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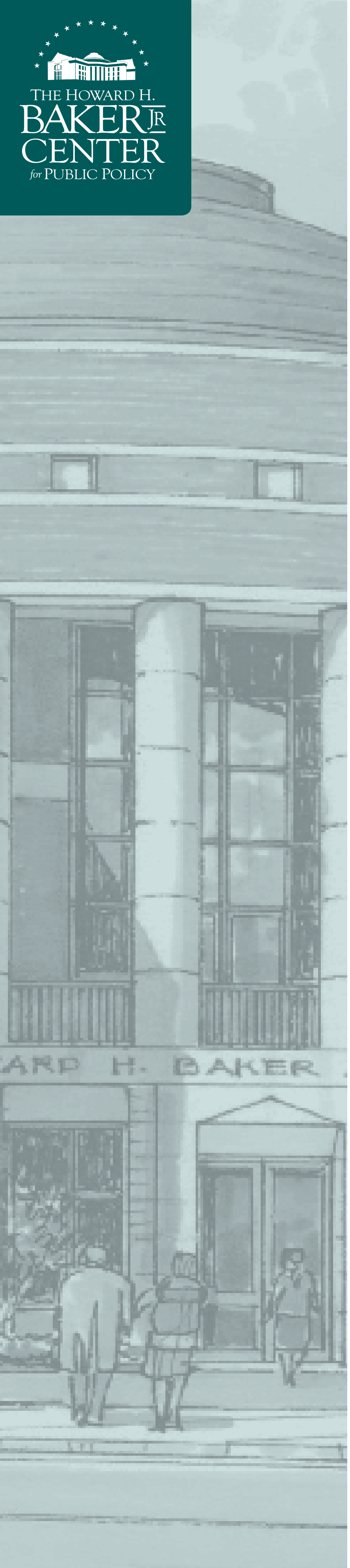

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Executive Summary

Since a previous study of the North American non-automotive fuel cell industry by Greene et al. in 2011, the industry has achieved major cost reductions while at the same time improving the durability and reliability of its products. This report estimates the impact of government subsidies provided by 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. The additional impact of those policies and their effects on the outlook for the industry in the future are estimated using an updated version of a model of the non-automotive fuel cell market in North America (Greene et al., 2011; Upreti et al., 2012). North American firms have been producing fuel cell BuP and MHE systems for demonstration and commercial sales for about a decade. Fuel cell technologies typically compete with battery and diesel generator systems in the BuP market, and battery-powered forklifts in indoor, warehousing MHE applications where emission-free operation is a priority.[1]

The most attractive market for fuel cell BuP systems appears to be telecom towers. There are approximately 300,000 telecom towers providing coverage to nearly all of the US and roughly 5 million worldwide (Qi, 2013, ch. 5). Telecom BuP systems are typically replaced every 15-20 years, implying an average annual demand for BuP systems of 15,000 to 20,000 units in the U.S. alone. Global markets, especially in developing economies are not saturated however, and present a potentially larger opportunity for North American fuel cell BuP manufacturers. Telecom towers built before 2010 require 5 to 10 kW of BuP while newer towers need only about 2.5 kW, a development beneficial to fuel cell technology.

Electrically powered forklifts (MHE) are divided into three classes, with class I being the largest, and class III the smallest. Fuel cell systems are available for all three classes I to III. US sales for classes I and II in 2012 amounted to approximately 50,000 units with an equal number of class III walk-behind units sold (HD Systems, 2015). The power requirements of MHE depend on the weight that must be lifted and the lifting speed. 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 (Qi, 2013).

There have been important changes in the structures of the MHE and BuP hydrogen polymer electrolyte membrane (PEM) fuel cell industries since the 2011 study (Greene et al., 2011). Mergers and acquisitions have reduced the number of North American firms from seven to four. Consolidation has allowed manufacturers to achieve greater economies of scale as sales have increased (Figure ES-1).

[1] Typically, fuel cell systems do not compete with internal combustion powered forklifts, which are more frequently used in manufacturing and outdoor operations.

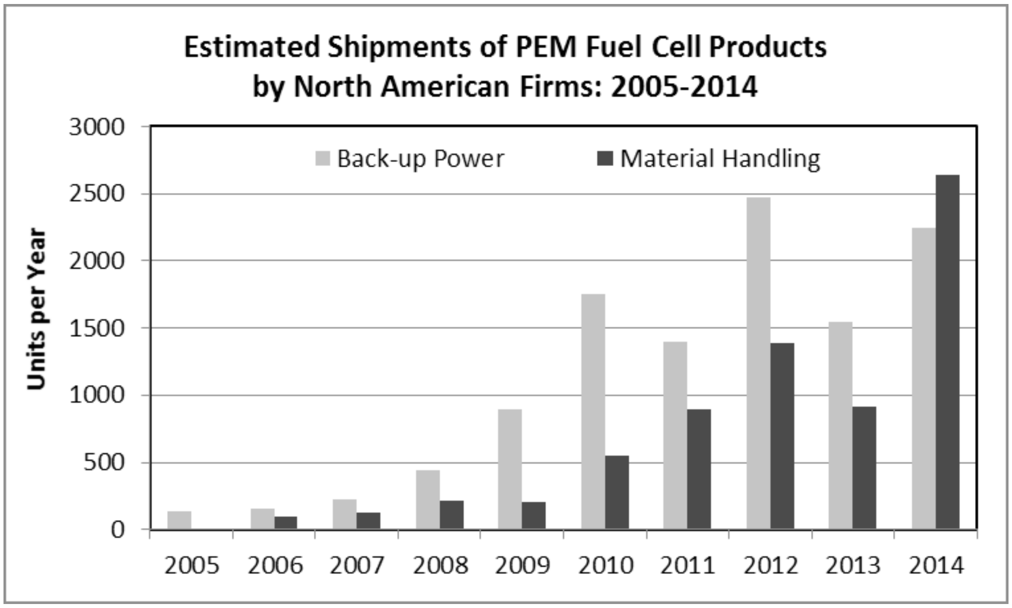


Figure ES-1. Estimated Shipments of PEM Fuel Cells for Backup Power and Material Handling Equipment

In 2009 the ARRA provided funds to subsidize purchases of fuel cell BuP and MHE systems, in order to stimulate economic growth and promote advanced, low-emission energy technologies (Figure ES-2). The Department of Energy reports that the ARRA partially funded sales of 524 MHE units and 824 BuP units (Devlin and Kiuru, 2015a; 2015b). Since 2009, firms have purchased 5,568 BuP units and 8,340 MGE units without DOE support. All of these sales benefitted directly or indirectly from the ARRA deployments which enabled firms to reach higher production volumes and realize additional process improvements through learning by doing. The sales also benefitted from the ITC and in many cases state subsidies, as well. The objective of this report is to estimate the additional sales of fuel cells that would not have occurred without the ARRA and to assess the impact of ending the ITC in 2017.

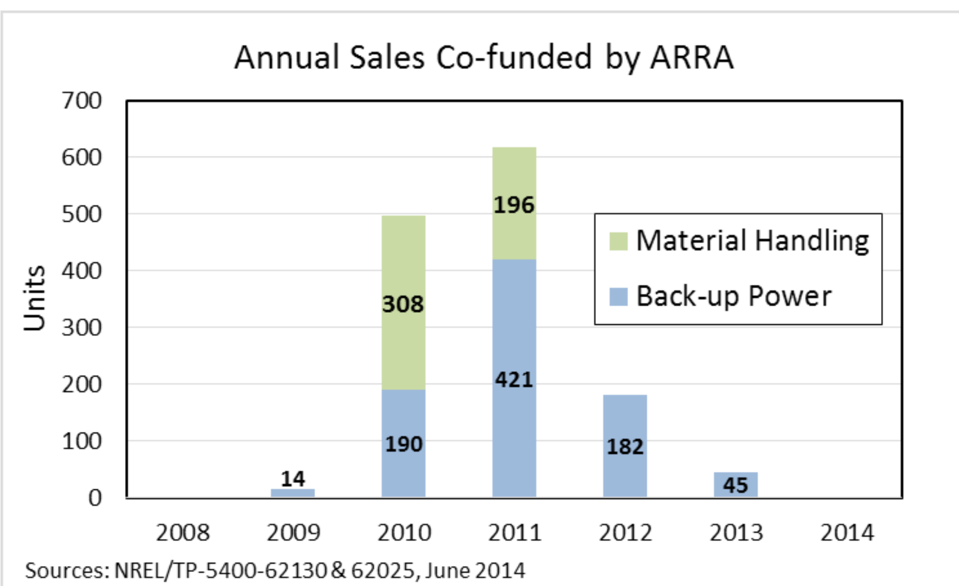


Figure ES-2. Annual Sales of Fuel Cell BuP and MHE Units Co-funded by ARRA.

Several important analyses of the costs of MHE and BuP fuel cell systems have been published since the report by Greene et al. (2011) that provide detailed assessments of the manufacturing costs of fuel cell BuP and MHE systems (e.g., Renquist et al., 2011; Larriba et al., 2013; Ramsden, 2013; Kurtz et al., 2014a; Contini et al., 2013, HD systems, 2015). These studies, interviews with OEMs and other publicly available information were used to update the model used in the 2011 study to reflect recent developments in technology and manufacturing processes. The model and its updates are described in section IV of the full report.

To estimate the impacts of ARRA subsidized purchases the model was first calibrated to historical sales and then used to backcast what sales would have been without the ARRA. The process consisted of the following three steps.

1. Calibrate the choice model to exactly predict non-ARRA purchases in 2009-2013 but allowing the total sales in each year (including ARRA-subsidized purchases) to influence scale and learning effects.

2. Zero out the ARRA deployments and predict what non-ARRA sales would have been without them. This eliminates the added scale economies and learning-by-doing induced by the ARRA sales.

3. Calculate the ARRA-induced additional sales as (Actual Sales) – (ARRA deployments) – (Predicted Sales without the ARRA).

The model was then used to predict annual sales from 2010 to 2025. Because of the calibration procedure, the model exactly predicted the estimated sales from 2006 to 2014.

At the same time, the model was calibrated to predict within +/- $5 the 2014 capital costs of the following fuel cell components: 1) for BuP, the stack, balance of plant (BoP) and on-site infrastructure, 2) for MHE, the stack, BoP and hydrogen storage tank plus controls and battery. The capital costs and other assumptions are shown in tables 2 and 3 in the full report under the heading "This Study".

A key premise of the method described above is that all of the ARRA sales are additional. That is, 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% or 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 scale economies and learning effects induced by the ARRA purchases, the assumption of 100% additionality is considered reasonable.

The ARRA subsidized purchases of 1,356 fuel cell BuP and MHE units are estimated to have induced additional sales of over 4,300 units from 2009-2014 (Figure ES-3). For the period 2009 to 2025, the model estimated that the ARRA purchases induce total additional sales of 4,500 BuP units and 1,100 MHE units, or approximately 4 additional units for every ARRA purchase. These estimates assume that none of the ARRA-subsidized purchases would have occurred without the ARRA subsidies. Given the lingering effects of the economic recession in 2009, and the low sales volumes in 2009 and earlier years, this assumption seems a reasonable approximation even though it is an upper bound on the estimated impact. If it is assumed that half of the ARRA-subsidized purchases would have occurred without the ARRA subsidies, the ARRA subsidies induce 2,800 additional sales of BuP units and 450 additional MHE sales through 2025. An approximate 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. Thus, 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).

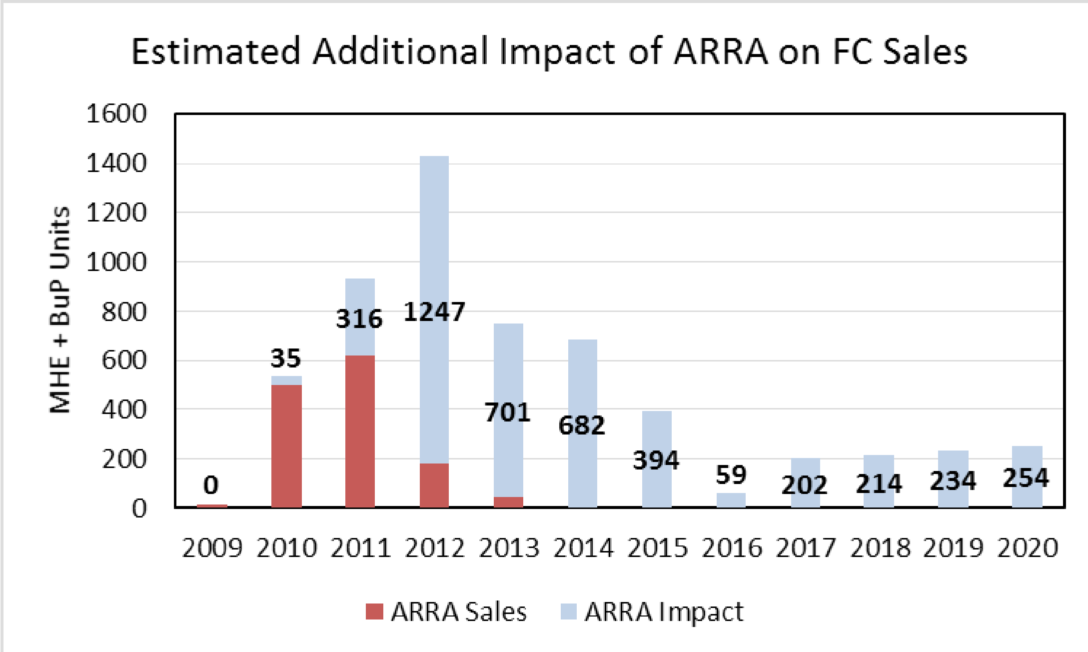


Figure ES-3. Estimated Additional Impact of ARRA on Fuel Cell BuP and MHE Sales.

Sales are increased because production costs are reduced via scale economies and learning by doing. The cost reductions are assumed to be passed on to purchasers. In 2009-10 the cost impacts are less than $100 per unit but they grow over time to a reduction of $2,600 per unit for MHE in 2012 and almost $3,100 per unit for BuP in 2013. The impact of the ARRA initially grows with increasing ARRA-subsidized sales but then declines after ARRA sales peak. However, once the ITC expires after 2016, the impact of the ARRA increases slightly. In a market without the ITC, sales volumes are sharply reduced and the relative benefit of the ARRA sales is greater because of the greater sensitivity of fuel cell choice to price at low market shares.

Even as late as 2016 the ITC reduces the capital costs of fuel cell systems by $7,000 to $8,000 off the purchase price of a BuP or MHE unit. The disappearance of this credit in 2017 is estimated to sharply reduce sales of fuel cell units. Both markets are projected to recover but a return to 2016 sales levels might take almost a decade. Whether all the North American OEMs could remain in business for that length of time depends on many factors not considered in the model, such as overseas sales and access to capital. A gradual phase-out of the credit would have a much less dramatic impact on the industry. A linear phase-out would reduce the 30% credit to 25% in 2017, 20% in 2018 down to 5% in 2021 and 0% in 2022. Given such a phase-out very small decreases in sales are predicted for both BuP and MHE. Despite the limitations of the model and the inherent uncertainties in such predictions, it is clear that some form of gradual phase-out would be far less damaging to the industry than a sudden termination of the ITC.

I. Introduction

This report estimates the impact of government subsidies provided by 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, a.k.a. forklifts) by North American firms. The objective is to estimate the additional impact of those policies and their effects on the outlook for the industry in the future. This study extends previous analyses that assessed the status of the non-automotive fuel cell industry and estimated the impacts of past and future government policies (Greene et al., 2011; Upreti et al., 2012). North American firms have been producing fuel cell BuP and MHE systems for demonstration and commercial sales for about a decade. Fuel cell technologies typically compete with battery and diesel generator systems in the BuP market, and battery-powered forklifts in indoor, warehousing MHE applications where emission-free operation is a priority.[2] Because fuel cells are novel technologies in these applications, fuel cell original equipment manufacturers (OEM) are striving to reduce costs, prove the advantages of fuel cells to potential customers and establish a durable market for fuel cells in non-automotive applications.

The most attractive market for fuel cell BuP systems appears to be telecom towers. There are approximately 300,000 telecom towers providing coverage to nearly all of the US and there are roughly 5 million worldwide (Qi, 2013, ch. 5). Telecom BuP systems are typically replaced every 15-20 years, implying an average annual demand for BuP systems of 15,000 to 20,000 units in the U.S. alone. However, the market depends on the capital investment decisions of a handful of large firms and therefore tends to be volatile. Global markets, especially in developing economies are not saturated however, and present a potentially larger opportunity for North American fuel cell BuP manufacturers. Newer telecom towers in the US and globally are far more energy efficient than towers built before 2010. 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 (Qi, 2013, p.200).

Electrically powered forklifts are divided into three classes, with class I being the largest, usually operated by a seated driver. Drivers of class III forklifts typically walk behind the units or operate them in a standing position, with class II of intermediate size and capacity. Fuel cell systems are available for MHE classes I to III. Class IV and V forklifts are powered by internal combustion engines and are typically larger. The worldwide market for classes I through V totals approximately 1 million in annual sales. In the US, class I-V sales were about 175,000 in 2012. US sales for classes I and II in 2012 amounted to approximately 50,000 units with an equal number of class III walk-behind units sold (HD Systems, 2015). The power requirements of MHE depend on the weight that must be lifted and the lifting speed. 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 (Qi, 2013).

II. Industry Status

There have been important changes in the structures of the MHE and BuP hydrogen polymer electrolyte membrane fuel cell industries since the 2011 study (Greene et al., 2011). Mergers and acquisitions have reduced the number of North American firms. Ballard Power Systems acquired IdaTech, a leading producer of methanol reforming and hydrogen-fueled BuP units. Plug Power acquired Relion, another major manufacturer of fuel BuP equipment. This leaves four (down from seven) North American manufacturers in the BuP market: Altergy, Ballard, Hydrogenics and Plug Power (ReliOn). With Nuvera's decision to focus on research and development, Plug Power is the only remaining North American manufacturer of fuel cell MHE systems, although at time of writing Ballard Power Systems was the sole supplier of Plug Power's fuel cell stacks. This consolidation has allowed manufacturers to achieve greater economies of scale as sales have increased (Figure 1).

[2] Typically, fuel cell systems do not compete with internal combustion powered forklifts, which are more frequently used in manufacturing and outdoor operations.

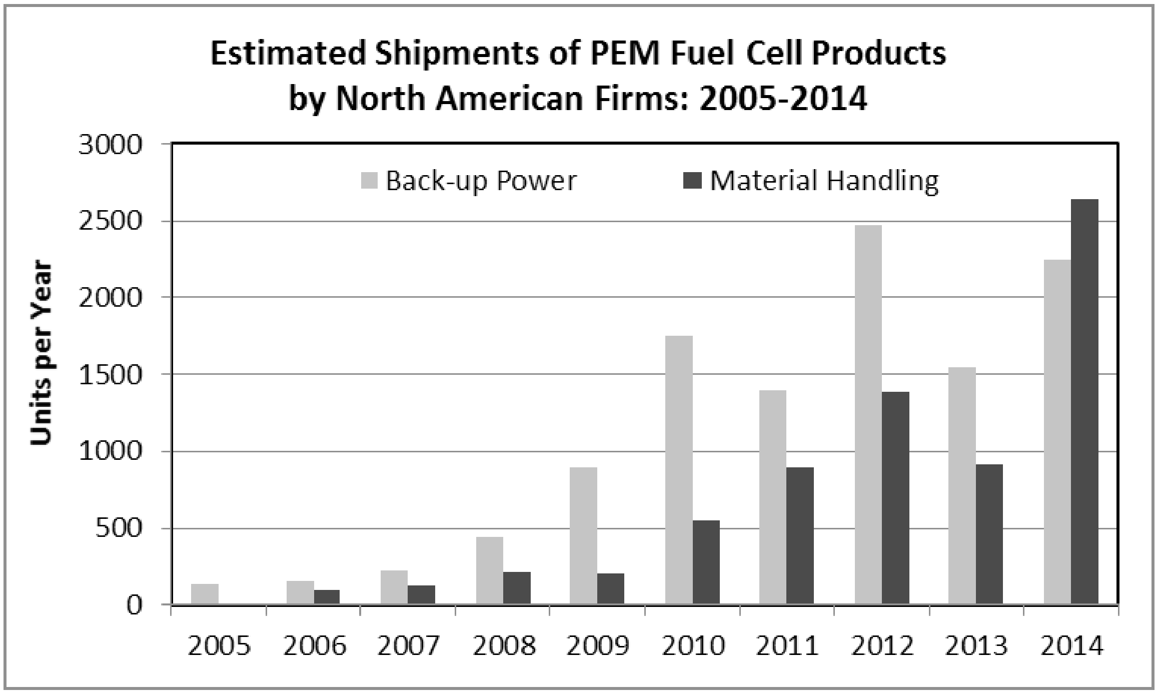


Figure 1. Estimated Shipments of PEM Fuel Cells for Backup Power and Material Handling Equipment

In 2009 the ARRA provided 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 Department of Energy reports that the ARRA partially funded sales of 524 MHE units and 824 BuP units (Table 1) (Devlin and Kiuru, 2015a; 2015b). The ARRA expenditures for fuel cell MHE support was $9.7 million, while the industry cost share was $11.8 million. The corresponding numbers for ARRA funded BuP sales were $18.5 million from DOE and $30.8 million from industry. In addition, the Department of Energy has subsidized 83 BuP units and 189 MHE units out of its departmental appropriations (Table 1). 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 MGE units without DOE support. All of these sales benefitted directly or indirectly from the ARRA deployments which enabled firms to reach higher production volumes and realize additional process improvements through learning by doing. The sales also benefitted from the ITC and in many cases state subsidies, as well.

Table 1. Fuel Cell Unit Sales (Delivered and Planned) by North American OEMs Since 2009

Equipment Type	DOE ARRA	DOE Budget	DOE Total	Industry	Total
Backup Power	824	83	907	5,568	6,475
Material Handling	524	189	713	8,340	9,053

Source: Devlin and Kiuru, 2015a and 2015b.

The distribution of sales co-funded by the ARRA by year is shown in Figure 2. In the peak ARRA years of 2010 and 2011, sales supported by ARRA co-funding were a large fraction of estimated total sales. In fact, the majority of MHE sales in 2010 are estimated to have been co-funded by the ARRA.

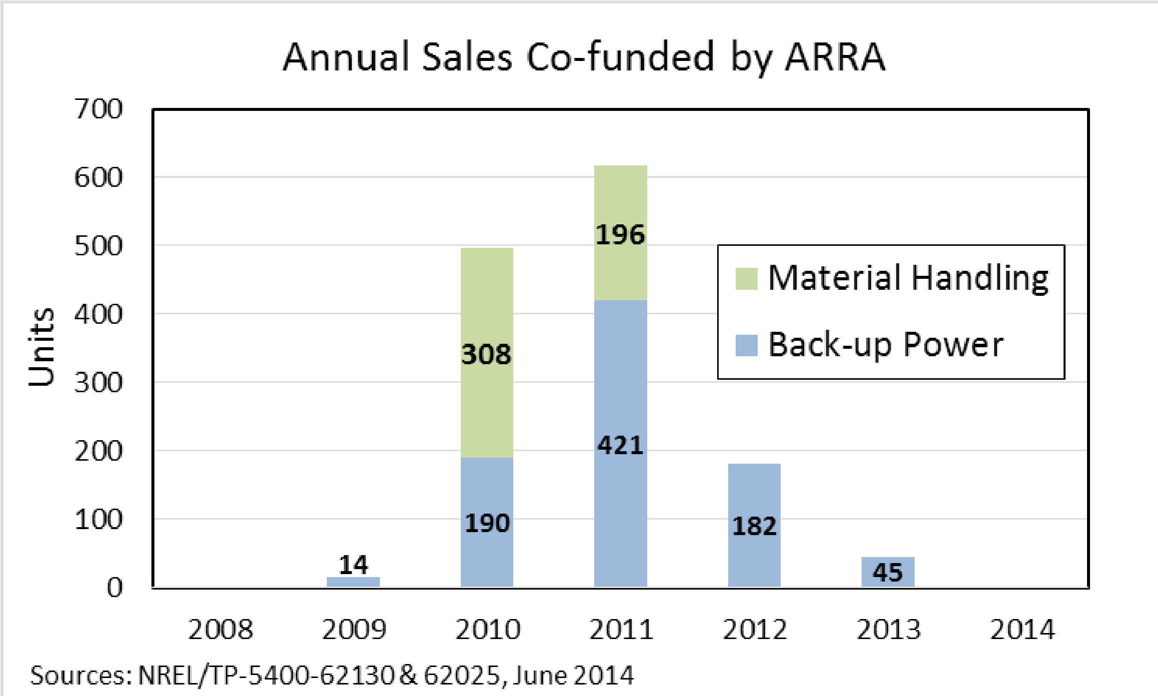


Figure 2. Annual Sales of Fuel Cell Material Handling and Backup Power Equipment Co-funded by ARRA.

Estimates developed for this study of total annual sales of BuP and MHE units by North American firms in 2010-2014 are shown in Figure 3. The numbers were obtained in discussions with OEMs and from published sources, including firms' annual reports, press releases and the trade press. Estimates of BuP sales for 2013-14 are known to be incomplete.

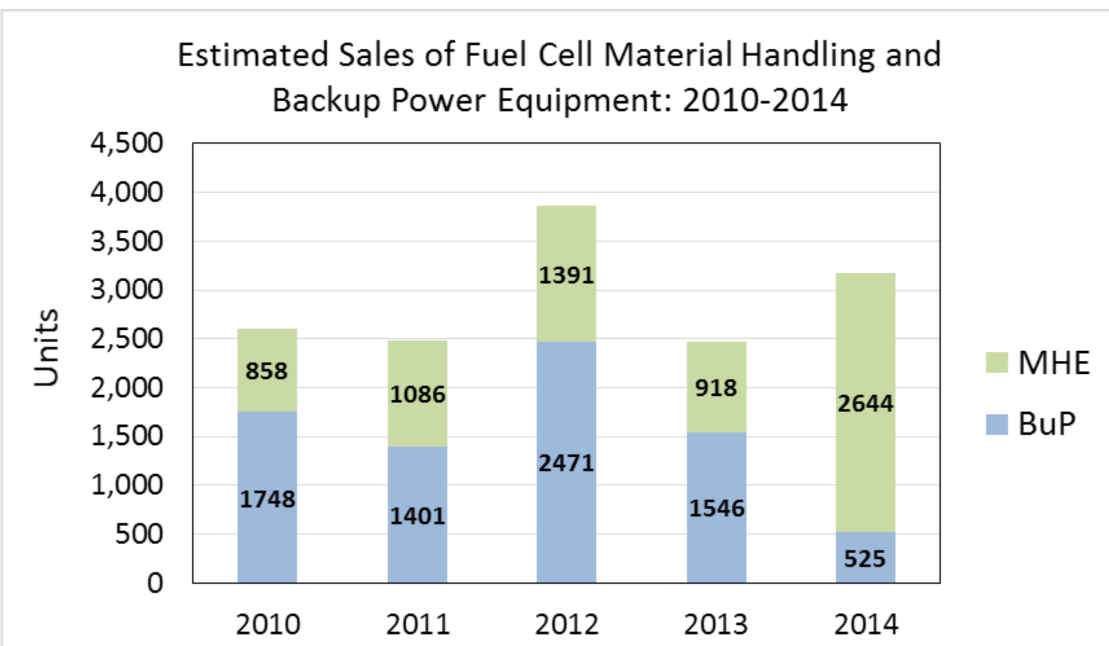


Figure 3. Estimated Sales of Fuel Cell Material Handling and Backup Power Equipment: 2010-2014.

III. MHE and Backup Power PEM Fuel Cell Costs and Benefits

Several important analyses of the costs of MHE and BuP fuel cell systems have been published since the 2011 report (e.g., Ramsden, 2013; Kurtz et al., 2014a). Contini et al. (2013) provide a detailed analysis of the manufacturing costs of a 10 kW fuel cell MHE unit. Although the class of the forklift in question is not given, the 10 kW power rating suggests that it is most likely a class I or possibly a class II forklift. After determining design requirements based on a market assessment, a detailed bill of materials was developed, manufacturing processes were specified and equipment requirements estimated. Component costs were estimated based on vendor quotes, material costs and assembly processes. All of these were reviewed by stakeholders and revised, if necessary. Costs were also estimated for a 25 kW MHE systems.

Other system costs consist of capital costs for stack manufacturing and system assembly and testing costs. Both decline rapidly with scale as largely fixed costs are spread over a larger number of units (Figure 4). Stack costs are driven by the cost of the membrane electrode assembly (MEA). MEA costs decrease with scale from $3,333 at 100 units/year to $2,964 at 1,000 and $2,415 at 10,000 units/year. The remaining stack manufacturing costs are almost insensitive to scale. The greatest economies of scale are estimated to be in the balance of plant (BoP). The largest cost components for the BoP are the battery, hydrogen storage tank, and DC/DC converter.

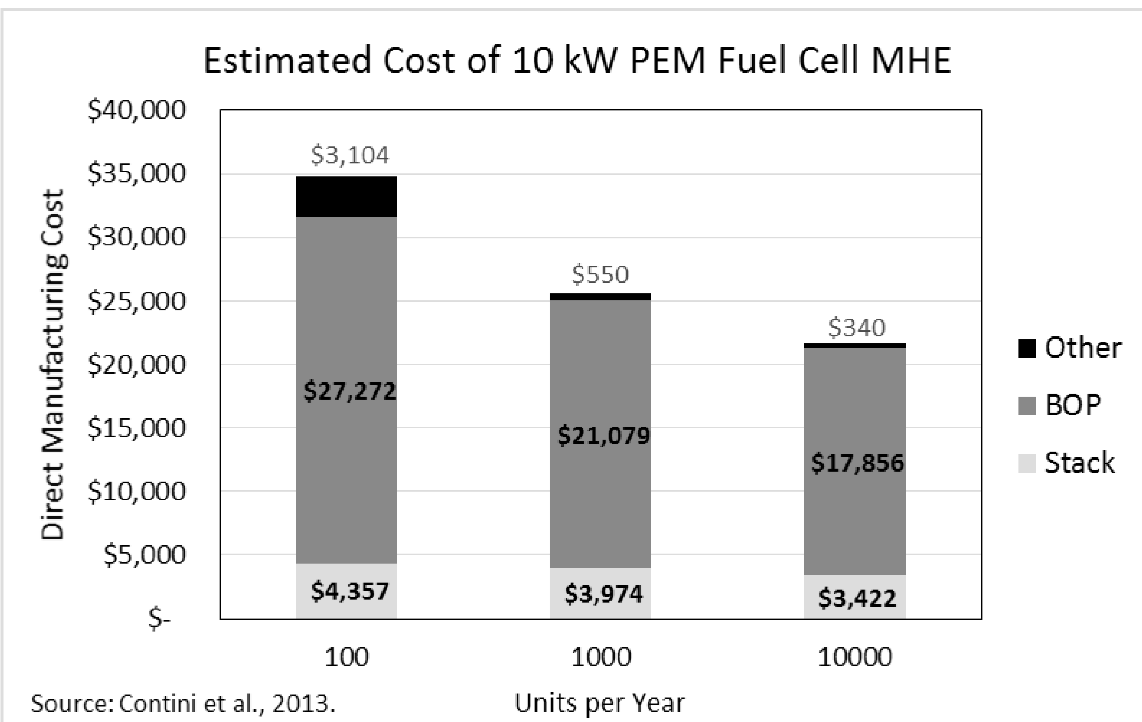


Figure 4. Estimated cost of 10 kW PEM Fuel Cell Material Handling Unit (Contini, et al., 2013).

All of the major components of the BoP appear to be subject to important scale economies, with the exception of the on-board hydrogen storage tank (Figure 5). Major components of the "Other" category are the humidifier, hydrogen recirculation system, and hydrogen regulator, radiator, blowers, and more. BOP components are rarely designed exclusively for application to PEM fuel cells. As a consequence, it is likely that costs will be reduced by learning and redesign as the industry expands and matures. Contini et al. (2013) identified the carbon fiber composite hydrogen storage tank as an important target for cost reduction. In fact, the industry has moved in this direction already, not only to reduce cost but also because the added weight of an all-steel tank is an advantage in forklifts since it helps counterbalance the weight of the payload. Contini et al. (2013) estimated the cost of a steel tank at $804 at a volume of 100 units/year, decreasing to $731 per tank at 10,000 units/year, a cost savings versus carbon fiber of over $2,500.

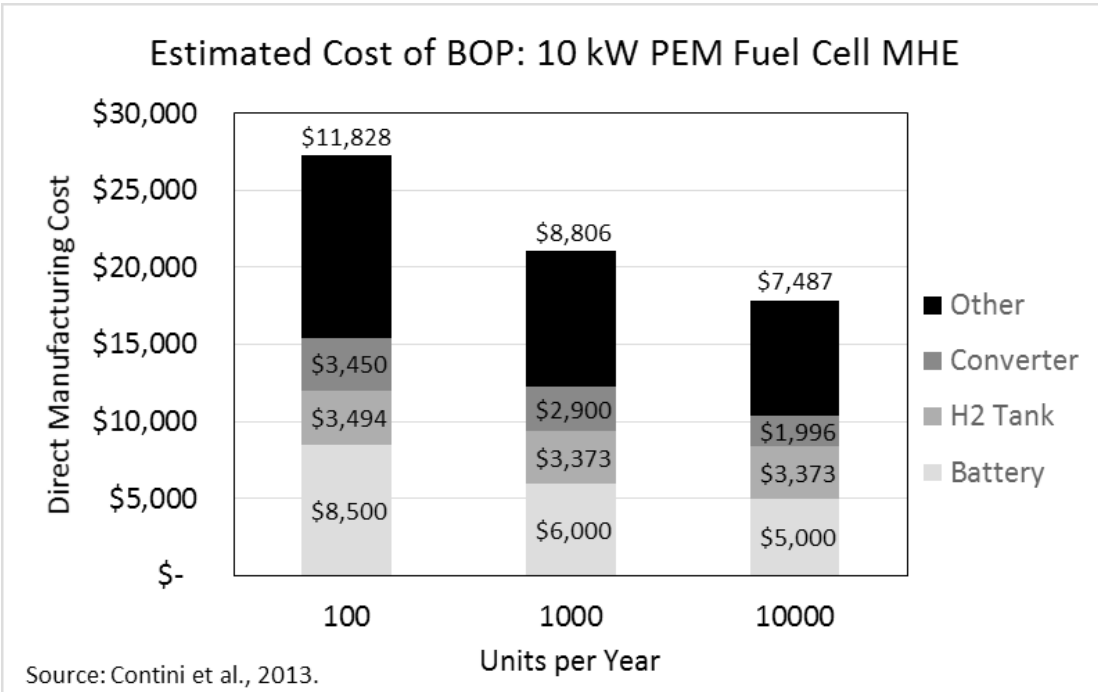


Figure 5. Estimated Cost of Balance of Plant for 10 kW PEM Fuel Cell MHE (Contini et al., 2013).

Even assuming an all-steel tank, the direct manufacturing cost of a complete 10 kW fuel cell MHE system (excluding the forklift and electric motor) was estimated to be $32,000 at a production volume of 100/year, $23,000 at 1,000/year and $19,000 at 10,000/year. Contini et al. (2013) assume a markup from direct manufacturing cost to retail price of 50%. While this is reasonable, it does not appear that to date the industry has been able to fully recover its indirect costs and return a normal rate of profit.

Other estimates of MHE fuel cell systems costs include Rhenquist et al.'s (2012) estimate of $11,000 for the fuel cell powerplant for a forklift. Although they do not specify the power rating of the forklift, it is intended to be comparable to a battery-powered forklift with a nameplate storage capacity of 50 kWh and 35 kWh of usable electricity, which suggests that it is most likely a class I forklift. Larriba et al. (2013), on the other hand, 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. These prices do not include the forklift truck. Both price estimates are dated, however. Larriba et al. (2013) cite a 2010 report by Ballard Power Systems as the source of their cost estimates, while Renquist et al. cite a 2010 U.S. Department of Energy model. Ramsden (2013) estimated the capital cost of fuel cell systems at $33,000 for class I and II forklifts and $15,000 for class III. HD systems (2015) 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 tank.

Kurtz et al. (2014a) estimated costs of BuP systems as a function of required run times ranging from 8 to 176 hours. Complete fuel cell unit costs ranged from $30,700 for the 8 hour system to $76,000 for a system capable of handling a 176 hour outage. HD Systems (2015) 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.

The Ramsden (2013), Kurtz et al. (2014a) and HD Systems cost estimates are compared in greater detail to the cost estimates adopted for this study in section VI.

Kurtz et al. (2014a) and HD Systems (2015) conclude that fuel cell BuP systems are roughly cost-competitive with battery and diesel generators today. In comparison to battery systems, the cost advantages of fuel cells increase as the duration of an outage increases. In areas where low emissions or quiet operation are especially important, fuel cell BuP systems have non-cost advantages over diesel generator systems (DOE, 2014). Potential advantages of fuel cells in BuP applications include longer run time, reduced maintenance, reduced noise and zero emissions (DOE, 2014). Much less frequent maintenance than either battery or diesel systems is cited as a key advantage of fuel cell BuP systems (Kurtz et al., 2014, table 1).

The degree to which hydrogen fuel cell MHE enables increased productivity versus battery-powered forklifts is an important factor in the economic competitiveness of fuel cell MHE. Qi (2013) states increased productivity of 15% and up to 30% lower operating costs. Although Qi (2013) does not provide a citation, these figures appear to come from Plug Power's literature. Dominguez et al. (2015) estimated a savings for fuel cell forklifts of 20 minutes per battery recharging event. Assuming two battery swaps per day, a 340 day year and a $24/hr. labor cost, this amounts to well over $5,000 per year in potential labor savings.

Testimonials by customers of Plug Power assert substantial productivity advantages. 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. On the other hand, the operator alone can refuel a fuel cell forklift in approximately 3 minutes without assistance from another employee.

> "With the GenDrive fuel cells, we are saving time and money. For the 98 units of equipment, we estimate that about 1,200 hours or approximately $24,000 is saved per fiscal quarter."[3]

On an annual basis the savings is roughly $1,000 per unit. United Natural Foods, Inc. also cited time savings as a key advantage of fuel cell MHE.

> "Additionally, it allowed us to eliminate the typical two to three battery changes per shift that would each take equipment operators between 12 and 30 minutes to complete before they could get back to the floor."[4]

UNFI estimated the cost of battery charging time for 160 operators at $1,900 to $3,000 per week, while the cost of refueling fuel cell MHE was estimated to be only $176 per week, for a total estimated savings

[3] This implies a savings of approximately $1,000 per truck per year or roughly 10 minutes per day (50 hours per year for a 300-day year). Sysco Houston also noted that the failure to charge a battery causes a significant disruption of a work schedule, failure to refuel a fuel cell forklift does not.

[4] For a three hundred day operating year and two changes per day, this implies a time savings of approximately 100 to 250 hours per forklift per year.

of $146,000 (or about $900 per operator per year). Wegmans Food Markets, Inc. also reported savings on equipment and maintenance.

> "We have saved over $250,000 on equipment and expect to save another $250,000 through the overall term of the service and maintenance contract."

With 127 fuel cell forklifts in operation this is nearly $2,000 per forklift for equipment and $2,000 anticipated savings on service and maintenance. Wegmans reported savings of 42% to 48% over battery operated MHE and anticipated savings of 65% once their conversion to fuel cell was fully implemented.

The Plug Power testimonials also cite the environmental benefits of fuel cell MHE. VW and BMW who are using fuel cell MHE at their manufacturing facilities emphasize 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 assigned a value in the technology choice models used in this study. Rather we interpret these 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. Firm-specific utilities imply that even at equal annualized costs, some firms will prefer fuel cells while others prefer batteries.

IV. The Non-Automotive Fuel Cell Market Model

Analysis of the impacts of the ARRA and ITC was carried out using the North American Non-Automotive Fuel Cell Market Model. The model's structure is illustrated in Figure 6 and a brief description of the model is provided here. The model is described in greater detail in Greene et al. (2011) and Upreti et al. (2012). The first step is calculation of an equivalent annualized cost (EAC) for each technology in the Cost Analysis module. Capital investments are translated into annual costs based on their expected lifetimes, L, and the cost of capital, r, by dividing by an annuity factor, A.

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

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 a time-dependent R&D effect.

Component Cost = (Reference Cost) x (Learning Effect) x (R & D Effect) (2)

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

System Cost = [(Stack Cost) + (Reformer Cost) + (BoP Cost)] x [(OEM Scale) x (OEM LBD) x (OEM R&D)] (3)

The size, Q, of the potential market is estimated from annual sales data, if available, or calculated by dividing the total number of units in use by the expected lifetime of a unit.

$$Q = \text{(Market Size)/(Expected Life)} \quad (4)$$

Annual sales of FC systems are assumed to equal the addressable market size times a market share function that depends on the EAC of the FC system and of its competition. Less tangible attributes, such as better environmental performance, could be represented by an alternative-specific constant term, A_i, where i indexes the choice alternatives. However, the analyses in this study do not include intangible factors. 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 specific to firm j and alternative i. 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.

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

Multinomial logit (MNL) choice models are used to estimate the market share of FCs as a function of their generalized cost and that of their competition. The probability that a fuel cell BuP system would be chosen over battery (b) or diesel generator (d) alternatives, for example, is given by the following equation.

$$P_{FC} = \frac{e^{A_{FC}+BG_{FC}}}{e^{A_{0b}+BG_b} + e^{A_d+BG_d} + e^{A_{FC}+BG_{FC}}} \quad (6)$$

Given estimates of the total market size for each of the different types of equipment, Q_{BuP}, Q_{MH}, and Q_{mCHP}, Q_{CHP} , sales of FCs are computed by multiplying the total annual market size by the logit probabilities.

$$Q_{FC} = Q\rho_{FC} \quad (7)$$

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 (the total annual volume of production X_t divided by the number of manufacturers, N) divided by the reference volume x_o 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 8.

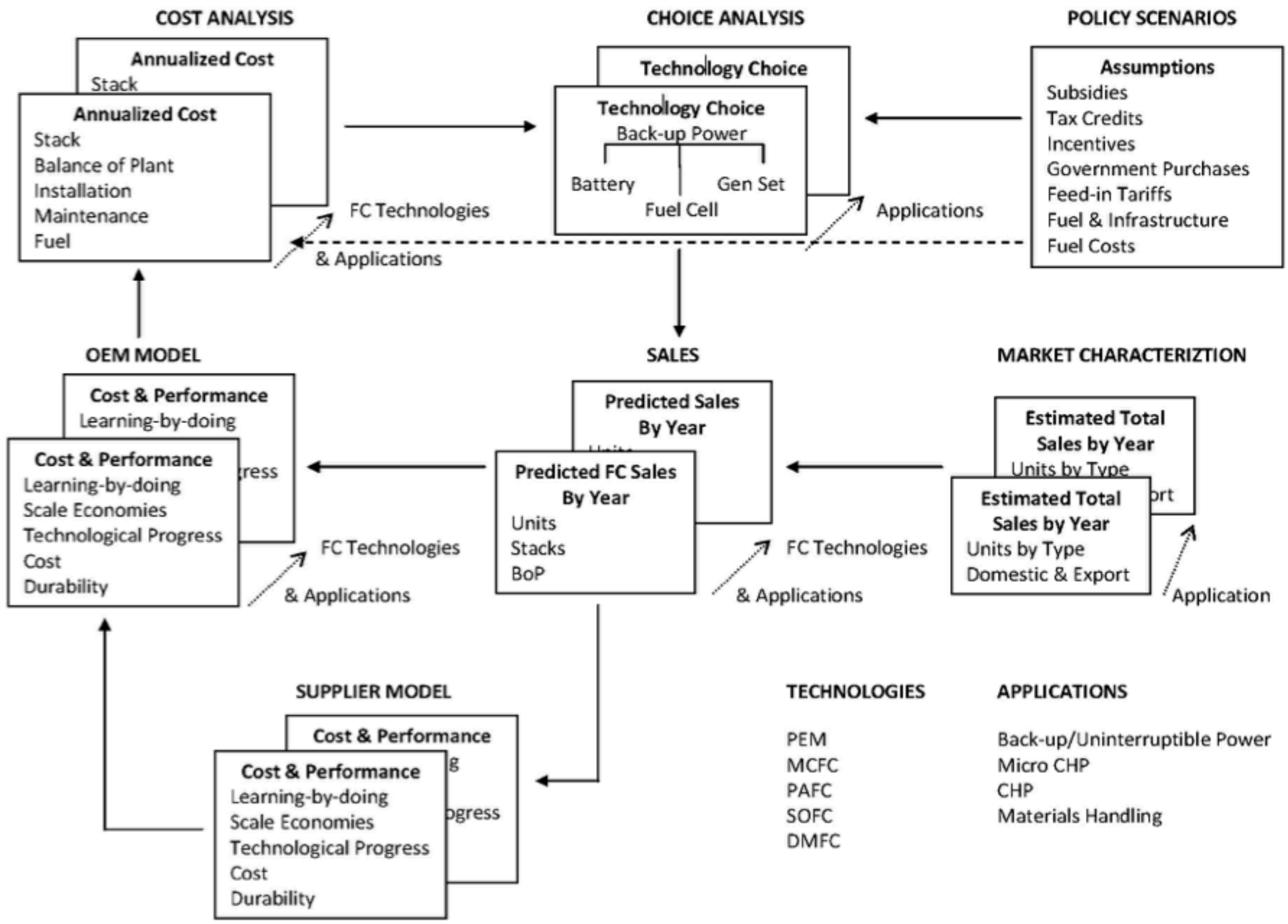
$$\text{If } \frac{X_t}{N} = x_t \geq x_{\max} \text{ then } \left(\frac{x_{\max}}{x_0}\right)^{\eta} \text{ otherwise } \left(\frac{x_t}{x_0}\right)^{\eta} \quad (8)$$

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

$$P_t = P_0 X^{-\lambda} \tag{9}$$

The flow of the market model is illustrated in Figure 6. EACs are calculated in the Cost Analysis module for each FC technology and application, as well as for the main competitors. Expected lifetimes vary by component (e.g., stack vs. BoP) but a uniform 10% cost of capital is used throughout. EACs in years before 2015 are input data. Costs in future years are determined by the prior year's production volumes (scale), cumulative production (learning) and exogenous technological progress (time). EACs are also influenced by policies that change the capital and operating costs of FCs, either directly through tax credits or other incentives or feed-in tariffs, or indirectly via government purchases or induced sales. Policy assumptions are specified in the Policy Scenario spreadsheet.

EACs from the Cost Analysis model are passed to the Choice Model, in which market shares are estimated based on EACs of fuel cells and competitive systems. For each technology, a price elasticity of -2 at 50% market share is assumed. Price elasticities are a function of price and market share; at lower market shares typical of FC technologies, price elasticities are much higher. Market shares from the Choice Model are passed to the Sales spreadsheet, where they are multiplied by estimates of 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 combined into cost multipliers which are then passed back to the Cost Analysis spreadsheet. Individual cost multipliers are calculated for PEMFC stacks, and for the manufacture of each PEMFC application



Predicting sales for new industries selling chiefly to early adopters is challenging. It may be possible to improve models by evaluating past predictions and incorporating more recent information about market conditions and model parameters. Sales predictions made by the 2011 study are compared with estimated actual sales for MHE in Figure 7 and BuP in Figure 8. Given the many factors influencing sales from 2010 to 2014, such as the ARRA and industry consolidation, the MHE projections seem reasonable but generally underpredicted estimated actual sales. BuP projections, on the other hand, generally overpredicted estimated actual sales, although the data for 2013 and 2014 are incomplete due to the absence of data for one firm in 2013 and two firms in 2014. In both cases the model's predictions are of the correct order of magnitude but not much better than +/- 50% for any given year.

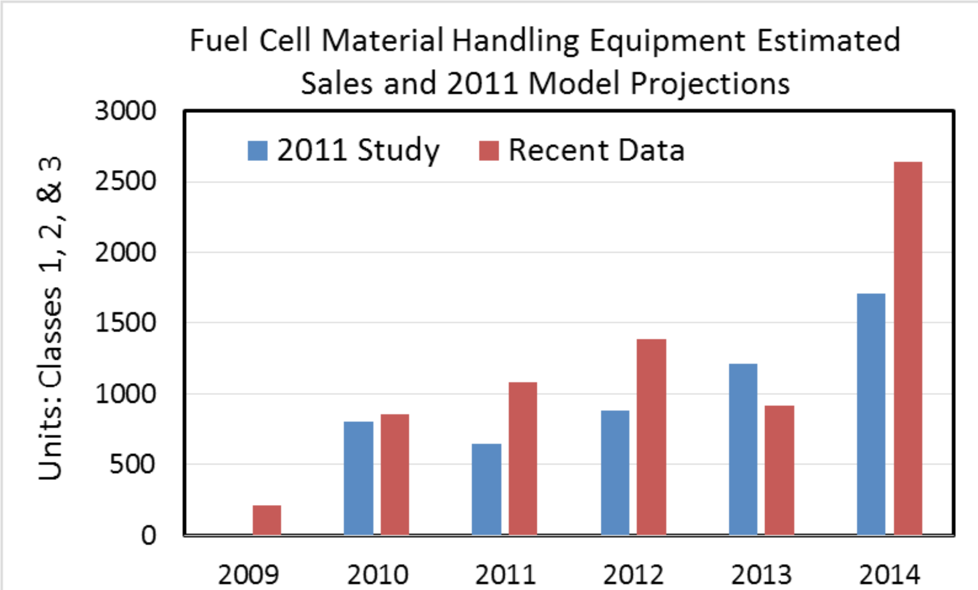


Figure 7. Fuel Cell Material Handling Equipment Estimated Sales and 2011 Model Projections

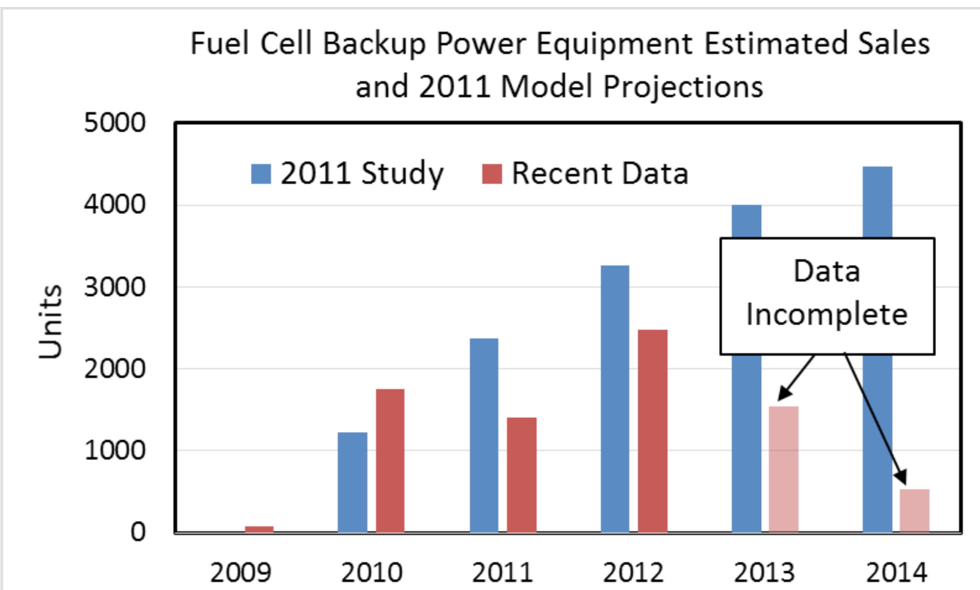


Figure 8. Fuel Cell Backup Power Equipment Estimated Sales and 2011 Model Projections

The more recent cost analyses cited above and discussions with OEMs indicate that key parameters in the 2011 model 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. HD Systems (2015) cost estimates are consistent with scale economies for fuel cell stack production in the range of -0.07 to -0.1. This range is also consistent with Wei et al.'s (2013) analysis of scale economies for a much larger 50 kW PEM backup power system. Their estimates imply a scale elasticity of -0.19 for the transition from 100 to 1,000 units per year but declining to -0.07 for the transition from 1,000 to 10,000 units and to -0.044 when increasing from 10,000 to 50,000 units. Thus, using a constant elasticity of -0.2 substantially overestimates the impacts of scale elasticities for production volumes above 1,000 units per year. For fuel cell stacks for material handling equipment, cost estimates by Contini et al. (2013) imply scale elasticities of -0.04 for the transition from 100 to 1,000 and -0.07 for the transition from 1,000 to 10,000 units per year. Scale elasticities inferred from their cost estimates for the balance of plant are -0.11 for 100 to 1,000 units per year and -0.07 for 1,000 to 10,000. As a consequence of this new information, the model's scale elasticities were adjusted downward from -0.2 to -0.15.

Estimates of progress ratios were also adjusted downward, based largely on confidential discussions with OEMs. The 2011 study assumed a learning parameter of $\lambda = -0.15$, which implies a progress ratio of 0.90 (a 10% reduction in cost with every doubling of cumulative production). OEMs, however, think of learning in terms of production process and design changes incorporated in discrete product "generations". A typical pattern of cost reduction due to learning for succeeding generations of fuel cell MHE systems is shown in Figure 9. As a consequence, the progress ratio for fuel cell systems was increased to 0.95 (a 5% reduction in cost with each doubling of cumulative production).

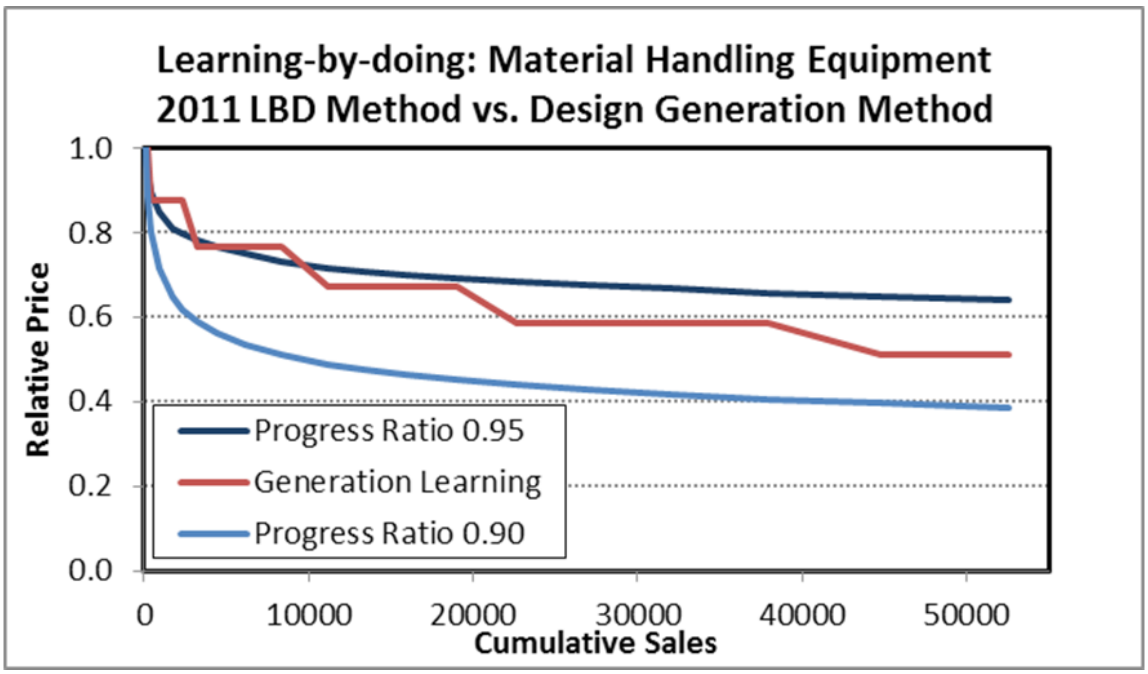


Figure 9. Learning by Doing in Fuel Cell MHE Systems: Comparison of Continuous and Generational Learning.

At the same time, the 2011 study assumed that time-dependent technological progress (independent of scale or cumulative production) would occur at the rate of 1% per year for both stacks and systems. Discussions with OEMs indicated cost reductions of 10-15% per product 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. The faster rate of 3%/year for BuP and MHE systems was incorporated in the updated model.

The recalibrated model predicts a price of $33,000-34,000 for the MHE stack and balance of plant in 2010 but with a wide range of uncertainty (Figure 10). Prices and uncertainty decline sharply in 2011 and continued progress is predicted through 2014. The prediction for 2013 ($17,000) is close to HD System's (2015) estimate of $15,000-16,000 for a complete MHE fuel cell system in that year, based on manufacturer interviews, company annual reports and other public sources. In contrast to Contini et al. (2013), HD Systems (2015) assumes that the markup over direct manufacturing cost for a fuel cell OEM unit was only 10-15% because market conditions in 2013 did not allow full cost recovery.

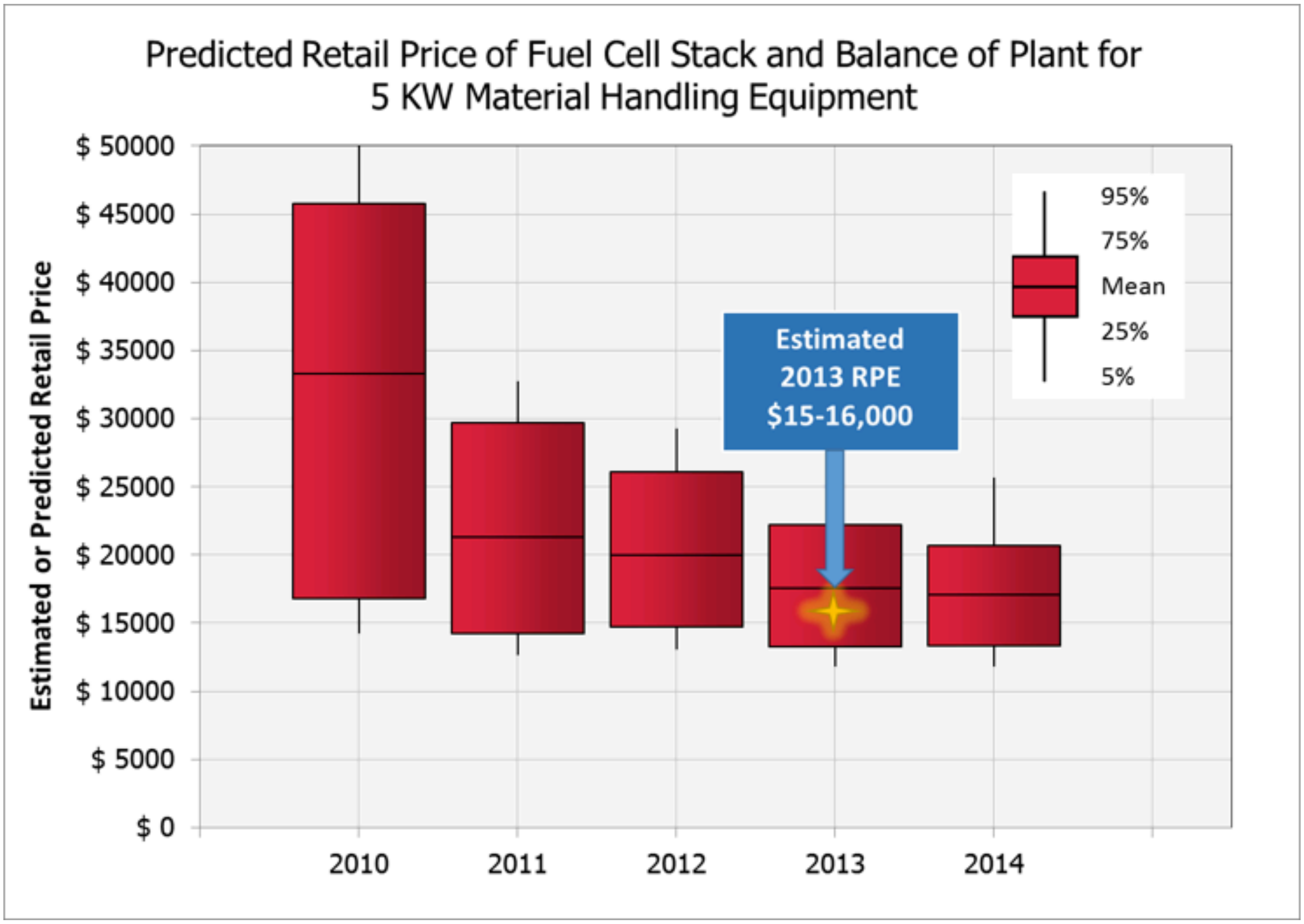


Figure 10. Predicted Retail Price of Fuel Cell Stack and Balance of Plant for a Representative 5 kW Forklift.

The recalibrated model also slightly overpredicts the price of fuel cell BuP systems in 2013, compared to HD Systems (2015) estimate of $11,000 to $11,500 (Figure 11). Once again, the HD Systems estimate assumes that firms are not yet able to fully recover their indirect costs.

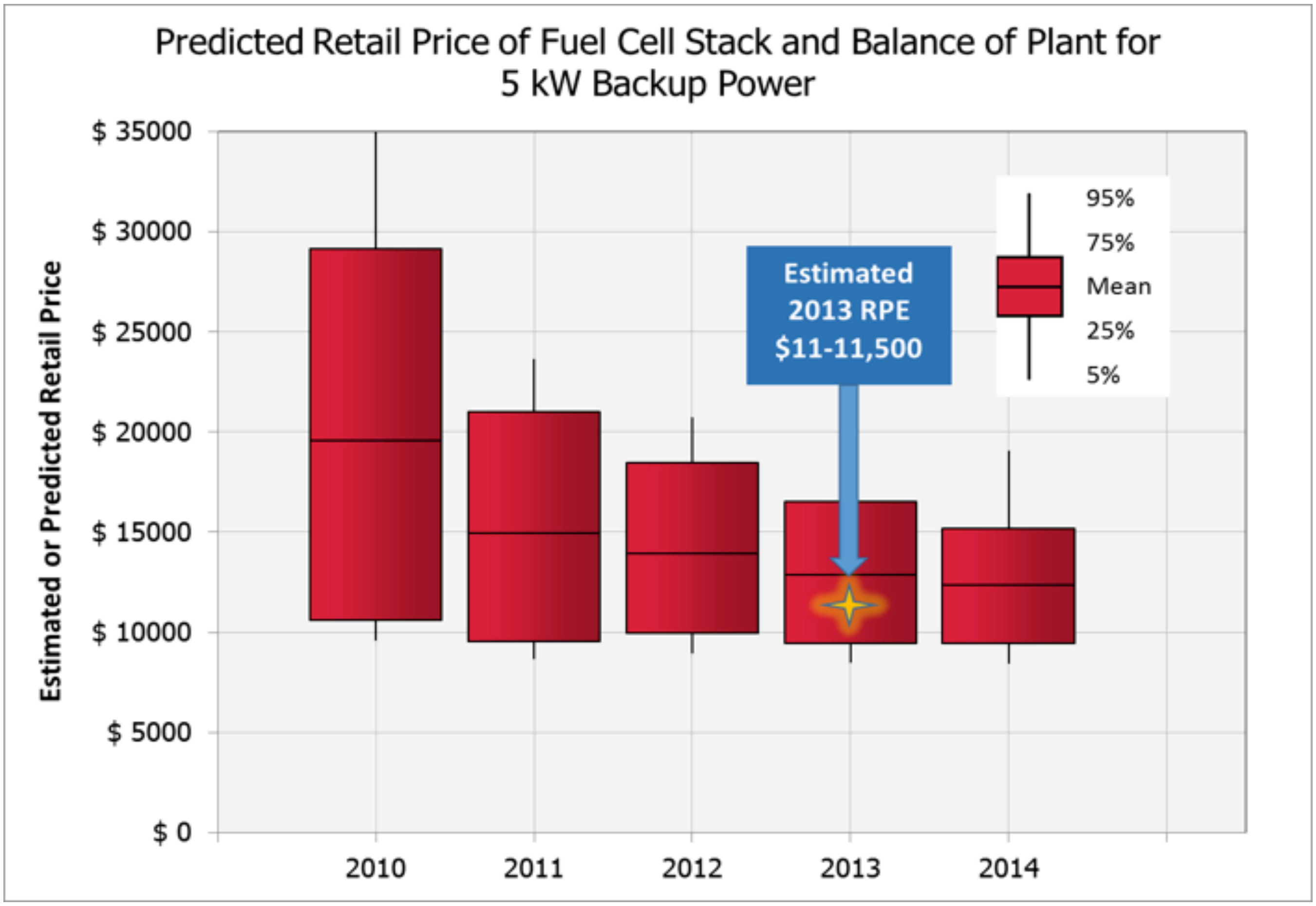


Figure 11. Predicted Retail Price of Fuel Cell Stack and Balance of Plant for a Representative 5 kW Backup Power Unit.

V. Estimating ARRA and ITC Impacts

To estimate the impacts of ARRA subsidized purchases, the model was used in a back-casting mode. The actual historical case is fuel cell system sales with ARRA while the counterfactual historical case is without ARRA-subsidized purchase. Initially, the ARRA purchases were assumed to be exogenous to the model. For the years 2009-2013, the model was calibrated to exactly predict the total purchases of BuP units minus ARRA deployments and, separately, MHE units minus the ARRA deployments. The implication (relaxed in subsequent sensitivity analysis) is that none of the ARRA-subsidized purchases would have occurred in the absence of the ARRA program. The method can be summarized in three steps.

1. Calibrate the choice model to exactly predict non-ARRA purchases in 2009-2013 but allowing the total sales in each year (including ARRA-subsidized purchases) to influence scale and learning effects.
2. Zero out the ARRA deployments and predict what non-ARRA sales would have been without them. This eliminates the added scale economies and learning-by-doing induced by 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 to the utility functions of the fuel cell MHE and BuP options (the Ai in equation 5). Because the ARRA sales were included in the calculation of scale economies and learning by doing, the equipment prices to all purchasers were somewhat lower than they would have been without the ARRA subsidies. Because the scale economies and learning effects 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 then used to predict annual sales from 2010 to 2025. Because of the calibration procedure, the model exactly predicted the estimated sales from 2006 to 2014.

At the same time, the model was 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. These capital costs are shown in tables 2 and 3 under the heading "This Study".

A key premise of the method described above is that all of the ARRA sales are additional. That is, 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 scale economies and learning effects induced by the ARRA purchases, the assumption of 100% additionality is probably not far off the mark. However, the sensitivity of the predicted impacts to alternative assumptions about additionality was tested by assuming that an upper bound of 50% of the ARRA-supported fuel cell purchases would have occurred even without the ARRA subsidies. This was accomplished 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 procedure described above. The results indicated that the ARRA's impacts decrease approximately linearly with the percent of sales re-assigned to the non-ARRA category.

In the opinion of the authors, the great majority of ARRA subsidized sales was probably additional. Furthermore, the model does not attempt to reflect the effects of the ARRA sales on firms' aversion to the riskiness of a novel technology like hydrogen fuel cells or the increased diffusion of information resulting from more firms having experience with hydrogen fuel cell powered equipment. Such phenomena are real and generally important to the diffusion of novel technologies although their effects are difficult to measure.

VI. Data and Assumptions

This section reviews changes in data and assumptions adopted in the updated Non-automotive Fuel Cell Market Model. As noted above, recent studies provide much better information about economic and operational factors than was available when the 2011 study was carried out. Data and assumptions used in this study are derived primarily from HD Systems (2015), Kurtz et al. (2014a) and Ramsden (2103). In comparing cost estimates from those studies with the ones adopted in this analysis, the original studies' operational assumptions are retained but a uniform cost of capital of 10%/year is assumed.

For MHE, the number of shifts and the intensity of forklift use during a shift are critical determinants of the fuel cell's economic competitiveness. HD Systems (2015) assumes moderate intensity of use (3.5 hours per shift) and two shifts per day which could enable opportunistic recharging during breaks and idle time. As a result, HD Systems estimates that a single battery pack is sufficient for one forklift.

Based on responses to questionnaires from seven sites participating in ARRA subsidized fuel cell forklift deployments, Ramsden (2013) estimated an average of two battery packs per forklift. The facilities surveyed operated 2 or 3 shifts per day (2.25 on average) and, like HD System's (2015) assumptions, averaged 2,400 hours and 340 days of operation per forklift per year (3.5 hours per shift, assuming two shifts per day). The cost implications of these two different sets of assumptions are large, in terms of labor and capital costs. Ramsden's (2013) assumptions are supported by data obtained from forklift operations and are also consistent with testimonials by firms operating fuel cell forklifts (Plug Power, 2015). Although data from a comprehensive, statistically-designed survey of forklift operations would be preferable, no such data exist and so the models used in this report are therefore calibrated using the premises of Ramsden (2013) which appear to be based on the best available data. Incumbent technologies typically improve when challenged by a new competitor, however, so the possibility that future battery systems could more closely resemble HD Systems' assumptions cannot be dismissed.

Labor costs are a key factor in the competition between fuel cell and battery forklifts. Based on a survey of 7 different forklift operations, Ramsden estimated an average of 10.5 minutes for a battery swap and 3 minutes to refuel with hydrogen. Renquist et al. (2012) estimate 15 minutes and 5 minutes, respectively for the same operations. Larriba et al. (2013) report 10-30 minutes to complete a battery change and 3-5 minutes for hydrogen refueling, including time traveling to the recharging location and waiting time. Assuming automated battery charging, HD Systsems (2015) estimates that both battery and fuel cell forklifts require 3 minutes or less to complete the processes.

HD Systems (2015) asserts that for intensive use applications the most appropriate competitor for fuel cell forklifts is the battery forklift with automated battery swapping. It estimates that automated battery swapping equipment costing $400,000 can support 50 forklifts and can replace a depleted battery with a fully charged battery in under two minutes. Although the automated swapping equipment adds capital cost, it also reduces the labor required to swap batteries. HD Systems also contends that modern forklift trucks are equipped with AC motors with voltage-regulated inverters that eliminate the effect of battery voltage droop as the battery approaches depletion. These assertions are not supported by other sources, however. Trends in battery MHE technology should be monitored since incumbent technologies tend to respond to challenges by improving.

The cost assumptions used in this study are compared with two recent, comprehensive assessments of fuel cell MHE costs in table 2 (HD Systems, 2015; Ramsden, 2013). HD Systems (2015) assessed costs of a hypothetical 5 kW MHE unit, the same size used in this study. Ramsden (2013) 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. Both studies also estimated costs for equivalently capable battery powered forklift. Ramsden (2013) based his operational assumptions (fleet size, number of shifts, etc.) on data provided by firms operating over 600 forklifts co-funded by the DOE and Defense Logistics Agency (DLA). HD Systems' (2015) assumptions are based on interviews with MHE fuel cell manufacturers and published sources.

The assumptions used in this study are similar to the other two studies, which do not agree on all points. This study uses a slightly higher cost of labor than the other two studies. It assumes a $34,000 annual salary, 1,840 active labor hours per worker per year, and employers' total overhead of 50% on wages (including payroll tax, benefits and other indirect costs). The labor time required for hydrogen refueling and swapping a battery pack includes travel to the change location and refueling or recharging time. HD Systems asserts that modern, automated battery changing equipment can replace a forklift battery in the same time required to refuel a fuel cell forklift. However, as noted above, firms that have deployed fuel cell forklifts report labor-time savings similar to those used in this study and Ramsden (2013). Until documentation of the costs and benefits of automated battery swapping is available, substantial time savings are assumed. In table 2, HD Systems' estimates have been replaced with those used in this study for the purpose of comparing total annualized cost estimates on an equivalent basis. Annual labor costs for battery exchanges are estimated to be about three times the labor cost of hydrogen refueling and are large relative to the annualized costs of owning and operating the MHE units.

The purchase price of the fuel cell plus BoP plus hydrogen tank, controls and battery ($23,800) falls between the HD Systems estimate ($26,450) and synthesized 5 kW estimate based on Ramsden ($21,000). The maintenance cost assumptions used in this study are based on Ramsden's estimates, rounded to the nearest $100. HD Systems reports lower battery maintenance costs because it assumes only one battery pack is required per day due to an assumed availability of "opportunity charging". HD Systems' fuel cell maintenance costs are almost twice Ramsden's. Ramsden's are used here because they are based on data obtained from actual operations. Infrastructure costs for this study are based on Renquist et al. (2012) who provide detailed costs estimates by type of equipment. Note that the capital costs are distributed over an assumed fleet of 50 forklifts. The annualized costs for hydrogen infrastructure are substantially lower than those reported by Ramsden but much higher than HD Systems' estimates. Battery infrastructure costs based on Renquist et al. (2012) are lower than both Ramsden and HD Systems. Energy use assumptions are again based on rounding Ramsden's estimates but a higher price of hydrogen, $10/kg, is assumed. Again, Ramsden's estimates are preferred over HD Systems' higher energy use estimates because they are based on data from actual operations.

Annualized costs assume a 7.5 year lifetime for the fuel cell MHE components and 10 years for hydrogen infrastructure. Battery life is set at 4 years and recharger life at 5, which is similar to both HD Systems' and Ramsden's assumptions. MHE life is assumed to increase over time reaching 10.5 years by 2025. A 10% cost of capital is assumed in all cases.

Total annualized fuel cell costs are very close to the synthesized 5 kW unit based on Ramsden's estimates but almost $5,000/yr. lower than the estimates based on HD Systems. Almost all of the $5,000 difference can be attributed to the cost of hydrogen. The annualized cost of battery forklifts is higher in this study due to mainly to higher recharging labor costs and higher battery capital costs. Battery capital costs would have been nearly identical to HD Systems if that study had assumed two battery packs per MHE unit instead of one.

The cost estimates for BuP systems (fuel cell, battery and diesel) were developed in a similar manner by comparing cost estimates from HD Systems (2015) and Kurtz et al. (2014). The costs of fuel cell BuP systems were compared to battery and diesel systems by Kurtz et al. (2014c) and HD Systems (2015). HD Systems (2015) presents estimates for a 5 kW BuP system, although it notes that modern 4G telecom towers require only about 2.5 kW. Kurtz et al. (2014) collected and analyzed data on 134 of the 1,300 BuP units partially funded by the ARRA. Of these 78% were rated at between 4 and 6 kW, although a few were larger than 10 kW. As a consequence, Kurtz et al. developed estimates for a 4-6 kW BuP system, which should correspond to the 5 kW BuP unit represented in the model used in this report.

In the case of BuP, HD Systems' estimates are adopted with the exception of the cost of hydrogen for which Kurtz et al.'s estimate of $10/kg is adopted (table 3). The capital cost estimates of Kurtz et al.

(2014) were not used for several reasons. Kurtz et al. assume a much more powerful diesel generator (25-35 kW) than is required to provide the required 4-6 kW of electrical power and it is therefore much more costly. 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. Kurtz et al.'s BoP costs also include permitting and other site costs not included in this study. Finally, Kurtz et al. assess costs for outages of different durations ranging from 8 hours to 176 hours but assume only one outage per year. The data for the 8 hour shortage are shown in table 3. HD Systems assumes several outages of short duration which is a much more likely scenario for the U.S. market. A consequence of using the HD Systems estimates is that the total annualized costs used in this study are much lower than Kurtz et al. for all three BuP systems (approximately half). The relative costs are similar, except for Kurtz et al.'s oversized diesel generator.

Table 2. Comparison of Recent Estimates of the Annualized Cost of Battery and Fuel Cell Systems for Material Handling Equipment.

Material Handling Equipment Assumptions (2013/4)											
								Classes I & II MHE 8-10 kW		Class III MHE <3 kW	
		This Study		HD Systems (2015)		Synthetic 5 kW MHE		Ramsden (2013)		Ramsden (2013)	
	Units	Battery MHE	Fuel Cell MHE	Battery MHE	Fuel Cell MHE	Battery MHE	Fuel Cell MHE	Battery MHE	Fuel Cell MHE	Battery MHE	Fuel Cell MHE
OPERATIONS											
Number of Forklifts		50	50	50	50	97.00	58.00	97	58	97	58
Number of Shifts		2.0	2.0	2.0	2.0	2.1	2.1	2.3	2.3	2.0	2.0
Refuel/Recharge/Shift		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Operating Hrs./Shift	hrs.	3.5	3.5	3.5	3.5	4.1	4.1	3.5	3.5	4.4	4.4
Days of Operation	days	340	340	300	300	340	340	340	340	340	340
Labor Cost	$/hr.	$ 28.00	$ 28.00	$ 24.00	$ 24.00	$ 24.00	$ 24.00	$ 24.00	$ 24.00	$ 24.00	$ 24.00
Refueling/charging Time	hrs.	0.25	0.08	0.25	0.08	0.21	0.08	0.24	0.11	0.20	0.07
Annualized Refueling Cost	$/Lift	$ 4,760	$ 1,587	$ 3,600	$ 1,200	$ 3,579	$ 1,426	$ 4,376	$ 1,928	$ 3,210	$ 1,197
STACK/BATTERY											
Price	$	$ 5,350	$ 10,800	$ 5,100	$ 11,500	$ 3,467	$ 21,000	$ 4,800	$ 33,000	$ 2,800	$ 15,000
Batteries/Stacks per Lift		2	1	1	1	2	1	2	1	2	1
Lifetime	yrs.	4.0	7.5	4.0	7.5	4.5	9.3	4.4	10.0	4.5	9.0
Cost of Capital	%/yr.	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%	10.0%
Annualized Stack/Battery	$/Lift	$ 3,376	$ 2,115	$ 1,609	$ 2,252	$ 2,000	$ 3,564	$ 2,803	$ 5,371	$ 1,606	$ 2,605
BALANCE OF PLANT											
Price	$		$ 5,700		5750	Included in stack cost, above.		Included in stack cost, above.		Included in stack cost, above.	
Lifetime	yrs.		7.5		7.5						
Cost of Capital	%/yr.		0.1		10.0%						
Annualized BoP	$/Lift		$ 1,116		$ 1,126						
TANK+CONTROLS+BATTERY											
Price			$ 7,300		9200	Included in stack cost, above.		Included in stack cost, above.		Included in stack cost, above.	
Lifetime			7.5		7.5						
Cost of Capital			0.1		10.0%						
Annualized T+C+B	$/Lift		$ 1,429		$ 1,801						
OTHER MHE											
Maintenance	$/yr	$ 1,500	$ 1,100	$ 1,100	$ 2,015	$ 1,467	$ 1,067	$ 3,600	$ 2,200	$ 400	$ 500
Productivity Advantage	%/shift	0%	0%								
Intangible ("Green")	$/yr.	$ -	$ -								
Annual Other	$/Lift	$ 1,500	$ 1,100	$ 1,100	$ 2,015	$ 1,467	$ 1,067	$ 3,600	$ 2,200	$ 400	$ 500
INFRASTRUCTURE											
Refueler/Recharger	$	$ 2,700	$ 340,000	$ 4,200	$ 1,700	$ 1,767		$ 2,800		$ 1,250	
Units/Lift		1	0.02	1	1	1.10	-	1.1	-	1.1	1
Lifetime	yrs.	5	10	5	10	6.50	-	7.5	-	6	1
Cost of Capital	%/yr.	10.0%	0.1	10.0%	10.0%	10.0%	-	10.0%	-	10.0%	1
Maintenance	$/yr		$ 13,000			$ 900		$ 900	-	$ 900	$ 3,700
Annualized Infrastructure	$/Lift	$ 712	$ 1,367	$ 1,108	$ 277	$ 1,411	$ 3,639	$ 1,593	$ 3,517	$ 1,306	$ 3,700
ENERGY											
Cost	$/kg, $/kWh	$ 0.10	$ 10.00	$ 0.100	$ 13.00	$ 0.08	$ 8.00	$ 0.075	$ 8.00	$ 0.075	$ 8.00
Usage Rate per Hour	kg, kWh/hr.	2.0	0.125	3	0.286	1.98	0.09	2.4	0.17	1.8	0.06
Annual Energy Cost	$/Lift	$ 476	$ 2,975	$ 630	$ 7,800	$ 433	$ 1,799	$ 495	$ 2,500	$ 394	$ 1,396
TOTAL ANNUALIZED COST		$ 10,824	$ 11,688	$ 8,047	$ 16,471	$ 8,890	$ 11,495	$ 12,866	$ 15,516	$ 6,915	$ 9,397
Stack life of 20,000 hrs., 2.25 shifts/day, 340 days/yr., 3.5 hrs. use per shift.											
Numbers for the Synthetic 5 kW MHE are a weighted average of class I, II and class III, assuming that two thirds of the fuel cell MHE units are class III.								67% of fuel cell MHE sales assumed to be class III.			

Table 3. Comparison of Recent Estimates of the Annualized Cost of Battery and Fuel Cell systems for Backup Power.

Backup Power Assumptions (2013/14)																			
		This Study						HD Systems (2015)						Kurtz et al. (2014)					
		Battery BuP		Fuel Cell Bup		Diesel Generator		Battery BuP		Fuel Cell Bup		Diesel Generator		Battery BuP		Fuel Cell Bup		Diesel Generator	
	Units	Datum	Cost	Datum	Cost	Datum	Cost	Datum	Cost	Datum	Cost	Datum	Cost	Datum	Cost	Datum	Cost	Datum	Cost
OPERATIONS																			
Outages per Year	No./yr.	8		8		8		8		8		8		1		1		1	
Hours per Outage	hrs.	12		12		12		12		12		12		72		72		72	
Hours per Year		96		96		96		96		96		96		72		72		72	
BATTERY/STACK/GENERATOR																			
Price	$	52 kWh	$ 8,000	5 kW	$12,650	6.5 kW	$ 6,500	52 kWh	$ 8,000	5 kW	$12,650	6.5 kW	$ 6,500	4-6 kW	$16,800	4-6 kW	$30,700	25-35 kW	$28,300
Lifetime	yrs.	yrs.	5	yrs.	15	yrs.	15	yrs.	5	yrs.	15	yrs.	15	yrs.	5	yrs.	15	yrs.	15
Cost of Capital	%/yr.	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%
Annualized Cost		$/yr.	$ 2,110	$/yr.	$ 1,663	$/yr.	$ 855	$/yr.	$ 2,110	$/yr.	$ 1,663	$/yr.	$ 855	$/yr.	$ 4,432	$/yr.	$ 4,036	$/yr.	$ 3,721
BALANCE OF PLANT																			
Price	$		$ 4,000		$ 5,750		$ 4,500		$ 4,000		$ 5,750		$ 4,500		$12,000		$29,300		$24,000
Lifetime	yrs.	yrs.	15	yrs.	15	yrs.	10	yrs.	15	yrs.	15	yrs.	10	yrs.	15	yrs.	15	yrs.	15
Cost of Capital	%/yr.	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%
Annualized Cost		$/yr.	$ 526	$/yr.	$ 756	$/yr.	$ 732	$/yr.	$ 526	$/yr.	$ 756	$/yr.	$ 732	$/yr.	$ 1,578	$/yr.	$ 3,852	$/yr.	$ 3,155
MAINTENANCE, ETC.																			
Maintenance	$/yr	N.A.	$500		$ 500		$ 1,200	N.A.	$500		$ 500		$ 1,200	N.A.	$300		$ 100		$ 800
Intangible ("Green")	$/yr.																		
INFRASTRUCTURE																			
On-Site Storage/Equipment	$	Included in BoP		3.7 kg	$ 6,900		$ 500	Included in BoP		3.7 kg	$ 6,900		$ 500						
Lifetime	yrs.	yrs.	15	yrs.	15	yrs.	15	yrs.	15	yrs.	15	yrs.	15			Included in BoP			
Cost of Capital	%/yr.	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%	%/yr.	10%						
Annualized Cost		$/yr.	$ -	$/yr.	$ 907	$/yr.	$ 66	$/yr.	$ -	$/yr.	$ 907	$/yr.	$ 66						
ENERGY																			
Cost	$/kg, kWh	$/kWh	$ 0.10	$/kg	$ 10	$/gal.	$ 4.00	$/kWh	$ 0.10	$/kg	$ 15	$/gal.	$ 5.00	$/kWh	$ 0.07	$/kg	$ 10	$/gal.	$ 3.89
Usage Rate per Year	energy/yr.	kWh/yr.	420	kg/yr.	30	gal./yr.	50	kWh/yr.	420	kg/yr.	30	gal./yr.	40	kWh/yr.	29	kg/yr.	2	gal./yr.	7
Annual Energy Cost	$/yr.	$/yr.	$ 42	$/yr.	$ 300	$/yr.	$ 200	$/yr.	$ 42	$/yr.	$ 450	$/yr.	$ 200	$/yr.	$ 2.03	$/yr.	$ 35	$/yr.	$ 28
TOTAL ANNUAL COST			$ 3,178		$ 4,126		$ 3,053		$ 3,178		$ 4,276		$ 3,053		$ 6,312		$ 8,023		$ 7,704

The size of the potential market for fuel cells systems is a critical determinant of sales. A weakness of the North American Non-Automotive Fuel Cell model is that it does not contain a detailed segmentation of the relevant markets according to factors that affect the competitiveness of fuel cell systems. Instead, it limits the markets addressable by fuel cells. Because that approach is part of the model calibration process, it has been retained in this analysis. 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. Not all of these forklifts go to multiple shift, intensive-usage operations. The previous study (Greene et al., 2011) assumed a relevant market size of 17,000 units in 2005, increasing by 2% per year. That assumption is retained in this study (Figure 12). Likewise, fuel cells cannot compete equally in all telecom applications. Convenient access to commercial hydrogen supply is a critical issue, as are such factors as expected frequency and duration of outages. Local emissions regulations are an issue for diesel generators in some areas. Greene et al. (2011) assumed a potential market of 15,000 units in 2005, increasing to 20,000 by 2025 and that assumption is retained in this analysis, as well. The global market in which fuel cell systems compete is approximately an order of magnitude larger than the U.S. market. Unfortunately, neither this study nor the 2011 study adequately address the potential of overseas markets. Qi (2013), for example, reports that there are approximately one million telecom towers in China alone.

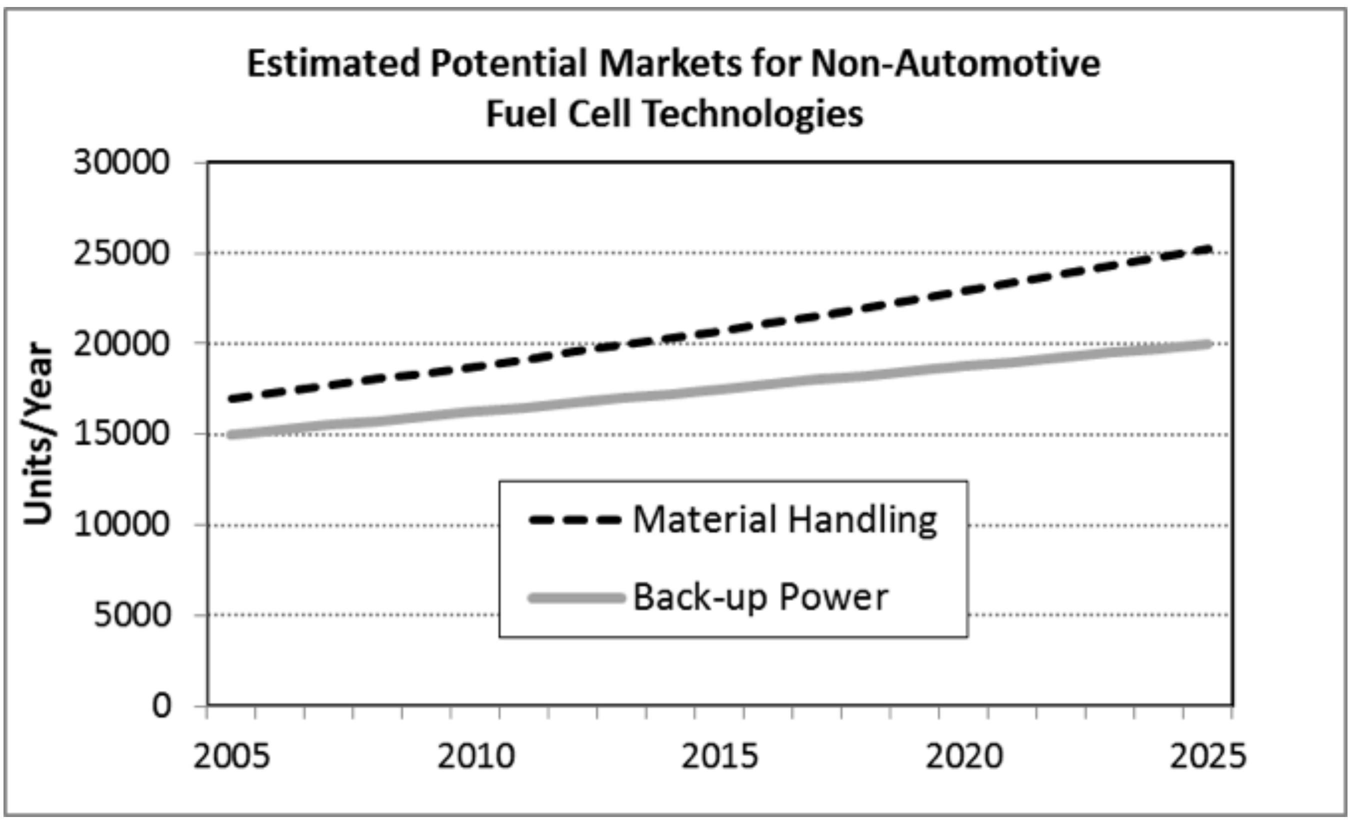


Figure 12. Estimated Potential Markets for Non-Automotive Fuel Cell Technologies.

VII. Results: Impacts of ARRA and ITC and Outlook

The ARRA subsidized purchases of 1,356 fuel cell BuP and MHE units are estimated to have induced additional sales of over 4,300 units from 2009-2014 (Figure 13). From 2009 to 2025, the model estimates that the ARRA purchases will generate total additional sales of 4,500 BuP units and 1,100 MHE units, or approximately 4 additional units for every ARRA purchase. These estimates assume that none of the ARRA-subsidized purchases would have occurred without the ARRA subsidies. Given the lingering effects of the economic recession in 2009, and the low sales volumes in 2009 and earlier years, this assumption seems a reasonable approximation even though it is an upper bound on the estimated impact. If it is assumed that half of the ARRA-subsidized purchases would have occurred without the ARRA subsidies (an improbably large fraction in the authors' judgment), the ARRA impact is still substantial. The ARRA subsidies are estimated to induce 2,800 additional sales of BuP units and 450 additional MHE sales through 2025. An approximate 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. Thus, 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).

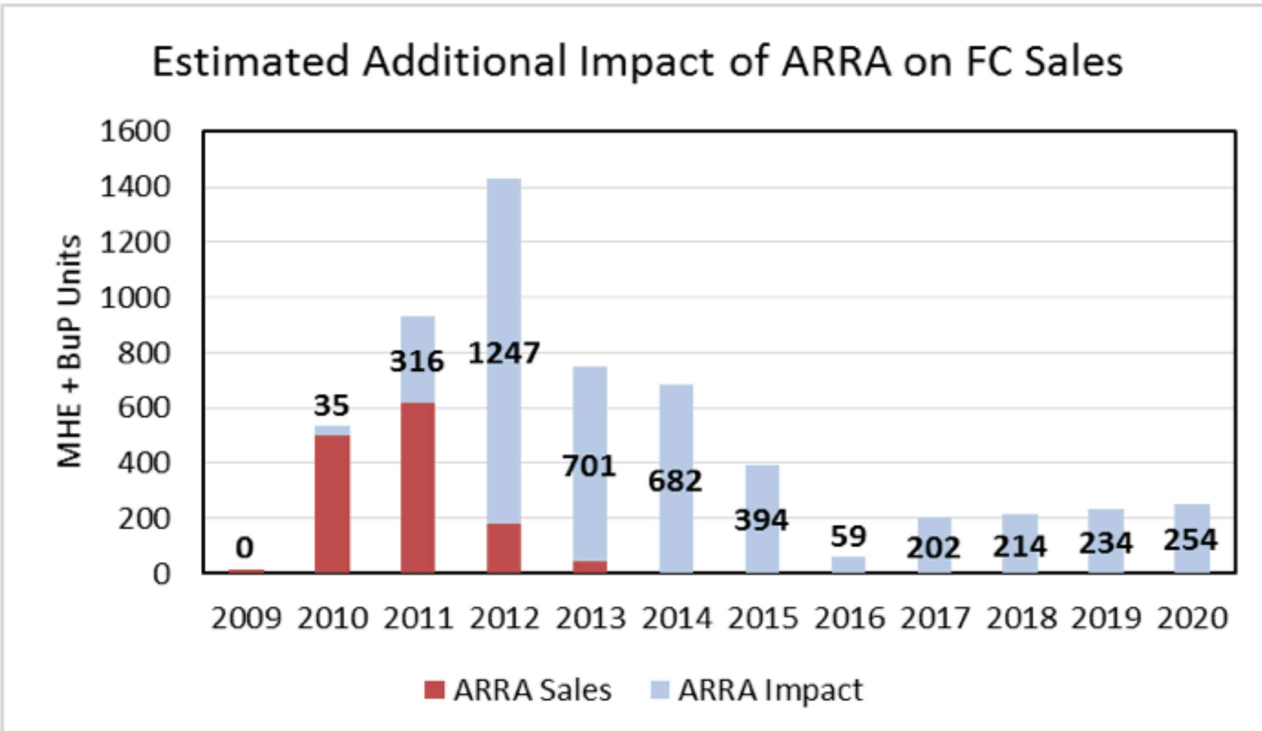
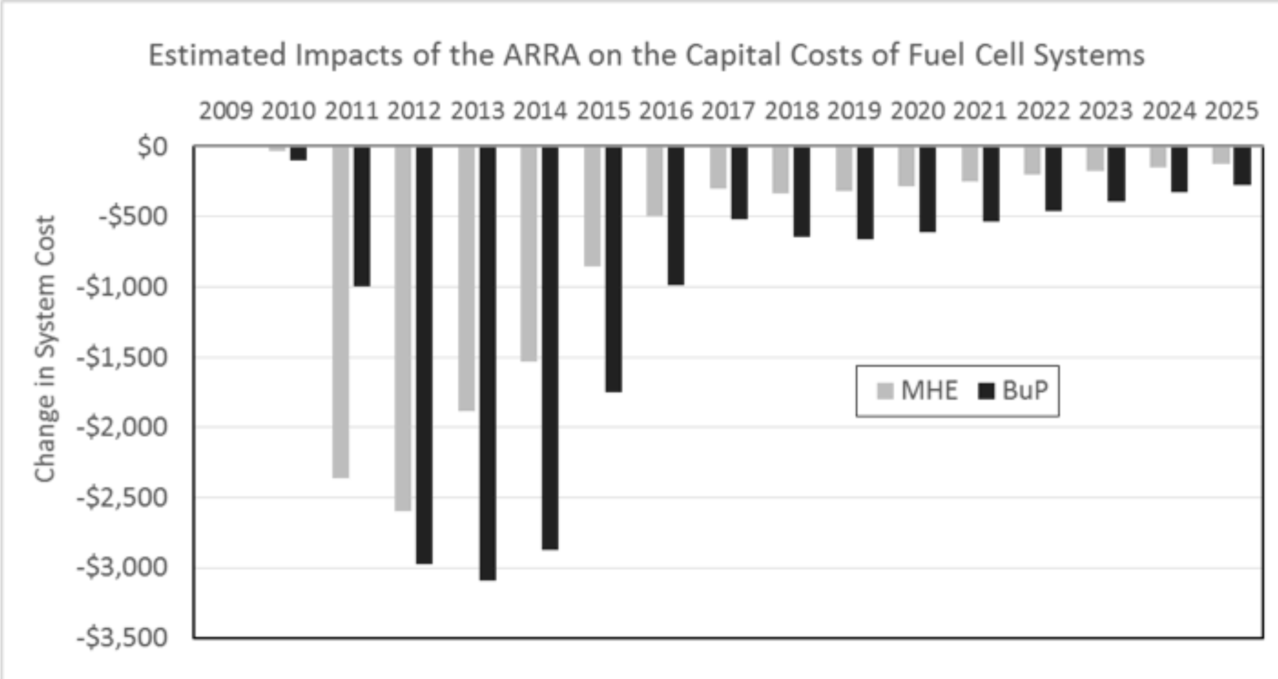


Figure 13. Estimated Additional Impact of ARRA on Fuel Cell BuP and MHE Sales.

Sales are increased because production costs are reduced via scale economies and learning by doing. The cost reductions are assumed to be passed on to purchasers. Initially, in 2009-10 the cost impacts are less than $100 per unit. They grow over time to a reduction of $2,600 per unit for MHE in 2012 and almost $3,100 per unit for BuP in 2013 (Figure 14). The impact of the ARRA initially grows with increasing ARRA-subsidized sales but then declines after ARRA sales peak. However, once the ITC expires after 2016, the impact of the ARRA increases. The reason for this is that the termination of the ITC causes a sharp reduction in sales in 2017. In a market without the ITC, the relative benefit of the ARRA sales is greater. The ARRA induced additional sales which generated transitory scale economies at the time but also persistent cost reductions due to learning-by-doing. The persistent cost reductions lead to higher levels of sales and thus somewhat increased scale economies in comparison to the no-ARRA case. These effects are relatively greater at lower sales levels because of the greater sensitivity of fuel cell choice to price at low market shares.



Even as late as 2016 the ITC reduces the capital costs of fuel cell systems by $7,000 to $8,000 off the purchase price of a BuP or MHE unit. The disappearance of this credit in 2017 is estimated to severely reduce sales of fuel cell units (Figures 15 and 16). Both markets are projected to recover but a return to 2016 sales levels might take almost a decade. Whether all the North American OEMs could remain in business for that length of time depends on many factors not considered in the model, such as overseas sales and access to capital.

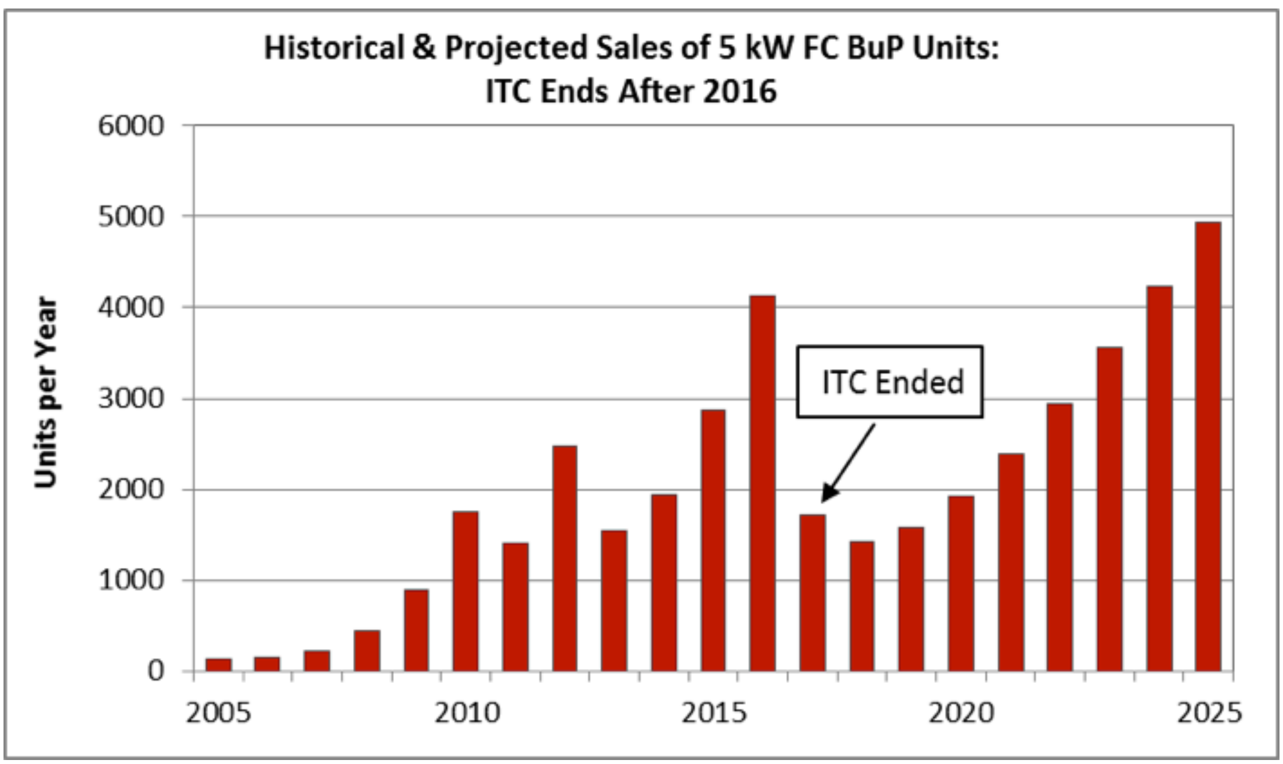


Figure 15. Historical and Projected Sales of 5 kW Fuel Cell BuP Units, Assuming the ITC Ends after 2016.

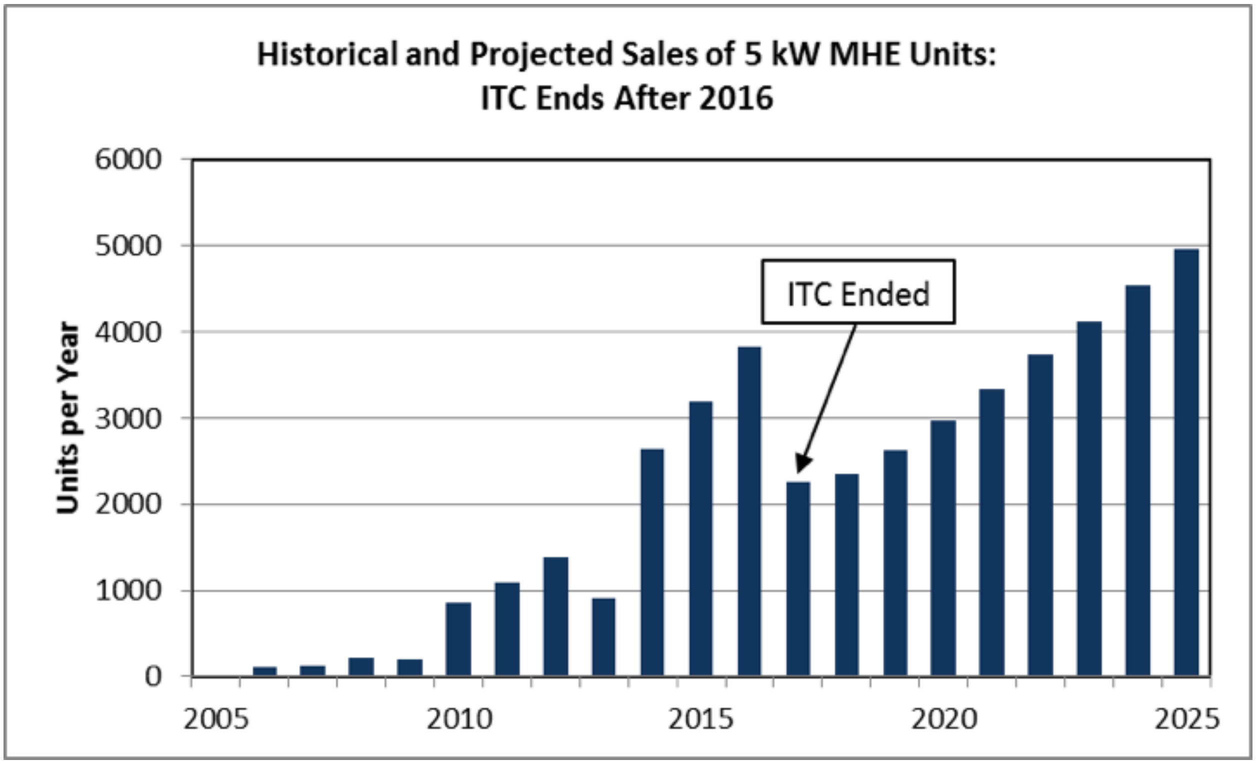


Figure 16. Historical and Projected Sales of 5 kW MHE Units Assuming the ITC Ends After 2016.

Given the size of the ITC relative to the prices of fuel cell BuP and MHE units, abruptly ending the tax credit in 2017 would likely be stressful for North American OEMs. A gradual phasing out of the credit would have a less dramatic impact on the industry. A linear phase-out would reduce the 30% credit to 25% in 2017, 20% in 2018 down to 5% in 2021 and 0% in 2022. Figures 17 and 18 show the model's sales predictions assuming such a linear phase-out. For both BuP and MHE very small decreases in sales are predicted. Despite the limitations of the model and the inherent uncertainties in such predictions, it is clear that some form of gradual phase-out would be far less damaging to the industry than a sudden termination of the ITC.

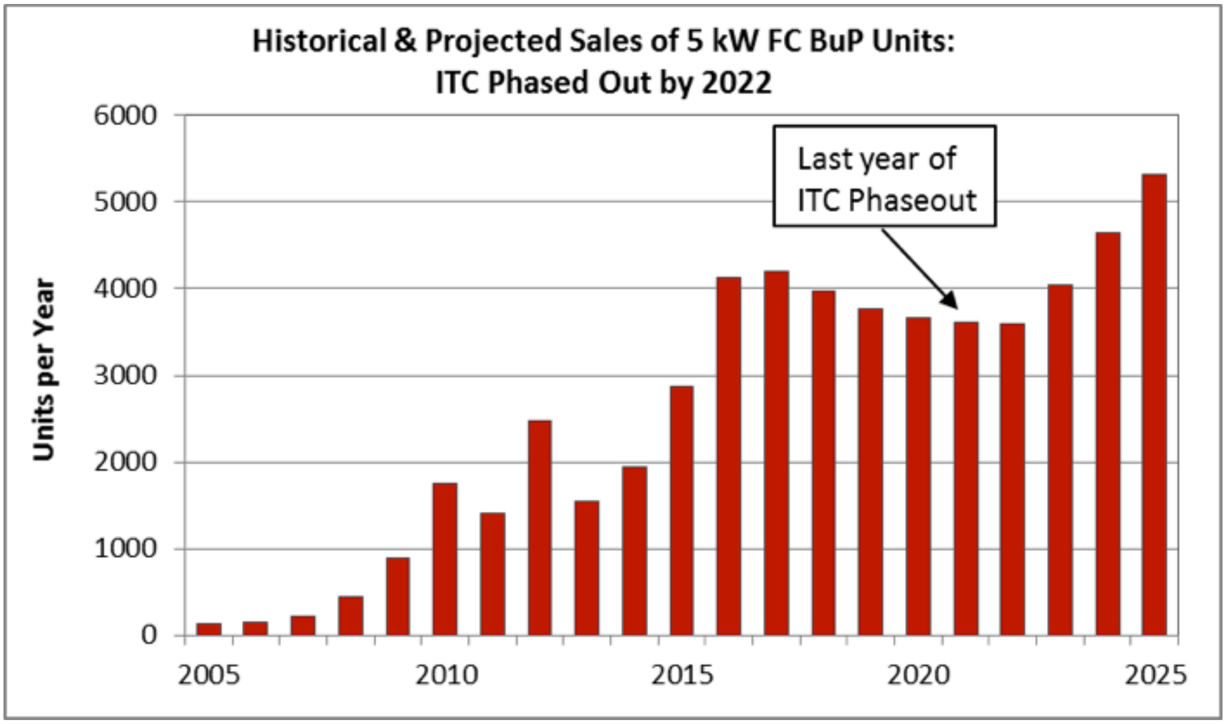


Figure 17. Historical and Projected Sales of 5 kW Fuel Cell BuP Units Assuming ITC Phaseout.

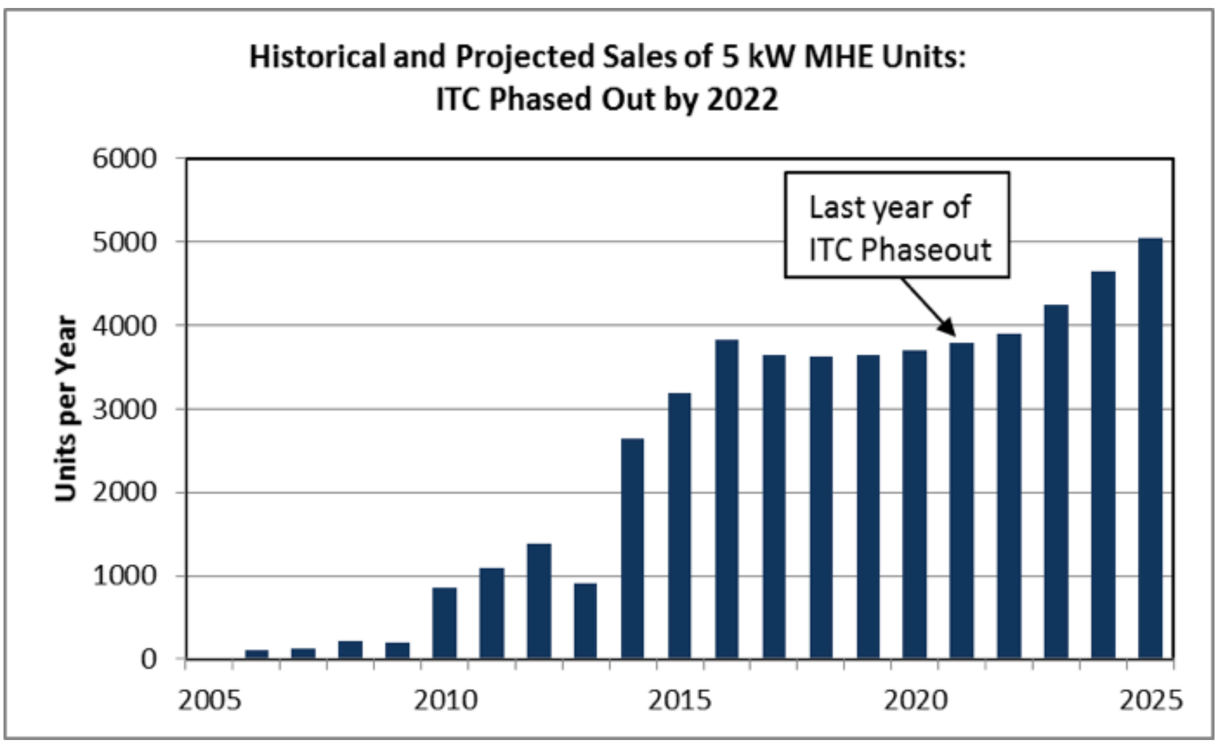


Figure 18. Historical and Projected Sales of 5 kW Fuel Cell MHE Units Assuming ITC Phaseout.

VIII. Conclusions

Since the study by Greene et al. in 2011, the North American fuel cell industry has achieved major cost reductions, at the same time improving the durability and reliability of its products. In an effort to stimulate the economy and promote advanced, low-emission energy technologies, the ARRA provided funds to subsidize approximately 40% of the purchase costs of 504 MHE and 852 BuP fuel cell units. At the same time the ITC provided a tax credit for up to 30% of the capital cost of these fuel cell systems or $3,000 per kW, whichever was smaller. The combination of industry progress and government support led to rapid sales growth, albeit from a very small base. At the same time, 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 version of the North American Non-Automotive Fuel Cell Market Model (Greene et al., 2011) estimated that the ARRA subsidized purchases of 1,356 fuel cell BuP and MHE units induced additional sales of over 4,300 units from 2009-2014 (Figure 13). From 2009 to 2025, the model estimates that the ARRA purchases will generate total additional sales of 4,500 BuP units and 1,100 MHE units, or approximately 4 additional units for every ARRA purchase. These estimates assume that none of the ARRA-subsidized purchases would have occurred without the ARRA subsidies. The authors believe that to be a reasonable approximation. However, if one assumes that a fraction $0<X<1$ of the ARRA sales would have occurred even without the ARRA subsidies, the model predicts that the additional sales would be approximately $(1-X)\cdot 100\%$ of the estimates given above.

The ITC is scheduled to end in 2017. The Non-Automotive Fuel Cell Market model predicts that this is likely to cause a sharp reduction in North American 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 might remain approximately constant during the phase-out period. Beyond 2022, the model predicts increasing sales, driven by continuous improvement in the durability of fuel cell systems and reductions in cost.

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