

The recent cost analyses and discussions with OEMs indicate that some key model parameters assumed in the 2011 study describing scale economies, learning by doing and time-based technological progress should be modified. The elasticity of scale in fuel cell stack production used in the 2011 study was -0.2 which implies a 20 % reduction in cost for a doubling of production volume. HD Systems cost estimates are consistent with scale elasticities for fuel cell

stack production in the range of -0.07 to -0.1. This range is also consistent with Wei et al.'s analysis of scale economies for a much larger 50 kW PEM backup power system [21]. Their estimates imply a scale elasticity of -0.19 for the transition from 100 to 1,000 units per year but decline to -0.07 for the transition from 1,000 to 10,000 units and to -0.044 for 10,000 to 50,000 units. Thus, using an elasticity of -0.2 would overestimate the impacts of scale elasticities for production volumes above 1,000 units per year. Cost estimates by Contini et al. for fuel cell forklift stacks imply scale elasticities of -0.04 to -0.07 when increasing from 100 to 1,000 and then 1,000 to 10,000. Scale elasticities inferred from their cost estimates for the balance of plant are also smaller, -0.11 for 100 to 1,000 units per year and -0.07 for 1,000 to 10,000. Based on this new information, the model's scale elasticities were adjusted downward from -0.2 to -0.15.

Progress ratios were also adjusted based on confidential discussions with OEMs. The 2011 study assumed a learning exponent of $\lambda = -0.15$, which implies a progress ratio of 0.90 which implies a 10 % reduction in cost with every doubling of cumulative production. A typical pattern of cost reduction from learning in succeeding generations of fuel cell MHE systems based on discussions with OEMs is shown in Figure 4. As a consequence, the progress ratio for fuel cell systems was increased to 0.95 which implies a 5 % reduction in cost with each doubling of cumulative production. Time-dependent technological progress (independent of scale or cumulative production) assumed in the 2011 study was 1 % per year for both stacks and systems. Discussions with OEMs indicated cost reductions of 10–15 % per generation due to technological progress. New product generations are introduced every 3–5 years, indicating a rate of technological progress of about 3 % per year, which was used in the updated model.

Figure 4. here

The same market sizes used in 2011 study were retained for this study. We acknowledge that we do not have a good representation of the global market. We have chosen to conservatively limit the markets to those North American markets in which fuel cells appear to have a reasonable chance of competing with established technologies. We have also limited our analysis to the established markets for MHE and BuP, excluding advanced applications such as solar/voltaic fuel cell power systems for remote radio towers [22]. Fuel cells cannot compete equally in all telecom applications. Convenient access to commercial hydrogen supply is a critical issue and

also factors such as expected frequency and duration of outages. Hydrogen or fuel cell service is not available everywhere. Local emissions regulations are an issue for diesel generators in some areas. The 2011 study assumed a market size for backup power to 15,000 units in 2005 increasing to 20,000 units in 2025. Annual U.S. sales of battery electric forklifts are approximately 50,000 units for classes I and II and another 50,000 for class III. According to Elgowainy et al., 31% of class I and II forklifts operate two or more shifts per day (corresponding to annual sales of 15,000 units) [3]. Not all of these forklifts go to multiple shifts, intensive-usage operations. The 2011 study assumed a relevant market size of 17,000 units in 2005, increasing by 2 % per year.

5. Methodology

Impacts of the ARRA and ITC are analyzed using the Non-Automotive Fuel Cell Market Model. A simpler version of this model was first developed by Greene et al. in 2008. The model simulated how increased government purchases of FCs could reduce costs through learning-by-doing and scale economies, and how such cost reductions might affect FCs' market success, with lower costs leading to higher sales, in turn helping to further reduce costs [23]. A more complex model was developed in 2011 to estimate the potential impacts of government policies on the non-automotive fuel cell market and to explore the potential to establish a self-sustaining U.S. industry. The model includes the effects of learning-by-doing, scale economies and exogenous technological progress on component and system costs, estimates customer choices between fuel cell and competing established technologies. The 2011 model is described in Greene et al. and Upreti et al. [7, 24]. For this study, we did not change the structure of the 2011 model but rather updated the model's data and parameters as described above. Although the model's representation of the North American fuel cell market is highly generalized it includes the critical processes of market transformation: production costs and technological change, scale economies, learning-by-doing and customer choice among competing products. The model produced reasonable predictions of fuel cell equipment sales for the period 2011 to 2014 and relatively accurate price forecasts for the same period which gives reason to believe that it may also perform well for the near-term future [25].

The current model is used to estimate the impact of ARRA and ITC and the steps involved are described in next section. The model's structure is illustrated in Figure 5. The model is comprised of seven sub models. The first step is calculation of an EAC for each technology in the Cost Analysis module. Capital investments are translated into annual costs based on their expected lifetimes, L , the cost of capital, r , and by dividing by an annuity factor, A .

Figure 5. here

$$A = \frac{1 - \left[\frac{1}{(1+r)^L} \right]}{r} \quad (1)$$

The OEM module estimates the effects of scale economies, learning-by-doing, and R&D driven technological progress on the costs of stacks, reformers and BoP components. The cost in each year is a product of a reference cost times a learning effect, a scale effect and R&D effect. The reference cost is chosen in such a way that the product of it and the learning effect, scale effect and R&D effect is equal to the component cost data in tables 1 and 2.

$$\text{Component Cost} = (\text{Reference Cost}) \times (\text{Learning Effect}) \times (\text{Scale Effect}) \times (\text{R \& D Effect}) \quad (2)$$

The FC system cost is the sum of the component costs, multiplied by OEM scale, learning and technology effects.

$$\text{System Cost} = [(\text{Stack Cost}) + (\text{Reformer Cost}) + (\text{BoP Cost})][(\text{OEM Scale}) \times (\text{OEM LBD}) \times (\text{OEM R\&D})] \quad (3)$$

The size, Q , of the potential market is estimated by dividing the total number of units in use by the expected lifetime of a unit.

$$Q = (\text{Number of existing units})/(\text{Expected Life}) \quad (4)$$

Annual sales of FC systems is equal to the total market size times a market share function that depends on the EAC of the FC system and of its competition. Other attributes are represented by an alternative-specific constant term, A_i , where i indexes the choice alternatives. However, we do not include intangible factors such as firm specific environmental values in this study. The overall value, or utility, of alternative i to potential customer j , is the sum of its intercept term and its generalized cost multiplied by a price-sensitivity coefficient, B , plus a utility component, ε_{ij} specific to firm j and alternative i . The ε_{ij} are unobserved terms related to factors not included in the model such as number of shifts, intensity of use of equipment, cost of electricity or green image. The individual component is intended to reflect factors that vary from one firm to another that are not adequately represented by the other terms in the utility equation.

$$U_{ij} = A_i + BG_i + \varepsilon_{ij} = A_i + B(EAC_i) + \varepsilon_{ij} \quad (5)$$

Multinomial logit (MNL) choice models are used to estimate the market share of FCs [7, 24]. The probability that a decision maker will choose a fuel cell BuP system over battery (b) or diesel generator (d) alternatives, is given by the following equation.

$$p_{FC} = \frac{e^{A_{FC} + BG_{FC}}}{e^{A_{ob} + BG_b} + e^{A_d + BG_d} + e^{A_{FC} + BG_{FC}}} \quad (6)$$

where e is base of Napierian logarithm, and G is the EAC. A is a constant term that represents less tangible attributes. B is a price-sensitivity term and is expressed as

$$B = \frac{\text{price elasticity}}{G(1 - \text{market share})} \quad (7)$$

Given estimates of the total market size for each of the different types of equipment, FC sales are computed by multiplying the total annual market size by the logit probabilities.

$$Q_{FC} = Qp_{FC} \quad (8)$$

The capital costs of FCs decrease when manufacturers achieve scale economies, learning-by-doing, and technological progress. Scale economies are assumed to be a function of the average output per manufacturer divided by the reference volume x_0 corresponding to the economical production volume. Scale economies are assumed to cease if the average output per manufacturer exceeds a “full scale” production volume ($x_t \geq x_{\max}$). Otherwise, the scale effect is equal to the output ratio raised to a constant elasticity of scale parameter, η , as shown in equation 9.

$$\text{If } \frac{X_t}{N} = x_t \geq x_{\max} \quad \text{then} \quad \left(\frac{x_{\max}}{x_0} \right)^{\eta} \quad \text{otherwise} \quad \left(\frac{x_t}{x_0} \right)^{\eta} \quad (9)$$

Traditional learning curves are a function of cumulative production (X) raised to an exponent ($-\lambda$) that represents the rate at which costs fall (Wene, 2000).

$$P_t = P_0 X^{-\lambda} \quad (10)$$

EACs are calculated in the Cost Analysis module for each FC technology including the main competitors. Expected lifetimes vary by component (e.g., stack vs. BoP) but a uniform 10 % cost of capital is used throughout. EACs between 2005–2014 are input data. Costs for future years are determined by the prior year’s production volumes (scale), cumulative production (learning) and exogenous technological progress (time). EACs are also affected by policies that change the capital and operating costs of FCs. Policy assumptions are specified in the Policy Scenario spreadsheet.

EACs are passed to the Choice Model where market shares of fuel cells and competing systems are calculated. A price elasticity of -2 at 50 % market share is assumed for each technology. Market shares are then passed to the Sales spreadsheet, where they are multiplied by the total potential market size from the Market Characterization spreadsheet. Potentially strong feedback effects are generated when sales are passed back to the OEM model, which calculates the effects of scale economies, learning-by-doing as a consequence of cumulative production, and exogenous technological change. These are integrated into cost multipliers which are then passed back to the Cost Analysis spreadsheet.

6. Estimating ARRA and ITC impacts

Impacts of ARRA subsidized purchases were estimated by using the model in a back-casting mode. The actual historical case is fuel cell system sales with ARRA while the counterfactual historical case is without ARRA. The method used to estimate ARRA impacts can be summarized as:

1. Calibrate the choice model to exactly predict non-ARRA purchases in 2009–2013, allowing the actual sales (including ARRA sales) in each year to influence scale and learning effects.
2. Remove the ARRA deployments and predict what non-ARRA sales would have been without them. This eliminates the scale and learning benefits of the ARRA sales.
3. Calculate the ARRA - induced additional sales as (Actual Sales) - (ARRA deployments) - (Predicted Sales without the ARRA).

The calibration was accomplished by adding constant terms, A_i to the utility function in equation 5. Since ARRA sales were included in the calculation of scale economies and learning by doing, the purchase prices were lower than they would have been without the ARRA subsidies. Since the effect of scale economies and learning induce positive feedbacks on sales, the estimation of constant terms was done sequentially, beginning with 2006 and proceeding one year at a time until 2014. The model was also simultaneously calibrated to predict within +/- \$ 5 the 2014 capital costs of the following fuel cell components: 1) for BuP, the stack, BoP and on-site infrastructure, 2) for MHE, the stack, BoP and hydrogen storage tank + controls + battery. The capital costs are listed in tables 1 and 2 under “This Study”.

A key assumption of the method described above is that all the ARRA sales are additional. It assumes that none of the firms that purchased hydrogen fuel cell MHE or BuP units with the benefit of ARRA subsidies would have purchased any fuel cell units without the subsidy. Given the very substantial size of the subsidies (about 40 % of purchase price), the novelty of the technology, and the fact that fuel cell prices would most likely have been higher in the absence of the ARRA purchases, the assumption of 100 % additionality is probably not far off the mark. However, the sensitivity of the predicted impacts to additionality was tested by assuming that an upper bound of 50 % of the fuel cell purchases would have occurred even without the ARRA subsidies. This was done by shifting 50 % of the purchases from the ARRA category to the non-

ARRA category and recalibrating the model to predict the larger quantities of non-ARRA purchases, using the same method described above.

7. Results

The ARRA subsidized purchases of 1,356 fuel cell BuP and MHE units between 2009 and 2014 is estimated to induce additional sales of over 4,300 units through 2014. Similarly between 2015 and 2025, the model estimates that the ARRA subsidies are estimated to generate more than 1,300 fuel cell units. Most of the induced sales occur between 2011 and 2015. These estimates assume that none of the ARRA-subsidized purchases would have occurred without the ARRA subsidies. If half of the ARRA-subsidized purchases would have occurred without the ARRA subsidies, the ARRA impact is still significant. The ARRA subsidies are estimated to induce 2,800 additional sales of BuP units and 450 additional MHE sales through 2025. A reasonable rule of thumb is that the additional ARRA sales scale linearly with one minus the fraction of ARRA subsidized sales assumed to be free riders. That is, if 25 % were assumed to be free riders, the estimated additional sales would be approximately 75 % of the full impact (4,500 BuP and 1,100 MHE units).

Figure 6. here

The increase in sales is due to reduction in the production cost of fuel cells via scale economies and learning by doing. The reduction in cost is assumed to be passed to purchasers. The cost reduction is substantial over time as shown in figure 8. Initially, in 2009–10 the cost reduction is less than \$ 100 per unit and grows to \$ 2,600 per unit for MHE in 2012 and almost \$ 3,100 for BuP in 2013. The impact of the ARRA initially grows with increasing ARRA-subsidized sales but then declines after ARRA sales peak. However, the impact of the ARRA increases after the expiration of the ITC in 2017. This is because the termination of the ITC causes a sharp reduction in sales in 2017. In a market without the ITC, the benefit of the ARRA sales is relatively greater. The ARRA induced additional sales generate transitory scale economies at the time but also cause persistent cost reductions through learning-by-doing. This leads to higher

levels of sales and thus somewhat increased scale economies in comparison to the no-ARRA case. Even as late as 2016 the ITC reduces the capital costs of fuel cell BuP or MHE unit by \$ 7,000 to \$ 8,000.

Figure 7. here

The impact of the ITC on fuel cell sales are shown in figures 8 and 9. In the reference case the ITC is zeroed out in 2017. Fuel cell sales are sharply reduced after the termination of the ITC in 2017 (Figure 8 and 9). Although we are not accounting for international sales this would clearly be a serious setback for the fuel cell industry.

Figure 8. here

Figure 9. here

The impact of a gradual phase-out of the ITC on fuel cell sales is shown in figures 10 and 11. A linear phase-out of the 30 % credit to 25 % in 2017, 20 % in 2018 down to 5 % in 2021 and 0 % in 2022 would have a much less dramatic impact on the industry. For both BuP and MHE very small decreases in sales are predicted. Thus, some form of gradual phase-out would be far less damaging to the industry than a sudden termination of the ITC.

Figure 10. here

Figure 11. here

8. Conclusions

The North American fuel cell industry has achieved major cost reductions via scale economies, learning-by-doing, and technological progress since the study by Greene et al. in 2011[7]. The combination of industry progress and government support led to rapid sales growth. Industry consolidation reduced the number of firms enabling the remaining firms to cut costs.

This study has estimated the impacts of the ARRA on the North American non-automotive fuel cell industry in terms cost reductions due to scale economies and learning by doing, which resulted in additional sales of fuel cells for MHE and BuP. An updated revision of the non-automotive fuel cell market model of 2011 estimated that the ARRA subsidized purchases of 1,356 fuel cell BuP and MHE units between 2009 and 2014 induced additional sales of over 4,300 units for 2009–2014 and between 2015 and 2025, the model estimates that the ARRA subsidies will generate additional sales of more than 1,300 fuel cell units. Thus the model estimates that the ARRA purchases will generate approximately 4 additional units for every ARRA purchase assuming none of the ARRA-subsidized purchases would have occurred without the ARRA subsidies.

The model predicts that if ITC expires in 2017, there is likely to be a sharp reduction in the sales of fuel cells for BuP and MHE, on the order of 50 %. On the other hand, if the ITC is gradually phased out by 2022, North American sales of fuel cells might remain approximately constant during the phase-out period and increase beyond 2022, driven by continuous improvement in the durability of fuel cell systems and reductions in cost.

REFERENCES

- [1] Qi Z. Proton Exchange Membrane Fuel Cells: CRC Press; 2013.
- [2] H-D Systems. Non Automotive Fuel Cell Applications: Analysis of Technology, Cost and Markets. Washington, DC. 2015.
- [3] Elgowainy A, Gaines L, Wang M. Fuel-cycle analysis of early market applications of fuel cells: forklift propulsion systems and distributed power generation. *Int J Hydrogen Energy* 2009;34:3557-70.
- [4] Dodds PE, Staffell I, Hawkes AD, Li F, Grünewald P, McDowall W. Hydrogen and fuel cell technologies for heating: A review. *Int J Hydrogen Energy* 2015;40:2065-83.
- [5] Sharaf OZ, Orhan MF. An overview of fuel cell technology: Fundamentals and applications. *Renewable and Sustainable Energy Reviews* 2014;32:810-53.
- [6] Garland NL, Papageorgopoulos DC, Stanford JM. Hydrogen and fuel cell technology: progress, challenges, and future directions. *Energy Procedia* 2012;28:2-11.
- [7] Greene DL, Duleep KG, Upreti G. Status and outlook for the US non-automotive fuel cell industry: impacts of overnment policies and assessment of future opportunities. ORNL/TM-2011/101. Oakridge, TN: Oak Ridge National Laboratory; 2011 [May].
- [8] Devlin P, Kiuru K. Industry Deployed Fuel Cell Backup Power (BuP). Record 15004, DOE Hydrogen and Fuel Cells Program Record. Washington, DC: U.S. Department of Energy; 2015 [May].

- [9] Devlin P, Kiuru K. Industry Deployed Fuel Cell Powered Lift Trucks. Record 15003, DOE Hydrogen and Fuel Cells Program Record. Washington, DC: U.S. Department of Energy; 2015 [May].
- [10] Mintz M, Mertes C, Stewart E. Economic Impact of Fuel Cell Deployment in Forklifts and for Backup Power under the American Recovery and Reinvestment Act. Argonne National Laboratory (ANL); 2013.
- [11] Vince Contini FE, Jennifer Smith, Gabe Stout, , and, Kathya, Mahadevan. Stationary and Emerging Market Fuel Cell System Cost Analysis Material Handling Equipment FC097. 2013.
- [12] Larriba T, Garde R, Santarelli M. Fuel cell early markets: techno-economic feasibility study of PEMFC-based drivetrains in materials handling vehicles. *Int J Hydrogen Energy* 2013;38:2009-19.
- [13] Renquist JV, Dickman B, Bradley TH. Economic comparison of fuel cell powered forklifts to battery powered forklifts. *Int J Hydrogen Energy* 2012;37:12054-9.
- [14] Ramsden T. An evaluation of the total cost of ownership of fuel cell-powered material handling equipment. NREL/TP-5600-56408. Golden, CO: National Renewable Energy Laboratory; 2013 [April].
- [15] Domínguez I, Contreras A, Posso F, Varela F. Simulation of the operation of a fleet of materials handling and transport vehicles, powered by fuel cells. *Int J of Hydrogen Energy* 2015;40:7678-88.
- [16] Kurtz J, Saur G, Sprik S, Ainscough C. Backup power cost of ownership analysis and incumbent technology comparison. NREL/TP-5400-60732. Golden, CO: National Renewable Energy Laboratory: National Renewable Energy Laboratory; 2014 [September].
- [17] Kurtz J, Sprik S, Peters M. ARRA material handling equipment composite data products. NREL/TP-5400-62130. Golden, CO: National Renewable Energy Laboratory; 2014.
- [18] U.S.D.O.E. (DOE). Early Markets: Fuel Cells for Backup Power. 2014.
- [19] Hosseinzadeh E, Rokni M, Advani SG, Prasad AK. Performance simulation and analysis of a fuel cell/battery hybrid forklift truck. *Int J Hydrogen Energy* 2013;38:4241-9.
- [20] Kurtz J, Sprik S, Saur G. Spring 2014 composite data products: backup power. NREL/TP-5400-62025. Golden, CO: National Renewable Energy Laboratory; 2014.
- [21] Wei M, McKone T. A Total Cost of Ownership Model for Design and Manufacturing Optimization of Fuel Cells in Stationary and Emerging Market Applications. presented by Lawrence Berkeley National Laboratory at Department of Energy Annual Merit Review for Fuel Cell Research, Arlington, VA; 2013.
- [22] Bruni G, Cordiner S, Mulone V, Giordani A, Savino M, Tomarchio G, et al. Fuel cell based power systems to supply power to Telecom Stations. *Int J of Hydrogen Energy* 2014;39:21767-77.
- [23] Greene DL, Duleep K. Bootstrapping a sustainable North American PEM fuel cell industry: could a federal acquisition program make a difference. ORNL/TM-2008/183, Oak Ridge National Laboratory, Oak Ridge, Tennessee; 2008 [October].
- [24] Upreti G, Greene DL, Duleep K, Sawhney R. Fuel cells for non-automotive uses: Status and prospects. *Int J Hydrogen Energy* 2012;37:6339-48.
- [25] Greene DL, Upreti G. Impacts of the American Recovery and Reinvestment Act and the Investment Tax Credit on the North American Fuel Cell Backup Power and Material Handling Equipment Industries. Baker Reports 7:15. Howard H. Baker Jr. Center for Public Policy, University of Tennessee, Knoxville, TN; 2015 [December].