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Status and Outlook for the U.S. Non-Automotive Fuel Cell Industry: Impacts of Government Policies and Assessment of Future Opportunities

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ACRONYMS

AGM	-	Absorbed Glass Mat (battery)
APU	-	Auxiliary Power Unit
ARRA	-	American Recovery and Reinvestment Act of 2009
BoP	-	Balance of Plant
BuP	-	Backup Power
C	-	Celsius
CHP	-	Combined Heat and Power
DMFC	-	Direct Methanol Fuel Cell
DOE	-	United States Department of Energy
EAC	-	Equivalent Annualized Cost
EU	-	European Union
EV	-	Electric Vehicle
FC	-	Fuel Cell
GW	-	Gigawatt
H_2	-	Hydrogen
HDD	-	Heating Degree Days
ICE	-	Internal Combustion Engine
ITC	-	Investment Tax Credit
Kg	-	Kilogram
kW	-	Kilowatt
kWh	-	Kilowatt-hour
LNG	-	Liquefied Natural Gas
MCFC	-	Molten Carbonate Fuel Cell
MEA	-	Membrane Electrode Assembly

MNL	-	Multinomial Logit
MW	-	Megawatt
NOW	-	National Organization Wasserstoff
NREL	-	National Renewable Energy Laboratory
OEM	-	Original Equipment Manufacturer
ORNL	-	Oak Ridge National Laboratory
PAFC	-	Phosphoric Acid Fuel Cell
PEMFC	-	Proton Exchange Membrane Fuel Cell or Polymer Electrolyte Fuel Cell
PURPA	-	Public Utilities Regulatory Policy Act
PV	-	Photovoltaic
R&D	-	Research and Development
RPE	-	Retail Price Equivalent (long-run average cost)
RV	-	Recreational Vehicle
SGIP	-	Self-Generation Incentive Program
SOFC	-	Solid Oxide Fuel Cell
W	-	Watt
Wh	-	Watt hour

ABSTRACT

Fuel cells (FCs) are considered essential future energy technologies by developed and developing economies alike. Several countries, including the United States, Japan, Germany, and South Korea have established publicly funded R&D and market transformation programs to develop viable domestic FC industries for both automotive and non-automotive applications. Important non-automotive applications include large scale and small scale distributed combined heat and electrical power, backup and uninterruptible power, material handling and auxiliary power units. The U.S. FC industry is in the early stages of development, and is working to establish sustainable markets in all these areas. To be successful, manufacturers must reduce costs, improve performance, and overcome market barriers to new technologies. U.S. policies are assisting via research and development, tax credits and government-only and government-assisted procurements. Over the past three years, the industry has made remarkable progress, bringing both stack and system costs down by more than a factor of two while improving durability and efficiency, thanks in part to government support. Today, FCs are still not yet able to compete in these markets without continued policy support. However, continuation or enhancement of current policies, such as the investment tax credit and government procurements, together with continued progress by the industry, appears likely to establish a viable domestic industry within the next decade.

1. INTRODUCTION

Non-automotive FCs play a critical, early role in the U.S. Department of Energy's (U.S. DOE's) plan for the development of hydrogen (H_2)and FC technology (U.S. DOE, 2010a). Markets such as stationary primary or back-up power, material handling equipment, and portable power are key early markets for proton exchange membrane (PEM) and direct methanol fuel cell (DMFC) technologies. Residential and commercial combined heat and power (CHP) has been established as an early market in Japan and is planned for development in the United States over the next five years. In the detached home residential market, PEM FCs have already established a toehold in California. Phosphoric acid (PAFC) and molten carbonate fuel cells (MCFC) are operating in hundreds of larger-scale applications today (Curtin and Ganji, 2010). The scientific, technical and manufacturing knowledge, as well as the infrastructure developed thereby, are intended to contribute to the establishment of a much larger transportation market after 2015.

FCs have established an early presence in selected non-automotive markets. Industry media report that at least 500 forklifts powered by FCs were in operation in the United States at the beginning of 2010 and 1,000 more were expected to be shipped during the year (USFCC, 2010). In Japan, over 3,352 micro-CHP FC units had been installed in new single family homes as of April, 2009 and close to 8,500 by mid-2011 [1]. Thousands of FC units now supply back-up power for telecom sites around the world. Larger CHP FCs ranging from 200 kW to 3 MW have been installed to provide CHP to businesses and institutions from New York to California.

A 2008 study for the U.S. DOE (Greene and Duleep, 2008) evaluated the status of the non-automotive PEM FC industry in the United States and estimated its potential for future progress as well as the role that government procurements might play in helping to establish a viable domestic industry. The 2008 study concluded that a substantial government effort to procure FCs for back-up power and material handling, sustained over a period of 5 years from 2008 to

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[1] Personal communication, Dr. Iain Staffell, University of Birmingham, UK, March 25, 2011.

2012, could lead to a sustainable FC industry if cost reductions and performance improvements matched expectations.

DOE tasked Oak Ridge National Laboratory (ORNL) to update and extend the 2008 study and the model developed for it to address the current status of the non-mobile FC market, including residential and commercial markets for CHP, and including non-PEM FC technologies. Building on the results of the 2008 study, this study further analyzes the degree to which technology goals are being met and the impacts of government policies on the current and potential future market for non-mobile FCs.

This report examines the progress that has been made in U.S. FC manufacturing in recent years, how fuel cell manufacturers are competing with established technologies in these markets, the role that policies have played in the early development of the U.S. FC industry, and the potential for a sustainable U.S. FC industry. Small FC stacks of up to 10 kW in size are now competing in applications such as back-up power, material handling, and micro-CHP. Larger FCs ranging from 100 kW to 1 MW in size have demonstrated exceptional energy efficiency in larger CHP applications. However, except for the smallest DMFC applications for computers and other small electronic devices (generally less than 100 W in size) FCs in all these applications are still reliant on government policies to compete successfully against established technologies.

The study presented in this report first assesses the current status of the industry and progress made over the past 2-3 years. Considerable progress has been made; cost reductions and performance improvements projected for 2010 by the 2008 study have been met or exceeded. The status of the industry today and recent progress are described in Section 3.

The potential U.S. markets for back-up power, material handling, micro-CHP and CHP appear to be large enough to support a viable domestic FC industry provided that FCs can compete successfully on cost and performance. There is considerable potential for export markets, as well (Jerram and Anderson, 2010). The size and attributes of U.S. markets for back-up power, material handling, micro-CHP and CHP are evaluated in Section 4.

Government policies have been critically important to the U.S. FC industry. Indeed, tax credits and other financial incentives (such as the Investment Tax Credit (ITC) and California's Self-Generation-Incentive-Program) are essential to the early industry's ability to compete with established technologies. Procurements under that American Reconstruction and Recovery Act (ARRA) and its 1603 provision have clearly benefited the industry but some firms have benefitted far more than others. The impacts of these policies are examined in Section 5.

Other countries, most notably Japan, the European Union (EU) member states, and South Korea have policies in place to promote PEM as well as other FC technologies, especially for CHP applications. In Japan, the emphasis is on micro-CHP for residential heating and electric power. Three companies dominate the Japanese FC CHP market: Toshiba, Panasonic and JX Energy. In Germany, the National Organization Wasserstoff und Brennstoffzellentechnologie (NOW) sponsors a comprehensive program of FC research, development, demonstration and market transformation in collaboration with industry. These programs and their impacts on the EU and Asian non-automotive FC industry to date are reviewed in Section 6.

Like the 2008 report, this report develops a mathematical framework for estimating the impacts of government programs to date and projecting the potential impacts of future programs on the U.S. non-automotive FC industry. The industry model includes representations of FC system components and their effects on equivalent annual cost (EAC), the effects of learning-by-doing, scale economies and exogenous technological progress on component and system costs, customer choices among competing technologies, and the impacts of government policies. The modeling methodology is described in Section 7 and validation of the model, to the extent possible, is taken up in Section 8.

In Section 9, the non-automotive FC industry model is then used to estimate the impacts of current and possible future government policies, and to assess the potential for achieving a sustainable non-automotive FC industry in the United States. Section 10 presents concluding observations.

2. FUEL CELL TECHNOLOGIES

Although, several different FC technologies are discussed in this report, the focus is on proton exchange membrane fuel cells (PEMFC) also known as polymer electrolyte FCs, phosphoric acid fuel cells (PAFCs) and molten carbonate fuel cells (MCFC) (U.S. DOE, 2010b).

PEMFCs employ a solid polymer as an electrolyte and have porous carbon electrodes that contain platinum as a catalyst. They require pure hydrogen fuel but can take oxygen from the air. PEM cells operate at low temperatures (~80° C) and can respond relatively quickly to changes in power demand. Stationary PEMFCs produce electricity with a net energy efficiency of about 35%.

PAFCs also use porous carbon electrodes but use liquid phosphoric acid as the electrolyte. Operating at higher temperatures than PEMFCs (about 230° C), PAFCs can tolerate less pure hydrogen. PAFCs are 37% to 42% efficient for electricity production but about 85% efficient when operating in the combined heat and power (CHP) mode, and up to 90% efficient when able to take full advantage of the thermal output.

MCFCs employ a molten carbonate salt electrolyte suspended in a porous ceramic matrix. Operating at very high temperatures (~650° C) enables MCFCs to use a variety of fuels, including natural gas, with internal reforming and to use non-precious metals as catalysts. Also, MCFCs can achieve 47% net electrical efficiency as a stand-alone power plant and can approach net electrical efficiencies of 60% in combined cycle operation with a gas turbine. MCFCs achieve up to 85% efficiency in CHP operation.

SOFCs use a non-porous ceramic as an electrolyte and operate at very high temperatures, about 1,000° C, although versions that operate under 800° C are in development. As a consequence SOFCs can internally reform a variety of fuels, including natural gas, and tolerate slightly more sulfur impurities than other FCs. Net electrical efficiency is very high: potentially

50-60%, with overall efficiency in the range of 80-85% in CHP operation. The high temperature of SOFCs also means that start up is slow but byproduct heat can be used for a wider range of purposes.

DMFCs are low-temperature, (50º C to 120° C) proton exchange FCs that can electrochemically oxidize methanol as a fuel. DMFCs generally use platinum as a catalyst on both the fuel and air electrodes. Their overall efficiency is relatively low, in the range of 20-30%. To date, DMFCs have been used in low-power applications, for example to power laptop computers or toys, or to trickle charge batteries.

3. THE U.S. INDUSTRY IN 2010

This study included in-depth interviews with 10 FC manufacturers in the United States, and 7 in the EU and Japan. We would like to express our gratitude to the OEMs who took time from their busy schedules to meet with us and share information about their firm and their industry. Some of the information provided in those discussions was proprietary but most was not. The following firms were interviewed.

- In the North America
  - Altergy (PEM)
  - Ballard (PEM)
  - ClearEdge (PEM)
  - FC Energy (MCFC)
  - IdaTech (PEM)
  - Nuvera (PEM)
  - Oorja (DMFC)
  - PlugPower (PEM)
  - Relion (PEM)
  - UTC Power (PAFC)
- In Japan
  - JX Energy (PEM)
  - Panasonic (PEM)
  - Toshiba (PEM)
- In the European Union
  - NedStack (PEM)
  - SFC Energy (DMFC)
  - RWE (Electric Utility)
  - CFCL (SOFC)

The interviews with OEMs produced the following general observations:

- Non-automotive FC manufacturers are attempting to establish themselves in a limited number of markets: for PEMFCs, back-up and uninterruptible power (especially for telecommunications), material handling equipment (forklifts), micro-CHP; for larger PAFC and MCFCs, CHP and grid-independent stationary power. In all these markets, FCs are competing at a cost disadvantage against established technologies.

- Most PEM FC manufacturers have reduced the number of products they offer and specialized in order to reduce costs and increase sales volumes per product.
- All manufacturers have achieved large cost reductions over the past 2-5 years. Cost reductions on the order of 50% are the norm, a continuation of the progress observed in our 2008 report.
- Nonetheless, all manufacturers believe that costs must be further reduced by 40% to 50% in order to compete successfully in the marketplace without government support.
- In the current market, government incentives are essential to sustaining the U.S. FC industry. Our analysis of future prospects indicates this is likely to remain the case for the next five years. Continuing or strengthening government incentives appears to be necessary to enable FC manufacturers to achieve sufficient cost reductions to continue without government support in the future.
- Most manufacturers believe that future cost reductions will come primarily though economies of scale and cost reductions in the supply chain, with technological advances playing a somewhat smaller role than in the past. Estimated scale elasticities (the percent reduction in cost for a 1% increase in annual production) are typically in the range of -0.2 to -0.3, implying that doubling output would reduce costs by 20% to 30%.
- Most manufacturers believe that production volumes must increase by somewhere between a factor of 3 and an order of magnitude to achieve sufficient scale economies to become competitive.
- Almost all of the manufacturers were operating well below their existing production capacity and all had the capability to expand capacity by 50% to 300% within one year.
- Substantial improvements in the durability of FCs have also been achieved. PEM FC stacks today are expected to operate under real-world conditions for 5,000 to 10,000

hour lifetimes in backup power applications and 40,000 to 50,000 hours in CHP applications. Large scale (>300 kW) PAFCs and MCFCs for CHP and stationary power already exceed 40,000 hours before requiring replacement. Still, manufacturers believe that durability must and can be further improved.

- Today, FC OEMs depend on government incentives or government procurements for viability. Without policies such as the Investment Tax Credit, California's Self-Generation Incentive Program, or feed-in tariffs for electricity delivered to the grid, most companies' sales would be drastically reduced.
- For U.S. manufacturers, the key domestic markets are in California and the northeast states. South Korea is an important overseas market today, with sizable potential markets in the EU.
- For FC CHP and micro-CHP manufacturers, both purchase incentives and high electricity prices (or feed-in tariffs) are essential to creating a viable market.
- For PEM FCs in back-up power and material handling, the cost and availability of hydrogen is a significant impediment to commercial success. While the ARRA and other programs have provided important incentives for purchasing FCs, the problem of providing low-cost hydrogen on site for non-automotive applications has not yet been addressed.

3.1 PRODUCTION, COST AND PERFORMANCE, 2005-2010

Production of FCs in the United States has increased dramatically over the past three years. The data shown in Figure 1 have been compiled from a variety of sources. They do not include all firms in the industry and are based on incomplete data for 2010. Backup power leads the industry in total shipments (Figure 1) and has achieved roughly a five-fold increase over 2007 production levels. Due largely to purchases subsidized by the ARRA of 2009, production of FC forklifts has also greatly increased. The one U.S. firm now producing micro-CHP units has found a promising niche market in sales to larger single family homes in California, created by a combination of early adopter interest in green, advanced technology, relatively high electricity rates, and the substantial subsidy provided by the California Self-Generation Incentive Program (SGIP). This progress is all the more impressive given the extremely adverse economic conditions prevailing in 2009-2010.

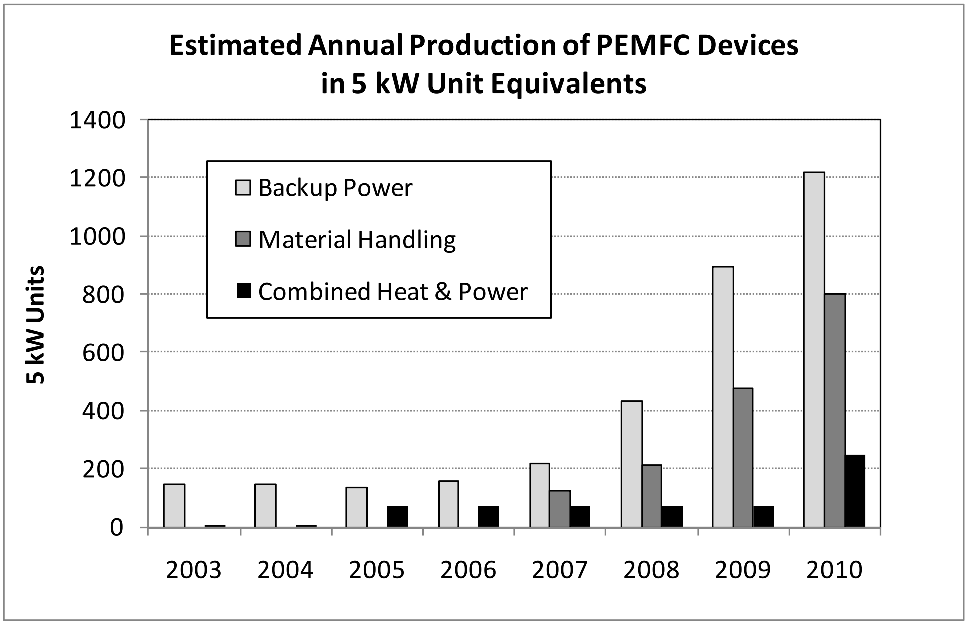


Figure 1. Estimated Annual U.S. Production of PEMFC Devices in 5 kW Unit Equivalents.

Production of larger (> 100 kW) FCs for CHP and independent power have also increased significantly in the past two years (Figure 2). Manufacturers of both PAFC and MCFCs have found emerging markets in California, Northeast states and South Korea, where subsidies for clean energy technologies and relatively high electricity prices make FCs an attractive alternative for CHP.

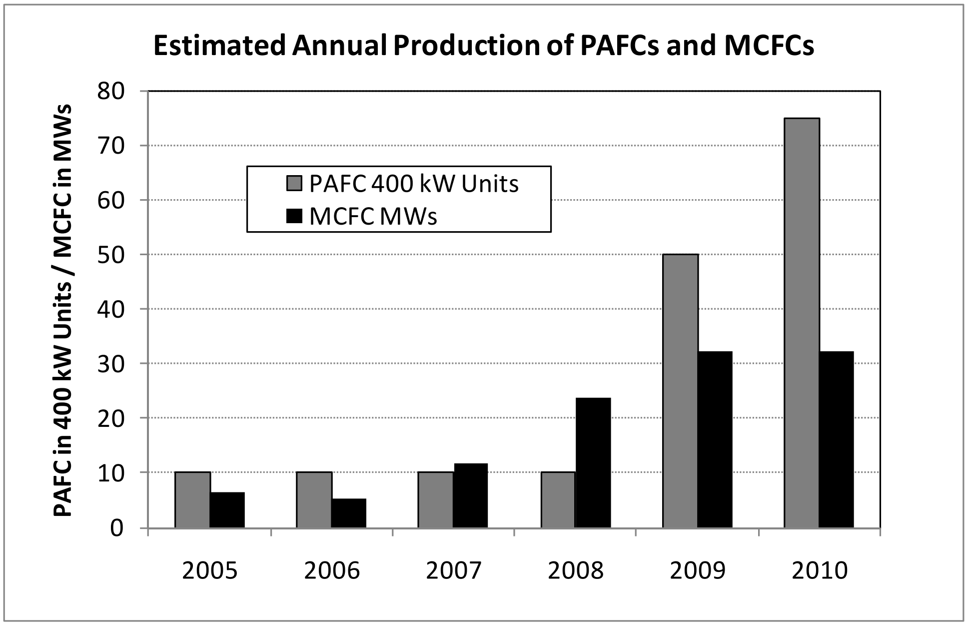


Figure 2. Estimated Annual Shipments of PAFCs and MCFCs by Two U.S. Firms.

Today, FC OEMs have gained experience producing hundreds to thousands of PEMFC products and approximately 200 MW of larger, high-temperature FCs (Figure 3). The estimates shown in Table 1 were compiled from various sources and are believed to be a useful approximation of actual production volumes. From 1996 to 2005, approximately 5-10 MW of large PAFC and MCFC units were installed annually (Adamson, 2008). The market shares of the two technologies were approximately equal in years prior to 2008.

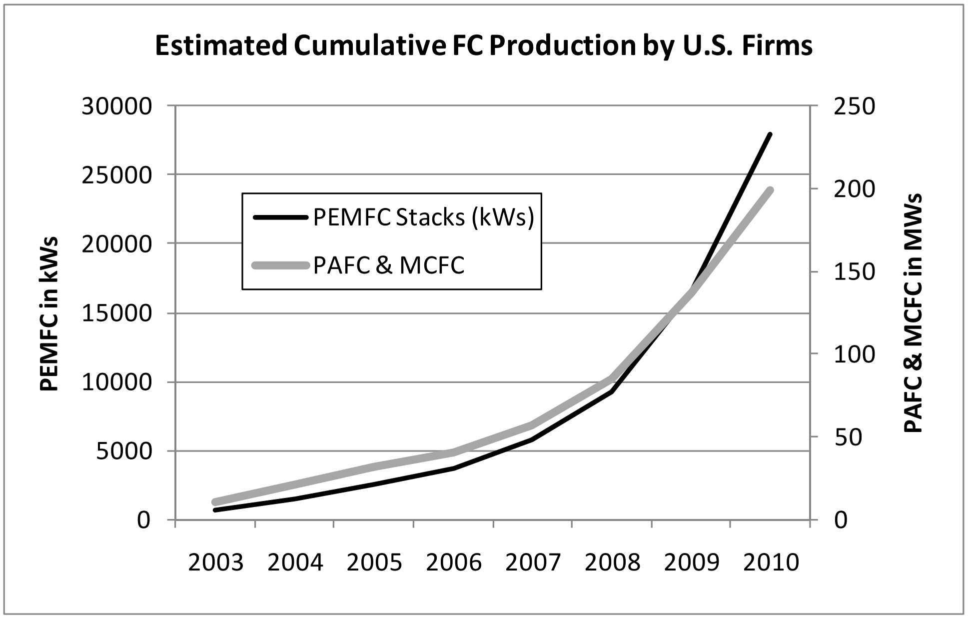


Figure 3. Estimated Cumulative Production of Fuel Cells by U.S. Firms, 2003-2010.

Table 1. Estimated Production of Non-Automotive Fuel Cells by

U.S. Manufacturers, 2005-2010‡

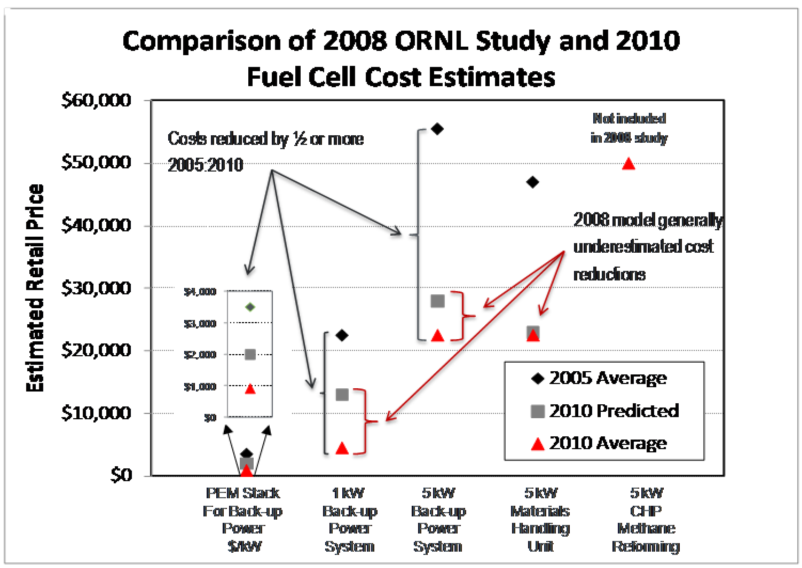
Application	2005	2006	2007	2008	2009	2010
PEM Fuel Cells (5 kW equivalent units)						
PEM Material Handling	0	0	123	211	477	803
PEM Backup Power	135	158	219	435	894	1221
PEM Combined Heat and Power	71	71	71	71	71	250
Larger non-PEM Fuel Cells						
PAFC (400 kW equivalent units)	10	10	10	10	50	75
MCFC (MWs)	6	5	12	24	32	32

‡These estimates have been compiled from information provided by manufacturers, annual reports when available, and other published sources. It is not expected that these numbers are precise or complete. Rather, they are intended to serve as approximate measures of the historical output of the U.S. industry for purposes of calibrating learning and scale effects in our industry model.

Cumulative experience gained in producing FCs has enabled learning by doing, modest scale economies accompanying higher levels of production, and continued technological progress supported by research and development. The result has been major reductions in the costs of FCs of all types.

The 2008 report (Greene and Duleep, 2008) estimated 2005 costs for PEM FC stacks and products and projected costs to 2010 based on assumed production levels, scale elasticities of approximately -0.2 and progress ratios of 0.95 for stack suppliers and 0.91 for OEMs. These estimates, together with cost data gathered in the course of this study are shown in Figure 4. In every case, manufacturers have equaled or exceeded the manufacturing cost reductions projected by the 2008 study. Large cost reductions were achieved over the period 2005-2010 in several areas:

- PEM stack costs have come down from roughly $4,000/kW to $1,000/kW[2]
- The cost of 1 kW backup power systems have also been reduced by a factor of 4
- The cost of 5 kW backup power units is down from about $55,000 to $22,000
- The cost of 5 kW forklift systems declined from $48,000 to about $22,000[3]



2005 and 2010 averages based on estimates supplied by OEMs. 2010 predicted assumed government procurements of 2,175 units per year, total for all market segments. Predictions assumed a progress ratio of 0.9 and scale elasticity of -0.2.

Figure 4. Comparison of 2008 ORNL Study and 2010 FC Cost Estimates.

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[2] Schoots et al. (2010) estimated global market fuel cell stack costs at € 362 (approximately $480 using a 1.33 conversion rate) for the year 2007, assuming a production volume of 500 units per year. The cost of a 5 kW system including balance of plant was estimated to be €20,500.

[3] At the time interviews were conducted for this study (May-July 2010), US OEMs were manufacturing 5 kW fuel cell systems for class I and II material handling equipment. Since then, they have increased the power of fuel cell systems for class I and II forklifts to the range of 8 to 12 kW and are now also manufacturing smaller, 2-3 kW systems for the class III forklift market. These changes in a dynamic, evolving market are not reflected in this study.

Similar cost reductions have been achieved by large, high-temperature FC manufacturers. Fuel Cell Energy, for example, has reported cost reductions of a factor of five for its MCFC product over the period 1996 to 2008 (Adamson, 2008). Empirical data on the lifetime of these units is not yet available.

Foreign manufacturers whose governments have also supported FC research, development and deployment have achieved similar cost reductions. Data provided by Japanese 1 kW PEMFC micro-CHP manufacturers are summarized in Figure 5. Japanese manufacturers also accomplished a four-fold reduction in costs from the beginning of their pilot program in 2005 to the conclusion of the large-scale demonstration effort at the end of 2009. Government subsidies covered approximately half of the cost of each CHP unit sold. Subsidies from the Japanese government will continue in the future but will steadily decline as FC costs are reduced. Figure 5 also shows the government-industry cost target of approximately ¥600,000, expected to be reached in 2018. The Japanese data are consistent with a rate of technological progress of 8% per year, a progress ratio of 0.8 and a scale elasticity of -0.2. A progress ratio of 0.8 implies a 20% reduction in costs for every doubling of cumulative production. If costs can be reduced at the average rate of 15% per year through 2018, the Japanese cost goal will be met.

Detailed cost and production data were also provided by SFC Energy, a German manufacturer of direct methanol FCs. SFC Energy does not receive government subsidies for its production although it has received substantial R&D support from the German government and the U.S. military. SFC's products are sold largely to recreational markets (yachts, recreational vehicles, vacation cabins, etc.) for slow-charging of batteries providing electrical power in remote locations. SFC Energy's experience is well described by identical scale economies and somewhat slower rates of technological progress and learning-by-doing (Figure 6).

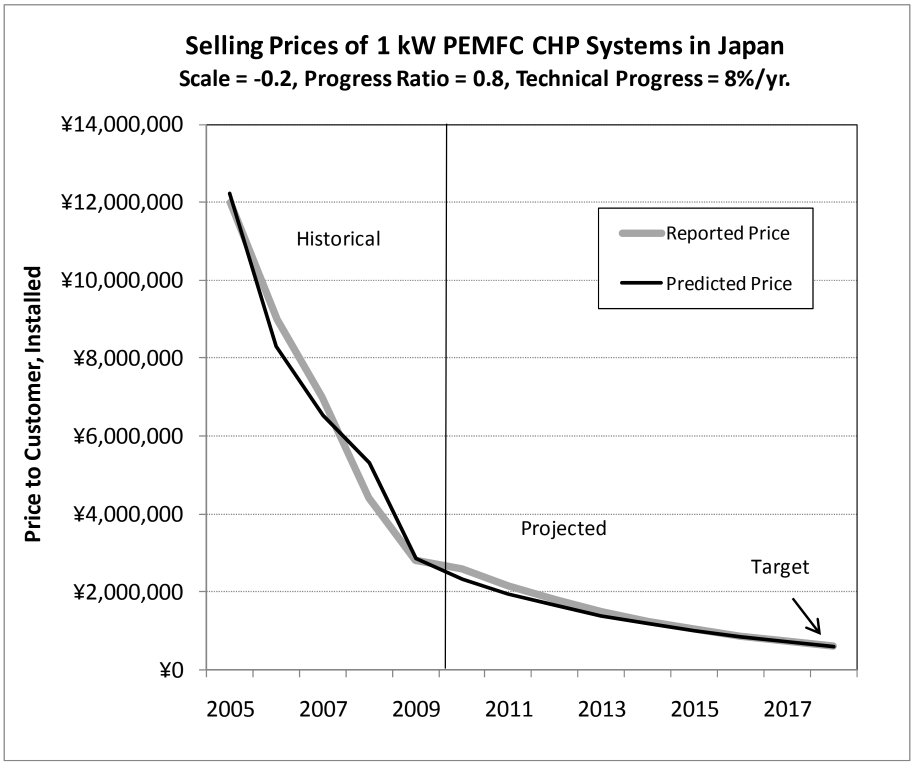


Figure 5. Historical and Projected Selling Price of 1 kW PEMFC CHP Units in Japan, 2005-2018.

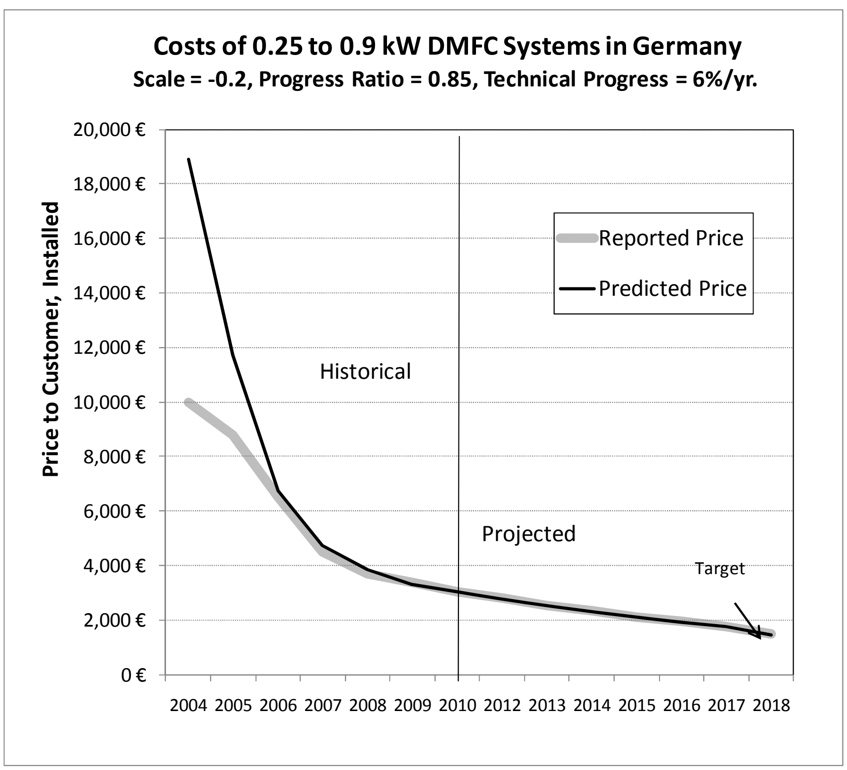


Figure 6. Historical and Projected Selling Price of DMFC Appliances in the EU, 2004-2018.

The experience of U.S. and foreign manufacturers strongly supports a scale elasticity of approximately -0.2. Values in the range of -0.2 to -0.3 were also endorsed by several of the U.S. manufacturers interviewed. The assumed progress ratios of 0.9 and 0.95 used in the 2008 study appear to have been conservative in comparison to the experience of foreign manufacturers but predicted U.S. cost experience reasonably well. Manufacturers interviewed did not expect the rapid technological progress achieved over the past 5 years to continue at the same rate. Thus, in the analysis below, we use rates of reduction in manufacturing costs of between 1% and 2% per year to reflect technological progress achieved by means of research and development, as opposed to cumulative experience or increased production volumes.

3.2 LEARNING-BY-DOING, TECHNOLOGICAL PROGRESS AND SCALE ECONOMIES

The United States' and Japanese estimated rates of learning-by-doing are slower than progress ratios estimated by Schoots et al. (2010). They estimated a progress ratio of 0.75 ± 0.03 for PAFCs produced by UTC Power over the period 1993-2000 and of 0.70 ± 0.09 for PEMFCs manufactured by Ballard between 2002 and 2005. Their global industry analysis indicated learning rates of 0.79 ± 0.04 for PEMFC fuel cells over the period 1995-2006. This could indicate a slowing of the rate of learning-by-doing over time, but might also be due to the relatively small sample sizes available (n=6 for UTC, and n=4 for Ballard). Schoots et al. (2010) also provide estimates of the cumulative global production of PEMFCs by 2005 (136 MW) and PAFCs by 2000 (40 MW).

Schoots et al. (2010) used a scale elasticity of -0.31 to adjust various cost estimates to a standard production rate of 500 units per year. Scale elasticities measure the percent reduction in cost for each 1% increase in annual production volume. In the analysis presented below in Sections 7, 8 and 9, a more conservative elasticity of -0.2 is used for all technologies, which implies that a 10% increase in production volume will yield a 2% reduction in cost. Schoots et al. (2010) also estimated the effect of FC capacity (kW/unit) on cost and found that costs declined with the 0.4 power of capacity (Figure 7). Their estimates (in Euros) for larger fuel cell systems (>50 kW) are roughly consistent with the estimates presented below (1 Euro ≈ 1.33 Dollars).

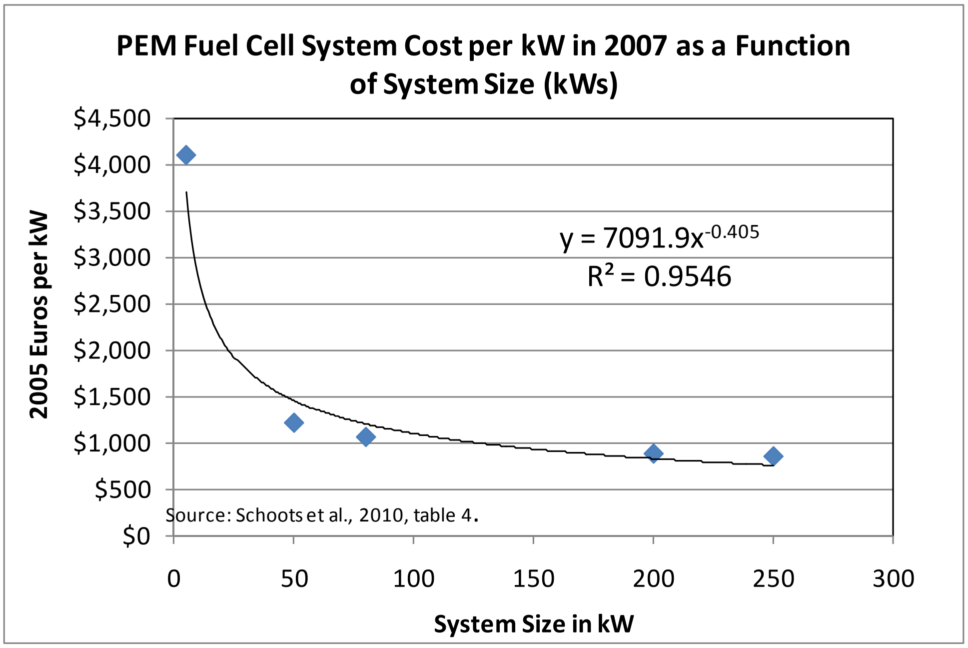


Figure 7. Effect of PEMFC System Capacity (kWs) on Cost per kW (Schoots et al., 2010) (Assumes a production rate of 500 units per year for all sizes).

Learning rates for Japan's PEM fuel cell CHP program were estimated by Staffell and Green (2009). Sensitivity to key assumptions was included to produce a range of learning rates. Based on data for the period 2004 to 2008, they estimated that cost reductions of between 19.1% and 21.4% were achieved for each doubling of production, implying progress ratios of 0.79 to 0.81. Their model includes the effects of scale economies and exogenous technological progress in the learning rate.

4. CURRENT MARKETS AND THEIR POTENTIAL

Small FCs in the 0.1 kW to 10 kW electrical power output range are being commercialized in three sectors – material handling, remote site/ backup power and in residential /small commercial buildings for CHP. The sizes of the markets for and the competitiveness of FC systems vary considerably between these markets and are explored separately in this report.

Broadly speaking, Japan, Germany, the United States, and South Korea are the largest fuel cell markets.[4] The FC market in Japan is almost completely focused on residential CHP and uses very small PEMFC units ranging in power from 0.7 to 1 kW electrical output with about twice as much heat output. The unit sales, however, were quite high, with sales of over 3,500 units in 2009 and over 5,000 in 2010. In Germany, the Callux demonstration project is planning to deploy 1 kW and 5 kW units in residential CHP applications where utilities are installing a few hundred units a year to monitor performance. The goal is to deploy at least 800 units. Most are PEMFCs but both SOFC and PEM technology are being demonstrated. Separately, one company has been commercially successful in selling very small direct methanol FCs in the 20W to 50W range as battery chargers in recreational vehicles and pleasure boats. Both Japan and Germany have very stable power grids in backup power applications. Nonetheless, NOW considers backup power as an area of significant potential for fuel cells. In both countries, the material handling market has not been seen as one in which the FC could compete against the battery.

In the United States, the total market for FCs in this range is estimated at about 1,200 units in 2009, split approximately evenly between three markets: material handling (forklift trucks), remote site and backup power, and residential units for CHP. Remote site power has primarily been for telecommunication towers, while the residential CHP market has been primarily

[4] This paragraph contains corrections to observations about Germany's NOW programs that are not in the original printed version of this report.

confined to large homes in California. Each of the three markets has significantly different requirements, different market sizes and different competitors.

In the United States, almost all of the units sold in the 0.1 to 10 kW size class currently use PEM FCs (both low temperature and high temperature types) with the only exception being one supplier of direct methanol FCs). The PEM FC unit integrated into an end use device has five levels of suppliers

- basic components suppliers such as the suppliers for the carbon felt for the anode and cathode, the membrane and the catalysts
- membrane electrode assembly (MEA) suppliers that provide a 3 layer or 5 layer assembly that is the basic element of the FC
- the FC stack which is an assembly of MEA units and collectors for the stack inputs and outputs
- the “balance of plant” which include the pumps, compressors, cooling and control systems for the stack
- an integrated FC system that provides the desired power and heat outputs.

Most of the manufacturers examined in this analysis buy the MEA from suppliers and develop the stack, balance of plant and system integration in house. At present there are 4 to 5 suppliers of the MEA and they include Gore, 3M, BASF and Ballard in North America. These companies in turn buy components such as the anode and cathode materials from a small number of suppliers who are primarily Japanese. Nevertheless, the existence of so many MEA suppliers for the small North American market suggests that economies of scale have not yet been attained in MEA manufacturing. Two manufacturers purchase the entire stack (from Ballard) and Ballard may have some modest scale economies relative to others in the PEM FC business.

4.1 BACK-UP POWER

FC manufacturers have targeted the telecommunications towers at remote sites as markets for FC back up power units. In this case, the system operates only when the grid supply to the site fails. At present the main competitor is battery power although some use a diesel generator on site. The remote site power requirements in the United States are generally in the 5 kW to 10 kW range. Typically, one or two 4 to 5 kW FC systems are used and the U.S. market so far has favored hydrogen powered systems over systems that include reforming of methanol or natural gas. Because the systems are stationary and do not require long operational life (but do require long calendar life), the FC systems have the potential to be cheaper than those used in forklifts. Most of the analysis is relevant for the 5 kW system.

Current FC stack and balance of plant costs are in the $2,500 to $3,000 per kW range making the cost of a 5 kW unit in the $12,500 to $15,000 range. The retail price of a 5 kW system installed with about 2 to 3 kilogram (kg) of hydrogen storage is in the $22,000 to $24,000 range. These systems would use replaceable hydrogen storage cylinders where the cylinders were leased from the hydrogen supply company. The system consumes about 1 kg of hydrogen every 3 to 4 hours and 3kg of storage capacity allows operation for 9 to 12 hours. The space taken up by hydrogen storage and the costs of the storage make storing much more hydrogen at a remote site difficult. Systems for hydrogen storage capable of multi-day backup have also been developed, and these feature fixed storage systems but are significantly more expensive. No cost data are available yet but discussions with manufacturers suggest that a system with 3 days' storage capability could be in the vicinity of $50,000. The desire for longer backup duration (e.g., in the event of a multi-day power disruption due to a storm) has led one company to use a methanol reformer in conjunction with a FC. The reformer would add about $8,000 to the cost of a 5 kW FC and consume about 1 gallon of methanol per hour, so that 3 day backup would not be difficult. At present, three companies in the United States- Idatech, Relion and Altergy - offer PEM FCs for this application and Idatech offers a system with a methanol reformer. A methanol reforming FC system would cost around $30,000 to $35,000 installed.

The main competitors are (lead-acid) battery power and generator sets with smaller batteries. Battery power in these applications with about 30 kWh capacity capable of sustaining 10 ± 2 hours operations costs around $6,000, with an additional $4,000 for installation and battery charging equipment. However, batteries must be replaced every 6 to 7 years so that if a FC system can last for 12 to 15 years (possible now but not proven), two sets of batteries are required to match the life of a FC, making FC system costs near competitive. Diesel generator sets are more common to provide multi-day backup capability and are typically oversized for the application at 12 to 15 kW (or more) so that a standard generator set can be used across multiple locations. A 15 kW generator set installed with some battery capacity to support 1 to 2 hour outages without starting the engine also costs about $30,000 to $35,000 installed. However, the generator set can also support the air-conditioners used to cool the telecom equipment. This may be required to support multi-day usage, which the FC system cannot provide. In cases where the telecom system can operate without air-conditioning, the FC system may be competitive.

Fuel costs in backup power applications can be small since the annual expected usage is small (100 to 200 hours) and operating costs for maintenance and refueling are dominant. In this case, delivery of hydrogen to remote sites has sometimes proved difficult. In addition, the relative costs of battery versus FC maintenance over a long period are not well established but may be comparable and are relatively low.

The total U.S. market size for telecom towers is estimated to be around 300,000 units, based on our interviews with industry sources. However, the 2008 report suggested that the population of these sites is growing at 2% per year, but this may not be occurring since telecom coverage is nearing geographic saturation in populated areas. Systems are replaced over a 15 to 20 year life so that new systems are purchased at a rate of about 15,000 to 20,000 thousand per year for the 4 kW to 8 kW systems. Hence, the total market size in the United States for backup power may be too small to support 3 to 4 competitors at full economies of scale. It is likely for this reason that the industry has been looking to expand backup power to telecom sites in developing countries where grid stability is poor and backup power usage is much higher.

However, in developing countries FCs face cost-competitive diesel generator sets, and customers are more cost sensitive, so it is not clear if this strategy will produce enough sales volumes to attain scale efficiencies.

4.2 MATERIAL HANDLING

When US OEMs were interviewed for this study (May-July, 2010), they were manufacturing 5 kW FC systems, along with batteries (to supply short term peak power) for class 1, 2 forklifts. In this market they competed primarily against battery powered forklifts used in multiple shifts in indoor operations. Since that time, the manufacturers have increased the power of their FC systems for classes 1 and 2 to the range of 8 to 12 kW and have developed new, 2-3 kW systems for the class 3 forklift market, evidence that this market is dynamic and evolving. The modeling and analysis presented below in chapters 7-9 is highly generalized and is based on the costs and market for 5 kW material handling systems in class 1 and 2 forklifts.

In 2010, the FC systems for class 1 and 2 forklifts with the batteries and hydrogen storage tank were being sold at $35,000 to $40,000 retail price before accounting for any tax credits.[5] The cost of the system is estimated at $27,000 to $29,000 with the FC at about $20,000 to $22,000 and the rest of the system costing about $5,000 to $8,000 to manufacture. Costs for class 3 forklift fuel cell systems are about half that of the class 1 and 2 forklift systems. These costs are associated with sales volumes of about 150 to 200 units per year. FCs for forklifts must have more rugged construction than FCs in stationary applications due to the shock and vibration associated with the application. At present, Nuvera, Plug Power and Hydrogenics (a Canadian company) offer PEM FC power systems for forklifts that are interchangeable with the standard battery systems. Oorja Protonics offers a different type of system with a direct methanol FC that acts as a battery charger rather than as a direct source of motive power.

[5] The retail prices for larger FC systems being sold for class 1 and 2 forklifts in 2011 ranges from $32,000 to $48,000, roughly $4,000 per kW retail price for the full system.

The PEM unit competes with conventional battery powered units in the class 1 and 2 markets, where the batteries cost about $5,000 per pack for an advanced lead acid battery with a capacity of about 20 kWh. For a 2 shift operation, 2 battery packs are required and the charger costs about $2,000. Batteries have a life of about 5 years assuming 250 deep discharge cycles per year, while the lift truck appears to have a 10 to 12 year useful life. Hence, undiscounted battery+ charger costs will be about $22,000 over the life a truck for 2 shift operation and about $32,000 for a 3 shift operation.

In 2010 a FC stack had a target life of about 20,000 hours which translates to at least a 5 year life on a 2 shift operation or 3.5 years on a 3 shift operation after which the stack only must be replaced at a cost of about $10,000. The fuel cell forklift's batteries need to be replaced every 2.5 to 3.5 years at a cost of about $1,000.[6] Other part replacements for the balance of plant would add about $5,000 over the life of the truck. Hence the undiscounted life cycle capital cost for the system was about $57,000 for a 2 shift operation and $68,000 for a 3 shift operation (not including policy incentives).

Fuel costs are also much higher for FC powered vehicles. The battery powered truck uses approximately 15 kWh per shift, which costs about $1.50 to $2 for electricity at 10 to 13 cents/kWh. For a FC operating at a mean efficiency of 45%, the vehicle would consume about 1kg of hydrogen per shift. Thus, the fuel cost is $7 to $8 per shift due to the high delivered price of hydrogen. In addition, current FCs systems have not quite attained the same level of reliability as lead-acid batteries and may need more maintenance than comparable battery powered lift trucks. The FC powered lift truck performs better at the end of the shift when battery powered lift trucks lose performance as battery state-of-charge goes to low levels. FC powered trucks can produce a 10% productivity advantage due to better performance during the last 2 hours of the shift. FC cell trucks can also be refueled in 2-3 minutes; exchanging battery packs takes considerably longer.

[6] In 2011, one manufacturer reports that improved batteries are now used with an anticipated life of 10 years.

To be competitive on capital cost, FC system costs must be reduced by a factor of 2, and stack life increased by a factor of 2. However, operating costs will still be much higher as FC efficiency of much above 50% is not possible with current designs and delivered Hydrogen costs much below $4/kg are unlikely given production costs are around $2.50 to 3 per kg. At current economics, the fuel cost disadvantage is about $3,000 per year for a 2 shift operation and $4,500 per year for a 3 shift operation. For fuels cells to compete effectively with batteries their greater end-of-shift productivity, shorter refueling time, and elimination of battery swapping would have to outweigh their apparent cost disadvantage.

In addition, the overall market size is relatively small. The Industrial Truck Association reports that sales of Class 1 and 2 electric lift trucks have been in the 50,000 to 70,000 units per year range for the last decade (except in 2009 when they were much lower due to the recession). Of these about 70 percent are used in single shift operations according to anecdotal information, while the remaining 30% are used in 2 or 3 shift operations. Hence, the long-run target market for class 1 and 2 FC powered forklifts is, conservatively, this 30% of the market which equates to 18,000 ± 3,000 units per year. With 3 to 4 competitors, the maximum likely volume is 5 to 6 thousand units per manufacturer per year, even assuming that FCs capture the entire market. Of course, markets exist outside of the United States that are not considered in this study. Also, there is potential to repower battery forklifts already in operation with fuel cell systems. In addition, OEMs are now selling FCs to power class 3 forklifts, and that market has not been included in this analysis.

4.3 COMBINED HEAT AND POWER (CHP)

In general, CHP systems can offer very high levels of energy use efficiency if the waste heat can be utilized. In typical installations, waste heat is used for hot water, space heating or for heating pools or spas in systems with large quantities of waste heat. The ratio of electric power to waste heat differs among the different types of systems. The electric power produced competes with the grid based electricity while the waste heat typically competes with gas fired boilers; hence, the value of electric power is higher and the higher the conversion rate of fuel to electric power, the higher the net value achieved assuming that the system is sized to meet electricity average loads.

Figure 8 shows the relative conversion efficiency for electrical energy and thermal energy, with the line representing an 85% overall (electrical + thermal) efficiency line. Most systems lie close to the 85% total line but the solid oxide FC has the highest electrical efficiency followed by the PEM FC at 30 to 34 %. The ICE is relatively close to the PEM with an electrical efficiency of 25% to 28%. PAFC and MCFC which have efficiencies between those of the PEMFC and SOFC are not shown in this figure.

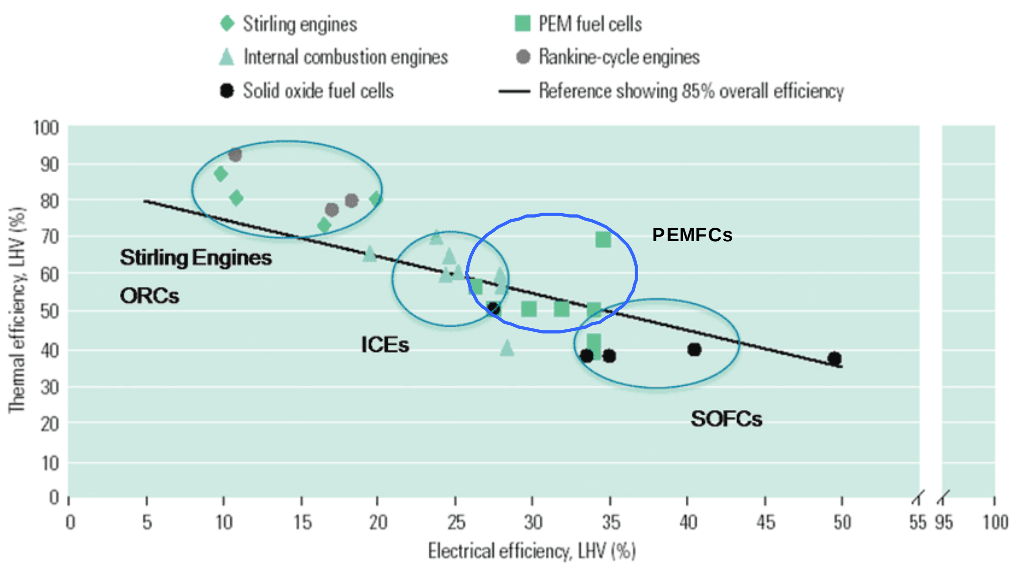


Figure 8. Relative Electrical and Thermal Conversion Efficiencies of FC Technologies (Hedman, 2010).

The United States has a long history of using CHP, and, according to 2010 data[7], the U.S. total CHP generating capacity was 84.2GW at 3,635 facilities. The large base of installed capacity in the United States is the result of supportive federal policies in the 1970s and 80s, including PURPA, the Public Utilities Regulatory Policy Act, which required utilities to purchase electricity from CHP plants at a set rate. A number of U.S. States, including California, New York and other

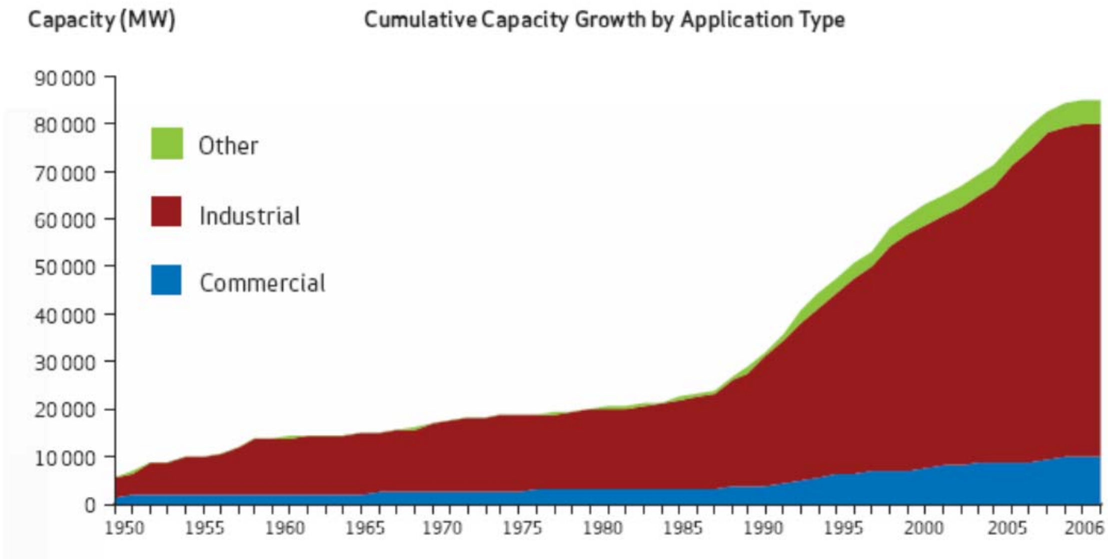
[7] CHP Installation Database. Maintained by ICF International for Oak Ridge National Laboratory. 2010. http://www.eea-inc.com/chpdata/index.html

Northeastern states, also provide incentives. However, the partial repeal of PURPA, as well as a wide diversity in state support, has resulted in a patchwork of CHP markets.

While PURPA promoted the CHP development, it also had unforeseen consequences. PURPA was enacted at the same time that larger, more efficient, lower-cost combustion turbines and combined cycle systems became widely available. These technologies were capable of producing greater amounts of power in proportion to useful thermal output compared to traditional boiler/steam turbine CHP systems. Therefore, the power purchase provisions of PURPA, combined with the availability of these new technologies, resulted in the development of very large merchant CHP plants designed for high electricity production. The third-party CHP developers, who had greater interest in electric markets than thermal markets, enabled large CHP facility construction (greater than 100 MW) paired with industrial facilities. As a result, in 2006 65% of existing U.S. CHP capacity – 55 000 MW– was concentrated in plants over 100MW in size.

Figure 9 shows the cumulative growth of CHP capacity in the United States since 1950, highlighting the rapid increase in growth starting in the late 1980s. In the past four years growth flattened due to generally weak economic conditions and capital restrictions.

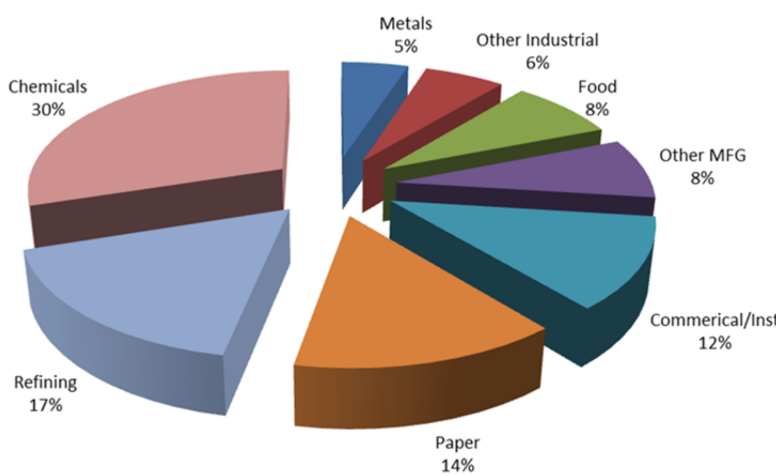
Smaller scale CHP projects started growing in mid-90s supported by the federal government and state incentives. The policy makers at different levels realized the benefits of locally deployed CHP systems as more efficient means of generating energy in cleaner and less carbon-intensive manner. The U.S. DOE and Environmental Protection Agency established a number of CHP-focused programs.



Source: ICF, EEA CHP Installation Database, 2010, accessible at http://www.eea-inc.com/chpdata.

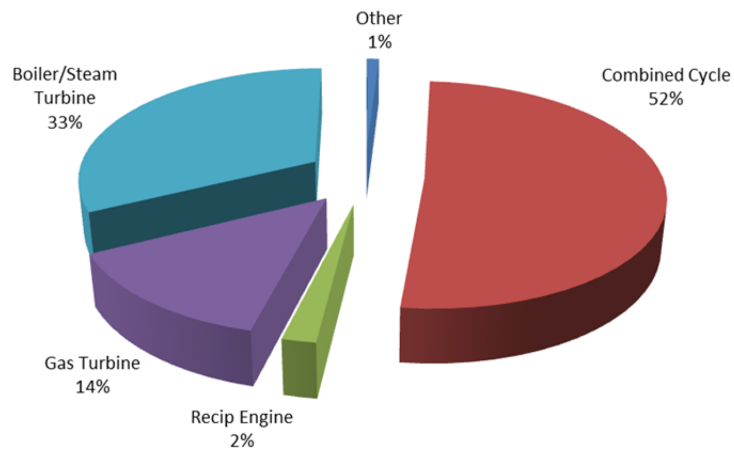
Figure 9. CHP Cumulative Capacity Growth in the United States, by Sector.

The CHP capacity is used in broad range of applications, although the vast majority, about 88% is in large-scale industrial sector projects, including chemicals, paper, refining, food processing and metals production. The CHP applications in commercial and institutional applications was about 12% in 2006, in facilities including hospitals, universities, schools, apartment complexes and farms . Figures 10 and 11 provide further breakdown of the CHP capacity.



Source: ICF, EEA CHP Installation Database, 2010, accessible at http://www.eea-inc.com/chpdata.

Figure 10. The U.S. CHP Capacity by Sector, 2006.



Source: ICF, EEA CHP Installation Database, 2010, accessible at http://www.eea-inc.com/chpdata.

Figure 11. The U.S. CHP Capacity by Technology, 2006.

The CHP installations in the United States use a diverse mix of fuels, with natural gas being the most common fuel at 72% of the CHP capacity. Coal and process waste make up the remaining fuel mix (14% and 8% respectively), followed by biomass, wood and oil. There has been increased interest in biomass and waste fuels in recent years as policymakers and consumers seek to use more renewable fuel sources.

The prominent use of natural gas as a fuel for CHP in the United States is driven by the extensive use of gas turbine and combined cycle (gas turbine/steam turbine) technology. Figure 11 shows that the combined cycles and gas turbines represent 52 and 14% of existing CHP capacity, respectively. Boiler/steam turbine systems represent 33% of the total. Reciprocating engines, primarily fueled by natural gas, represent 2% of CHP capacity. Together, microturbines (small, recuperated gas turbines in the 60 to 250 kW size range), FCs and other technologies such as organic Rankine cycles represent less than one percent of installed CHP capacity.

There are significant regional differences in the distribution of CHP sites and capacity. Some states are far ahead of others in terms of adopting policies that encourage CHP growth, most notably New York and Connecticut, which offer financial and other incentives to CHP. Other regional variations can be traced to industrial development. For example, chemicals and refining are common in the Gulf Coast states and paper production in the Southeast. The U.S. DOE estimates that there is 70 – 90 GW of additional industrial CHP potential, and 40 – 60 GW of commercial/institutional CHP potential in the United States, for a total of 110 to 150 GW of additional capacity. The DOE analysis has shown that over one-half of the technical potential is in systems below 5MW in size in commercial and institutional applications.

4.4 MICRO (0.1 kW to 10 kW) AND SMALL (100 kW to 5 MW) CHP APPLICATIONS,

Micro-CHP is defined as appliances of less than 10 kW of electricity output used to provide both electricity and heat, typically for residential or small commercial buildings. Micro-CHP systems may be driven by FCs, or internal combustion engines (reciprocating, rankine or Stirling engines). Micro-CHP systems can be fueled by natural gas, liquefied petroleum gas (LPG), diesel fuel, or biomass energy. Although micro-CHP FCs could be powered by any of these fuels, natural gas is generally the fuel of choice due to its availability, low cost and relative ease of reforming.

Climate Energy is utilizing Honda’s engines to offer a micro-CHP unit under the trade name Freewatt(R). The system is currently marketed in the Northeastern states, where sales are boosted by the relatively cool climate and legislation promoting net-metering, which allows owners of alternative energy systems to recover costs by feeding electricity back into the grid. The system can be configured to power a hot-water boiler system in addition to the home heating baseline configuration. The Freewatt is powered by Honda's GE160EV natural gas engine and produces 3.26 kW of heat and 1.2 kW of electricity. The price for Freewatt micro-CHP with warm-air heater is about $13,000 installed (implying about 10,800$/kW), depending upon the complexity of the installation.

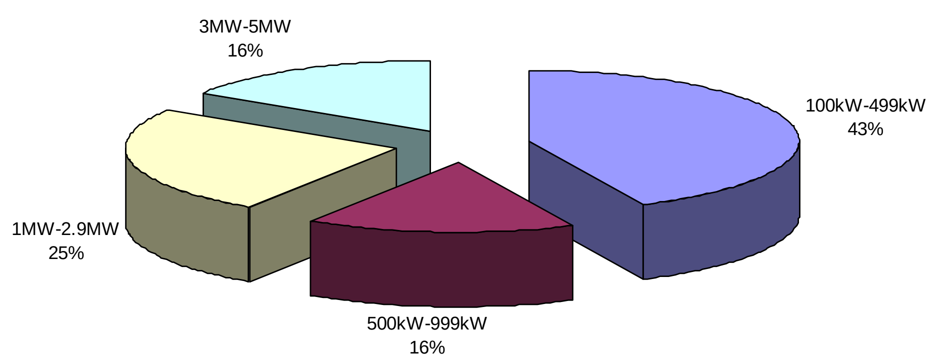
Marathon is marketing a micro-CHP system called Ecopower™. The 4.7 kW system is Marathon™ engine-based and designed for residences or small commercial buildings, using natural gas or propane. Since the early 2000s the Ecopower™ has been available in Europe, where almost 1,600 systems have been installed (according to 2008 data). The system is now available in the United States and combined with installation costs is being quoted up to $35,000 (or up to $7,400/kW) depending on locale and whether it's a retrofit or a new construction.

ClearEdge markets a 5 kW FC unit at about $50,000 with a typical installation cost of $2,000, which leads to a net cost of $10,000 per kW, which is close to the competitive range of the engine based systems. However, the Federal Investment Tax Credit (ITC) of $15,000 ($3,000/kW or 30% of capital cost) and the California SGIP credit of $12,500 reduce net cost after tax to $24,500 or $4,900/kW. System electric efficiency is greater than the competing engine powered systems. In a residential case study for a 5500 square foot home ClearEdge claimed an annual electricity bill savings of $11,000 and gas heating bill savings of $2,500, but the implied electricity cost in this example is almost 39 cents per kWh. At 19 cents per kWh, savings would be $5,400 on electricity and total savings would be $7,900 for a 3 year simple payback which could be attractive to homeowners.

Overall system economics are obviously highly dependent on local electric prices and the ability to use waste heat. If the waste heat can be used only half the year or less, then savings would be smaller. More importantly, with annual use of 4,000 to 5,000 hours, it is not clear what the stack life would be, but based on other system estimates, a 20,000 hour stack life would imply stack replacement every 4 to 5 years for a cost of $10,000 to $12,000 plus installation cost. Nevertheless, a 7 to 10 year payback at current FC costs implies better payback if cost reductions through learning and scale are achieved.

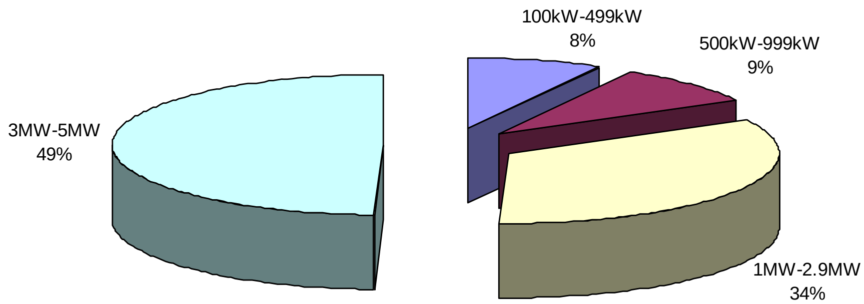
The total number of single family homes in the United States with natural gas supply is estimated at 55 million with an additional 0.8 to 1 million units in new construction every year (except in the 2008-2010 recession years). Census data shows that homes over $500,000 which may be the target market for CHP are about 10 to 12 % of sales in non-recession years leading to a market estimate of about 6 million existing units and 100,000 new units. Hence, the overall large house market size is on the order of 5 to 6 million, with about 100,000 new housing units per year. The market will be further limited to houses in geographic locations that can use waste heat. According to the Residential Energy Consumption Survey, about 70% of the houses in the United States require more than 4,000 heating degree days (HDD), while 14% require over 7000 heating degree days. The market requiring the most heat (over 7,000HDD) is about 700,000 to 850,000 existing homes. If heating systems are replaced on a 20 year cycle, the replacement market is about 35,000 to 42,000 units and the new installation market is in about 14,000 new homes. In addition, micro-CHP can also be used in small apartment buildings and light commercial establishments (like fast food sales outlets). Thus, the overall market is potentially large if the retrofit market accepts CHP replacements for existing heating units.

According to ICF data, in 2010 there were 1,771 “small” CHP (electric generation capacity between 100 kW and 5 MW) sites in the United States. These sites provide about 2.25 GW of the total CHP generation. Figures 12 and 13 illustrate that, while the smallest projects in this group, between 100 kW and 499 kW, comprise about 43% of the sites, its generating capacity is only 183 MW or 8% of the total in this group. The largest project, between 3 MW and 5 MW, count in the United States is 282, and these facilities provide about 49% of the small CHP generating capacity.



Source: ICF, EEA CHP Installation Database, 2010, accessible at http://www.eea-inc.com/chpdata.

Figure 12. Small CHP (100 kW to 5 MW) Site Count Distribution in the United States.



Source: ICF, EEA CHP Installation Database, 2010, accessible at http://www.eea-inc.com/chpdata.

Figure 13. Small CHP (100 kW to 5 MW) Generating Capacity Distribution in the United States.

The vast majority of the small CHP projects utilize natural or waste gas-fueled reciprocating engine or turbine technology. Other fuels such as oil-based and renewables are also utilized in boilers/steam turbine units. The commercial sector projects, mostly comprised of supplying heat and power to various types of buildings, was the leading small CHP market with combined capacity of about 1.14GW. The industrial sector is also a significant contributor with about 0.96GW generating capacity in the United States. Table 2 itemizes the generating capacity and facility count in the United States by fuel, sector and the prime mover technology.

Table 2. The Small CHP (100 kW to 5 MW) Capacity and Site Count Distribution by Technology, Fuel Type and Sector

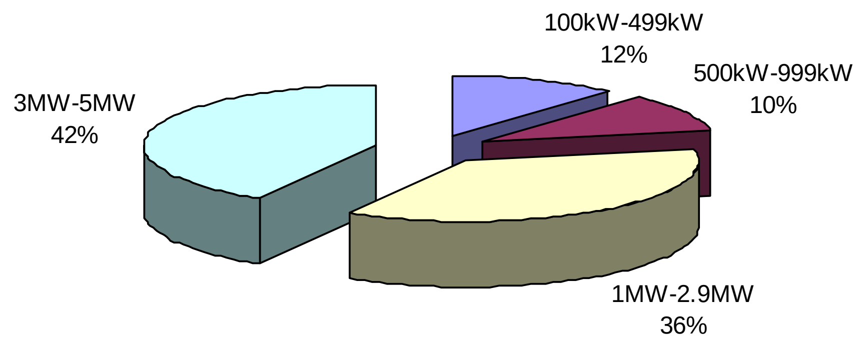
Fuel Class	# Sites	Capacity (MW)
Biomass	216	244.5
Coal	44	109.9
Natural Gas	1,147	1,346.9
Oil	177	241.1
Waste	49	100.8
Wood	80	130.6
Other	58	79.3
Total	1,771	2,253.0

CHP Technology	# Sites	Total Capacity (MW)
Boiler/Steam Turbine	312	653.2
Gas Turbine	156	483.1
Recip Engine	1,087	1,042.1
Fuel Cell	89	37.5
Microturbine	127	37.0
Total	1,771	2,253.0

CHP Sector	# Sites	Total Capacity (MW)
Industrial	522	962.0
Commercial	1,101	1,140.3
Other	148	150.7
Total	1,771	2,253.0

Source: ICF, EEA CHP Installation Database, 2010, accessible at http://www.eea-inc.com/chpdata.

The Commercial small CHP capacity is dominated by relatively large projects from 1MW to 5MW. There is large capacity installed in facilities such as hospitals, colleges/universities and office buildings. Figure 14 provides further small CHP capacity distribution by facility size in the commercial sector.



Source: ICF, EEA CHP Installation Database, 2010, accessible at http://www.eea-inc.com/chpdata.

Figure 14. The Commercial Small CHP Capacity Distribution in the United States by Size.

The CHP projects are developed on case-by-case basis and its economics are driven by wide variety of factors such as location, fuel supply (distance to the pipeline, landfill, etc.), need to construct enclosure buildings, local permitting regulations, etc. Sometimes the project decision is made because the CHP process results in other value added product revenues (for example fertilizer leftover from anaerobic digester process). Some economic benefits are taken into consideration but are hard to quantify and include local emissions and noise reduction, power quality and reliability, worker productivity improvement, etc.

The U.S. DOE has documented numerous CHP projects and the summary descriptions are publically available[8]. The project summaries are provided by sector and facility type. Table 3 provides basic economic factors for several building projects that range from 150 kW to 3.8 MW. The sample illustrates that the project costs are highly variable and highly dependent on local conditions. The cost spread on kW-basis is very high from hundreds of $/kW to thousands.

[8] http://www1.eere.energy.gov/industry/distributedenergy/projects_sector.html

Most of the reciprocating engine based systems are in the lower end of the range while turbine based systems are much more expensive. Many of the more expensive projects were initiated because the federal and local incentives were made available to reduce the upfront cost and/or operating expenses. The project simple pay-back period ranges from 3 to 9 years in this sample, before incentives.

Table 3. Selected Small CHP Building Project Basic Economic Factors. Source: the U.S. DOE3

Project	**Fuel**	**Electric Generating Capacity [kW]**	**Prime Mover**	**Installed Cost [$million] (w/o incentives]**	**$/kW**	**Estimated Payback w/o incentives [Years]**
Advocate South Suburban Hospital	Natural Gas	1,050	Reciprocating Engine	1.7	1,619	8
Beloit Memorial Hospital	Natural Gas	3,000	Reciprocating Engines (2)	1.2	400	5.4
Little Company of Mary Hospital	Natural Gas	3,800	Gas Turbine	1.2	316	3
Antioch Community High School	Landfill gas	360	Microturbines (12)	1.9	5,277	8.5
National Animal Disease Center	Natural Gas	1,200	Combustion Turbine	3.1	2,583	9.3
Evanston Township High School	Natural Gas	2,400	Reciprocating Engines (3)	1.5	625	4.2
East Bay Municipal Utility Building	Natural Gas	600	Microturbines (10)	2.5	4,183	8
Museum of Science and History, Chicago	Natural Gas	1,750	Reciprocating Engine	1.7	985	8.6

Source: ICF, EEA CHP Installation Database, 2010, accessible at http://www.eea-inc.com/chpdata.

5. U.S. POLICIES AND THEIR IMPACTS

At the federal level, two significant policies shape the market for FCs. The first is the Investment Tax Credit (ITC) which provides through 2016 a tax credit of $3,000 per kW for FCs up to a maximum of 30% of total capital cost. Which components represent the capital cost of a FC is a matter of interpretation. Internal Revenue Service publications state that the capital cost of the fuel cell system is eligible for the tax credit (IRS, 2009). In the analysis below we assume this includes BoP and reformer, if any. In response to the economic recession that began in 2008, section 1603 of the American Recovery and Reinvestment Act (ARRA) of 2009 allowed purchasers of FCs to claim a subsidy in lieu of the tax credit. The intent was to extend the subsidy to firms that might not have taxable profits in the recession years. As of March 1, 2010, only four 1603 grants had gone to fuel cell projects out of a total of 392 projects receiving 1603 grants (Bolinger et al., 2010). Second, the ARRA provided additional funds for subsidizing purchases of FCs, based on cost-sharing contracts awarded by the U.S. DOE. The state of California offers additional incentives to purchasers of FCs for use in CHP applications in the form of its Self Generation Incentive Program (SGIP). The size of the California SGIP incentives depend on the nature of the energy used to power the FC. Other states, including Connecticut and New York also offer incentives.

The ARRA program administered by the DOE awarded $41.9 million in federal funding for FCs, matched by $54 million in cost-sharing from industry (U.S. DOE, 2010a, p. 32). About half of the federal funding went for backup power units. The funding is expected to deploy up to 1,000 FC systems in back-up power and material handling applications (Table 4). As of December 2010, 206 lift trucks had been delivered and eight back-up power installations were in operation with eight more scheduled. The impacts of the ARRA purchases vary from firm to firm. ARRA purchases account for the majority of Plug Power’s material handling business in 2009 and 2010 (Figure 15). Given that Plug Power has shut down its other product lines and is attempting to sell them, the ARRA procurements have been crucial to the firm’s survival. In total, it is estimated that the ARRA induced purchases of 77 5 kW material handling fuel cell systems in 2009 and 572 systems in 2010. In addition, the ARRA enabled the purchase of 52 systems of 5 kW equivalent backup power in 2010 (Figure 15). The great majority of ARRA financed units were material handling or backup power PEMFCs (Figure 16). Large stationary units though smaller in number were much larger in kW capacity.

Table 4. Awards of the ARRA FC Early Market Project (Kurtz et al., 2010)

COMPANY	AWARD	APPLICATION
Delphi Automotive	$2.4 M	Auxiliary Power
FedEx Freight East	$1.3 M	Specialty Vehicle
GENCO	$6.1 M	Specialty Vehicle
Jadoo Power	$2.2 M	Backup Power
MTI MicroFuel Cells	$3.0 M	Portable
Nuvera Fuel Cells	$1.1 M	Specialty Vehicle
Plug Power, Inc. (1)	$3.4 M	CHP
Plug Power, Inc. (2)	$2.7 M	Backup Power
Univ. of N. Florida	$2.5 M	Portable
ReliOn Inc.	$8.5 M	Backup Power
Sprint Comm.	$7.3 M	Backup Power
Sysco of Houston	$1.2 M	Specialty Vehicle

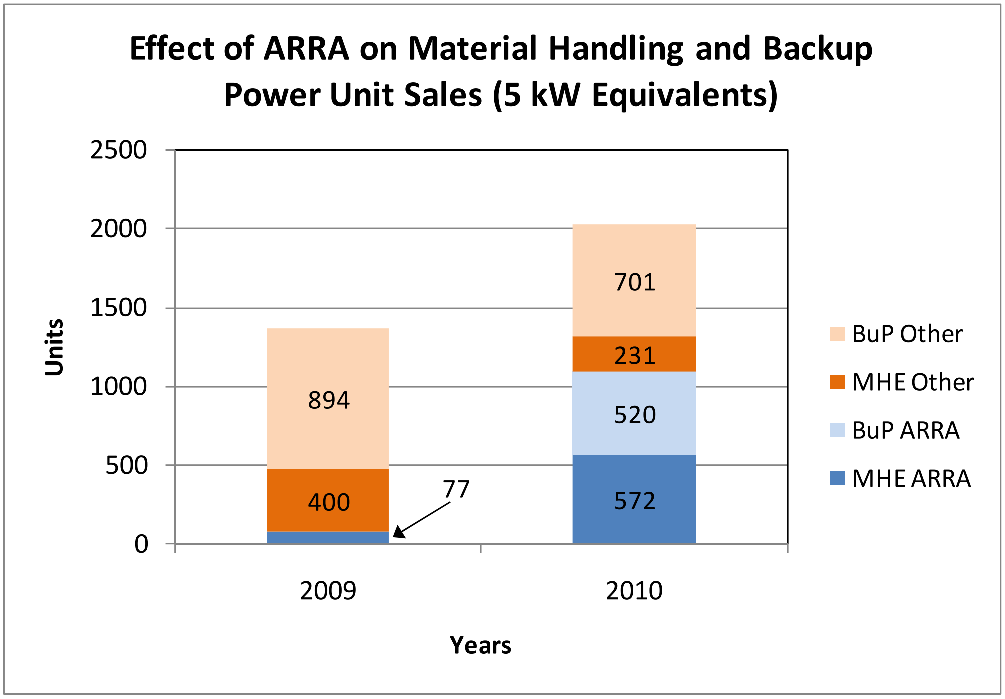


Figure 15. Estimated Effect of ARRA on Material Handling and Backup Power Unit Sales in 5 kW Equivalents.

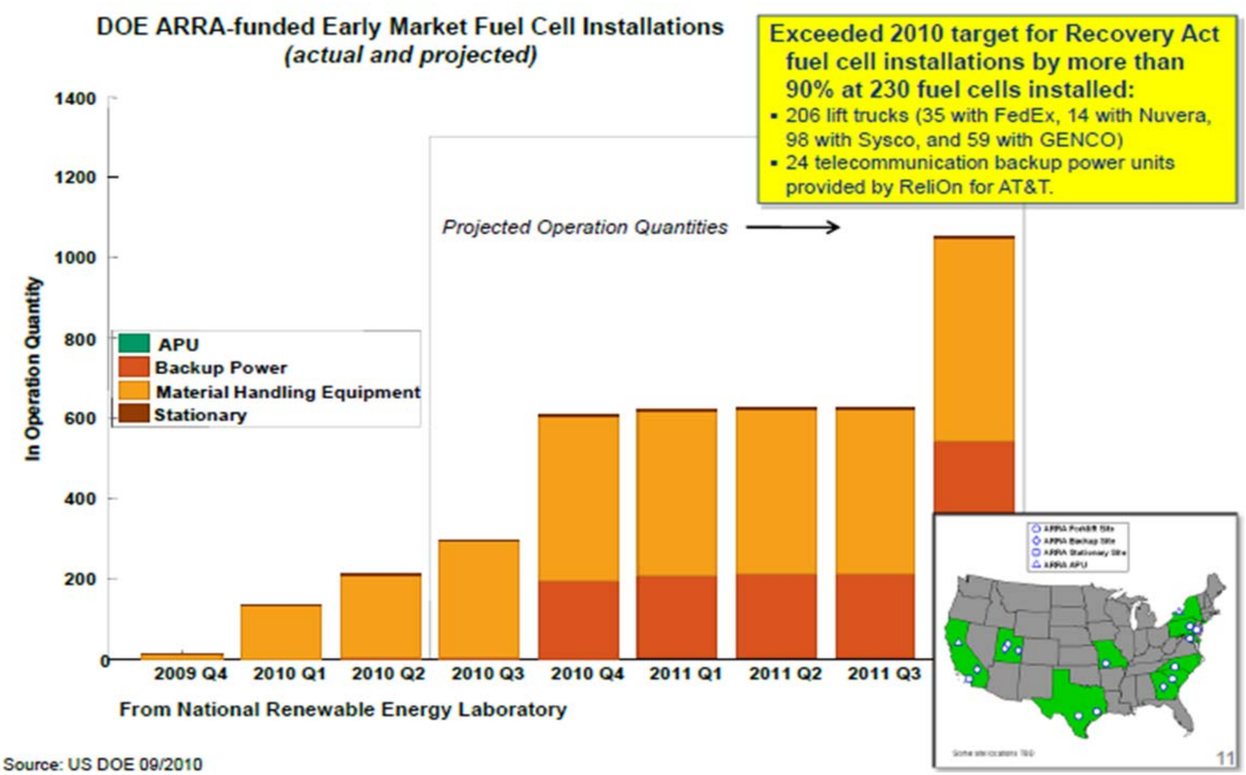


Figure 16. Cumulative ARRA-funded Sales of Non-Automotive Fuel Cells.

6. NON-AUTOMOTIVE FUEL CELL PROGRAMS IN JAPAN AND THE EU

6.1 JAPAN

Three companies, Toshiba, JX Energy, and Panasonic, account for nearly all of Japan's stationary FC program, which is focused on small, 1 kW, PEM CHP units chiefly for single-family homes. These three companies provided information on the progress and status of Japan's micro CHP program. In Japan, 45% of homes heat with natural gas, 45% with LPG and 10% with electricity. According to these firms the Japanese government considers stationary FCs to be one of 21 key technologies for the future. The government has also spent 1 ¥ billion (roughly $10 million) on FC vehicle demonstrations in Japan to date. There are 60 FC vehicles in operation and 15 public H_2 refueling stations. Japan has a small presence in larger fuel cell technologies. Fuji Electric is the only company in Japan making fuel cells larger than 100 kW.

The Japanese government and industry carried out a deployment program for home CHP FCs, beginning in 2000. The Japanese government played a large role in selecting the technology and targeting the market of home CHP. The period from 2000-2004 was used for technology verification. From 2005-2008 a large-scale demonstration program was implemented. There were 10 industrial partners, all "energy companies." They developed sales channels, principally via the gas utilities. The parties involved are Manufacturer → Energy Company → Builder → Customer. The sales are almost exclusively to new homes, although they plan to move into the replacement market once capital cost is sufficiently reduced. When the large-scale demo started there was great concern about reliability and, in fact, initially there were problems. The overall failure rate for fuel cell CHP systems was reduced to 6 to 7 percent by 2009 and in 2011 to 5%. Most of these are Balance of Plant (BoP) failures.

Toshiba's FC Power Systems Corporation includes approximately 100 engineers. Toshiba has had a close relationship with UTC in the United States since 1985 and had a joint venture with them in 2001. Toshiba began working on PAFC technology in 1978 but Toshiba has recently abandoned PAFCs to focus on the 1 kW home PEM CHP market. They are producing 0.7 kW CHP FCs which they believe is the best fit for the home CHP market in Japan. Japanese households use much less energy than U.S. households, so the 0.7 kW unit can provide most of the household's electricity while functioning closer to rated capacity most of the time. Peak demand comes from the grid. The heat produced is used to heat water in a 200 liter tank for domestic use. In the summertime, the FC operates only about 8-9 hours per day but in the winter it operates close to 24 hours. The system is approximately 85 percent efficient, 35 percent of the input energy coming out as electricity and 50 percent as heat. Their system is intelligent and learns the usage patterns of the household in order to operate more efficiently. The system can run on LPG or natural gas but the vast majority of installations use natural gas.

The Japanese electricity grid is highly reliable but electricity is also expensive. An average electricity price is 25 ¥/kWh ($0.25 to $0.30/kWh, depending on exchange rates) but may be only 6-7 ¥/kWh at night if the customer has a special kind of contract with the utility. Using natural gas, the FC can generate electricity at a cost of only 10 ¥/kWh. Toshiba estimates that households using the FC CHP system will save between 40,000 and 50,000 ¥ per year on electricity costs.

Commercial sales of the system, called ENEFARM, began in 2009. Toshiba, for example, has a sales target of 2,500 units for 2010. The ENEFARM system is sold as a package with a new house. The sales price is 3.2 to 3.5 ¥ million for the system including installation and maintenance for 10 years, but the government provides a large subsidy. In 2009 the subsidy was 1.4 ¥ million, it is now 1.3 ¥ million (2010) and will be reduced to 1.05 ¥ million in 2011. The entire supply chain for Toshiba's FCs is in Japan.

The current durability of Toshiba's product is more than 40,000 hours. Their goal is 80,000 hours, including 1,000 shut downs and restarts, which equates to 10 years of operation. They think this is a realistic target for 2011. Toshiba believes that SOFCs have better potential costs, fuel tolerance and efficiency than the PEMFCs. However, their problem is durability – only 20,000 hours for the current technology.

The alternative to the home FC system is the heat pump (EcoCute) of which the annual volume of sales is 500,000 units and the cost is typically 400-500,000 ¥. If FCs can capture 10% of this market, that will be enough to sustain the industry. The difference in cost, including the government subsidy is approximately 3,300,000 – 1,300,000 – 500,000 = 1.5 ¥ million. If the customer saves 50,000 ¥ per year, the payback period is 30 years, not cost-competitive with the heat pump. This limits the market for home CHP FCs to those with a special interest in the environment and advanced technology.

The industry-government demonstration program was divided into two stages. In the "R&D" stage from 2005 to 2008, a large-scale demonstration project was conducted. In this phase, utilities purchased PEMFC CHP systems from manufacturers and received a subsidy from the government. The government provided the following subsidies during the large-scale demonstration phase of the program.

2005: 6 ¥ million/unit
2006: 4.5 ¥ million/unit
2007: 3.5 ¥ million/unit
2008: 2.2 ¥ million/unit

In the second phase, consumers purchased CHP units from the manufacturers and received subsidies from the government, as follows.

2009: 1.4 ¥ million/unit
2010: 1.3 ¥ million/unit

These subsidies represent approximately 50% of the installed price of the units. The installed price is currently between 3 ¥ million and 3.5 ¥ million. This cost includes the cost of back-up boilers (250,000 ¥ to 300,000 ¥) which insure that hot water will be available in times of peak demand. It may be that the gas companies who market the FCs to builders and homeowner may also provide some subsidy.

The subsidies went to the buyers. There was no R&D cost-sharing by the government. The total budgeted subsidy for 2010 is 6 ¥ billion, enough to cover approximately 5,000 units, the sales target. The long-term target is 2.5 million cumulative sales by 2030.

JX Nippon Oil & Energy Corporation markets CHP FCs under the brand name ENEOS. ENEOS CellTech, which is 81% owned by JX, is a joint venture with Sanyo Electric Company. JX, which has 34% of the Japanese oil market, has the goal of being a comprehensive energy provider. ENEOS is also a partner in the government program in which Toshiba participates. JX has a SOFC program which is in the demonstration stage and is aimed at smaller families of 2 to 3 persons because SOFC systems produce less heat compared with PEMFCs. The SOFC system will be smaller than the PEMFC system and therefore it will be suitable for use by individual families living in large multistory condominiums in the future. JX's SOFC system, which will be introduced in the Japanese market in October, has a rated electrical output of 0.7 kW and produces 650 W of heat at a tank temperature of 75 degrees C. Their PEMFC program is aimed at 4-5 person families living in detached homes. Their product, which has already been successfully introduced in the Japanese market is a 0.75 kW rated CHP FC system that produces 1,070 W of heat at 65 degrees C.

JX's PEMFC capacity is currently 3,000 units per year, and they sold 1,200 units last year. Their long-term target price for a unit is 500,000 ¥, although it was hard to judge how realistic JX considers this target to be. If this target could be met without government subsidy the units would have a payback period of about 10 years.

Like others, they sell their units either to utilities or to home builders. The service life is 10 years, which JX takes to be 40,000 hours, or 4,000 hrs/yr (10-12 hrs/day). Their competition is the heat pump, but heat pumps cannot generate electricity at home (hence the name ENEFARM).

JX believes that SOFCs will ultimately cost less than PEMFCs. The SOFC will produce a greater share of electricity, as well. The challenge for SOFCs is durability. The market introduction for

SOFCs is 2011. The target market is the same, family houses, and the product size is as well, 0.7 kW. The FC + photovoltaic (PV) combination is attractive to some because PV electricity can be sold to the grid at 48 ¥/kWh, whereas the market price for electricity is 24 ¥/kWh. With a FC system, the homeowner can sell more PV electricity to the grid. Approximately 100,000 homes in Japan installed PV last year. The total number of PV systems in Japan is 600,000. JX sees the future as the PV+FC combination.

Sales of PEMFC CHP systems are to green, early adopters. These homeowners save about 40,000 ¥/yr on electricity but that is not enough to make the systems economical.

Panasonic is the third, remaining major participant in Japan's stationary FC program. Their FC operations are located at the headquarters of their Home Appliances Company in Kusatsu City near Kyoto City. Panasonic's Home Appliance Company has annual sales of approximately 1,000 billion ¥. They specialize in audio-visual and air conditioning, as well as refrigerators and other small home appliances. The entire Panasonic group has six strategic projects, one of which is "energy creation" which includes FCs. Development on FCs began in 2000 and by 2008 the stationary PEMFCs for CHP were ready for commercialization. In the government's large-scale demonstration program, Panasonic installed 500 units at homes.

They have already achieved a high energy efficiency of 85% (HHV), 35% of the input energy emerging as electricity and 50% as heat. They also have achieved 10-year durability with 40,000 hours of operation and 4,000 stop/start events. Their inverter technology, stack and fuel processor are the keys to the performance and durability of their equipment, which is rated at 1 kW but operates most of the time between 0.5 and 1.0 kW, achieving a net electrical efficiency of more than 34% in this range. Heat produces hot water at 60 degrees C, which is sufficient for the Japanese customer. Each unit has a "back-up" boiler for hot water.

The retail price was 3.3 ¥ million in 2010. The government subsidy was 1.4 ¥ million in 2009 and 1.3 ¥ million in 2010. The subsidy is not to exceed one half of the total of the "rated" price and installation cost. Like others, they deal with the utilities who deal with the customer. The customer receives this subsidy only after the unit is in operation. Their target is to price the PEMFC unit at less than 1,000,000 ¥, and for the customer to save 60,000 ¥ per year in costs by using the unit. They intend to realize this target by 2018. They believe they know how to achieve the cost reductions, so they are confident in achieving their goals.

Their target sales ("ideal" not business plan) is to sell 30,000 to 40,000 units per year. In 2009 they sold 2,200 units and in 2010 they expect to sell 3,000. Their customers are individuals motivated by high technology and environmentalism, and large families that use a lot of hot water. Panasonic had about 45% of the PEMFC CHP market in 2009. In Japan, there are approximately 1 million new housing units each year (homes and apartments). They hope for 5% of that market or 50,000 per year.

Panasonic Home Appliances has no plans to manufacture larger FCs. They believe smaller cells are a much larger market.

The long term goal is to establish a hydrogen economy. The home FCs will then run directly on hydrogen distributed via a national infrastructure. This will eliminate the need for a reformer and significantly reduce costs.

6.2 EU: GERMANY/NETHERLANDS

The German government's hydrogen organization (NOW), divides its FC program into automotive, stationary and special applications. NOW believes that the principle need for FCs at the present time is to achieve a critical mass of development. What is missing is the "big mass" of manpower and human capital. Because funds are limited, this means increased cooperation and collaboration. Unfortunately, some important collaborations have been ended, such as with FCE and MTU Onsite Energy (Molten Carbonate FC), and Vaillant and Plug Power.

NOW[9] is funded by the National Innovation Program, an R&D program with a focus on market preparation. To date, sufficient funds have not been available to support an adequate market creation program. NOW is attempting to overlap R&D with market introduction. There are certain, special markets in which FC technology is relatively mature. Maturity of the technology is critical because only a highly reliable final product can succeed in the marketplace.

In the micro-CHP area, where PEMFCs are now used to provide both heat and electricity to homes or other small buildings, PEMFC is the bridging technology but NOW believes that SOFC is the eventual technology. Two companies in Germany, CFCL in Heinsberg and Hexis have developed SOFCs that are close to market. Their stacks have shown durability of greater than 12,000 hours, they are less expensive than PEMFCs and about half as complex. Right now they are too expensive but costs will come down with production scale. They also still have temperature and corrosion problems, so materials research is necessary.

One “lighthouse” project of NOW is micro-CHP, 1 kW FCs that they are demonstrating today. The units are paid for by NOW and the utility company at a price negotiated between NOW and the manufacturer. Completely installed, including monitoring and data acquisition and evaluation, today the units cost about €140,000 each. Manpower is the major cost, the hardware is the minority of the cost. This compares with a heat pump (operating between 0 and 30 kW) that costs €20,000 but provides heat only. These numbers apply to a 3-4 person household using 3,600 kWh per year.

NOW had a lighthouse project for high-temperature FCs of about 300 kW, producing power in competition with diesel gensets or the grid. These were intended for hospitals, airports, breweries, etc. At present there are two installations in the field, and 10 were in the pipeline. However, the project is now on indefinite hold, due to the departure of MTU from the fuel cell business. The cost per kW installed was about €6,000, with 52% paid by the user and 48% by NOW. The MTU FC was considered to be about 90% of the way towards a mature product. The

[9] This page contains corrections to observations about Germany’s NOW program that are not in the original printed version of this report.

quality of the natural gas was the main problem, i.e., cleaning it up. The research problem is how best to integrate the FC into the end user's operation. Other potential early applications for large, high-temperature FCs are ships, for example cruise ships with 3,000 passengers. NOW sees synergies between large stationary FCs and ship energy needs. Here the quietness and absence of pollution will be key advantages. The ships would require a 500 kW FC APU, which could be fueled by methanol, ethanol, LNG or sulfur-free diesel.

NOW has a forklift program but considers the life of the FC stack and the lack of hydrogen availability at reasonable cost to be major hurdles for this application. Forklifts need to operate at least 12 hours per day and over 3,000 hours per year. Durability is of fuel cells in such applications remains an issue. In addition, the problem of availability of hydrogen must be addressed, for example, by providing a hydrogen reforming unit with FC forklifts. Unfortunately this solution is quite expensive at the present time. The forklift price alone is double that of the battery forklift. NOW considers hydrogen delivery as a problem in and of itself: someone at a firm must be responsible for the delivery, storage and safety issues.

SFC Energy (formerly known as Smart FCs) manufactures and sells small DMFCs for recharging batteries in applications such as motor homes, yachts and remote cabins. They have been in business for 10 years and have been selling commercially since 2004. SFC's vision is to take on a pioneering role by addressing FC markets with lower hurdles to entry. So far, the company has sold 20,000 units with no subsidies, mandates or other government support. The DMFC uses a specially-designed sealed methanol container, of which there are now 250,000 in commercial circulation.

The SFC DMFCs are packaged in a unit about the size and shape of a "boom box" portable radio. They range in power from 25 W to 90W. However, SFC markets their products in terms of energy output per day and names their products accordingly. The 25 W FC becomes the 600 Wh model, the 90 W unit is called the 2200. This is because their purpose is to charge batteries already owned by the customer, batteries in a boat, mobile home, etc. They are focused on this hybrid concept (batteries + FC) and therefore the issue is sustained energy output, not power. The FC cannot compete with a lead-acid battery in terms of the cost of peak power. The DMFC units provide continuous recharging (intelligent and therefore as needed).

SFC Energy's goal is to become a €100 million per year company, selling 20,000 units per year (implying €5,000/unit). A key market in the EU is motor home recreational vehicles (RVs), of which there are 2 million. Another is 8 to 20 meter boats, of which there are approximately 1 million in the EU and North America. For typical EU consumers owning such vehicles, the SFC DMFCs can provide sufficient recharging capability day in and day out. Of course, if one were to run the air conditioning of an RV 24 hrs/day, the DMFC could not handle that. Although the efficiency of their FCs is only 20-30%, that is sufficient for their customers and beats the competition. Their biggest strength is energy density, but quietness, low pollution and the ability to self-start are other advantages. A comparable ICE genset (silenced, low maintenance) costs €8,000. Affordable diesel gensets cannot self-start and are not reliable.

There are other stationary and mobile applications for their FCs. These range from mobile power for military and security personnel to stationary low-power applications, such as work zone traffic signals or surveillance cameras. Their experience is that units in such stationary applications actually run only about 20% of the time The U.S. Federal Bureau of Investigation has shown an interest in their units for covert operations in which silent, low temperature, non-polluting power is an advantage. Portable power for military operations is also one of their applications.

SFC Energy's market breaks down as follows: 80% leisure customers (RVs, yachts, etc.), remote power 10%, defense 5%, mobile APUs 5%.

The retail price of their units ranges from €2,000 for the 25W system to €6,000 for the 90W "professional" version. The professional version includes ruggedization, remote control and a 2-year warranty, although up to a 5-year warranty could be purchased. SFC believes a 5-year lifetime has already been achieved. In part this is because the DMFC architecture is simple.

Costs have been reduced dramatically over the past 5 years. Platinum loadings are down 75% to 80%. In fact, they have reduced total costs by 65% over the past 4 years. It is SFC's intention to stay below the 1 kW boundary. In part this is because the stack costs scale linearly with power output – there is really no economy to scale in the stack. Therefore they intend to focus their commercial efforts on the small scale market where they see a "sweet spot" for this technology.

SFC assembles their FC units but they source the components from suppliers. The supply chain is acceptable but more competition would help lower costs. For example, if they sell 5,000 units per year, the $20 pumps they use produce $100,000 in revenue for suppliers. No supplier will develop an optimal pump for their system for that small an amount of revenue.

The specially-designed methanol fuel cartridges come in various sizes and cannot be opened by the customer (except destructively). They have had no hazardous incidents to date, even with 250,000 units in circulation. There are 1,500 points of sale for these cartridges. They use commercial grade methanol at a volume of 100 tonnes per month. The cartridges have been certified for shipment by air cargo and thoroughly crash-tested. SFC believes that it is "impossible to ignite the cartridge."

Still, SFC is not yet profitable. They went public in May 2007, raising enough capital to have financial stability for the next 20 years. Despite having reduced costs by 65% over the past 6 years, they still foresee costs falling by about 10% per year for the near future. One factor likely to contribute to future cost reductions is scale economies in assembly and supply. They are still not in mass production mode and they expect their product to be largely hand-assembled for the next 5 years or so. At their current facility they could produce 10,000 units per year with existing equipment. They have space to expand to 20,000 units per year. Today, it requires only 2 person hours to assemble a unit.

They do receive research funding from NOW (with a 48% cost share). They do research for defense organizations as well. One of their projects is trickle charging of a BMW electric vehicle

(EV) to extend its range. The range can be more than doubled and heat provided besides. A 1 kW DMFC generates 2 kW of waste heat that can be used for cabin heating, or keeping a battery warm in cold weather. By extending the range of the battery pack, the DMFC allows either battery downsizing to reduce costs or increased range, or both. The DMFC starts in winter temperatures in a few minutes. It can operate at temperatures as low as -40° C and as high as +45° C.

Nedstack, which describes itself as the largest PEM stack manufacturer in the EU, is based in Arnhem, Netherlands. Nedstack produces PEM FC stacks; it does not integrate them into products. Nedstack does, however, have systems integration expertise that they use to assist their customers. Their focus is hydrogen PEM. Their two biggest markets are back-up telecom and the conversion of byproduct hydrogen from chlorine plants into electricity. 1 MW (168 stacks), low-temperature units are used in the latter application. There are hundreds of such plants worldwide but some already use the excess hydrogen produced in manufacturing chlorine. One Italian company has over 300 back-up units in operation that use Nedstack PEMFCs. The high reliability of the grid in Japan and the EU limits the market for FC back-up power units in these countries. The large markets appear to be in Indonesia and India.

Other markets they see in the mid-term are forklifts, generators, and buses. A range-extender for larger forklifts is a likely application. They are participating in demonstration projects including a hydrogen truck (16 kW, battery hybrid) and a city bus in Arnhem (30 kW, also hybridized). There is also a canal boat using two 30 kW stacks. For all such projects hydrogen availability is an issue. There are only 3 hydrogen refueling stations in the Netherlands.

Nedstack has customers all over the world, including the United States. They use EU and U.S. suppliers. They design their MEAs (their expertise is in materials) but they purchase them from others and make some themselves. Their XL (long-life) MEAs last 10,000 hours with a goal of achieving 20,000 hours. Their XP versions are designed for high performance.

Their FCs have close to 50% efficiency (more at peak power production). However, this is not a key selling point for their customers: safety and reliability are. They operate on pure hydrogen and ambient air at low pressure. This saves cost on pumps and air filters and improves reliability. Their stacks are typically 1 kW to 10 kW peak power, operating at 230 amps.

Nedstack sees considerable potential for cost reduction, mainly from improved production processes and increased scale of production with existing equipment and staff. They now have one production line and are planning to open another by the end of 2011. With that expansion they expect to triple their output. MEA cost reduction will be critical. There are 5-7 suppliers but it seems they talk to each other and there is some suspicion that they may not compete aggressively. From 2009 to 2010, Nedstack achieved a 20% cost reduction per unit. From 2010 to 2011 they expect a 30% cost reduction. Automation and scale economies are part of this achievement and they also expect suppliers to lower costs with increased volumes. Nedstack would not comment on the cost of its FC stacks; however, they noted that their customers tell them they are not overpriced.

Nedstack believes that further reduction in PEMFC catalyst loadings is needed and achievable; at present they design with a safety margin that includes “extra” platinum. In the current market, they believe there is not enough volume in PEMFCs to interest the catalyst makers. Even in the long run Nedstack believes it is inevitable that PEM cells will stick with Pt; alloys will improve but Pt will always be the key ingredient. Today, all their stacks are recycled and the Pt recovered.

In Nedstack’s view, SOFC technology appears to be 5 years behind. Their materials problems are extremely challenging. They also need a high-temperature balance of plant. However, SOFC is a fundamentally superior technology for carbon-containing fuels. With respect to PEMFCs in automotive applications, the cost targets for PEMFCs appear to be too aggressive: $30/kW seems nearly impossible ($50/kW is possible) even in the long run at very high volumes. Platinum price and content is a major source of uncertainty. Battery-powered EVs, however, will only be able to compete with FC vehicles in urban travel and will never be adequate for longer-distance travel. Most likely, hydrogen FC vehicles will happen first in Germany, not the Netherlands.

RWE, one of the largest electric and gas utilities operating in the EU and UK, ended its FC program in 2005, chiefly because they could not see a path to becoming competitive on price.

At one time RWE had a FC organization and considered manufacturing FCs themselves for CHP. They searched for viable household and industrial applications. Their small-scale FC CHP systems, like the Japanese program, were based on reforming natural gas and were intended primarily for households. In Germany, new homes must be heavily insulated, so the FC's ability to provide more electricity relative to heat than other CHP technologies appeared to be an advantage. They also had an agreement with MTU to develop larger applications. They carefully analyzed the ability of FCs to compete with existing technologies, gas turbine CHP, natural gas boilers, and so on. They saw substantial cost reduction over the years in FCs, and realized the potential for mass production to further reduce costs. Still, no one could explain to them how to reach target values that would allow FCs to compete with existing technologies in providing home heat and power. RWE saw a technological challenge (beyond scale economies) and was unable to identify a path to competitiveness. They ended their program because they could not see a business case in the next 5-10 years.

In RWE's view, the durability and energy efficiency of today's FCs are good. The FC CHP has a clear advantage in energy efficiency. But the cost is too high and there is no clear niche in the German energy concept. In a hydrogen economy (this is the Japanese long-term view) FC CHP can work. But this requires ready availability of low-cost hydrogen. In a hydrogen economy FC CHP would absolutely make sense.

Ceramic FCs Limited (CFCL) of Australia has established its new, principal manufacturing facility in Heinsberg, Germany. CFCL has 75 scientists and engineers in Australia who do research and development and limited manufacturing. The Heinsberg facility will be the main manufacturing plant for CFCL. CFCL does the entire supply chain from raw materials to assembly themselves.

They sell two products, BlueGen which is an integrated micro-CHP system and Gennex, which is the FC component of that system. Neither is fully market-ready at this time; both are placed in various demonstration efforts.

A key advantage of the SOFC is efficiency in electricity production and good part load performance. Their efficiency is over 50%, putting them in the same league as large-scale IGCC, which typically cannot use the waste heat. With an electricity production efficiency of 50% to 60% and usable heat production of 25% to 30%, SOFC achieves 80% to 85% efficiency in CHP applications. Their product is called "BlueGen," a 2 kW CHP unit aimed at the single-family housing market. The system includes a condensing boiler because the efficiency of the SOFC reduces the availability of heat. Unlike the Japanese micro-CHP program, BlueGen is aimed at the replacement market rather than new construction. The units produce 12,000 kWh/yr. operating at 1.5 kW and continuously heat 200 liters of hot water.

According to CFCL, the natural gas to produce 1 kWh of electricity using BlueGen costs 5 Euro cents. The marginal cost of electricity generated is 7.5 Euro cents. Germany has a feed-in tariff that pays 11 cents per kWh, so that the margin per kWh for electricity sold to the grid is 3.5 cents. Home use of the produced electricity is a better economic proposition. The average retail price of electricity is 23 cents, so the margin on electricity used in the home is 15.5 cents. The unit is designed to operate continuously in base load mode. Due to the high temperature of the SOFC, it is undesirable to stop it and start it frequently. This exacerbates problems with materials and seals (the key challenges for durability). The average home in Germany uses 4,000 kWh per year. This means (ideally) a savings of €620 per year on electricity not purchased from the grid and revenue of €280 per year from sales to the grid. If the cost is €10,000 and the stack must be replaced every 5 years and the system every 15, it is difficult to see how the economics will work out to the benefit of the customer under the current conditions.

CFCL acknowledges that their system is not yet where it needs to be. They believe that their system needs to last 15 years and the stack 5 years. They are half way to these goals today.

Thus, they are selling mostly field trials, and now have two years and 17,000 hours of durability accomplished. Extending life and reducing costs are their main technical development goals. Their cost target for Germany is to be under €10,000 (€5,000/kW for the full system). This is based on their assessment of the BlueGen's value in use. They are now at a price point at which smaller utilities can buy and test their units.

Unlike PEMFCs, they do not have inherently expensive materials, such as platinum. They believe cost reduction to achieve their target will come with experience and scale, perhaps at 20,000 units per year, or so. Eventually, they believe their FCs will become a commodity that they will purchase from others. They will do the assembly at their Heinsberg plant. That plant will have a capacity of 10,000 stacks per year (not necessarily 10,000 BlueGen units) and there is plenty of capacity to grow. Each layer in the FC stack includes four FCs and there are 51 layers in the stack. This means that 10,000 stacks would require approximately 2 million cells.

As of now, they have built 65 BlueGen units, and will have completed 100 by the end of the year. No units were being manufactured at the time we toured their facility. They plan to manufacture several hundred units next year. How many of these units they can operate in the field is a key question, since they must assist with monitoring and maintenance since their market is essentially for demonstrations at this time. The German value added content of their product exceeds 50%.

6.3 SOUTH KOREA

Partly because South Korea's energy system is 97% dependent on imported energy and partly because South Korea has committed to a low-carbon energy future, in July 2005 the South Korean government announced that the country would make a transition to a hydrogen economy (Lee, 2008). It selected hydrogen and fuel cells as one of ten "economy growth engines" for the next decade. The South Korean government has set a goal for 2040 of using hydrogen to provide 15% of the country's final energy needs and for fuel cells to comprise 5%

of the country's GDP (Jun, 2007). South Korea also has a significant program to promote FC use for power generation, reportedly spending $600 million on financial incentives (USFCC, 2010). These include feed-in tariffs of 23 to 28 cents per kWh for electricity produced from FCs using biofuel, and an 80% subsidy for early adopters of FC home CHP systems. The 1 kW home units reportedly cost $40,300 today but would cost only about $8,000 with the government subsidy (CleanTech, 2009).

South Korea has implemented three main policies to promote green energy: (1) a feed-in tariff of $0.10/kWh which expires in 2011, (2) a green home project which calls for 1 million homes powered by solar, geothermal or FC energy by 2020, of which at least 100,000 are to be powered by FCs, and (3) a Renewable Portfolio Standard requiring 2% of electricity to be produced by new and renewable sources by 2012 (Butler, 2010). The residential FC program calls for installation of 200 units in 2010, 300 in 2011 and 500 in 2012. An 80% subsidy is being offered through 2012, with a 50% subsidy from 2013-2015. The short-term technology goal for 2012 is a system cost of $20,000 with durability of 40,000 hours. The longer-term goal for 2020 to 2030 is cost between $3,000 and $5,000 and durability of 90,000 hours (Butler, 2010). South Korea's large-scale stationary FC program is developing 300 kW and 1 MW MCFCs in a technical alliance with Fuel Cell Energy. Smaller SOFC FCs are also a topic of R&D.

7. METHODOLOGY FOR ASSESSING FUTURE MARKET POTENTIAL AND POLICY IMPACTS

The ability of FCs to compete successfully in the material handling, back-up power and CHP markets will depend on achieving additional cost reductions and performance improvements. Today, the slim market shares achieved by FCs in these markets are highly dependent on government policies. There is no exact science for predicting such future developments. On the other hand, there is also no doubt that economies of scale are available and that further improvements in technology and manufacturing processes are achievable. The 2008 study developed a simple model to simulate 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, producing a "virtuous circle" feedback effect, with lower costs leading to higher sales, in turn helping to further reduce costs. A somewhat more complex model was developed for this study 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 is comprised of seven submodels that together calculate fuel cell cost, demand, and policy impacts (Figure 17). A cost analysis model estimates fuel cell purchase prices and operating costs and converts them to an equivalent annual cost (EAC, defined below). EACs, together with government incentives and purchases (Policy Scenarios) influence the choices among FCs and competing technologies. The Choice Analysis submodel predicts the market share of FCs in each application as a function of the EACs of competing technologies. The Market Characterization spreadsheet provides data on the expected annual sales in each target market, and related information. Market shares and total sales determine FC sales, which feedback to Component Supplier and OEM submodels. In these models, total market volumes determine scale economies and cumulative production determines cost reductions via learning-by-doing. These cost reductions recursively affect EACs in the Cost Analysis submodel.

7.1 COST ANALYSIS MODEL

The Cost Analysis Model translates assumptions and data about the costs of FCs and their components, their expected lifetimes, maintenance and fuel costs into an equivalent annual cost (EAC: the cost per year of owning and operating an asset over its useful life). Costs are defined as retail price equivalents and include normal rates of profit and indirect costs. EAC is equal to net present value divided by a annuity factor. Annuity factors, A, are calculated as a function of equipment life, L, and discount rate, r, using the following formula.

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

The EAC concept allows continuing and periodic costs to be expressed consistently. For example, for a high-temperature PEM CHP unit, the initial costs would be the stack, reformer, balance of plant and installation. Lifetimes for the stack, reformer and BoP might be 5, 10 and 10 years, respectively. Likewise, the installation cost may be assumed to have the same lifetime as the long-lived components, 10 years. Once these costs are annualized using, say r = 0.05, annual fuel and maintenance costs may be added to obtain the overall EAC. EAC is the principle variable used to determine the market shares of FC technologies.

The OEM model 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. Progress due to R&D is inherently uncertain. The model does not attempt to relate R&D expenditures to the rate of progress but simply assumes a certain percent per year reduction in cost that is consistent with but somewhat lower than historical experience.

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

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

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

The size 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.

$$Q = Market \quad Size = (Number \quad of \quad existing \quad units) \div (Expected \quad Life) \quad (4)$$

Annual sales of FC systems are assumed to equal the total market size times an economic market share function that depends on the *generalized costs* of the FC system and of its competition. Generalized cost, G, includes the EAC plus the estimated annual value of improved productivity and any other factors that can be reasonably converted into an equivalent dollar value per unit, Y_i . 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, in the analyses presented below we have not attempted to quantify intangible factors. Thus, 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 individual j and alternative i. The individual component is intended to reflect factors that vary from one individual to another that are not adequately represented by the other terms in the utility equation.

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

(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. If the distribution of individual-specific terms, ε_{ij} , follows an extreme value probability density function, then the probability that a representative individual will choose alternative i, given its generalized cost G_i , and constant term A_i , is given by the following equation. For example, for micro-CHP, FCs are assumed to compete with conventional heat and power and with internal combustion micro-CHP devices.

$$p_{FC} = \frac{e^{A_{FC}+BG_{FC}}}{e^{A_0+BG_0} + e^{A_{ICE}+BG_{ICE}} + e^{A_{FC}+BG_{FC}}}$$

(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.

$$Q_{FC} = Qp_{FC}$$

(7)

The generalized costs of FCs decrease over time as manufacturers achieve scale economies, via learning-by-doing and due to R&D driven 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 (equation 1).

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

(8)

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

$$P_t = P_0 Q^{-\lambda}$$

(9)

The chief weakness of traditional learning curves when used for forecasting is that there is no rigorous method of determining what future values of –λ will be. Even past experience with the same technology may not be the best prediction of future performance. At the same time, the effects of LBD can be decisive in a prospective analysis. While there is no definitive answer to this dilemma, Greene et al. (2007) recommend using asymptotic learning models when doing policy analysis. Asymptotic learning models have the advantage of converging on a fixed future cost that may be decided on via engineering analysis or some other method. *Learning-by-doing* is assumed to be an asymptotic function of cumulative production at time t, Z_t, a reference level of cumulative production, Z_o, and three coefficients, A_o, A_1, and b. The reference cumulative production serves as a scaling factor for b. A_o is the asymptotic cost eventually reached by learning-by-doing, since as Z_t gets large the remainder of the expression in equation 2 goes to zero. As cumulative production goes to infinity, the rate of learning also approaches zero.

$$A_o + A_1 e^{b\left(\frac{Z_t}{Z_o}\right)}$$

(10)

However, experimentation with both traditional and asymptotic learning functions revealed that the asymptotic function converged to long-run costs much more rapidly than the traditional learning function. To make the analysis more conservative, the traditional functions have been used in all cases. Learning is calculated separately for FC stacks by FC technology (PEM, MCFC, PAFC).

The flow of the market model is as follows (Figure 17). EACs are calculated in the Cost Analysis spreadsheet 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. Fuel and electricity costs are from the Reference Case of the EIA's 2010 Annual Energy Outlook. EACs in years before 2011 are input data. Costs in subsequent years are determined by the prior year's production volumes, cumulative production and exogenous technological progress. EACs are also influenced by policies which influence 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. Sales estimates are passed 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. The cost multipliers are assumed to affect production costs recursively in order to avoid having to solve for all factors simultaneously. This greatly simplifies the spreadsheet implementation but will cause a lag in scale economy effects when sales are not stable or growing or declining in a regular fashion. Separate cost multipliers are

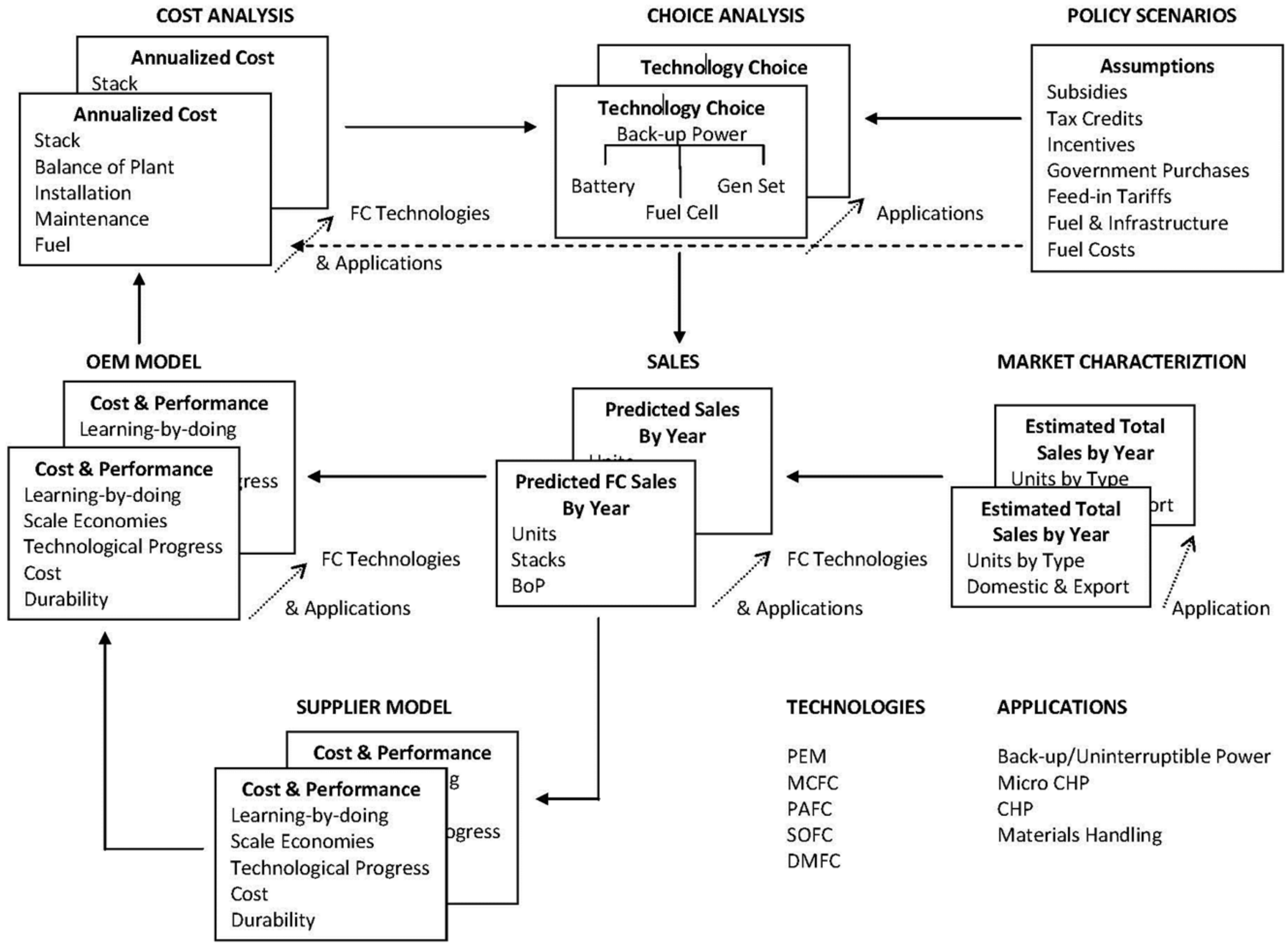


Figure 17. Structure of Non-Automotive FC Market Model.

calculated for PEMFC stacks, and for the manufacture of each PEMFC application, as well as for MCFCs and PAFCs.

7.2 KEY ASSUMPTIONS

The modeling analysis presented below is intended to be illustrative rather than definitive. The potential markets for FCs are complex; near-term success will depend not only on cost and performance but also on intangible factors (such as customers' desire for green technology or aversion to a riskier new technology), local conditions (e.g., electricity prices, availability of hydrogen) and government policies. Several, major simplifying assumptions have been made in the FC market model. In each of the five markets several products of differing sizes have been combined into a single size. For example, all micro-CHP, backup power and material handling products are represented as 5 kWs in size although actual products range from 1 kW to about 10 kWs. To some degree this is justified by the modularity of many FC products, but it must be acknowledged that this is a strong generalization. As Schoots et al. (2010) have shown, there are strong scale economies to larger size FC systems, mainly in the BoP. In general, we characterize a single, uniform market for each product. Thus, there is one electricity price, one cost of capital, and so on. And although heterogeneity of customers is implicit in the logit choice models used, it is not clear how well the logit models will represent real world differences.

In describing the size of the markets we have attempted to conservatively limit the markets to those in which FCs appear to have a reasonable chance of competing with established technologies. Thus, for micro-CHP we initially limit the market to large, new, luxury residences in California and gradually expand it to about twice that number. California provides a substantial subsidy for fuel cell CHP systems in the Self-Generation Incentive Program. California's electricity prices are also high relative to most of the rest of the United States. Larger homes also can take better advantage of both the electricity and heat produced by a 5 kW unit. For material handling, we limit the market to larger forklifts operating at least two shifts per day. While this makes our estimates inherently conservative, we also do not attempt to represent the natural barriers to novel products like FCs, barriers such as customer risk aversion and hydrogen availability in remote areas. Finally, we have not attempted to represent non-U.S. markets. For some FC manufacturers overseas markets are of central importance. Most, but not all of these assumptions should make our estimates more conservative.

Finally, our estimates of future system cost reductions are extrapolations of past relationships between production volumes, cumulative production, R&D driven technological progress and costs. There is, of course, no guarantee that cost reductions can be achieved at the same rate in the future.

For the above reasons, the analyses presented below ought to be considered illustrative of the current position of the FC industry, its prospects and the potential for public policy to influence its eventual success. They should not be considered definitive forecasts of the future of the U.S. non-automotive FC industry, nor definitive predictions of the impacts of policies on the industry. Given the novelty of the technology and the newness of the industry, it is not clear that a much more detailed modeling effort would produce more reliable information.

7.3 HYDROGEN SUPPLY

Hydrogen infrastructure, availability and cost are not explicitly modeled in this analysis. Hydrogen availability is likely to be important for BuP applications where some locations will be remote or not easily accessible and the quantity of hydrogen use per year will generally be small. Material handling operations may use hydrogen delivered in gaseous or liquid form, or may purchase on-site reforming, compression and refueling equipment. CHP units will reform natural gas on site to produce hydrogen.

In 2010, the DOE established a long-term target for the cost of delivered hydrogen of $2-$4/kg (U.S. DOE, 2010a, p. 41). However, these cost targets assume a large-scale, fully developed market. This will not be the case anytime soon for any of the three non-automotive FC markets. Instead, hydrogen will either be delivered in tanks holding approximately 1 kg of hydrogen each, in small tube trailers holding approximately 100 kg, or produced on-site by steam methane reforming. Thus, it is assumed that delivered hydrogen for material handling will cost $8 per kg, including delivery and storage on site in steel tanks (Ballard, 2010), and that costs will decline over time to just under $6/kg by 2025. This assumption is not appropriate for remote telecommunication back-up power applications. It is assumed that those applications will either include reformers and be fueled by methanol or will pay a much higher cost for hydrogen due to increased delivery and tank leasing costs. The cost of hydrogen for BuP applications is assumed to decrease from just over $25/kg today to $8/kg in 2025. Micro-CHP units are assumed to reform natural gas, priced at U.S. average residential prices, according to the Energy Information Administration's 2010 Annual Energy Outlook Reference Case.

For applications requiring limited back-up time (~8 hrs.) it is assumed that hydrogen will be used as the fuel and will be stored on-site in approximately four steel tanks. In this case, we assume the delivered cost of the hydrogen, including storage, will be $28/kg in 2011. For applications requiring extended back-up operation (~48 hrs.) we assume that methanol reforming will be preferred and that approximately 55 gallons of methanol will be stored on-site in a container whose cost is included in the estimated reformer cost (IdaTech, 2010).

7.4 ASSUMPTIONS FOR CALCULATING EQUIVALENT ANNUAL COST

The key assumptions for calculating equivalent annual cost are the initial capital cost of the fuel cell system components (their retail price equivalent: RPE) at 2010 production volumes and their expected useful life, as well as maintenance and operating costs. These assumptions are summarized for fuel cell systems in Table 5 and for competing systems in Table 6.

Installation costs are included in Retail Price Equivalent (RPE) costs.

Table 5. Key Assumptions for Calculating Equivalent Annual Costs: Fuel Cell Systems[10]

	Micro-CHP PEM	Backup Power PEM	Material Handling PEM	PAFC (costs/kW)	MCFC (costs/kW)
Size	5 kW	5 kW	5 kW	400 kW	3 MW
Stack Life (years)	5	10 increasing to 15 in 2015	5	10[11]	5 in 2005, up to 10 in 2010
Stack RPE in 2010	$19,500	$6,500	$19,500	$1,500	$2,000
BoP Life (years)	10	10 increasing to 15 in 2015	10 increasing to 15 in 2015	20	25
BoP RPE in 2010	$15,500	$5,000	$22,000	$2,500	$1,000
Reformer Life (years)	6	10 increasing to 15 in 2015	-	-	-
Ref. RPE in 2010	$15,500	$5,000	-	-	-
Capital Subtotal	*$50,500*	*$16,500*	*$41,500*	*$4,000*	*$3,000*
Installation	$2,000	$4,500	-	$700	$500
Maintenance $/yr	$500	$500	$700	$700	$500
Energy Costs $/yr	$850 (Methane)	H2 $4,700/ MeOH $1,000	$8,000	$1,000	$700

Table 6. Key Assumptions for Calculating Equivalent Annual Costs: Alternative Systems

	CHP: Electricity and NG	CHP: Natural Gas ICE	Batteries for Backup Power	GenSet for Backup Power	Batteries for Material Handling
Battery/GenSet Lifetime (years)	-	10	6	-	5
RPE in 2010	-	$35,000	$14,000	$12,500	$10,800
Battery Charger Life (years)	-	-	6	15	10
Charger RPE in 2010	-	-	$2,000	-	$2,500
Cost of Electricity $/yr	$1,000	-	$250	-	$1,500
Cost of Natural Gas $/yr	$500	$1,400	-	$500	-
Maintenance $/yr	-	$250	$500	$500	$1,000
EAC Cost $/yr	$1,500	$7,500	$5,000	$2,700	$6,000

[10] Costs for major components have been rounded to the nearest $500 to convey the imprecision of the estimates.

[11] Staffell (2009) has estimated the average lifetime of large-scale PAFC systems at just under 10 years assuming 6,000 hours of operation per year.

The numbers in Tables 5 and 6 have been rounded to the nearest $100 in hopes of avoiding conveying a false sense of accuracy. Numbers in the spreadsheet model are unrounded. The spreadsheet model is available from the authors to interested readers upon request. Documentation of the data sources used to arrive at these estimates is provided in Section 8.

7.5 SCALE ECONOMIES, LEARNING RATES AND TECHNOLOGICAL PROGRESS

In all cases, scale economies are represented by an elasticity of -0.2 (Table 7). This implies that a doubling of scale would reduce cost per unit by 20%. Scale economies are capped at an assumed "optimal" production volume per firm. The assumed optimal volumes are 5,000 units per year for micro-CHP and backup power OEMs, and 3,000 per year for material handling OEMs. For stack OEMs, scale economies are assumed to peak at 25,000 kWs per year[12]. Optimal output for larger MCFC and PAFC OEMs is assumed to be 200 units per year. A discussion of parameter estimates in the literature is provided in the following section, which addresses model validation. The number of firms in 2010 is based on our assessment of the number of OEMs in North America with significant production volumes. The number of firms in 2025 is an estimate of the model, allowing as many firms as possible to take advantage of scale economies.

Learning-by-doing and scale economies are modeled separately for OEMs and FC stack manufacturers, each having its own different learning curve parameters. For stack manufacturers experience is measured by the total number of kWs produced. For OEMs experience is measured by the total number of units produced, regardless of their power rating. The assumed rate of technological progress (2%/yr) is a fixed number, whereas in reality progress is uncertain. Two percent per year appears to be a slower rate than that indicated by

[12] Undoubtedly, even higher production volumes would yield greater scale economies. However, given the sizes of the markets defined for non-automotive fuels cells, allowing higher production volumes would greatly limit competition. The numbers used allow for some degree of competition while still reaching production volumes that will allow the use of automation and other cost-reducing production practices.

recent experience; however, there is no guarantee of any future rate of progress. The potential effects of uncertainty about key parameters are assessed in Section 8.

Table 7. Parameter Assumptions for OEM Cost Models

Parameter	Micro-CHP	Backup Power	Material Handling	PEMFC Stacks	300 kW PAFC	3 MW MCFC
Scale Elasticity	-0.20	-0.20	-0.20	-0.20	-0.20	-0.20
Economical Scale	5000 (units)	5000 (units)	3000 (units)	25000 (kW)	200 (units)	200 (units)
Progress Ratio	0.90	0.90	0.90	0.90	0.90	0.90
Learning Exponent	-0.152	-0.152	-0.152	-0.152	-0.152	-0.152
Rate of Tech. Progress	2%/yr.	2%/yr.	2%/yr.	1%/yr.	2%/yr.	2%/yr.
No. of Firms in 2010	1	3	3	3	1	1
No. of Firms in 2025	1	3	3	4	2	2

The number of firms is set at the current level and increased only when the scale of production per firm exceeds the "economical scale." When the number of firms is currently such that the economical scale is not reached, the number of firms is continued at the current level until the economical level is reached.

7.6 PRICE SENSITIVITIES

Price sensitivities in the Choice Model have been pegged to a price elasticity of -2.0 at a 50% market share and, approximately, the price (more precisely the EAC) of the FC option in question in the year 2025. An elasticity of -2 implies that a 10% increase in price would reduce market share by 20%, i.e., from 50% to 40%. In multinomial logit models price slopes are constant but elasticities vary with market share and price, according to equation (11). Thus, each application will have a different price slope (b) but all will have a price elasticity of $\beta = -2$ at a 50% market share (s) and the EAC (P) of the technology in 2025.

$$b = \frac{\beta}{P(1-s)} \tag{11}$$

In a logit choice model the price coefficient, b, is constant. As a result, the price elasticity of choice increases with increasing price, P, and decreases with increasing market share.

$$\beta = bP(1-s) \tag{12}$$

This means that price elasticities will be much higher than -2 in the early years when prices are high and market share is very low. Sensitivity to relative changes in price will decrease over time if prices fall and market share increases.

7.7 MINIMUM SALES VOLUMES

For each of the three PEMFC applications, all cases assume a minimum base production of 100 units per year for firms' own R&D and purchases by governments and private sector sources for demonstration and other special purposes. This assumption is consistent with historical experience, as reported by Staffell and Green (2009, p. 5622) and generally consistent with the lowest production levels shown in Table 1. The minimum production level is intended to reflect a continuing interest in FCs for research and demonstrations or special applications where customers may be willing to pay much more for an advanced technology with a green image, as well as continuing minimal government procurements for special applications. These minimum sales volumes are assumed to continue through 2020.

7.8 CAVEATS

The cost reductions estimated by the FC market model assume that past relationships between volume, cumulative production and technological advances over time continue into the future. Of course, there is no guarantee that this can be realized. For this reason, several alternative cases are tested to measure the sensitivity of the models' conclusions to these critical assumptions.

The demand models, in particular, are very simple in comparison to the heterogeneous nature of demand in the real world. Differences in equipment usage rates, in local environmental conditions, local availability and costs of hydrogen, in local costs for electricity, labor, and more, are not explicitly represented in the demand models. Instead, we have severely limited the sizes of the markets in which we believe FCs can be competitive. Export markets are not included at all. Exports have been and will continue to be important to the U.S. fuel cell industry however, inclusion of foreign markets was beyond the scope of this study. No attempt has been made to segment the market by aversion to the risk of novel technology (e.g., early adopters, early majority, late majority). The logit choice models and their price sensitivity parameters imply a certain degree of heterogeneity, consistent with an s-shaped market penetration curve. The first few customers for FCs may be relatively easily attracted; the last few will be very difficult. While these assumptions may do a reasonable job of approximating how the real-world market will respond, there is no rigorous way to empirically validate the model at the present time. Thus, its estimates should be considered indicative of the relationships between of FC manufacturing experience and market development and cost, and the ways in which the competitiveness is likely to change as a consequence of alternative policies.

8. MODEL VALIDATION

The model developed for and used in this study estimates the impacts of certain government policies on fuel cell costs, and also estimates the potential for successful commercialization of non-automotive fuels cells in limited markets. The model is not intended to precisely describe real-world fuel cell markets nor is it intended to fully represent the complexity of choices between fuel cells and competing technologies. The model's representation of the non-automotive fuel cell industry is intentionally simple. Each market segment (micro CHP, backup power, material handling, larger PAFC, larger MCFC) is represented by a single generic fuel cell product and a single generic competing product. The model attempts to quantify the key factors affecting the competitiveness of non-automotive fuel cells, and attempts to estimate how those factors are likely to be affected by policies, learning by experience, scale economies and continued technological progress. The model's estimates should not be interpreted as predictions of the future but rather quantifications of where fuel cells stand relative to their competition and what they are likely to achieve given certain assumptions.

The non-automotive fuel cell industry is only a few years old and much of the historical data on fuel cell production and costs is still considered proprietary by the small number fuel cell manufacturers. Much of the data on fuel cell costs used in this study was provided by manufacturers and was provided under the assurance that estimates for individual manufacturers would not be disclosed. Instead, average or typical values are shown in this report. As a consequence, the potential to validate the model by empirical testing is limited. Nonetheless, the credibility of the model's estimates depends on the validity of the model's logic, the data used to calibrate it, and the reasonableness of the key assumptions made. In light of this, the following five steps were taken to validate the model.

1. Peer review of the model and its estimates.
2. Comparison with estimates and inferences in the peer-reviewed literature.
3. Documentation of the sources of key data and parameter assumptions.

4. Comparison of estimates made in 2008 to data obtained in this study for 2010.
5. Sensitivity analysis.

8.1 PEER REVIEW

This report and the model have been reviewed by staff of the U.S. Department of Energy and Oak Ridge National Laboratory, as well as eight external peer reviewers listed in Appendix A. The authors are grateful for the improvements recommended by the reviewers.

8.2 COMPARISON WITH THE PEER-REVIEWED LITERATURE

The key parameter assumptions of the model are:

1. Future learning rates or progress ratios
2. Scale elasticities and optimal production volumes
3. Price elasticities of choices between fuel cells and competing technologies

8.2.1 Progress Ratios: Learning by Doing

There is no scientific method for selecting progress ratios for projecting ***future*** cost reductions for novel technologies (e.g., Wene, 2000; Staffell and Green, 2009). Researchers rely on estimates of historical progress ratios for the technology in question and comparison to measured rates of progress for analogous technologies. In an early study of the potential for cost reductions for PEMFCs for automotive applications, Tsuchiya and Kobayashi (2004) noted that fuel cells are likely to benefit from substantial cost reduction with experience.

> "The modular structure of the fuel cell implies that it is suitable for mass production and the cost could be greatly reduced if mass production would begin." (Tsuchiya and Kobayashi, 2004, p. 985)

By analogy with other manufactured products, these authors selected a range of progress ratios for fuel cell cost reduction ranging from 0.78 to 0.88.

Neij (2008) recommended that learning rates of 15% to 25% (progress ratios of 0.75 to 0.85) be used to project future costs of fuel cell technologies. The recommendation is again based on the modularity of fuel cell systems. Other types of modular systems have shown learning rates of 15% to 30%, however, learning rates as high as 30% are extremely rare.

> "Proposing a 'theoretical' experience curve for fuel cells is not easy. A best guess could be an experience curve with a learning rate of 20%. However, the sources of cost reduction are vague, and, a lower sensitivity value of 15% and an upper sensitivity value of +25% are recommended to underline the uncertainty of the cost reduction." (Neij, 2008, p. 2206)

The range of learning rates of +/-5% is considered by Neij to be necessary to describe uncertainties about future learning rates of fuel cell technologies.

Schwoon (2008) used a learning rate of 15% in modeling potential future cost reductions for automotive PEMFCs, and a range of 10% to 20% to reflect uncertainty. Schwoon also summarized learning rate assumptions from seven prior studies which show a range from 10% to 40% (see, Schwoon, 2008, table 8.1). Comparing estimates of PEMFC learning rates from nine studies with learning rates for other energy technologies, Staffell and Green (2009, figure 1) found a range of 9% to 27% for most energy related technologies and 15% to 30% for PEMFCs.

Staffel and Green (2009) estimated cost reductions due to learning by doing for Japan's home fuel cell CHP program between 2004 and 2008, finding cost reductions of 19.1% to 21.4% for every doubling of production (progress ratios of 0.79 to 0.81). These estimated learning rates, as well as those cited above, include all sources of cost reduction: learning by doing, scale economies and exogenous technological progress. The analysis of Japan's CHP data presented in this report in Section 3.1 and illustrated in Figure 5 shows that cost reductions from 2005 to 2009 can also be accurately fitted by a combination of a progress ratio of 0.8, a scale elasticity of -0.2 and a rate of exogenous progress of 8% per year. Similarly, 2005 to 2009 data for one German firm's production of direct methanol fuel cells was shown in Section 3.1 to be well described by a progress ratio of 0.85 combined with a scale elasticity of -0.2 and a rate of exogenous technological progress of 6% per year.

Schoots et al. (2010) estimated learning curves for alkaline (AFC), phosphoric acid (PAFC) and PEMFCs, with the data for each coming from a different producers. They found a learning rate of 21% (progress ratio of 0.79) for PEMFCs manufactured by Ballard Power Systems between 2002 and 2005, with a confidence interval of +/- 4%. Their best estimates of progress ratios for PAFCs (1993-2000) are 0.75 +/- 0.03 and for AFCs (1964-1970) 0.82 +/- 0.09, respectively.

In the non-automotive fuel cell industry model, learning by doing, scale economies and exogenous technological progress are modeled separately. Because of this, the model uses a learning rate of 0.9, which is near the slowest end of the range seen in the literature. It is faster than the rate of 0.95 assumed in Greene and Duleep (2008) because that study appears to have consistently under-predicted PEMFC cost reductions over the past two years, as shown in Figure 4, above. These rates are also slower than the recent experience with PEM micro-CHP in Japan and DMFC in Germany. Learning rates strongly influence estimates of future fuel cell costs, as will be shown in the sensitivity analysis below. Given that there is no rigorous method for selecting learning rates for the future, the rule of thumb used in this study is to select rates that are plausible based on past experience but biased toward slower learning rates.

8.2.2 Scale Elasticities and Optimal Production Volumes

Schoots et al. (2010) used a scale elasticity of -0.31 to adjust various cost estimates to a standard production rate of 500 units per year. Scale elasticities measure the percent reduction in cost for each 1% increase in annual production volume. The scale elasticity of -0.2 used in the previous study (Greene and Duleep, 2008) was discussed with all OEMs interviewed.

None considered this estimate to be unreasonable, although some offered estimates slightly higher, in the range of -0.2 to -0.3.

8.2.3 Price Elasticities of Choice between Fuel Cells and Other Technologies

Because the market for fuel cell technologies in all applications is so new, there are no empirical estimates of the sensitivity of choices between fuel cells and competing technologies. The assumed price sensitivity used in the fuel cell market model is based on the following premises: (1) choices among competing technologies will be sensitive to price because the services provided are similar, i.e., demand will be price-elastic, and (2) sensitivity to price will be limited by the fact that the model restricts the markets in which fuel cells compete. The initial assumption is that the price elasticity of choice will be approximately -2 at a 50% market share and a long-run target price well below current prices. An elasticity of -2 implies that a 1% reduction in price will result in a 2% increase in the probability of choice (market share). In the logit choice model, price elasticity increases with increasing price and decreases with increasing market share. Thus, if current fuel cell costs are twice the long run target and fuel cell market shares are close to zero, the current price elasticity will be -2, as well. Because this assumption is so uncertain, we test price elasticities of -3 and -1 in the sensitivity analysis presented later in this section.

8.3 DOCUMENTATION OF SOURCES OF DATA AND ASSUMPTIONS FOR FUEL CELL MARKET MODEL

8.3.1 MCFC

Ma et al. (2009) report a total fuel cell cost of $1.4 million and an installation cost of $1.5 million for a 250 kW MCFC (nominal rating of 300 kW) based on information provided by the manufacturer, Fuel Cell Energy. Although their paper was published in 2009, the initial version was submitted in December 2006 and the final revision was made in February 2008. It is reasonable to assume that the cost estimates apply approximately to the year 2007. The fuel cell and installation costs include two free overhauls at 5 years and 10 years with a value of $300,000 each. Discounted at the interest rate used by Ma et al. of 7.43%, the present value of the overhauls would be approximately $350,000. If costs scale linearly, the model used in this study which is intended to apply to a 3MW unit, estimates a total fuel cell cost for a nominal 300 kW unit of $1.3 million. If the discounted value of future free overhauls ($0.35 million) is added to the fuel cell purchase cost, the cost estimate used in this study would be $1.7 million. While fuel cell costs may scale roughly linearly, installation costs undoubtedly do not.

Remick and Wheeler (2010) estimated the current cost per kW of a 1 MW MCFC system at $4,200/kW for a complete, installed system, assuming the 2010 production volume of 30 MW per year. Component costs were estimated to be $2,400 for the fuel cell module, $1,100 for the BoP, and $700 for conditioning, installation and commissioning. The per kW cost estimates produced by our model for 2010 for a larger 3 MW unit are $2,150 for the fuel cell stack, $850 for the balance of plant and $550 for installation for a total of $3,550/kW for the installed system. This is very close to but slightly higher than the cost estimate that would be obtained by applying a scale elasticity of -0.2 to the Remick and Wheeler estimate ($\$4,200\cdot(3^{-0.2}) = \$3,370/kW$).

The model used in this study estimates an installation cost of $1.9 million for a 3 MW unit at the 2010 production volume. Costs for a 300 kW unit would be substantially less but certainly not one tenth of the cost. However, it is also assumed in this study that the fuel cell overhaul is about twice as expensive as Ma et al. (2009), but that the time between overhauls increases gradually from 5 years in 2010 to 8 years by 2025.

Remick et al. (2010) broke down the cost estimates of 2.8 MW MCFC manufactured by Fuel Cell Energy as follows: fuel cell stack is $2,150, cost of balance of plant is $850, and the cost of installation is $500 that gives a total of $3,500/kW for the whole system. Fuel Cell Energy reports an electrical efficiency of 47% with an overall efficiency of 90% in its product data sheet specifications. This study uses an overall efficiency of 85%. The annual fuel consumption is assumed to be 362 scfm as listed in the specification.

References

Robert Remick and Douglas Wheeler, Molten Carbonate and Phosphoric Acid Stationary Fuel Cells: Overview and Gap Analysis, Technical Report prepared for US DOE, NREL/TP-560-49072, Contract No. DE-AC36-08-GO28308, 2010, <http://www.nrel.gov/docs/fy10osti/49072.pdf> .

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< http://www.fuelcellenergy.com/files/FCE3000%20Product%20Design-lo-rez%20FINAL.pdf >
<http://www.fuelcellenergy.com/benefits-fuel-cell-technology.php>

Life of stack and BoP:
(http://www.utcpower.com/fs/com/Attachments/data_sheets/PRMAN69600D.pdf)
"FUEL CELLS, Cost-Effective,Reliable, and Ready Now," Robert J. Tierney, PE, LEED®AP**.** August 5, 2008 (http://www.govenergy.com/2008/pdfs/technology/TierneyTech6.pdf)
Electrical efficiency: http://www.fuelcellenergy.com/dfc300ma.php ; Electrical efficiency: http://www.loganenergy.com/pdf/DFC3000.pdf

Overall efficiency: (http://www.fuelcellenergy.com/benefits-fuel-cell-technology.php) and 90% (http://www.utcpower.com/fs/com/Attachments/data_sheets/DS0112_010411.pdf).
Quantity of fuel: Fuel Cell Energy website
(http://www.fuelcellenergy.com/files/FCE%20300%20Product%20Sheet-lo-rez%20FINAL.pdf)

8.3.2 PAFC

Staffell et al. (2008) report that by 2008, PAFC fuel cells had achieved lifetimes of 5 years with 95% probability. They also estimate an RPE of \$4,300 to \$5,700 per kW (converted from Euros at \$1 = 0.7 euro for October 1, 2007 when the paper was submitted for publication). An estimate reported by Remick and Wheeler (2010) put the full, installed cost (equivalent to RPE) of a 400 kW PAFC system at $4,375/kW. By comparison, the model used in this study estimated a retail price equivalent of $5,000 per kW for a fully installed system for the year 2010. Tierney (2008) provided a cost estimate of $3,000/kW for the UTC PureCell System 400, including both stack and balance of plant. This represents a reduction of more than 1/3 from the previous year. The model used in this study estimates the equivalent retail price at $4,250. At the same time, Tierney estimated an increase in stack life from 5 years to 10 years. In the model used in this study, stack lifetime is estimated to be 10 years in 2010, remaining constant thereafter. The total estimated installed cost reported by Tierney was $4,103, for an estimated installation cost of $1,000. The estimated installation cost in the model used in this study is $700 in 2010. The specification data sheets for the Pure Cell 400 kW reports 20 years lifetime of BoP. These estimates are also consistent with information provided by fuel cell OEMs. Energy use and the efficiency of conversion to electricity and heat were taken from UTC specification data sheets.

References

UTC Power, Stationary Fuel Cells, Pure Cell 400, http://www.utcpower.com/fs/com/bin/fs_com_Page/0,11491,0251,00.html , 2011.

Robert J. Tierney, Fuel Cells Cost-Effective, Reliable, and Ready Now, 2008 <http://www.govenergy.com/2008/pdfs/technology/TierneyTech6.pdf>

8.3.3 Micro CHP (5 kW CHP)

The Cost of fuel cell stack, BoP, reformer, installation, and the system were estimated based on information provided by the single U.S. manufacture, Clear Edge Power (http://www.clearedgepower.com). According to Clear Edge, the total cost of a 5 kW micro CHP unit is approximately $50,000. Other fuel cell manufacturers report that for fuel cell systems including natural gas reforming, the cost of fuel cell stack, BoP, and reformer were approximately equally in the past, but now the cost of stack is higher than either the BoP or reformer systems. Based on this, the total cost of the 5 kW micro CHP in 2010 was estimated to be $15,400 for the BoP and another $15,400 for the reformer, with the cost of the fuel cell stack somewhat higher at $19,700. This makes the total RPE in 2010 $50,500. We assume an additional cost of roughly $2,000 for installation in 2010, consistent with Clear Edge Power's estimate of $2-3,000 for installation. Clear Edge also put the life of the reformer is 5-7 years and thus an average of 6 years is used in this study. We have estimated a 5-year lifetime for the fuel cell stack and a 10-year life for the balance of plant.

References

Bill Sproull, Clear Edge Power, June 2010

8.3.4 Cost of ICE CHP (Other Micro CHP)

Marathon Engine Systems (2010) report a capital cost of $30,000 to $40,000 for their 5 kW ICE CHP, Ecopower, and natural gas genset. We assume an average cost of $35,000. Marathon reports 10 years life of the system with an efficiency of 90% (electrical-25%, thermal- 65%) for natural gas, and reports the maintenance cost of $250 and natural gas consumption of 67.09 cft/h for 4,000 hours per year. This system produces levels of electricity and heat comparable to the 5 kW fuel cell CHP.

References

Marathon Engine Systems (2010)

(i) Residential & Light Commercial Applications of MicroCHP NIST Micro-Generation Technology

<http://www.nist.gov/el/upload/5-2-Cocking-Ecopower.pdf>

(ii) The Future of Energy Supply . . ., Marathon ecopower microCHP

<http://www.marathonengine.com/downloads/ecopowerdatasheet.pdf>

(iii) Cogeneration, Marathon Engine Systems brochure
<http://www.marathonengine.com/intro_eco.html>

(iv) <http://www.marathonengine.com/microCHP_FAQ.html>

(v) The Future of Energy Supply <http://www.n-e
renewables.org.uk/lib/liDownload/133/ecopower.pdf?CFID=4591446&CFTOKEN=88894026>

8.3.5 Fuel Cell Backup Power

Based on conversations with OEMs, we estimate the cost of a 5 kW fuel cell back up power system at $16,700 in 2010, not including installation. OEMs indicate that the cost of fuel cell stack, BoP, and reformer were equally distributed in the past but now the cost of stack is higher than BoP and reformer. There is a consensus that for infrequently operating backup power units the lifetime of the fuel cell stack, BoP and reformer is at least 10 years. We assume the cost of BoP and reformer is $5,060 while the fuel cell stack is $6,570. Staffell et al. (2008) estimate high-volume PEMFC manufacturing costs (not retail prices) per kW of $430 to $1,300, in 2007 currency (Euros converted at $1 = € 0.7). This estimate is not specific to stacks built for backup power applications but may be useful as a general indicator. It implies that the cost of a 5 kW stack would be $6,500 in 2007, assuming high volume. Mahadevan et al. (2007) estimated an installation cost of $5,000 and fuel cost of $1,650. Installation cost for 2010 used in this study is estimated to be $4,520, which is close to $5,000 reported by Mahadevan but intended to reflect progress since that time. The maintenance cost used in the study is $470 based on a presentation made by NOAA that reports the maintenance cost of $600. The presentation from NOAA reports a fuel cost of $530 per year. The fuel cost assumed in this study is $1,020. Installation cost used in the study is estimated to be $4,520, close to the cost reported by Mahadevan. Ballard (2010) reports the cost of hydrogen, including storage tank rental to be $35/kg. We assume that the cost of hydrogen will decrease from that level to $8/kg by 2025.

References

K. Mahadevan, K. Judd, H. Stone, J. Zewatsky, A. Thomas, H. Mahy, and D. Paul, Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets, Battelle, report prepared for US DOE, DOE Contract no. DE-FC36-03GO13110, April 2007 (Page 67).

NOAA presentation, Automated Surface Observing System, Standby Power Options <http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/fuel_cell_mtng_leonardo.pdf>

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Price of Hydrogen: Economics of Fuel Cell Solutions for Emergency Backup Power Needs in Telecom
(http://www.ballard.com/files/pdf/Case_Studies/BUP_Emergency_Economic_Benefits_040110.pdf)

8.3.6 Battery Backup Power

Mahadevan et al. (2007) reported the price of battery and charger to be $14,000 and $2,000 respectively. They also estimated the annual maintenance cost at $560 per year. Kemmoku et al. (2002) assumed the life of battery and charger to be 6 years. Ballard uses a discount rate of 10% in a return on investment model for the comparison of battery with fuel cell back up power. These estimates are used in our study.

References

K. Mahadevan, K. Judd, H. Stone, J. Zewatsky, A. Thomas, H. Mahy, and D. Paul, Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets, Battelle, report prepared for US DOE, DOE Contract no. DE-FC36-03GO13110, April 2007 (Page 67).

Yoshishige Kemmoku,Keiko Ishikawa, Shigeyasu nakagawa, Teru Kawamoto, and Tateki Sakakibara, Life Cycle CO_2 Emissions of a Photovoltaic/Wind/Diesel Generating System, Electrical Engineering in Japan, Vol. 138, No. 2, 2002, Translated from Denki Gakkai Ronbunshi, Vol. 120-B, No. 7, 2000, pp. 923-930

Ballard, Economics of Fuel Cell Solutions for Emergency Backup Power Needs in Telecom, 2010 <http://www.ballard.com/files/pdf/Case_Studies/BUP_Emergency_Economic_Benefits_040110.pdf>

8.3.7 Genset Backup Power

The price of an internal combustion engine genset capable of replacing a 5 kW fuel cell backup power unit is assumed to be $12,500 at current production volumes, which is an average of $15,000 and $10,000, estimates reported by Plug Power and Mahadevan et al. (2007) respectively. According to Mr. Gary Flood of ReliOn, the price of fuel cell backup power is $15,000 and the price of genset is lower than fuel cell system. So $12,500 is a reasonable cost estimate. Satyapal (2009) reported 8 hours of maintenance required for an ICE genset per year. We assumed an hourly cost of maintenance of $50/hour that resulting in an annual maintenance cost of $400. The fuel cost for the ICE used in this study is $640; Mahadevan estimated $700.

References

K. Mahadevan, K. Judd, H. Stone, J. Zewatsky, A. Thomas, H. Mahy, and D. Paul, Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets, Battelle, report prepared for US DOE, DOE Contract no. DE-FC36-03GO13110, April 2007 (Page 67).

Sunita Satyapal, DOE Hydrogen Program and Vehicle Technologies Program, Annual Merit Review and Peer Evaluation Meeting, 2009 <http://www.hydrogen.energy.gov/pdfs/review09/program_overview_2009_amr.pdf>

8.4 MATERIAL HANDLING EQUIPMENT

8.4.1 Fuel Cell

Ballard (2009) reported the price of class 1 & 2 fuel cell based material handling equipment is $40,500. Mahadevan et al. (2007) reported the maintenance cost of $650 and the 5 years lifetime of stack. Based on discussions with OEMs we assume that a 5 kW fuel cell material handling unit cost approximately $41,800 in 2010, comprised of $19,700 for the fuel cell and $22,100 for the balance of the equipment, including hydrogen storage. To reflect the 10% greater productivity of fuel cell forklifts, their EAC is divided by 1.1.

References

Ballard, Economics of Fuel Cell Solutions for Material Handling, DC Velocity, 2009 (http://www.ballard.com/files/pdf/Case_Studies/Material_Handling_Economic_Benefits_041510.pdf)

K. Mahadevan, K. Judd, H. Stone, J. Zewatsky, A. Thomas, H. Mahy, and D. Paul, Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets, Battelle, report prepared for US DOE, DOE Contract no. DE-FC36-03GO13110, April 2007, page 97.

8.4.2 Battery

Ballard (2009) reported the price of batteries for an equivalent material handling unit is $10,780 (includes two complete battery packs). The cost of the charger is estimated to be $2,300. Consistent with Ballard's estimates, the battery life is assumed to be 5 years while the life of the charger is 10 years. Batteries also require storage and handling equipment for exchanging battery packs. These costs have not been explicitly modeled but an annual maintenance cost of $1,000 is included in calculating the EAC for batteries.

References

Ballard, Economics of Fuel Cell Solutions for Material Handling, FCvelocity, 2009 <http://www.ballard.com/files/pdf/Case_Studies/Material_Handling_Economic_Benefits_041510.pdf>

8.5 SENSITIVITY ANALYSIS

Projections of future costs and performance that rely on learning rates, scale economies and other such factors are strongly dependent on the values assumed for key parameters. Sensitivity analysis is able to quantify the influence of these critical assumptions on the estimated future costs and sales of fuel cells. This contributes to validating the model in two ways: (1) it provides insights about the robustness of the model's estimates of future costs and market performance, and (2) it can reveal anomalies or errors in the model if the model behaves in unexpected ways when parameters are changed from their default values. A sensitivity analysis was therefore conducted using the @Risk 5.0 simulation software (Palisade, 2007).

The following parameters were varied systematically by assigning each parameter a triangular probability distribution with the upper and lower limits listed below.

1. Learning-by-doing progress ratios: 0.90 ± 0.05
2. Scale elasticities -0.20 ± 0.05
3. Rates of exogenous technological progress 1%/yr ± 1%
4. Component costs (stack, BoP, reformer) ± 10% of original estimate
5. Rates of reduction in installation costs: 2%/yr ± 1%
6. Rates of reduction in maintenance costs: 1%/yr ± 0.5%

The probability distributions above were included in all simulations for all types of fuel cells. In addition, for the PEM fuel cell applications (micro-CHP, backup power and material handling) the market sensitivity to price was varied from a price elasticity of -2 at 50% market share to as low as -1 and as high as -3, reflecting the fact that little is known about the price sensitivity of the choice of fuel cells versus competing technologies in these markets.

The analysis measured the impacts of these parameters on the equivalent annual costs (EAC) and estimated sales. In all cases, current policies were maintained in place in the simulations. Since no future sales estimates are made for PAFCs and MCFCs only cost sensitivities were tested for these technologies. Results are summarized by graphs showing a range of two standard deviations and a 90% probability interval around the mean estimates for costs and sales from 2010 to 2025. Tornado charts are used to illustrate the relative influence of the different parameters on costs and sales.

Varying the key parameters has a very large impact on the cost of 5 kW micro-CHP fuel cells, as shown in Figure 18. The range of estimated EAC ranges from about $7,000 to almost $10,000 in 2010, and expands over time to $3,250 up to about $12,000 by 2025. The EAC estimates include the effects of subsidies; expiration of the California SGIP causes a jump in costs in 2012 as does the end of the ITC in 2017. Loss of these subsidies tends to offset gains due to learning, scale and technological progress, at the mean. The relatively high level of uncertainty this implies that the model's estimates of market success are also highly uncertain. As Figure 19 illustrates, the estimated sales range from nil to over 5,000 units per year. It is important to bear in mind that the model's estimates are also conditional on the assumed size of the market, which in the case of micro-CHP has been set at a maximum of 25,000 units per year in 2010 increasing to a potential limit of 55,000 units per year in 2025.

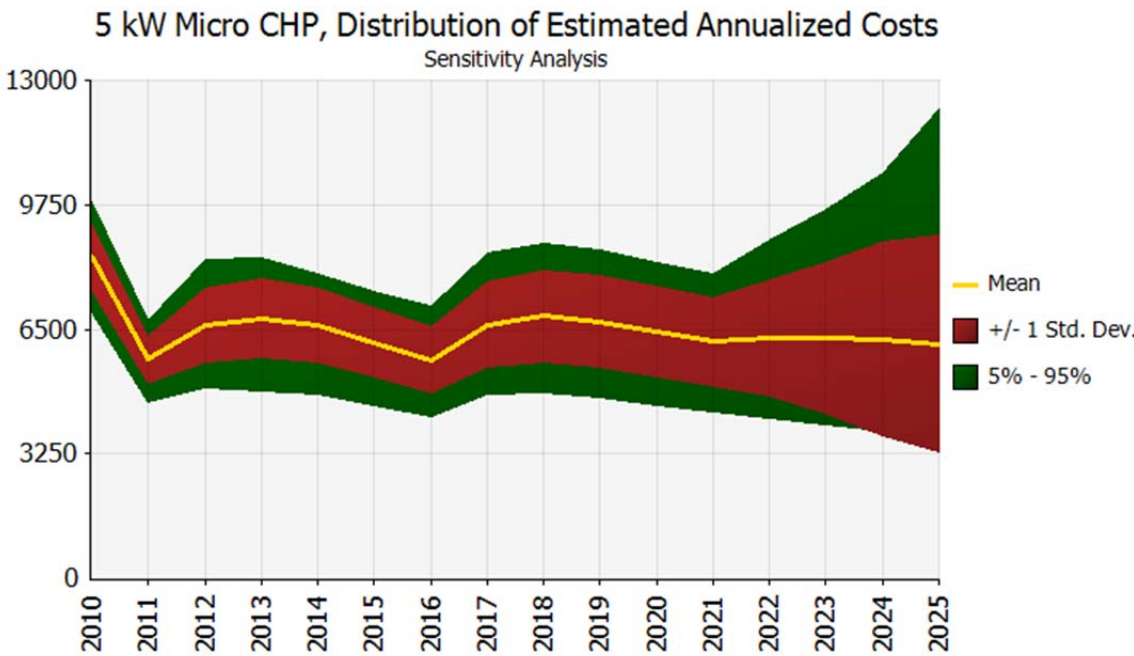


Figure 18. Results of Sensitivity Analysis for EAC of 5 kW Micro-CHP Fuel Cells.

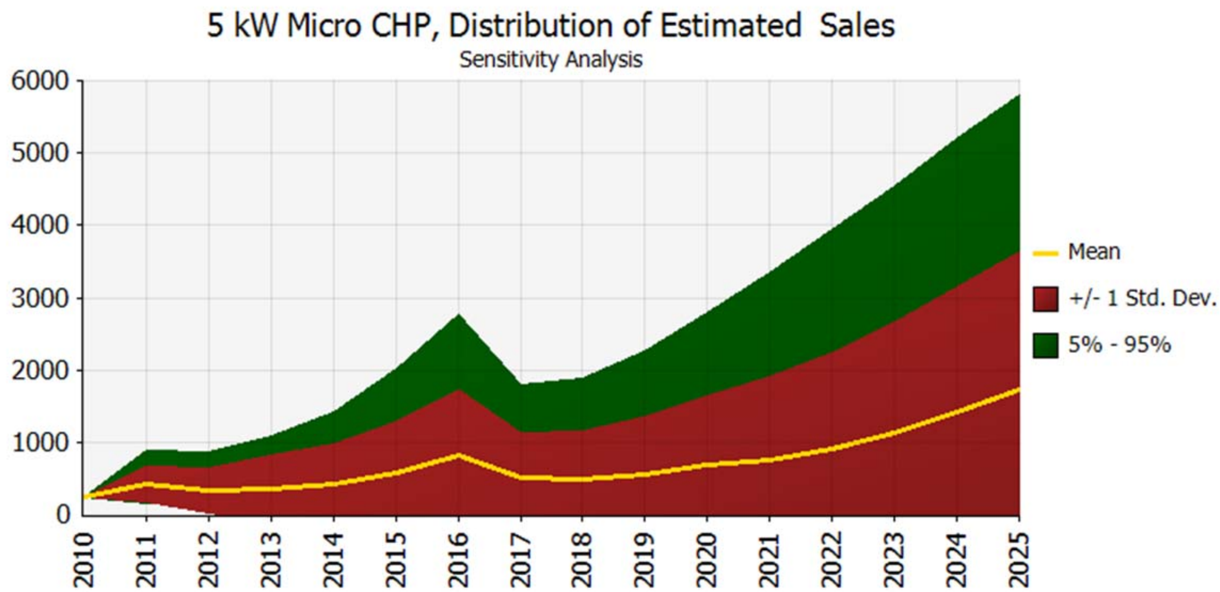


Figure 19. Results of Sensitivity Analysis for Estimated Sales of 5 kW Micro-CHP Fuel Cells.

Analysis of the relative importance of the key parameters that influence the model's sales estimates for micro-CHPs indicates that the most important factor is the sensitivity of the market to price. The tornado chart applies to the year 2025 but is reasonably representative of future years (Figure 20). The price coefficient is a negative number and the smaller it is (the larger in absolute value) the greater the negative effect on sales. That is, the more sensitive consumers' choices are to price, the more likely they are to prefer cheaper alternatives to micro-CHP. Next in importance are the rate of learning-by-doing for CHP manufacturing and the learning rate for PEM stacks, for all applications. This is followed by the rates of exogenous technological change for CHP and PEM stacks. Exogenous technological change depends on a number of factors ranging from the progress of scientific knowledge in general to investment in fuel cell CHP research in particular. The projection for 2025 is somewhat less sensitive to initial assumptions about the costs of a CHP reformer and the balance of plant. Of course, these factors were allowed to vary by only ± 10%.

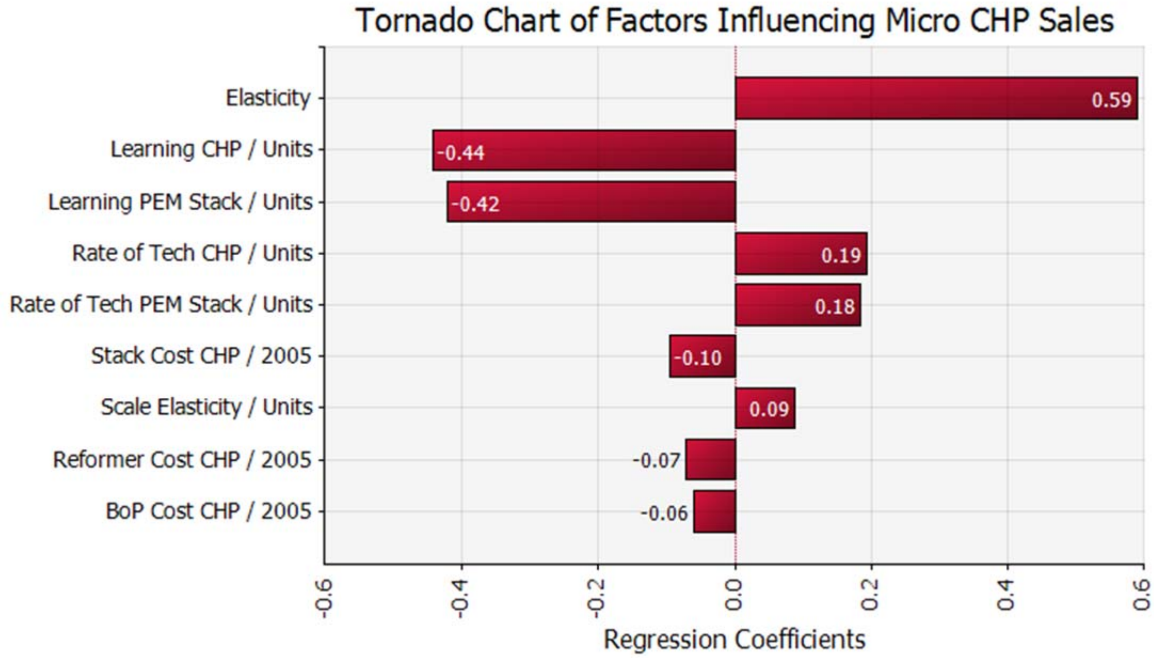


Figure 20. Tornado Chart: Regression Coefficients of Factors Affecting Micro-CHP Sales, 2025.

Results of the sensitivity analysis for 5 kW backup power units (Figure 21) show a much smaller relative impact than for micro CHP. The backup power fuel cell industry and market differs from the micro CHP market in several important ways: (1) far more units have already been produced, (2) current production volumes are higher, and (3) the costs of fuel cell backup power units are closer to the costs of their competition. As expected, the variation in estimated sales of backup power units is also smaller (Figure 22). One can also clearly see the impact of the termination of the Investment Tax Credit (ITC) after 2016, at which point costs jump by $300 to $400 per year, EAC. This has the expected negative impact on sales. However, the model’s sales projections are not highly sensitive to assumptions about the parameters listed above.

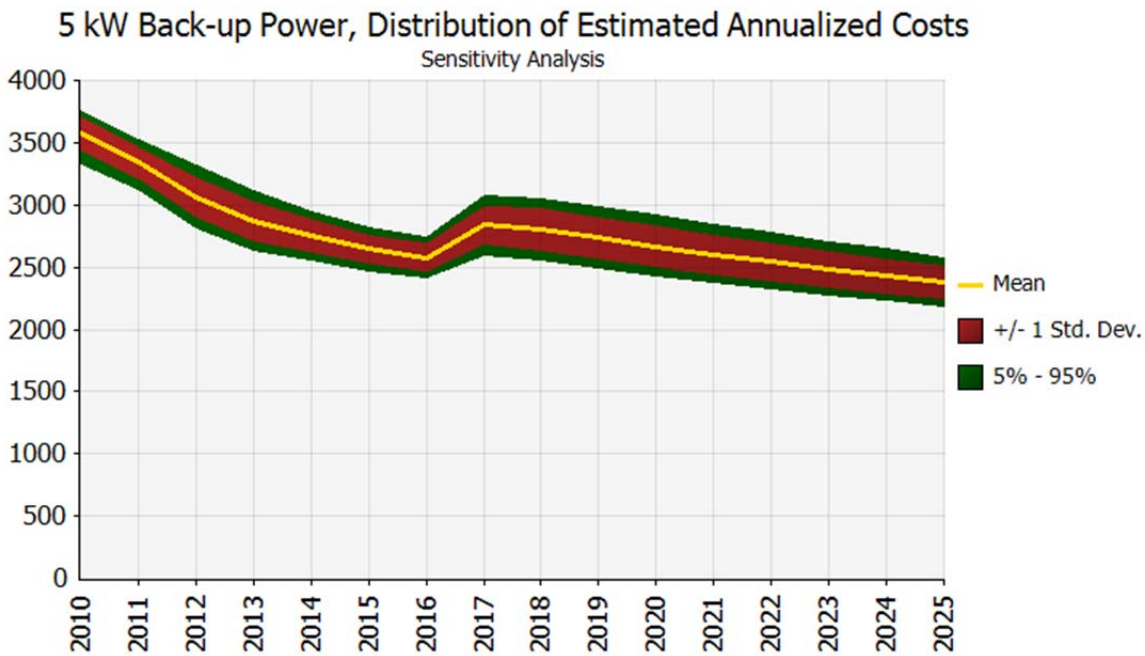


Figure 21. Results of Sensitivity Analysis for EACs of 5 kW Backup Power Fuel Cells.

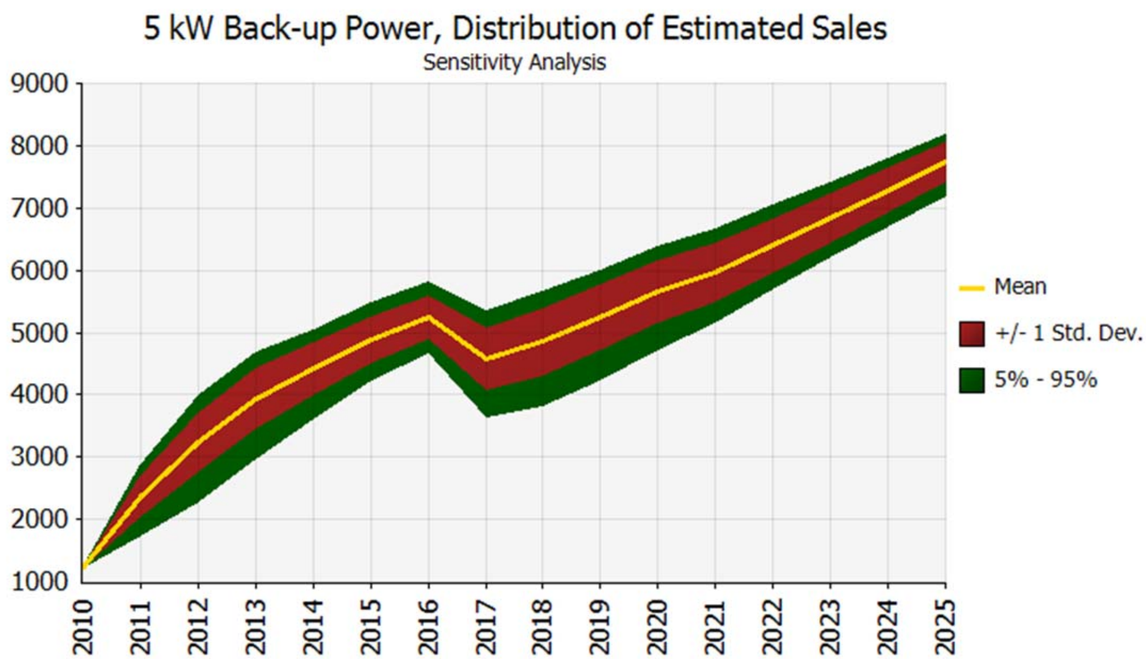


Figure 22. Results of Sensitivity Analysis for Estimated Sales of Backup Power Fuel Cells.

The tornado analysis shows that the model's estimates of future fuel cell backup power unit sales are most sensitive to the rates of learning (progress ratio) in manufacturing the units and in manufacturing fuel cell stacks (Figure 23). This is noteworthy because the progress ratio varies only between 0.85 and 0.95. The higher the ratio the slower the learning is and the lower the fuel cell sales. The choice elasticity comes in a close third followed by the initial cost estimate for the installation of a fuel cell backup power unit. The assumed rates of technological progress for backup power and PEM fuel cells in general are next.

The sensitivity analysis of estimated material handling equipment costs shows a range of uncertainty about future costs of $1,000 per unit, or more (Figure 24). Termination of the ITC in 2017 not only causes costs to increase but increases uncertainty as well. Still, the model projects declining costs, from the range of $13,000 to $15,000 today to the vicinity of $6,000 to $8,000 per unit in 2025.

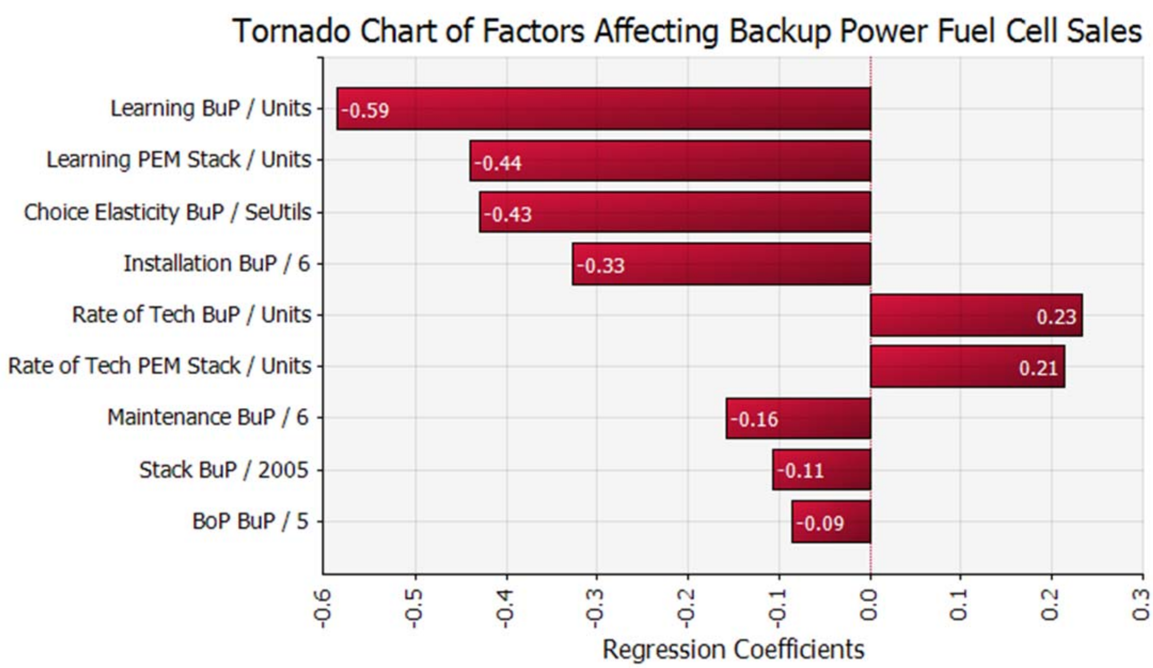


Figure 23. Tornado Chart of Factors Affecting Backup Power Fuel Cell Sales, 2025.

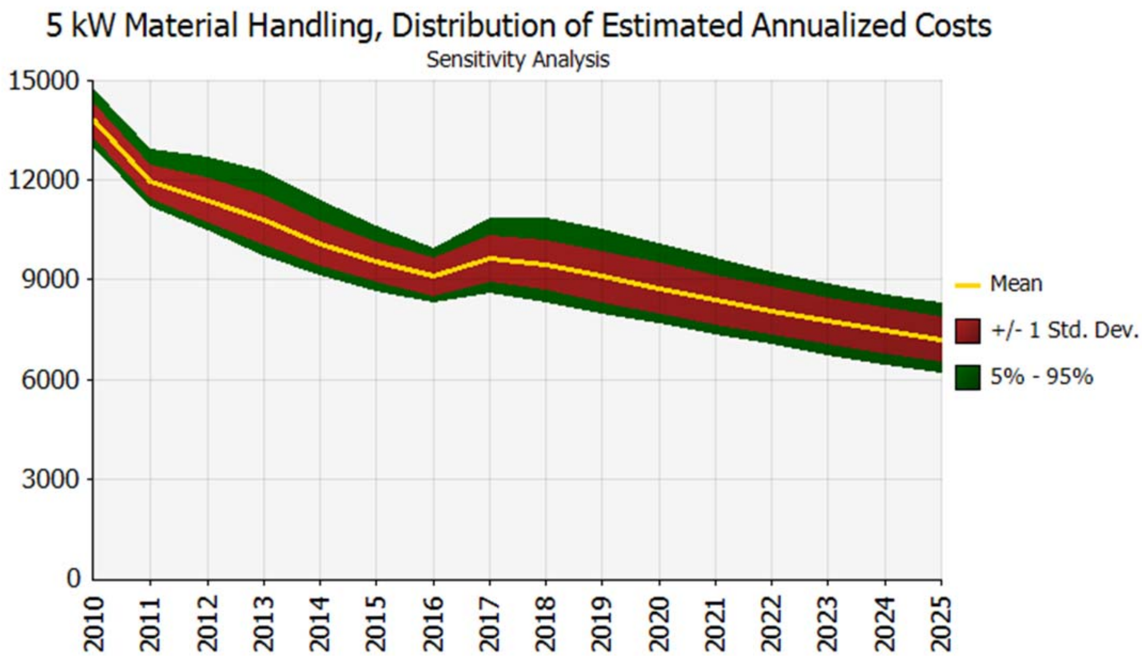


Figure 24. Results of Sensitivity Analysis for EACs of 5 kW Material Handling Equipment.

Uncertainty about future fuel cell material handling equipment sales is much greater (Figure 25), and it appears that the expiration of the ITC in 2017 could pose serious risks to the viability of the industry. Unlike CHP and Backup Power FCs, material handling equipment sales appear to be most sensitive to the cost of hydrogen fuel. Material handling equipment requires far more fuel than backup power units because of its continuous operation. In addition, material handling fuel cell units do not include reformers and therefore require hydrogen fuel. Developing low cost supplies of hydrogen appears to be critical to the viability of the fuel cell material handling industry.

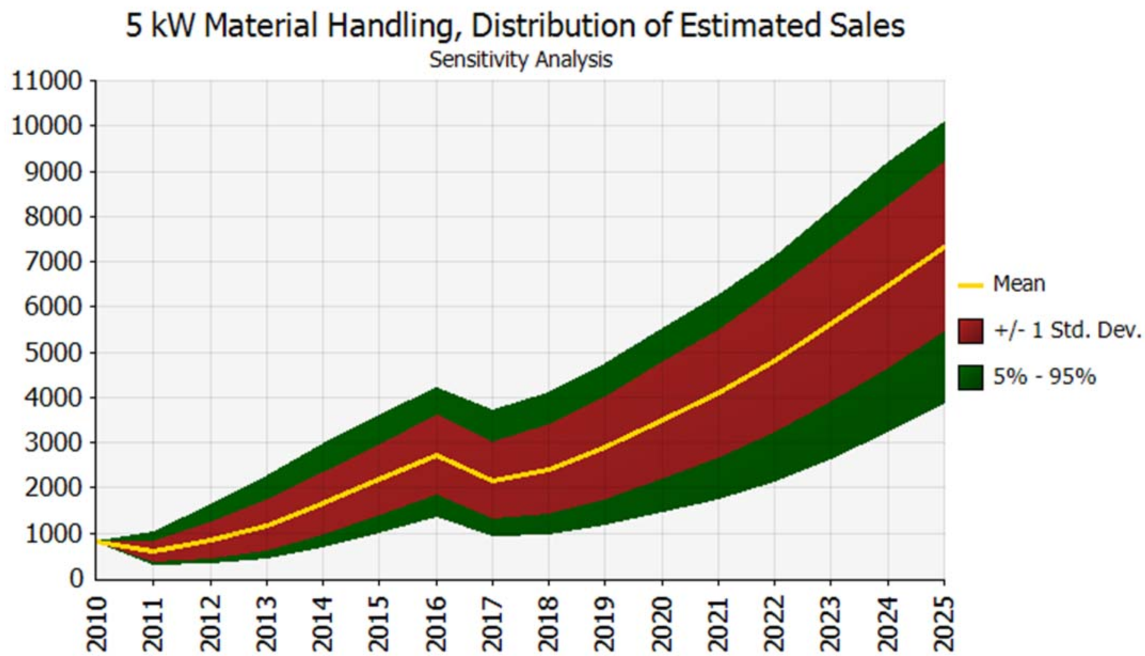


Figure 25. Results of Sensitivity Analysis for Sales of 5 kW Material Handling Equipment.

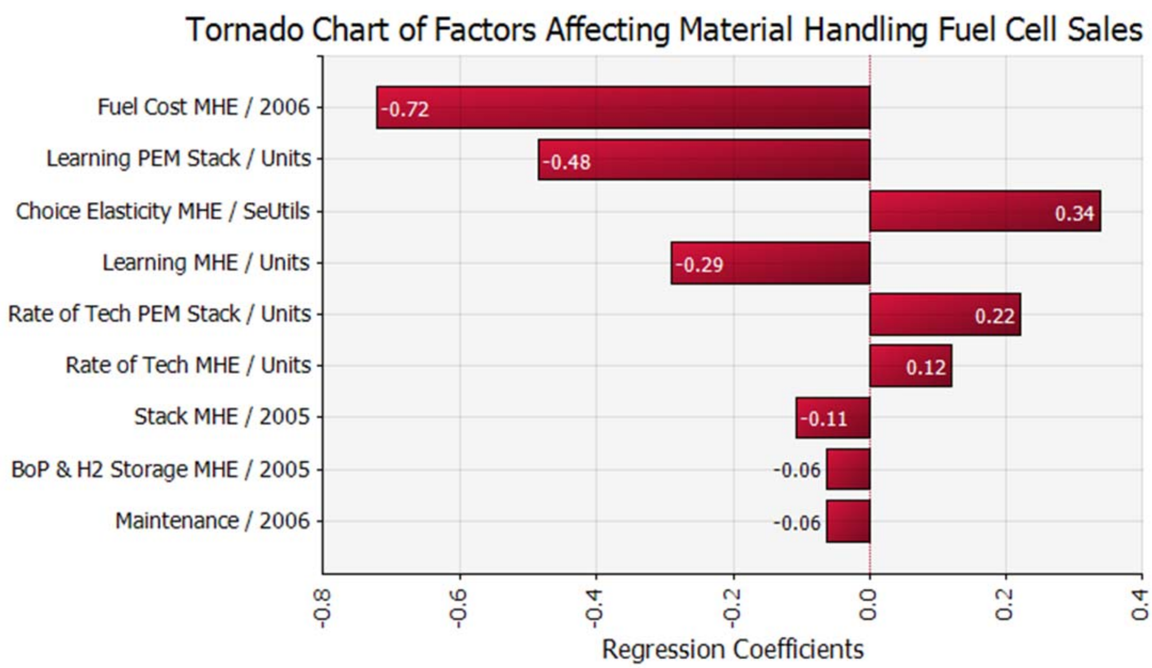


Figure 26. Tornado Chart of Factors Affecting Material Handling Fuel Cell Sales.

8.6 OBSERVATIONS ON MODEL VALIDATION

It is not possible at the present to empirically validate a model of the non-automotive fuel cell market. The objective of this section is therefore more limited. It has shown that key parameters of the model, in particular progress ratios and scale economies are well within the range of values in the published literature, and are consistent with what little empirical data are available. If anything, these assumptions appear to be conservative relative to recent experience. Other data used to calibrate the model have been documented. Finally, an analysis of the sensitivity of the models estimates of fuel cell cost and sales to key assumptions demonstrated that the model produces estimates that are at least plausible, and that no anomalous behavior was detected.

This is a long way from proving that the model's estimates will be realized. Strong, simplifying assumptions have been made about the potential sizes of markets in which fuel cells can compete and about the sensitivity of choices in these markets to fuel cell prices. Many important factors affecting decisions in these markets, such as aversion to risk and local factors affecting the costs and benefits of competing technologies, are not represented in the model. And, of course, past rates of learning and scale economies do not guarantee future performance. As a consequence, expectations about what can be learned from this model should be limited to general trends and are conditional on both key parameter values and simplifying assumptions. In this section we have shown that those assumptions are reasonable and that the model's behavior is plausible.

9. POTENTIAL FOR A SUSTAINABLE INDUSTRY AND POTENTIAL POLICY STRATEGIES

Government policies have been and continue to be critical to the survival of the fuel cell industry. Whether in the United States or elsewhere, most OEMs averred that they had benefitted from government support for R&D and that their current sales were substantially assisted by government tax credits or subsidies. In this section we first assess the impacts of current government policies on fuel cell costs and sales volumes. Next, future sales are estimated given the existing policy environment. Sensitivity tests are conducted next, followed by an exploration of how changes in policy might affect the industry.

The impacts of U.S. and California policies on the equivalent annual cost of large (3 MW) MCFCs is illustrated in Figure 27. Current policies are worth nearly $1,000 in EAC per kW. California's SGIP is today the largest portion of that benefit, accounting for two thirds to three fourths for installations using natural gas and an even greater share if renewable fuel is used. This is because the federal tax credit of $3,000/kW is capped at 30% of the capital cost of the unit. Manufacturers expect the California SGIP to run out of funds soon; we assume here it will expire after 2011 (CSEC, 2010). This is shown by the red line in Figure 26. If in 2012 the cap on the federal tax credit were removed so that every kW received a $3,000 credit, the total EAC of MCFCs would remain at about the same level, but slightly lower, shown by the purple line in Figure 27. The federal ITC is assumed to expire after 2016, by which time costs without policy support would equal approximately $1,500 per kW.

A similar result for 300 kW PAFCs is shown in Figure 28. We have not attempted to estimate future sales of larger FC units. The larger fuel cell market appears to be too idiosyncratic for a simple model to produce plausible estimates. Instead we have focused on the impacts of policies on fuel cell costs. In both figures, sales after 2010 are based on an arbitrary assumption that sales will grow at the rate of 20 MW per year. This is not intended to be a prediction of what will happen but is rather an assumption for the purpose of illustrating how steady growth in demand would lead to gradual reductions in costs.

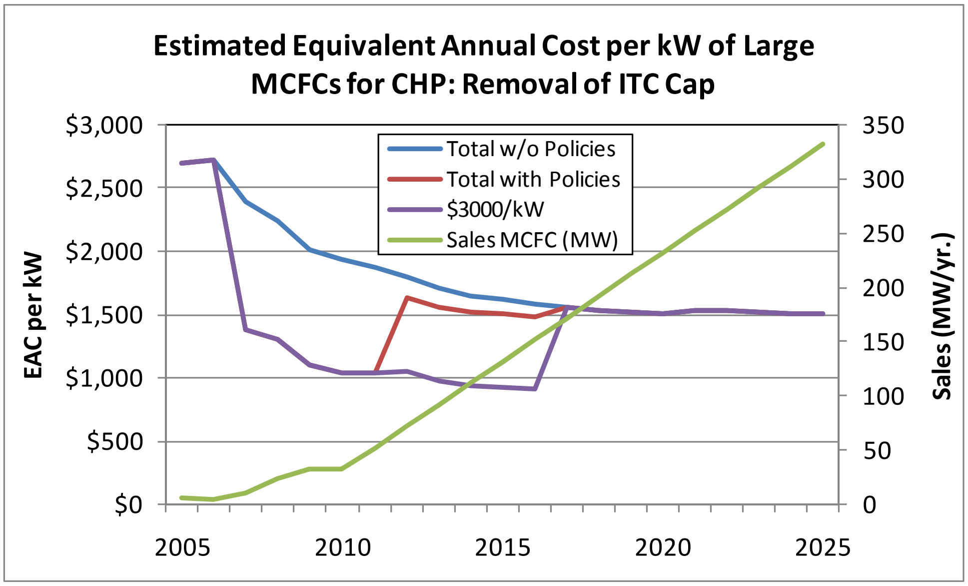


Figure 27. Estimated EAC per kW of 3 MW MCFCs for CHP.

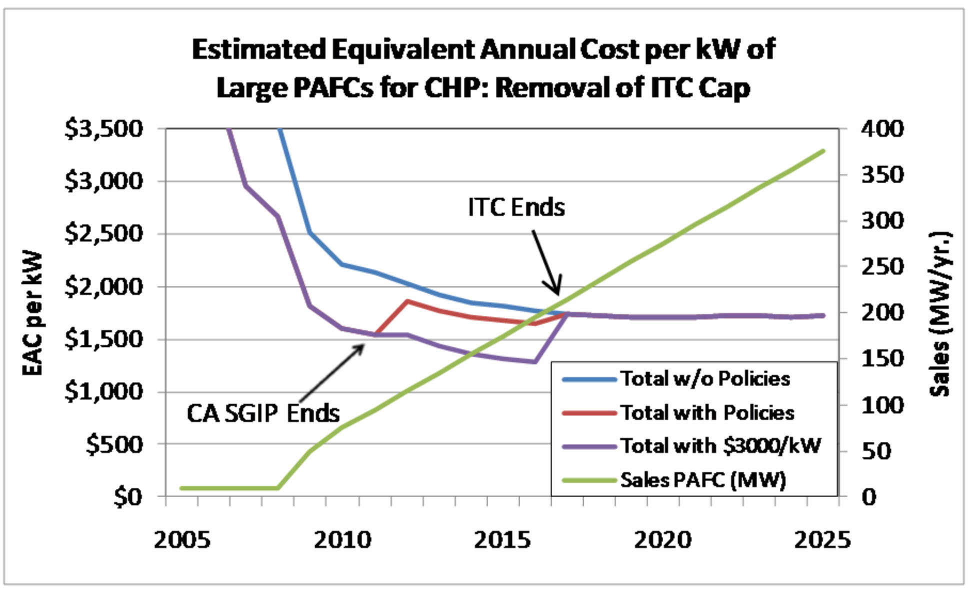


Figure 28. Estimated EAC per kW of 300 kW PAFCs for CHP.

Estimated impacts of the ARRA and continuation of the ITC on future costs of material handling fuel cells are shown in Figure 29. The estimated impact of the ARRA on backup power was similar. ARRA incentivized purchases of approximately 650 fuel cell units for material handling is estimated to have reduced the cost of the units by at least $1,000/kW through learning and scale economies. Continuation of current policies through 2015 is expected to cut costs per kW by almost half compared with a projection in which no polices were continued beyond 2009. The estimation assumes a progress ratio of 0.9, scale elasticity of -0.2 and a continuation of government procurements at the rate of 100 per year beyond 2010.

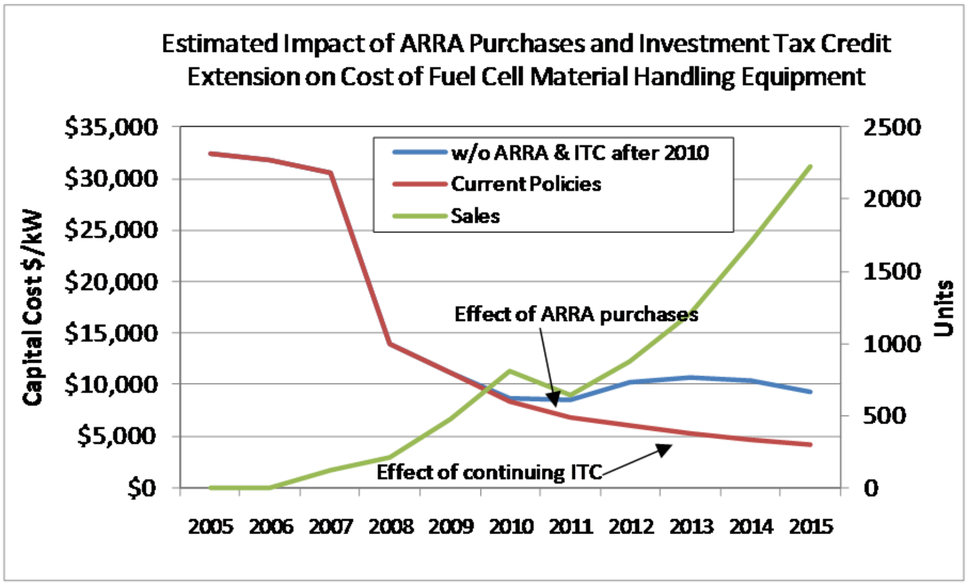


Figure 29. Estimated Impact of ARRA Purchases and ITC on Cost of Material Handling Fuel Cells.

In the PEMFC markets, estimates of future sales have also been made. However, because of the simplicity of our modeling methods, we do not intend that our model's estimates should be considered forecasts of future FC sales. Rather, our intent is to describe generally how the market is likely to be affected by reductions in the costs of FCs and by government policies. For non-automotive PEM FC products the full market model was used to predict future FC unit sales as a function of the EACs of FCs and their competition. However, the market has been greatly simplified in this analysis. First we limit the market to the United States only. In fact, several manufacturers reported that their biggest markets were foreign markets at the present time. No attempt was made to include overseas markets in the model, and so it is very likely to underestimate total demand for FCs. In addition, the competitiveness of FCs will depend strongly on local conditions. Rather than attempt to represent local conditions in detail, we have instead limited the size of the potential markets for FCs to just those that appear to be reasonable candidates based on local conditions.

For example, local electricity prices will strongly influence the sales of micro-CHP FC units, as will the diurnal pattern of electricity use and the ability to take advantage of by-product heat. We estimate that in California alone there are approximately 12,000 to 15,000 new housing units in the potential FC CHP market each year, and about 50,000 to 60,000 nationwide. We assume that the initial market will be limited to these homes in California. Over time, we expect the market in California to expand to include an equal number of small commercial buildings and, eventually, to include the entire United States.

FC backup power units come in sizes ranging from 1 kW to 5 kW and higher depending on the nature of the equipment requiring backup. The attractiveness of FCs will depend on the local cost and availability of hydrogen, the dependability of the local power grid, and the length of time power may be out. In addition, the choice between FC units powered by hydrogen and those powered by methanol and including a reformer will be chiefly determined by the length of time the unit is expected to operate continuously. If power may be out for 3-4 days, methanol reformer units will be favored. If power outages last no more than 8 hours, hydrogen (when available) is likely to be preferred. These important details are not included in our model at this time. Instead, both methanol-reformer and hydrogen FC units are included as potential choices, along with batteries and gen sets. Only 5 kW units are represented. The logit choice model estimates market shares based solely on equivalent annual costs. Again, we limit the number of potential sites to exclude those where FC units are not likely to be feasible.

Finally, a key advantage of FC material handling equipment is the ability to operate at constant power for the full length of their duty cycle and to be refueled quickly. Fast refueling is only important if forklifts are operated for two or three eight-hour shifts during the day. Thus, we limit the size of the potential market to only those sites where forklifts operate in two or more shifts, and add a 10% productivity increase for fuel cells by dividing their EAC by 1.1.

For PEMFC manufacturers, the ITC is assumed to apply to the cost of the FC stack and the balance of plant. Installation costs are not included. Because the total credit is capped at 30% of the capital cost of the stack, this limits the value of the tax credit as FC costs come down over time.

The assumed target market sizes are shown in Figure 30. The micro-CHP market grows most rapidly as small commercial sites and sites outside of California are added to the potential market. The other two markets are believed to be more stable but expand at the rate of 2% per year in the case of material handling, and linearly from 15,000 to 20,000 by 2025 in the case of backup power. Sales are predicted by multiplying market sizes times the market shares predicted by the technology choice models. For all three technologies a minimum sales level of 100 units per year is added through 2020 to reflect purchases for demonstrations and other purposes expected to be insensitive to the economics of the alternatives.

The model projects eventually rising sales shares for all three applications, although micro-CHP sales falter after 2011, which is assumed to be the final year of the important California SGIP (Figure 31). 2011 is the first year of the model's predictions; prior years' are data inputs. Sales also drop off after 2012, which is a consequence of the recursive structure of the model (i.e., scale effects from 2011 affect production costs in 2012). The model is suggesting that once the $2,500/kW SGIP subsidy ends, sales may fall off somewhat but will still be sustained by the investment tax credit at a reasonable level for a single manufacturer. The model does not take into account the higher electricity prices in California nor does it explicitly represent demand by "early adopters." If this scenario is approximately correct, the micro-CHP industry would experience a downturn immediately after the expiration of the ITC after 2016 but that sales would begin to steadily improve after 2018. However, the volume of sales is not large enough to support more than one manufacturer at an economical scale of production through 2025. According to the model's estimates, backup power applications appear to be the most likely to reach viable production levels soonest (Figure 32).

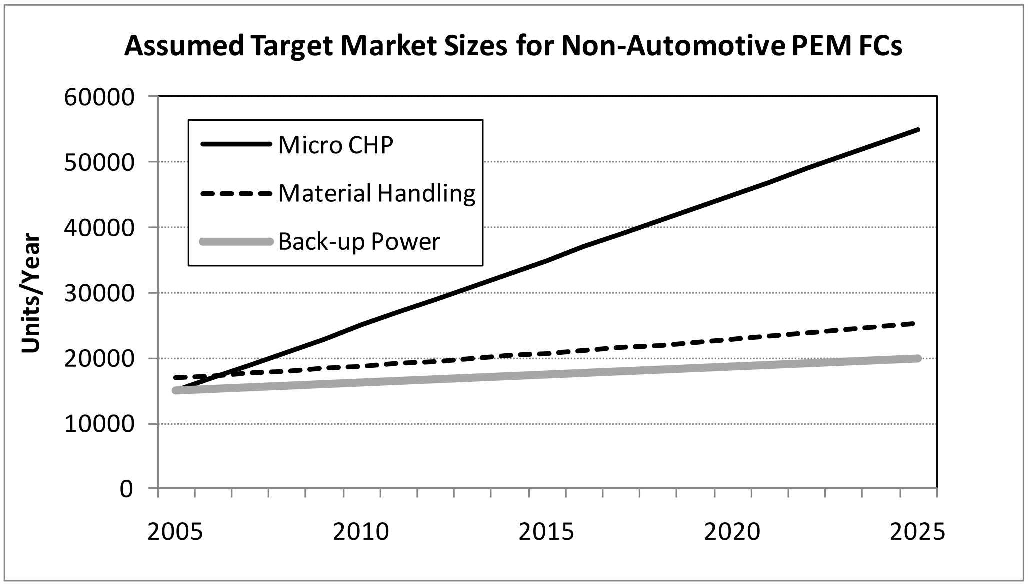


Figure 30. Assumed Target Market Sizes for Non-Automotive PEM FCs.

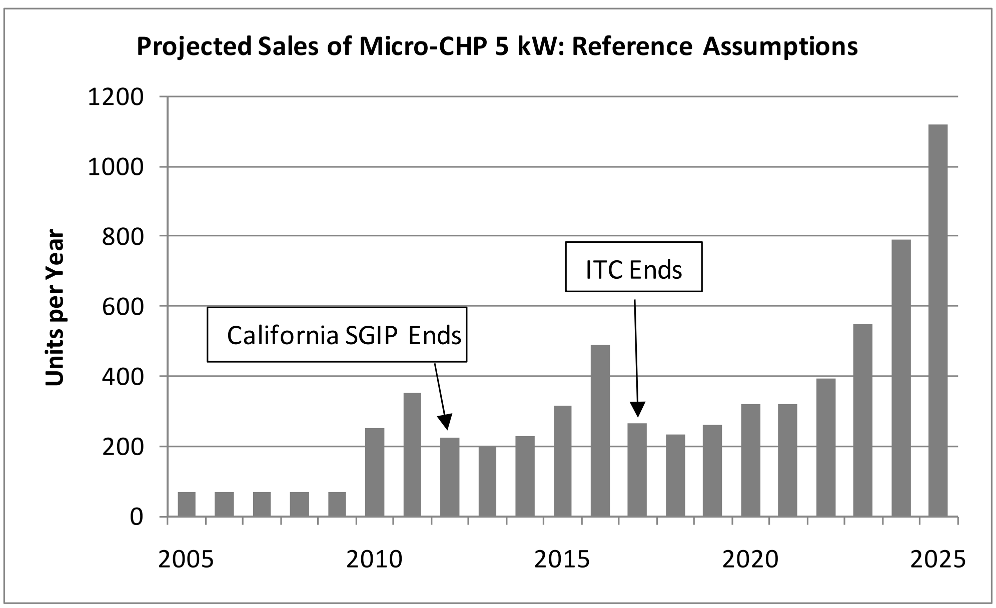


Figure 31. Projected Sales of 5 kW Micro-CHP Units: Reference Assumptions.

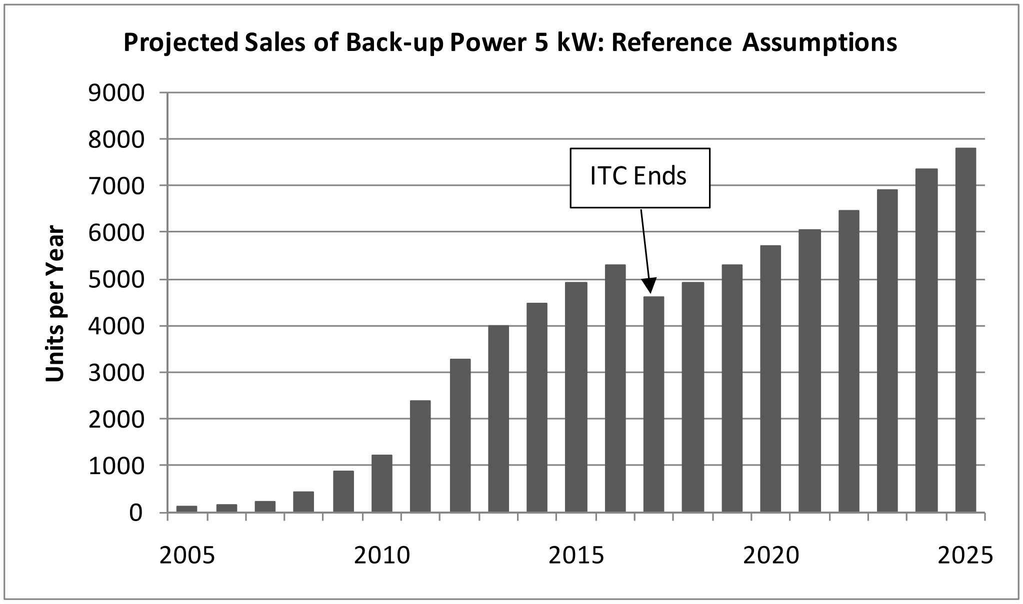


Figure 32. Projected Sales of 5 kW Backup Power Units: Reference Assumptions.

The model's estimates of backup power sales remain relatively strong and slowly increasing, dipping slightly when the ICT expires in 2017 and resuming slow and steady growth thereafter.

The model estimates that sales of material handling equipment may drop off a little after the boost due to ARRA supported purchases in 2010 but rise above the 2010 level in 2013 and increase steadily thereafter, except for the dip in 2017 when the ITC is expected to end (Figure 33).

Costs of all components for all PEMFC applications have been decreasing rapidly over the past five years. The model predictions show a slowing of cost reductions after 2011 as expected by OEMs. Still the cost of a micro-CHP unit in 2025 is estimated to become less than half its cost in 2010 (Figure 34). The cost estimates shown in Figures 34-36 include the impacts of current policies.

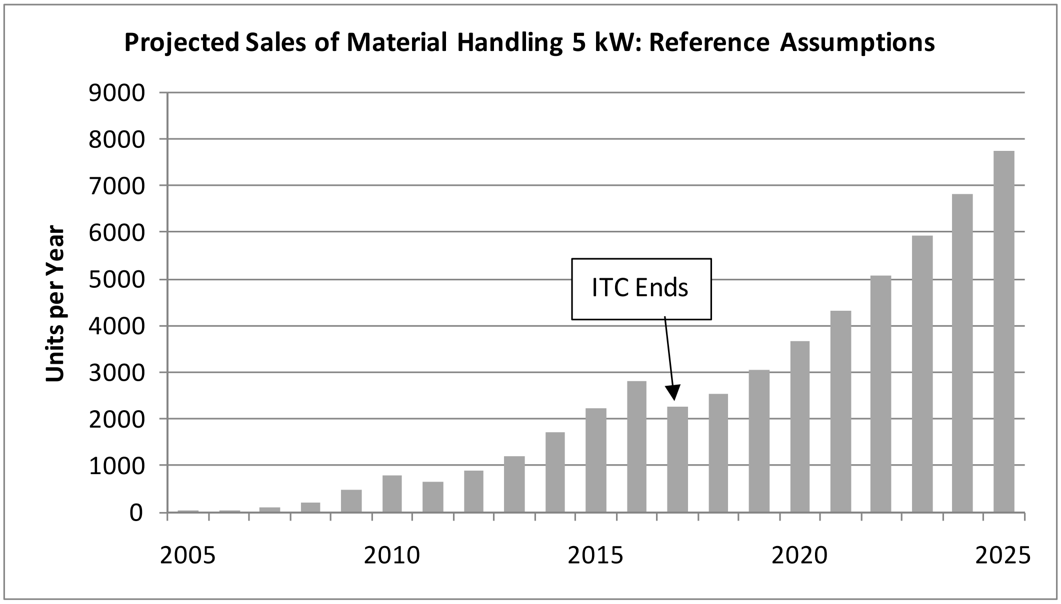


Figure 33. Projected Sales of 5 kW Material Handling Equipment: Reference Assumptions.

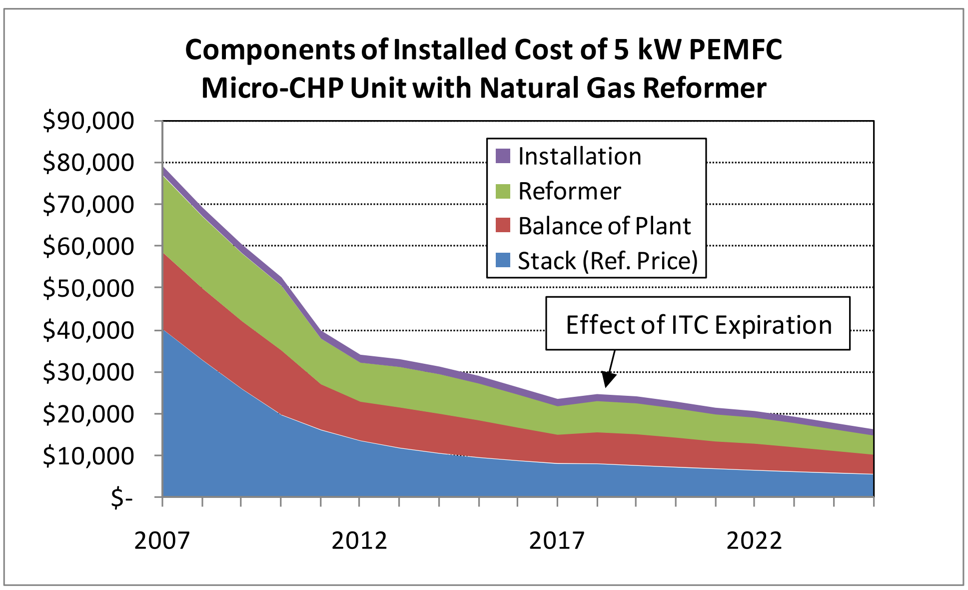


Figure 34. Components of Installed Cost of 5 kW PEMFC Micro-CHP Unit with Natural Gas Reformer: Reference Assumptions.

Similar patterns are seen for backup power units with methanol reformers (Figure 35) and material handling equipment (Figure 36). Estimated costs for 5 kW backup power units decline from the vicinity of $15,000-$20,000 in 2010 to under $10,000 after 2020. Costs for 5 kW material handling equipment show a greater estimated historical decrease due to the lower production volumes prior to 2010 and lesser cumulative production experience in that application in the early years.

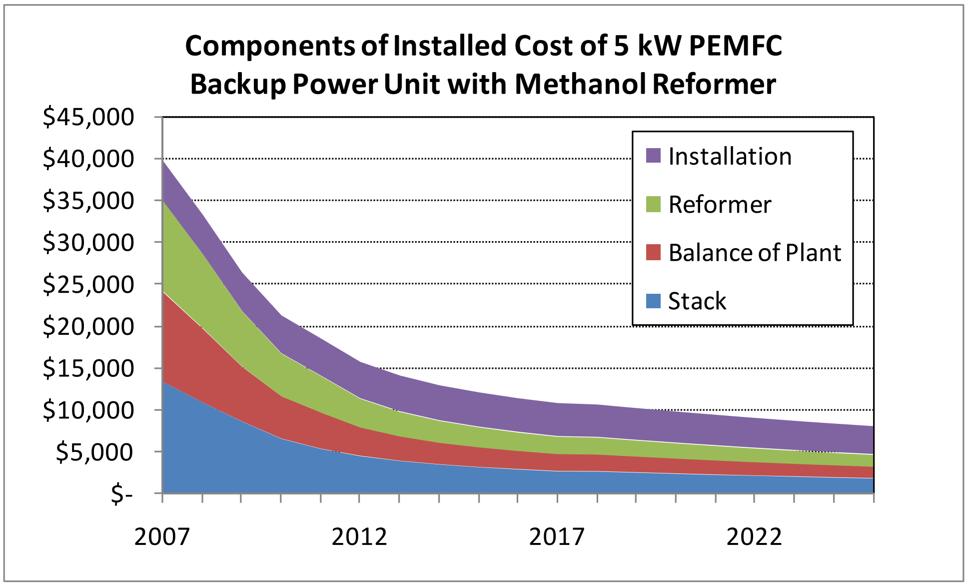


Figure 35. Components of Installed Cost of 5 kW PEMFC Unit with Methanol Reformer: Reference Assumptions.

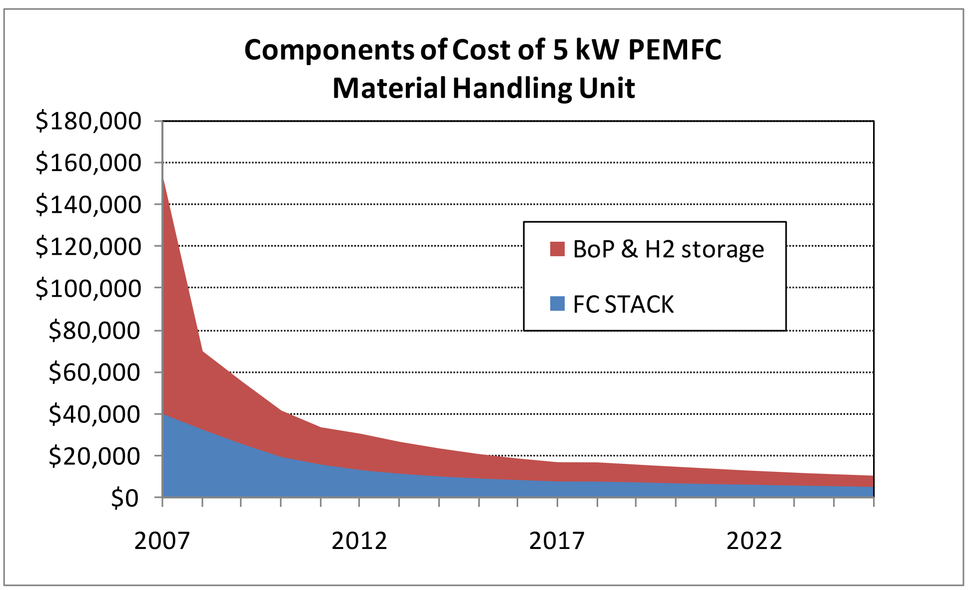


Figure 36. Components of Cost of 5 kW PEMFC Material Handling Unit: Reference Assumptions.

9.1 TESTS OF SENSITIVITY TO KEY PARAMETER ASSUMPTIONS

Sales of micro-CHP PEMFCs are highly dependent on the price-sensitivity of potential customers. Assuming markets are 50% more price sensitive reduces estimated micro-CHP sales to essentially the minimum level of 100 per year (Figure 37). This is because micro-CHP competes with electricity purchased from the grid and natural gas purchased from the utility company. Assuming that a homeowner or small business already has a natural gas furnace for heating, purchasing gas and electricity is substantially cheaper than adding a micro-CHP unit. Unless there are consumers who value the other attributes of the CHP unit (e.g., advanced technology and lower greenhouse gas emissions) and are therefore less sensitive to cost alone, the FC micro-CHP will have a difficult time competing with energy purchased from the utility companies. Because at present the market for home CHP is limited to high-end homes with the ability to use by-product heat in swimming pools or spas, the lower price sensitivity assumption seems more appropriate. However, for the near term at least, it appears that the micro-CHP market may be limited to market segments that are not price sensitive, such as luxury homes and image-conscious small businesses.

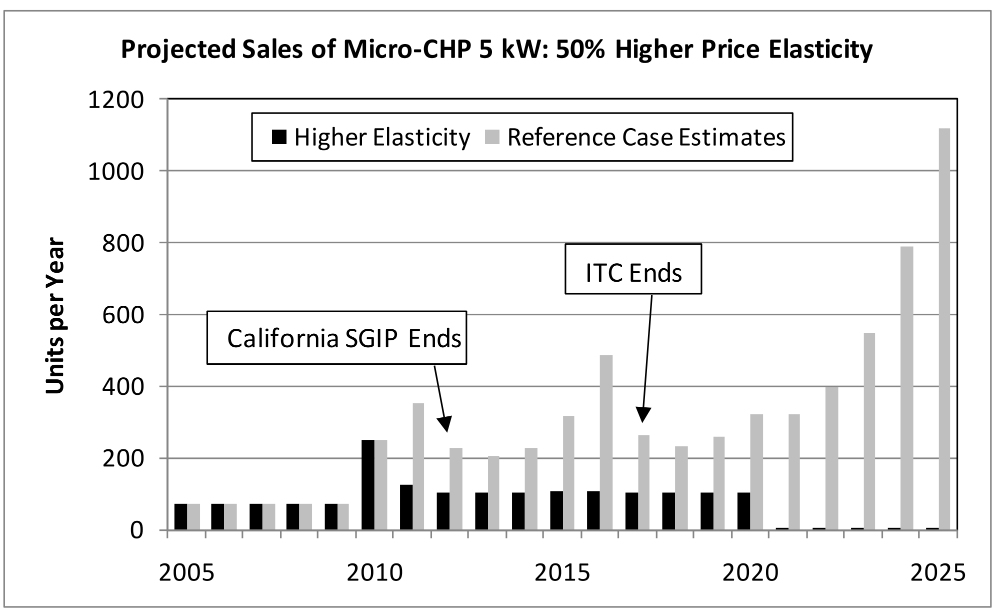


Figure 37. Estimated Effect of a 50% Increase in Customers' Sensitivity to Price on Micro-CHP Sales.

Greater customer sensitivity to price also causes sales of material handling fuel cells to struggle along at about 500 units per year until after 2020 (Figure 38). Only the backup power market is relatively unaffected by assuming 50% greater price sensitivity (Figure 39).

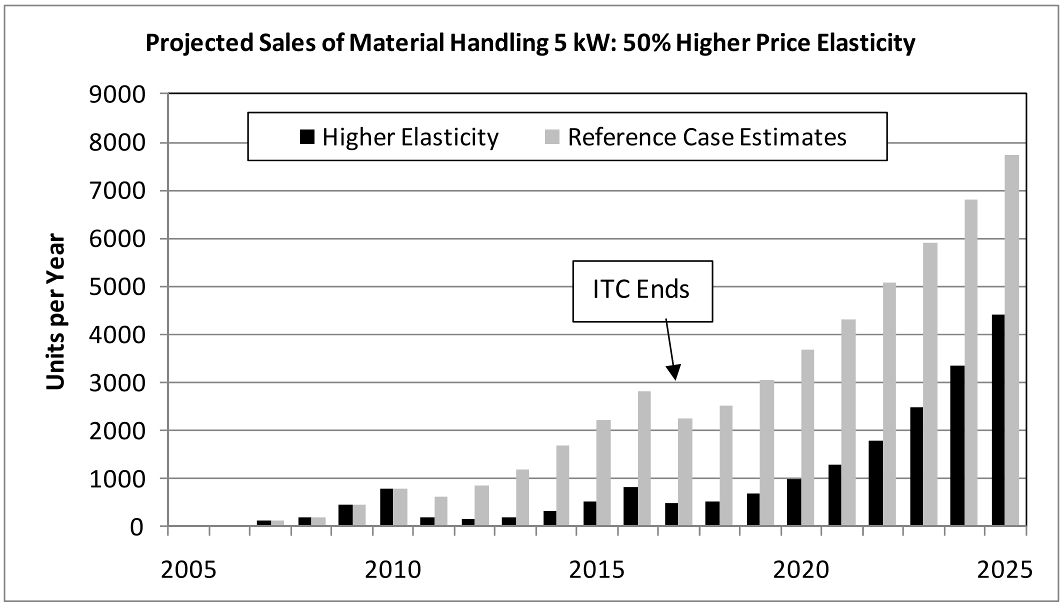


Figure 38. Estimated Effect of a 50% Increase in Customers' Sensitivity to Price on Backup Material Handling Equipment Sales.

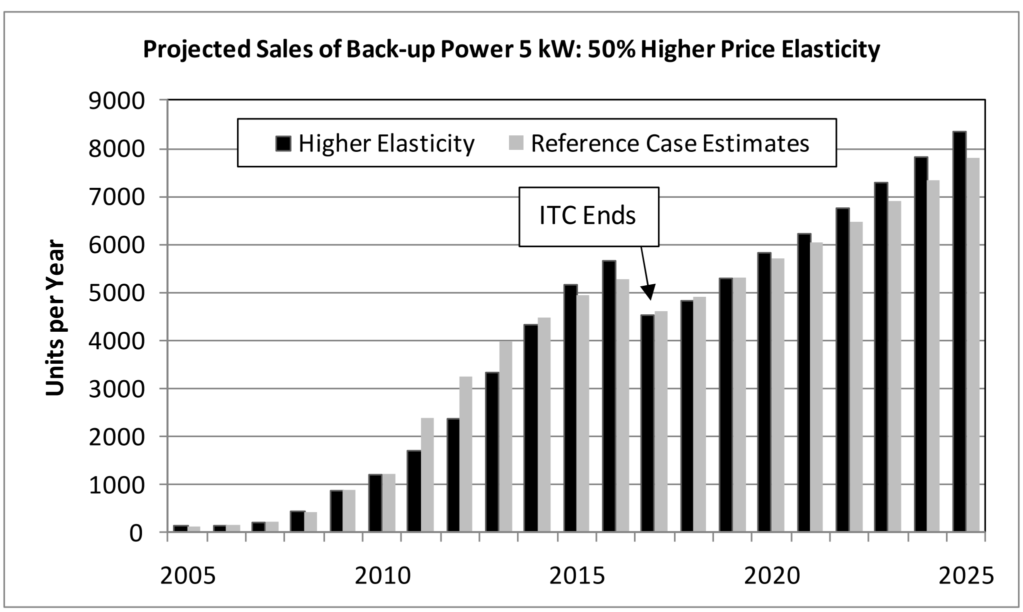


Figure 39. Estimated Effect of a 50% Increase in Customers' Sensitivity to Price on Backup Power Sales.

If progress ratios are only 0.95 instead of 0.90 (implying only a 5% reduction in costs for every doubling of cumulative production) the model estimates that the 5 kW micro-CHP market would be seriously affected; sales are estimated to drop immediately upon the anticipated exhaustion of SGIP funds after 2011 and remain near the minimum level (Figure 40). Capital costs decline only to $40,000 until 2020 because scale economies are not achieved and learning-by-doing is very limited (Figure 41). After 2020 costs jump due to the loss of all scale economies.

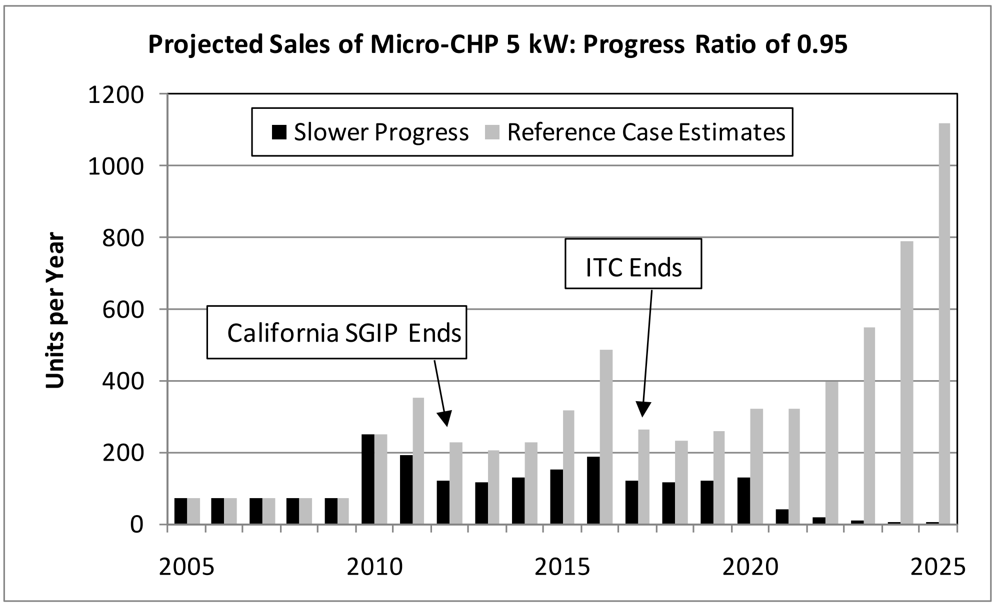


Figure 40. Estimated Sales of 5 kW Micro-CHP Assuming a Progress Ratio of 0.95.

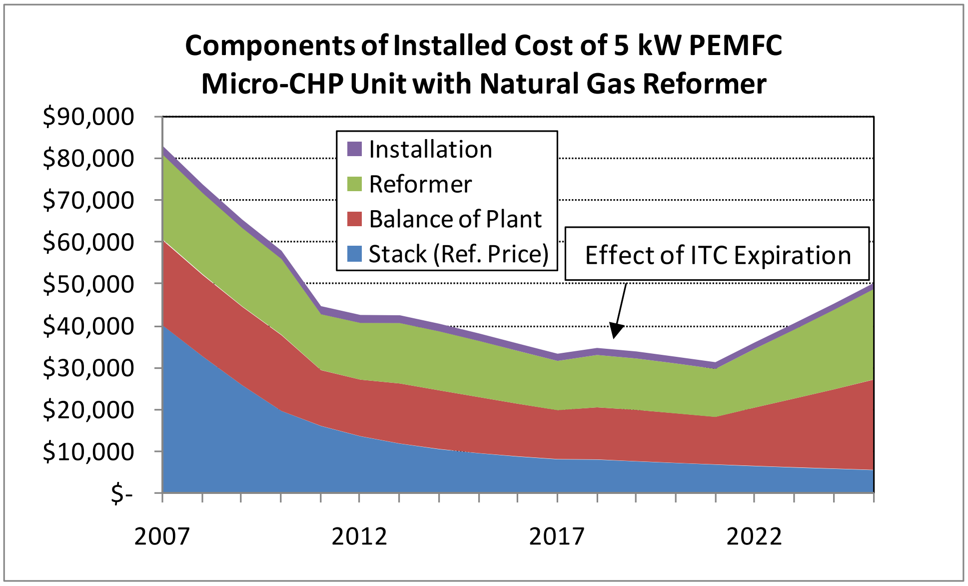


Figure 41. Estimated Cost of 5 kW Micro-CHP Assuming Progress Ratio of 0.95.

Estimated sales of backup power units are less affected by the assumed slower rate of learning (Figure 42). The estimated high level of sales allows scale economies to be achieved. Substantial learning still occurs, albeit at a somewhat slower rate, and costs eventually decline well below $15,000 per unit (Figure 43).

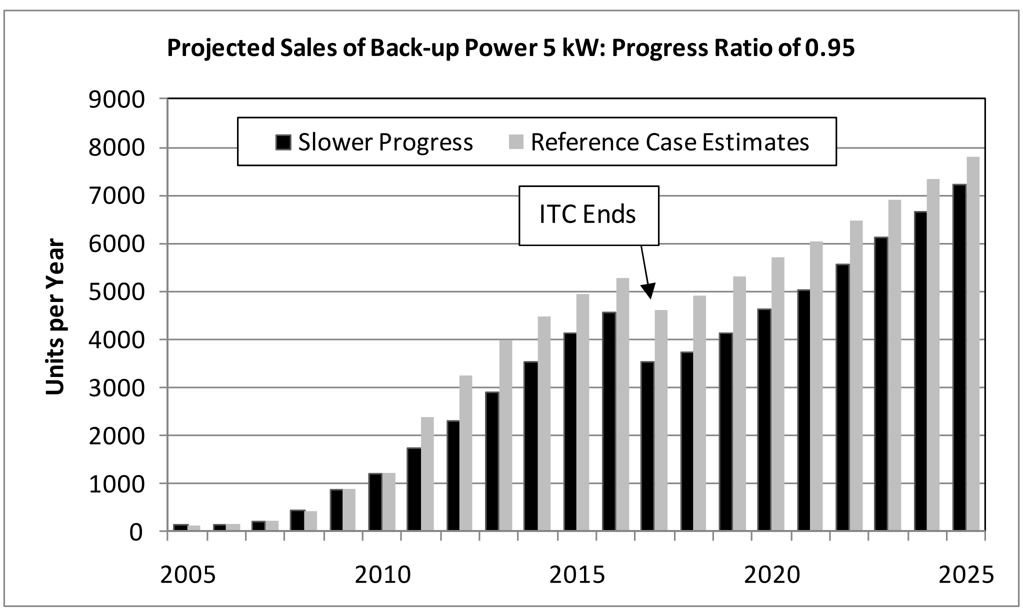


Figure 42. Estimated Sales of 5 kW Backup Power Assuming Progress Ratio of 0.95.

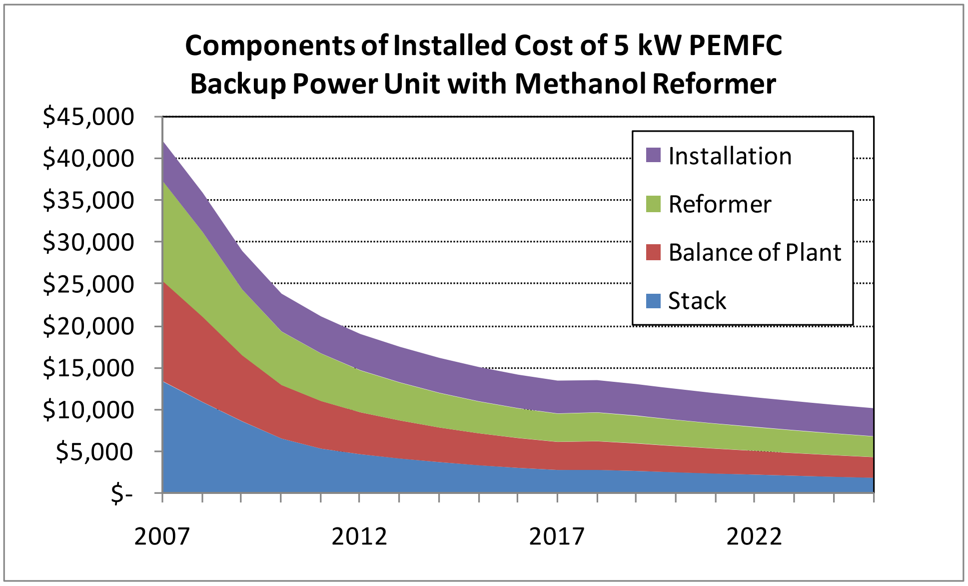


Figure 43. Estimated Cost of 5 kW Backup Power Assuming Progress Ratio of 0.95.

Estimated sales of material handling equipment are lower than the reference case but still exceed 1,000 units in 2014 and, after a setback due to loss of the ITC in 2017, grow to 6,000 units by 2025 (Figure 44). Costs eventually decline to less than $20,000 per unit (Figure 45).

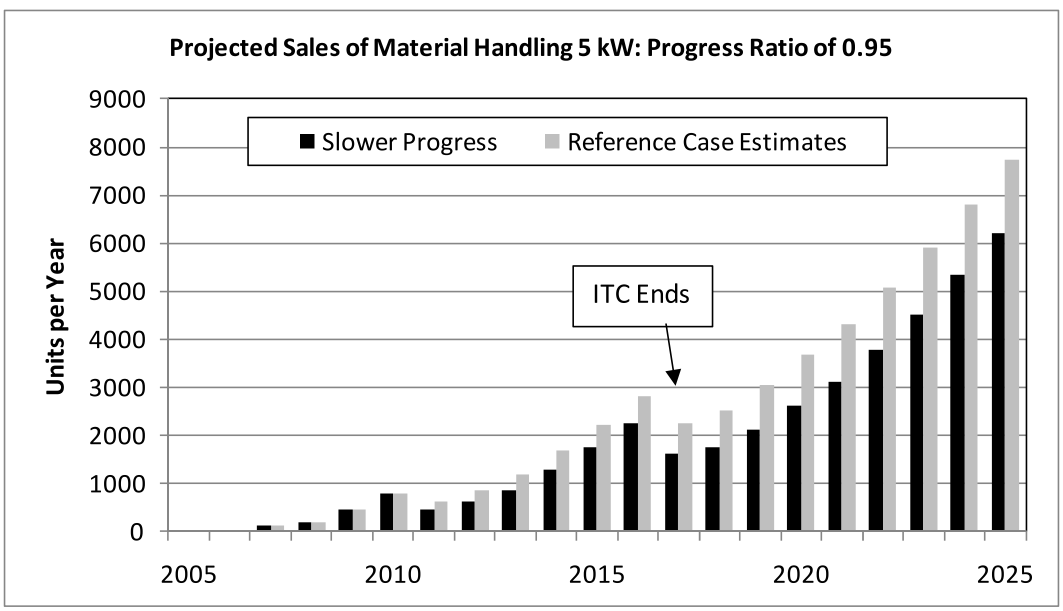


Figure 44. Estimated Sales of 5 kW Material Handling Equipment Assuming Progress Ratio of 0.95.

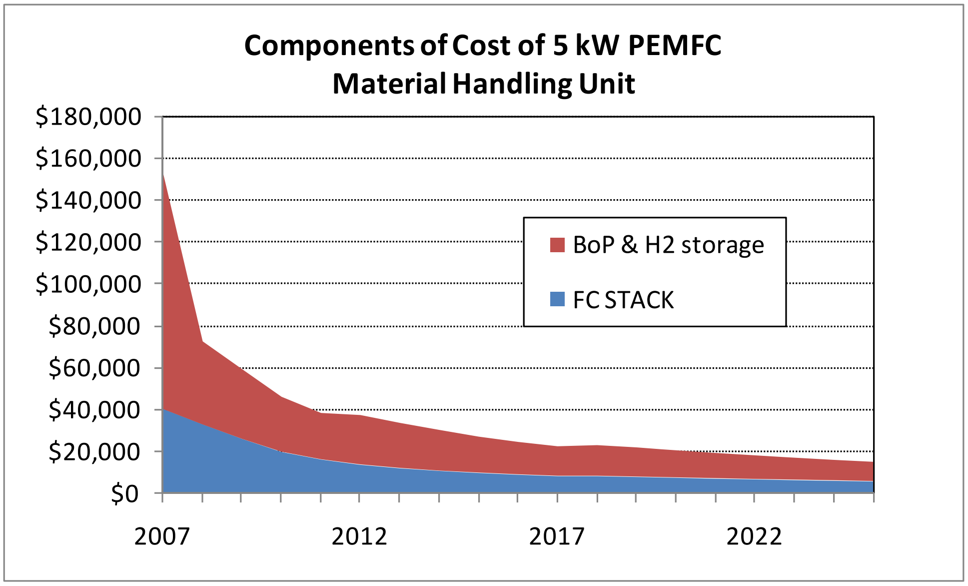


Figure 45. Estimated Cost of 5 kW Material Handling Equipment Assuming Progress Ratio of 0.95.

In the interviews conducted as part of this study, all segments of the FC industry reported important benefits to their technologies from government-sponsored R&D. Purchases of FCs subsidized by ARRA funds helped to sustain the industry, and most especially FC material handling manufacturers, during a difficult period. In addition, the ITC is crucial to the economics of non-automotive FC OEMs today, and appears likely to continue to be a critical sustaining policy for the next five years or so. If the ITC were eliminated in 2012, the model predicts a severe impact on the micro-CHP and material handling OEMs (Figures 46 and 47), and a significant loss of sales for FC backup power manufacturers (Figure 48). If these estimates are approximately correct, there is reason to doubt that the industry would survive long enough to see markets grow after 2020. The ITC appears to be a critical bridging policy for the non-automotive FC industry.

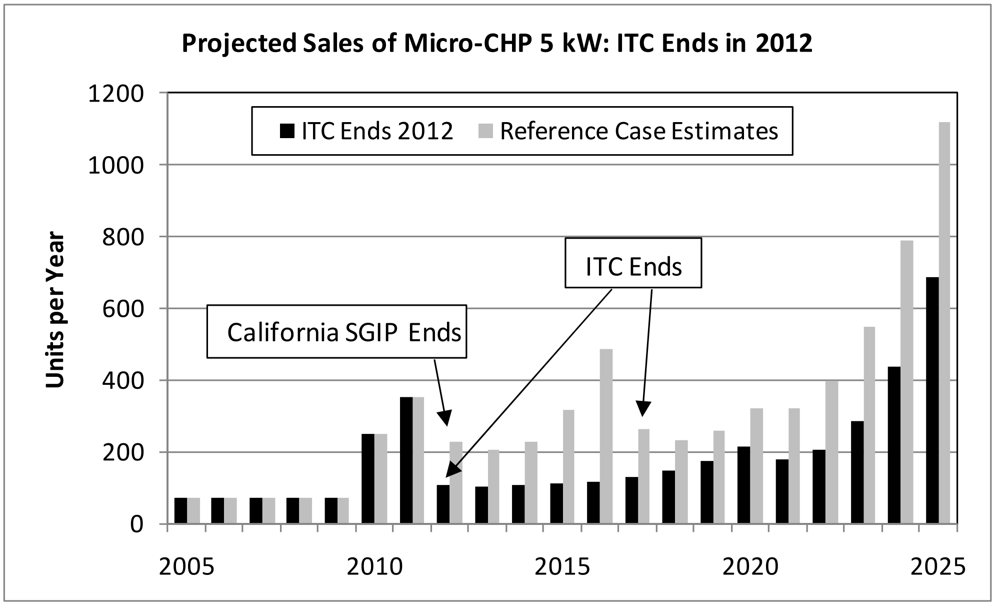


Figure 46. Estimated Sales of 5 kW Micro-CHP Assuming Termination of the ITC in 2012.

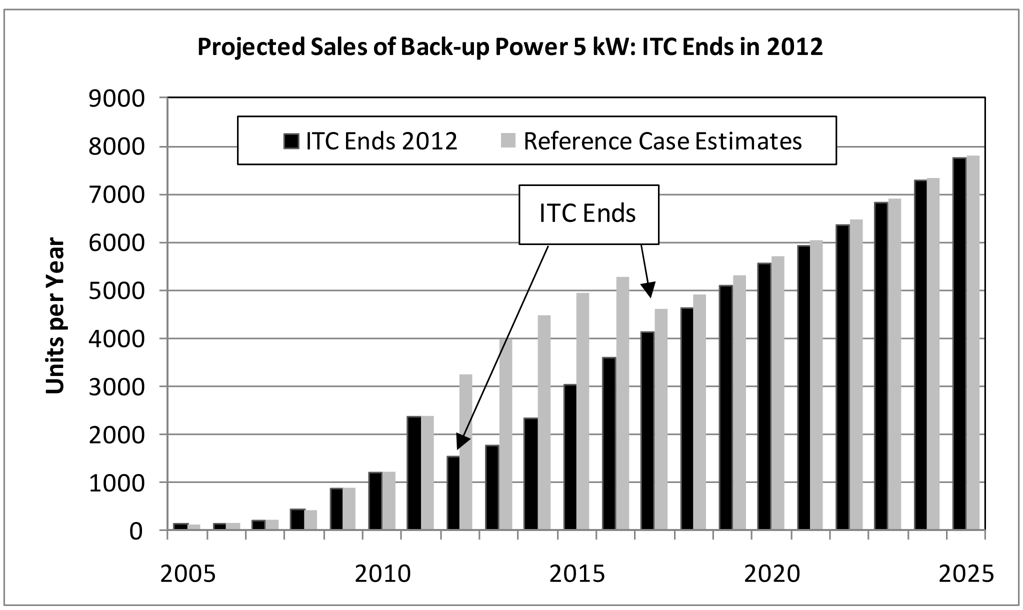


Figure 47. Estimated Sales of 5 kW Material Handling Equipment Assuming Termination of the ITC in 2012.

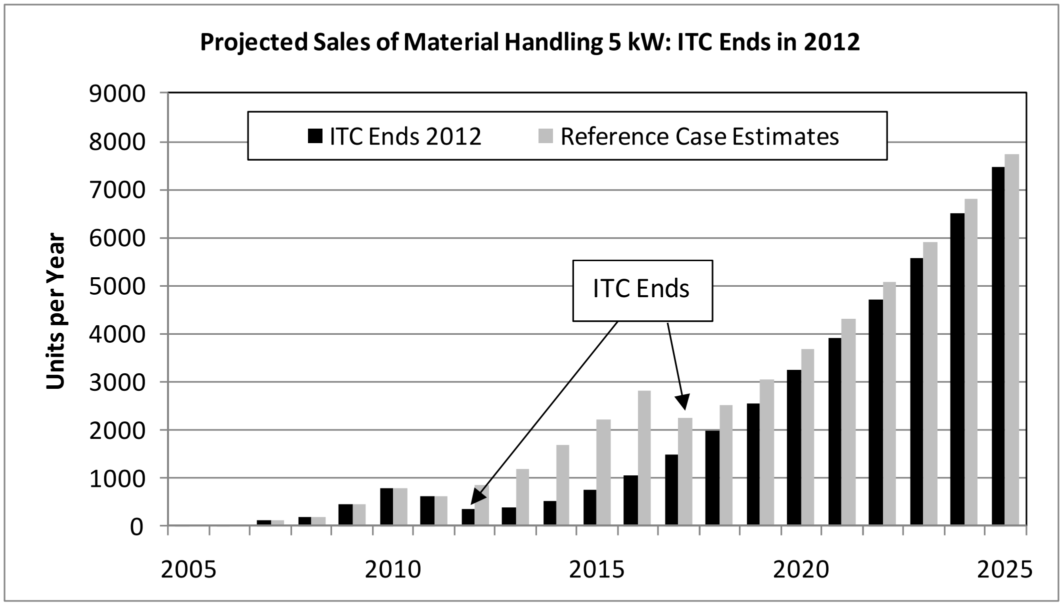


Figure 48. Estimated Sales of 5 kW Backup Power Assuming Termination of the ITC in 2012.

9.2 CONVERTING THE CAPPED $3,000/KW ITC TO AN UNCAPPED $1,000/KW CREDIT

As the costs of PEMFCs decline, the value of the ITC also declines. This is because the credit is defined as the lesser of $3,000 times the kW power of the FC or 30% of the capital costs of the FC system. Capital costs do not include installation or maintenance. As FC system costs decrease, the 30% rule becomes the determinant of the tax credit. Thus, as FC OEMs become increasingly successful in reducing costs, and therefore more competitive, the government's subsidy per unit decreases. Whether the subsidy will decrease at just the right rate or too quickly to allow the industry to become sustainable, or too slowly to make efficiency uses of public funds is a key question. The sales estimates of the reference case suggest that this could be an important issue for large CHP and grid-independent power FCs, especially if, as assumed, the California SGIP funding ends after 2011. The SGIP is worth a constant $2,500 per kW while the capital cost per kW of large PAFC and MCFC units is already well below $10,000 and is estimated to be closer to $2,000-$2,500. Thus, the ITC is today worth only about $1,000 per kW to the buyer of these larger units. When the SGIP is assumed to end in 2012, the EAC increases to approximately $100 less than the unsubsidized level (Figures 49 and 50).

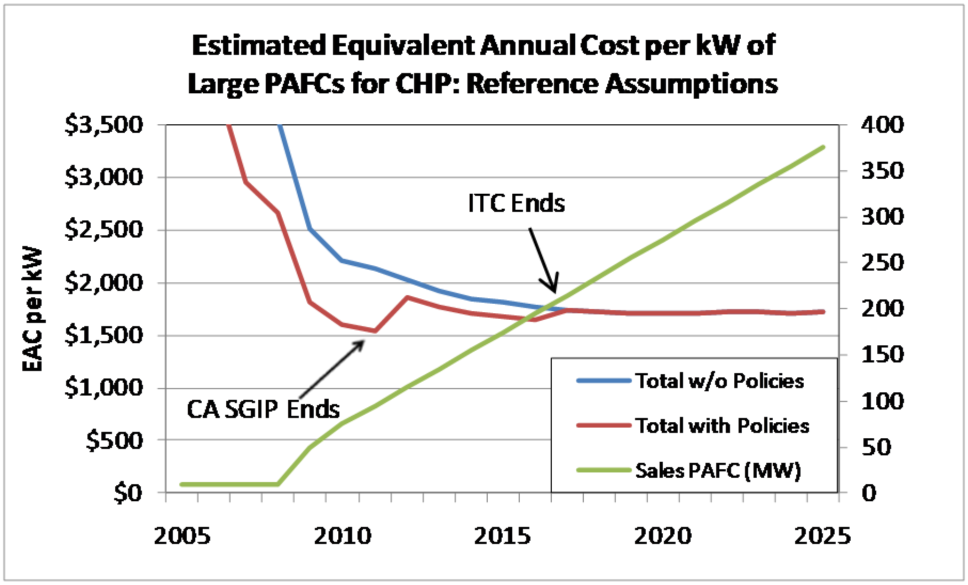


Figure 49. Estimated Equivalent Annual Cost per kW of Large PAFCs: Reference Assumptions.

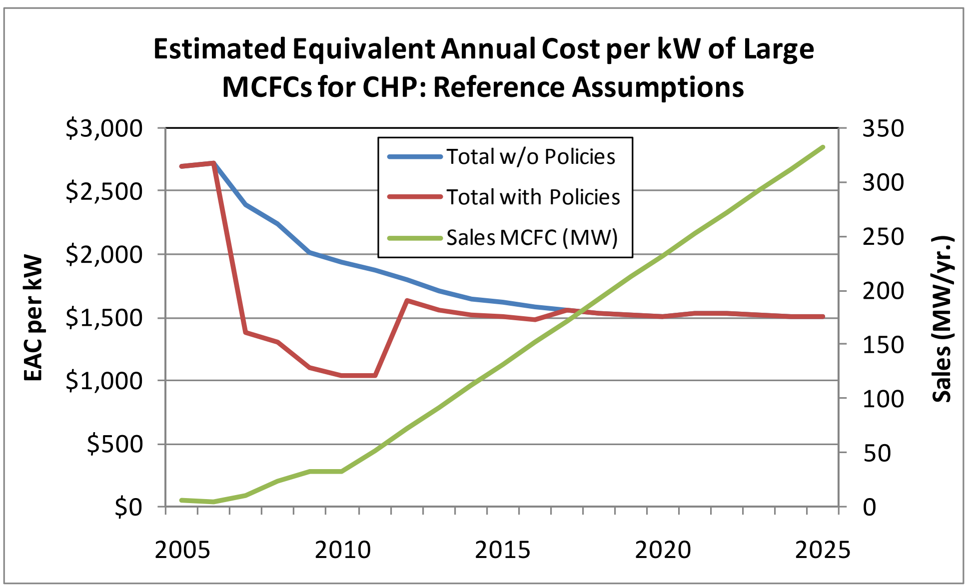


Figure 50. Estimated Equivalent Annual Cost per kW of Large MCFCs: Reference Assumptions.

If the 30% of capital cost cap on the ITC were converted to a fixed credit of $3,000 per kW, starting in 2012 and decreased by $500 annually to end by 2018, it would not only smooth the transition from the SGIP to long-run costs of about $1,000 per kW but provide an equal incentive to states outside of California (Figure 51 and 52). Sales projections are the same in figures 49-52 because sales are an exogenous assumption in the PAFC and MCFC models.

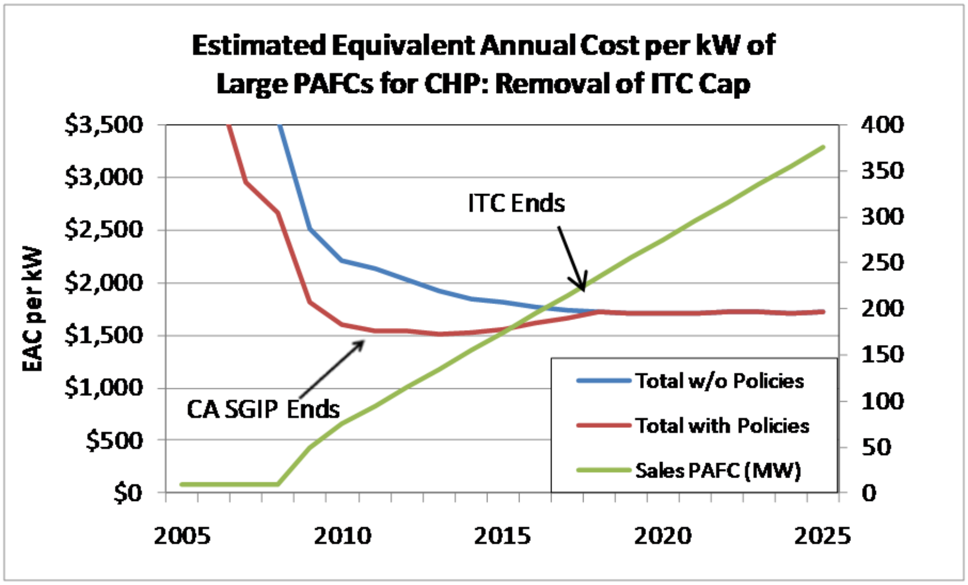


Figure 51. Estimated EAC per kW of Large PAFCs: Uncapped, Declining Investment Tax Credit.

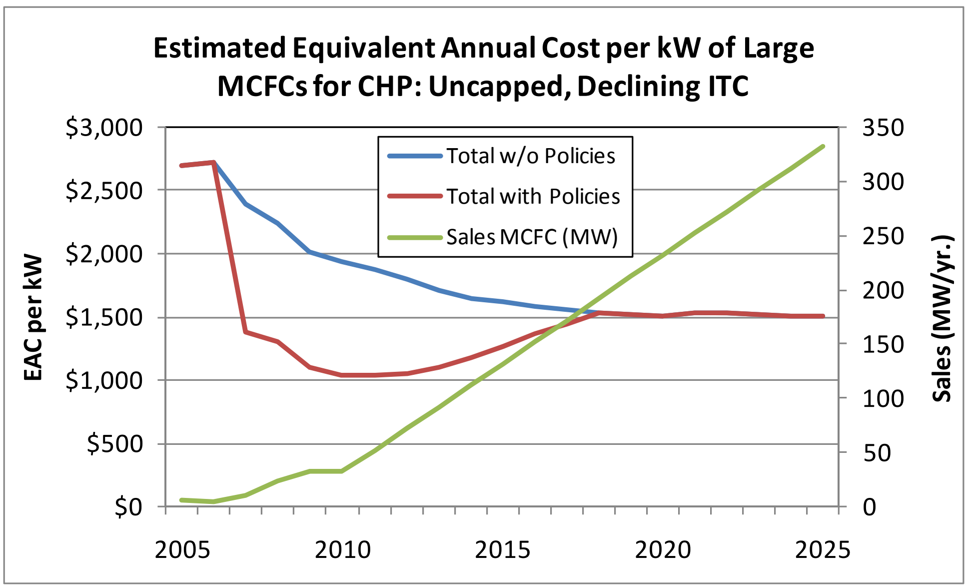


Figure 52. Estimated EAC per kW of Large MCFCs: Uncapped, Declining Investment Tax Credit.

Such a restructuring of the ITC would also greatly benefit the smaller PEMFC OEMs, particularly material handling equipment (Figure 53) which would see an immediate increase in sales and a faster transition to long-run volumes.

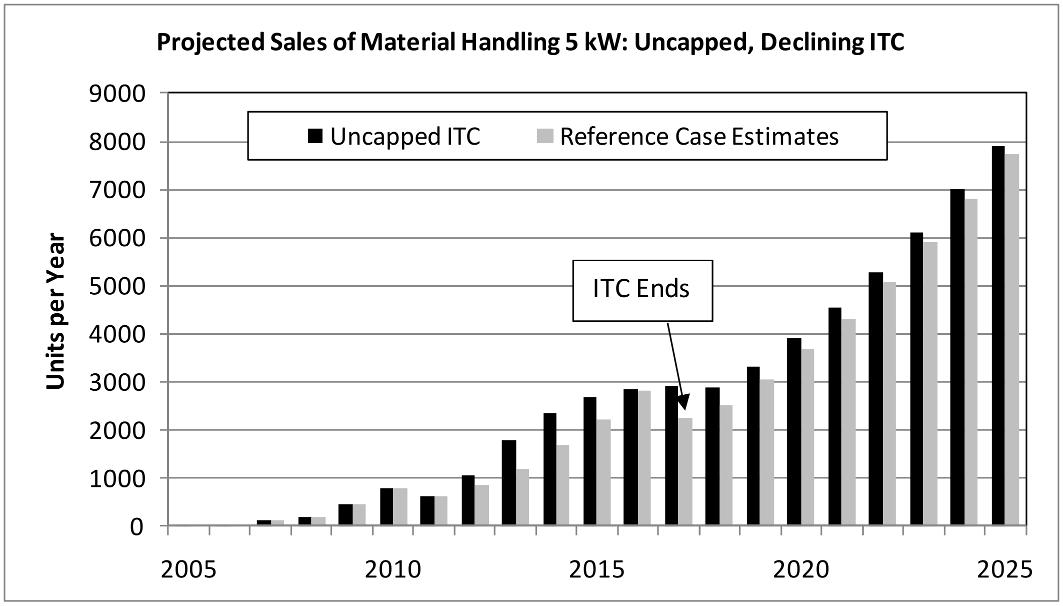


Figure 53. Estimated Effect of an Uncapped, Declining ITC on Sales of Material Handling Equipment.

9.3 $0.20/KW FEED-IN TARIFF FOR CHP PRODUCED ELECTRICITY

An alternative to uncapping the ITC that would be valuable to CHP applications would be the creation of a national feed-in tariff for FCs. The "Feed-in Tariff" case assumes that 70% of the electricity produced by the FC CHPs is utilized on site and that 30% is sold to the grid at a guaranteed price of $0.20/kWh starting in 2012. The feed-in tariff is assumed to begin phasing out after 5 years by decreasing by $0.05 per year until it becomes $0 in 2020. The ITC is restored to the 30% cap on capital expense, and the California SGIP is again assumed to expire after 2011. With all policies in place, the EACs of both FC technologies decline to approximately $1,000/kW before 2015 (Figures 54 and 55).

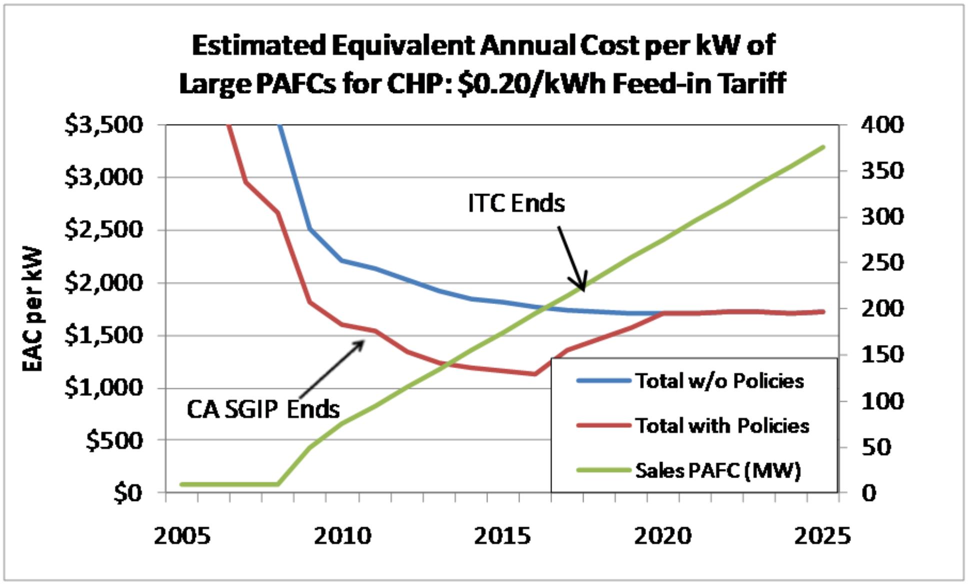


Figure 54. Estimated EAC per kW of Large PAFCs with $0.20/kWh Feed-in Tariff.

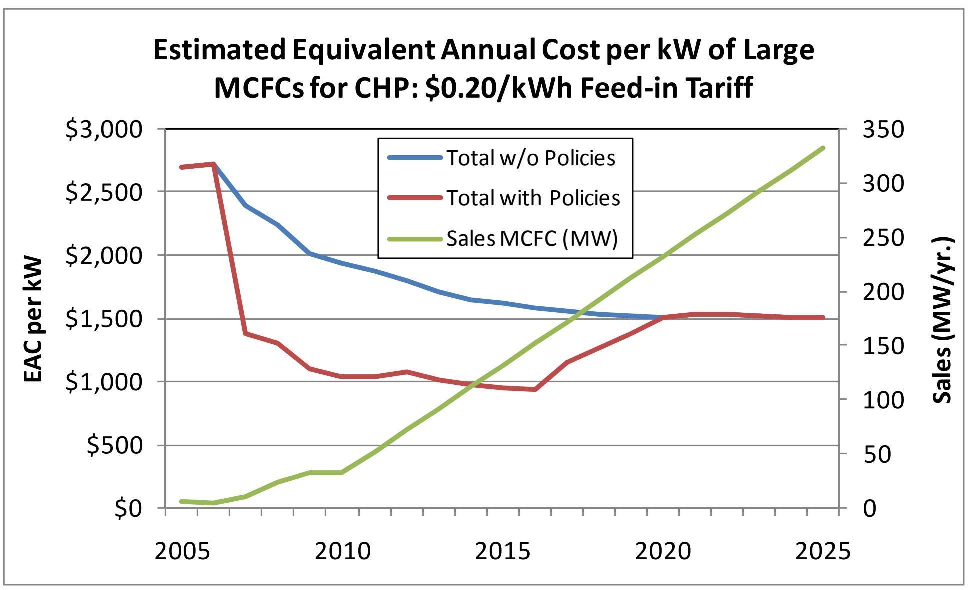


Figure 55. Estimated EAC per kW of Large MCFCs with $0.20/kWh Feed-in Tariff.

Feed-in tariffs may be a powerful incentive for micro-CHP applications, as well. If micro-CHP units qualify for the feed-in tariff of $0.20/kWh, even with the ending of the SGIP after 2011, sales are estimated to rise above 400 units per year by 2014 and to remain above 400 units per year through 2021 (Figure 56).

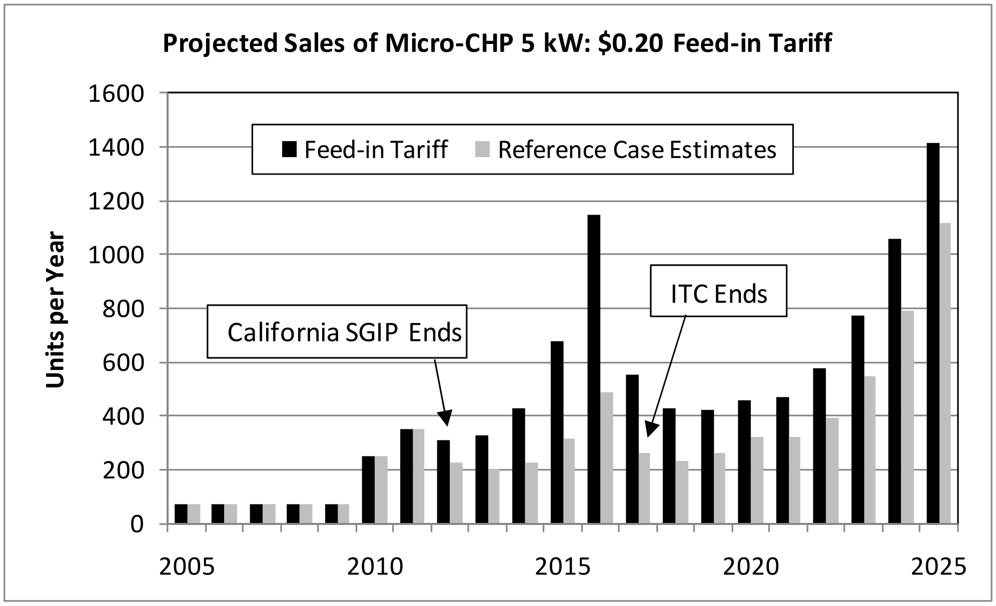


Figure 56. Impact of $0.20/kWh Feed-in Tariff on Estimated Sales of Micro-CHP Units.

9.4 IMPACTS OF GOVERNMENT POLICIES

FCs have received significant government R&D support since they were recognized as a key enabler of space travel. The FC research programs supported by the Departments of Energy and Defense have enabled the dramatic cost reductions described above in this report. More recently, the ITC, government purchases, and subsidization of FC sales have been a major support of the developing FC market. Without these efforts, the FC market model estimates that evolution of a U.S. FC industry would be delayed by at least five years and possibly indefinitely. The impacts of these policies were simulated by removing them from the model from 2011 on. No attempt was made to remove the effects of decades of R&D as well as policy support through 2010. For example, the ITC was ended after 2010 instead of expiring after 2016 as it is now scheduled to do. Thus, the simulation negates the effects of future policy impacts but not past policy impacts. The one exception is that DOE's ARRA-supported purchases in 2009 (77 material handling units) and 2010 (572 material handling units and 520 backup power units) were subtracted from the sales estimates for those years. The assumed minimum sales level of 100 units per year is cut to 50 and ends after 2015. The California SGIP program is retained but ends after 2011.

Only the backup power application is estimated to retain a level of sales that might allow it to survive the next five years. These estimates assume no reduction in the number of firms. If the backup power industry were to contract to only one or two firms, scale economies might improve to allow the market to grow steadily after 2012, instead of after 2014. The estimated consequences for micro-CHP sales are dire: sales plummet in 2011 and quickly disappear (Figure 57).

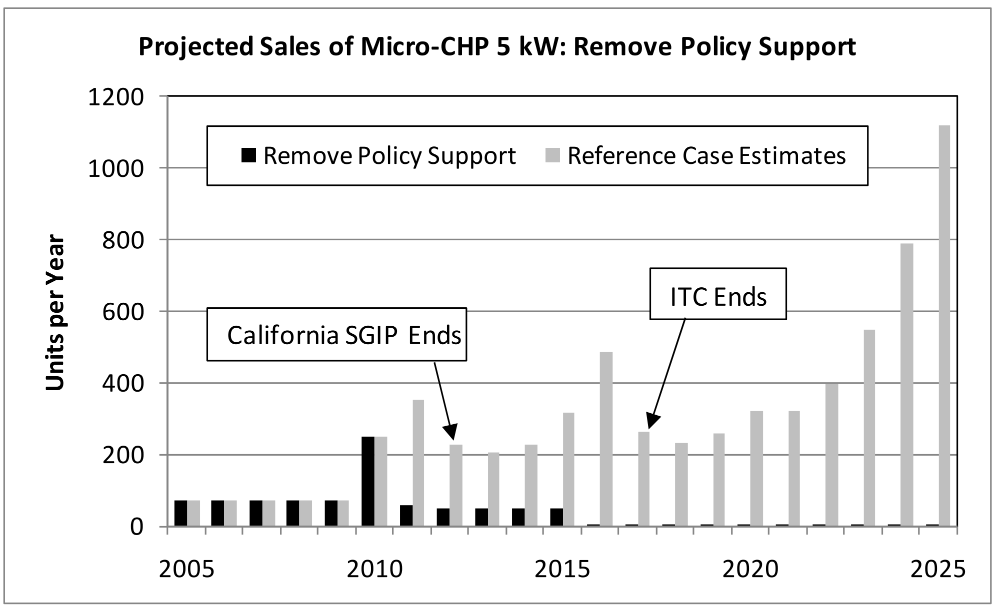


Figure 57. Estimated Sales of Micro-CHP Units Assuming No Policy Support After 2010.

The effect on estimated sales of material handling equipment is also extreme (Figure 58). Although the model projects that sales would eventually recover, it is doubtful that even one firm could survive until 2015, given the very low sales volumes.

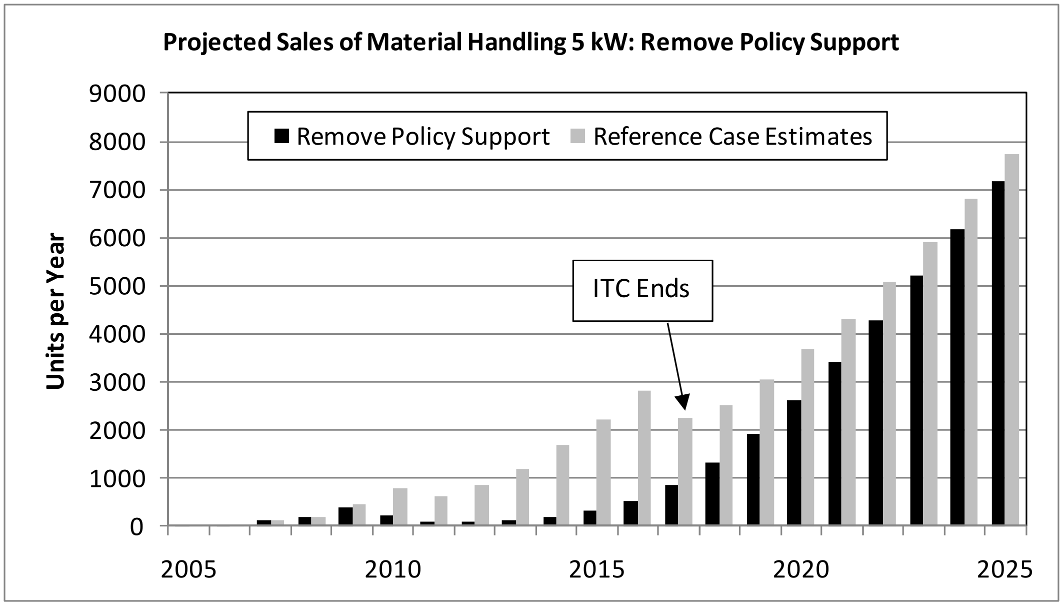


Figure 58. Estimated Sales of Material Handling Units Assuming No Policy Support After 2010.

10. CONCLUSIONS

Interviews with domestic and foreign manufacturers and government officials provided convincing evidence that the fuel cell industry, worldwide, has made impressive progress since our previous assessment in 2007. Still, the global industry is dependent on public support and is likely to be for several years.

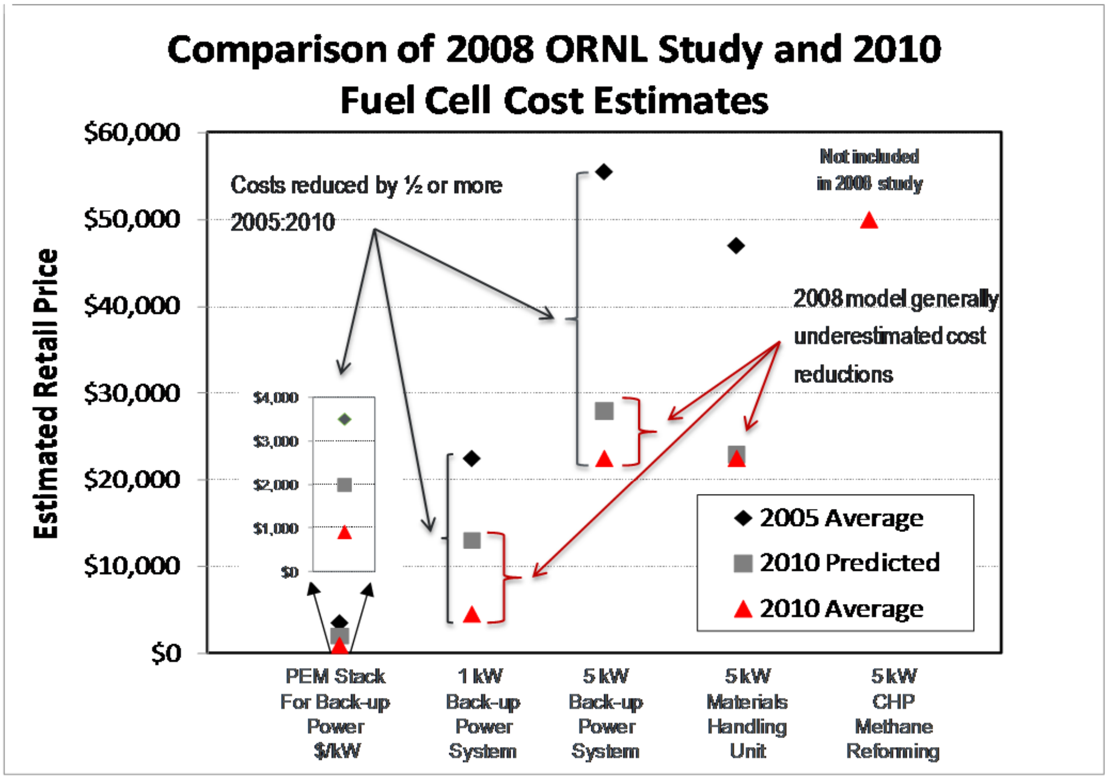
- Non-automotive fuel cell manufacturers are attempting to establish themselves in a limited number of markets: for PEMFCs, back-up and uninterruptible power (especially for telecommunications), material handling equipment (forklifts), micro-CHP; for larger PAFC and MCFCs, CHP and grid-independent stationary power. In all these markets, fuel cells are competing at a cost disadvantage against established technologies.
- All manufacturers have achieved large cost reductions over the past 2-5 years. Cost reductions on the order of 50% are the norm.
- Nonetheless, all manufacturers believe that costs must be further reduced by 40% to 50% in order to compete successfully in the marketplace without government support.
- In the current market, government incentives are essential to sustaining the U.S. fuel cell industry. Our analysis of future prospects indicates this is likely to remain the case for the next five years. Given continued or enhanced incentives the above analysis suggests that fuel cell manufacturers might achieve sufficient cost reductions to continue without government support sometime between 2015 and 2020.
- Most manufacturers believe that future cost reductions will come primarily though economies of scale and cost reductions in the supply chain, with technological advances playing a somewhat smaller role than in the past. Estimated scale elasticities (the percent reduction in cost for a 1% increase in annual production) are typically in the range of -0.2 to -0.3, implying that doubling output would reduce costs by 20% to 30%.

- Substantial improvements in the durability of fuel cells have also been achieved. PEM fuel cell stacks in backup power applications today are expected to operate under real-world conditions for 5,000 to 10,000 hour lifetimes. ENEFARM systems have been operating for 20,000 hours in Japanese homes and are guaranteed for 40,000 hour lifetimes. Large scale (>300 kW) fuel cells for CHP and stationary power already exceed 40,000 hours before requiring replacement. Still, manufacturers believe that durability must and can be further improved.
- Most manufacturers believe that production volumes must increase by somewhere between a factor of 3 and an order of magnitude to achieve sufficient scale economies to become competitive.
- Almost all of the manufacturers interviewed were operating well below their existing production capacity and all had the capability to expand capacity by 50% to 300% within one year.
- Today, fuel cell OEMs are dependent on government incentives or government procurements for viability. Without policies such as the Investment Tax Credit, California's Self-Generation Incentive Program, research and development funding and government procurements, most companies' sales would be drastically reduced.
- Most PEM fuel cell manufacturers have reduced the number of products they offer and specialized in order to reduce costs and increase sales volumes per product.
- For U.S. manufacturers, the key domestic markets are in California and the northeast states. South Korea is an important overseas market today, with sizable potential markets in the EU. In the backup power area, manufacturers believe that developing countries represent large potential markets.
- For FC CHP and micro-CHP manufacturers, both purchase incentives and high electricity prices (or feed-in tariffs) are essential to creating a viable market.
- For PEM fuel cells in back-up power and material handling, the cost and availability of hydrogen is a significant impediment to commercial success. While the ARRA and other programs have provided important incentives for purchasing fuel cells, the problem of

hydrogen availability for non-automotive applications has not yet been adequately addressed.

The 2008 report (Greene and Duleep, 2008) estimated current costs for PEM fuel cell stacks and products and projected costs to 2010 based on assumed production levels, scale elasticities of approximately -0.2 and progress ratios of 0.95 for stack suppliers and 0.91 for OEMs. These estimates, together with cost data gathered in the course of this study are shown in Figure 59. In every case, manufacturers have equaled or exceeded the manufacturing costs projected by the 2008 study. Large cost reductions have been achieved over the period 2005-2010:

- PEM stack costs have come down from roughly $4,000/kW to $1,000/kW
- The cost of 1 kW backup power units have also been reduced by a factor of 4
- The cost of 5 kW backup power units is down from about $55,000 to $22,000
- The cost of 5 kW forklift systems has declined from $48,000 to about $22,000



2005 and 2010 averages based on estimates supplied by OEMs. 2010 predicted assumed government procurements of 2,175 units per year, total for all market segments. Predictions assumed a progress ratio of 0.9 and scale elasticity of -0.2.

Figure 59. Comparison of 2008 ORNL Study and 2010 Fuel Cell Cost Estimates.

Similar cost reductions have been achieved by large, high-temperature fuel cell manufacturers. Fuel Cell Energy, for example, has reported cost reductions of a factor of five for its MCFC product over the period 1996 to 2008 (Adamson, 2008). Foreign manufacturers whose governments have also supported fuel cell research, development and deployment have achieved similar cost reductions.

A model of the domestic fuel cell industry was constructed to estimate the impacts of government policies and explore the conditions under which a viable domestic industry might be established. The model has numerous limitations and is dependent on key input data and assumptions, as explained in the text. Its estimates should be considered indicative of general conditions and descriptive of the likely size and direction of impacts, rather than as definitive predictions of the future. With that in mind, the model indicates that existing programs have important beneficial impacts on the industry, without which the industry might not become sustainable. The ARRA has contributed to reducing costs of fuel cell manufacturers in the material handling and backup power segments (Figure 60). Without either the ARRA or the ITC, it is estimated that the cost of fuel cell material handling systems would be about $4,000 higher than the actual costs in 2010. Continuation of the ITC through 2016 appears to be essential to sustaining a domestic fuel cell industry and could lead to a viable industry before 2020. The model's estimates suggest that continuing current policies could lead to growing markets in all three applications (Figures 61-63).

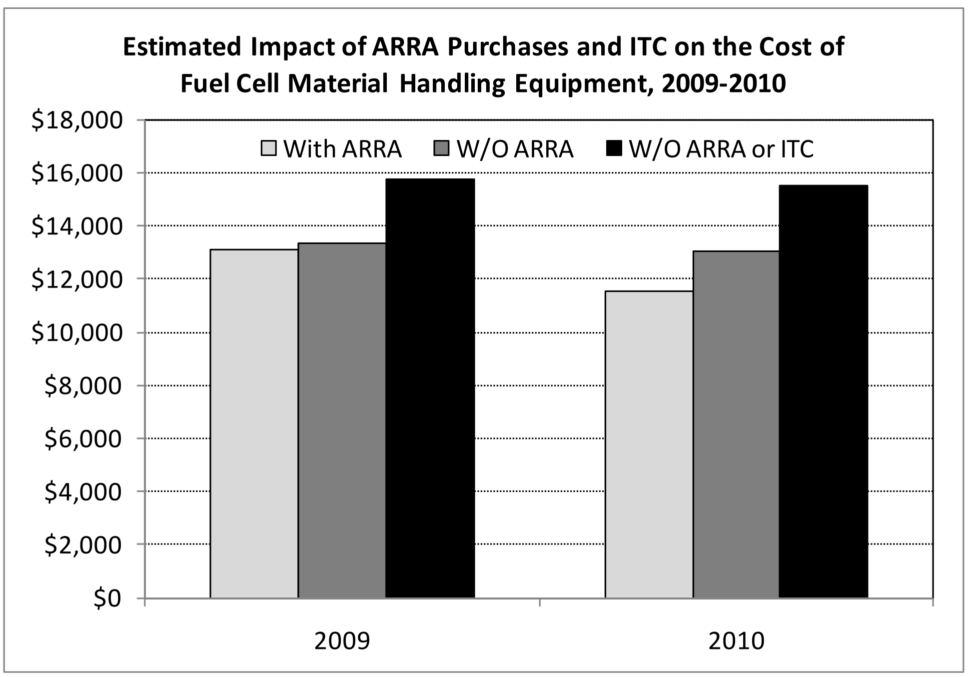


Figure 60. Estimated Impact of ARRA Purchases and Investment Tax Credits on the Cost of FC Material Handling Equipment in 2009 and 2010.

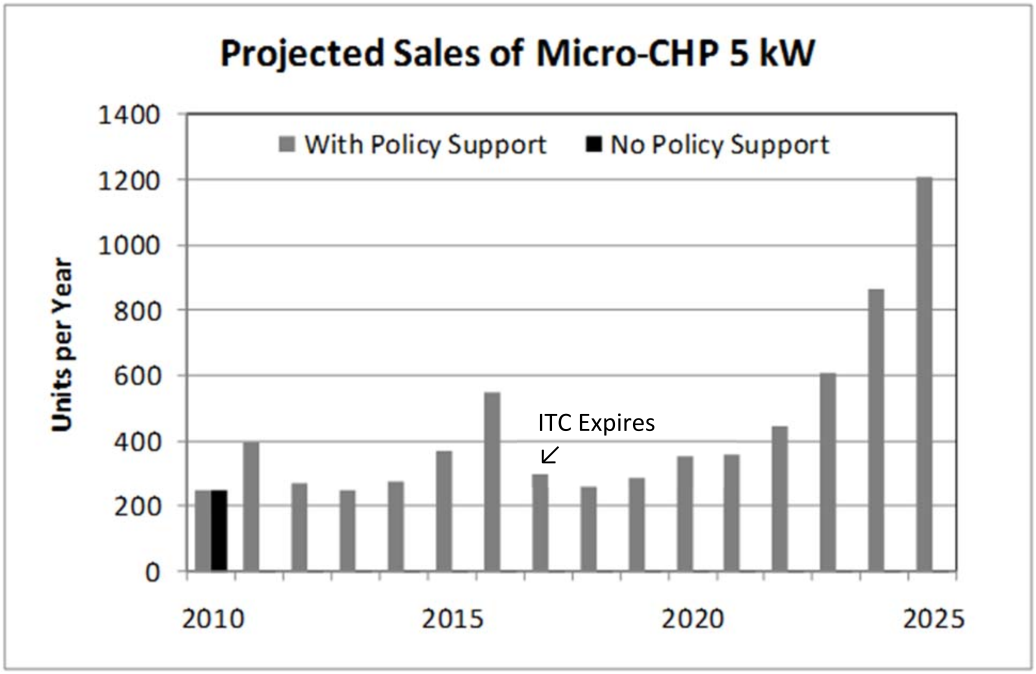
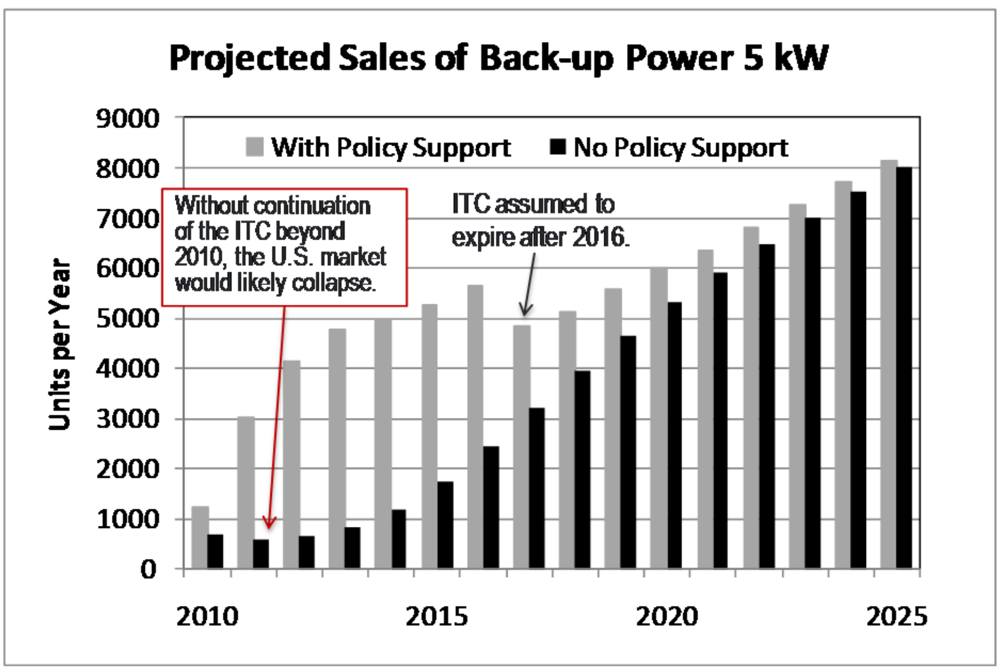
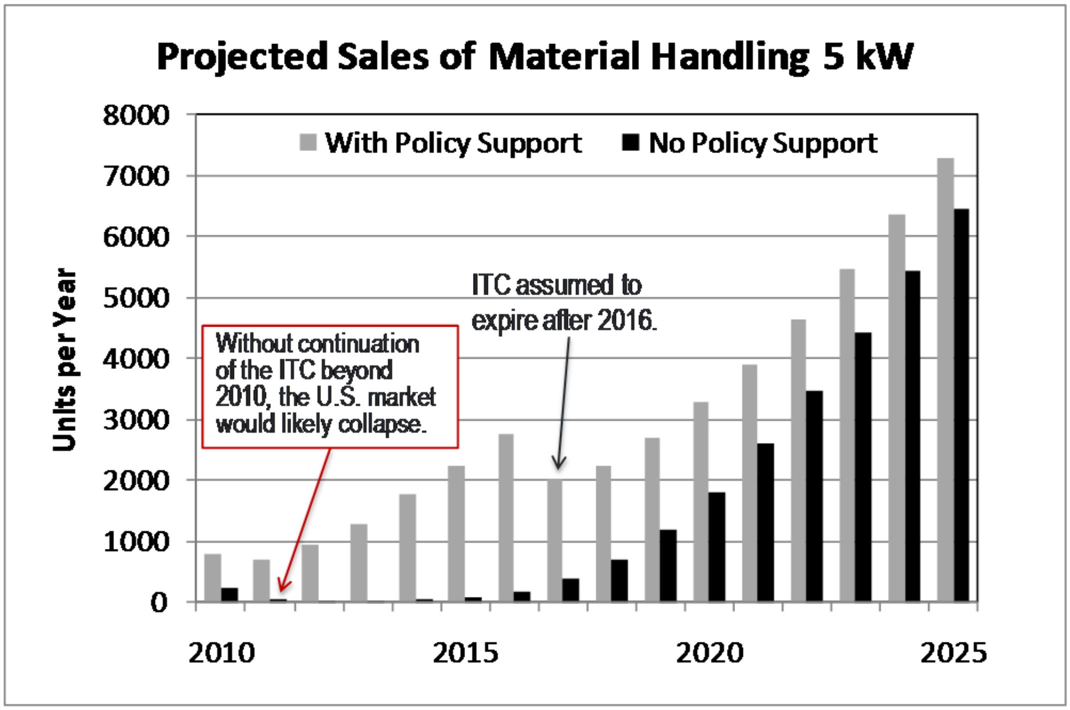


Figure 61. Projected Sales of 5 kW Micro-CHP Units Assuming Continued Current Policies.



Only ARRA purchases have been excluded from the "No Policy" case. Other government procurements prior to 2011 are included in both cases. Progress ratio of 0.9 and scale elasticity of -0.2. Number of OEMs is assumed to be 3. Government and private purchases for demonstrations are 100 units/yr. in the policy case.

Figure 62. Projected Sales of 5 kW Backup Power Units With and Without Current Policies.



Only ARRA purchases have been excluded from the "No Policy" case. Other government procurements prior to 2011 are included in both cases. Progress ratio of 0.9, scale elasticity of -0.2. Government and private procurements of 100 units/yr. for demonstrations continue in the policy case.

Figure 63. Projected Sales of 5 kW Material Handling Units With and Without Current Policies.

However, production volumes, especially for material handling equipment but also for micro-CHP and large-scale CHP may not be sufficient to sustain OEMs over the next 1-4 years. This is especially likely since it appears that the California SGIP may exhaust its funds by the end of next year, and because the estimates shown above do not attempt to account for market barriers to new technologies such as customer risk aversion. Enhanced incentives for fuel cell purchases should therefore be considered to increase the industry's chances for successful transition to viability. The most promising policy for all types of fuel cells appears to be conversion of the ITC now capped at 30% of capital cost to an uncapped $3,000/kW tax credit. The credit should be phased out over time, rather than ending abruptly. Feed-in tariffs are an especially attractive policy for large and small CHP. For example, a feed-in tariff of $0.20 per kWh for electricity produced by fuel cells would almost immediately reduce their costs to customers to the long-run, high volume costs for these technologies. The tariffs could very likely be phased out between 2015 and 2020, leaving a viable domestic industry able to compete effectively in many markets.

In brief, domestic and foreign fuel cell manufacturers have made remarkable progress reducing costs and improving performance over the past three years. Still, they face substantial barriers to market success, including further reducing costs via scale economies, learning by experience and for material handling applications, increasing the availability of moderately priced hydrogen. At present, none of the fuel cell OEMs appears to be economically viable without public policy support. Continuing or enhancing that support appears to be likely to lead to a self-sustaining domestic industry before 2020.

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APPENDIX A

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Koen Schoots – Energy Research Center of the Netherlands

Iain Staffell – University of Birmingham, UK

Takaaki Okude and K. Fujioka – Panasonic Corporation, Japan

APPENDIX B

QUESTIONS TO INFORM THE FUEL CELL INDUSTRY STUDY: IMPACTS OF GOVERNMENT POLICIES AND ASSESSMENT OF FUTURE POLICY NEEDS

David L. Greene, Corporate Fellow, Oak Ridge National Laboratory

Gopal Duleep, ICF, International

Thank you for taking the time to meet with us and help us with our study of the status of the US and global stationary fuel cell industries and the roles of government programs. We are doing this research for the US Department of Energy. Our discussions can be as confidential as you require. We will use the information you provide without attribution and only as averages or ranges reported for the industry as a whole. We do not need to know technical details of your products that are proprietary to your firm. Please feel free to decline to answer any question or to answer in general terms. We will be happy to give you the opportunity to review our report before it is released and will value your comments.

1. Status of Fuel Cell Technology

What is the current durability and performance of the fuel cells that you manufacture? What improvements have been made over the past 2 years?

What is your production volume and how has it changed over the past two years?

Where is your supply chain located? Do you manufacture your own stacks?

What is the current cost (or price) per kW? What price do you think you need to reach to be competitive? What are the prospects for future cost reductions?

2. Current Markets

What markets is your firm targeting? In which markets is the fuel cell competitive?

What do you see as your current and emerging competition?

What are current industry sales and FC penetration?

3. **Outlook for the Next 5 Years.** What are your expectations for:

   Cost reductions?

   Sales volumes?

   Market size and FC penetration?

   Future competition from advanced technologies (e.g., lithium ion batteries)?

4. **Impacts of Government Incentives and Procurements**

Has your firm been affected by government procurements of fuel cells?

How important are government purchase incentives to the current fuel cell industry?

What other government programs are important to your firm's success?