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2010 Manufacturing Readiness Assessment Update to the 2008 Report for Fuel Cell Stacks and Systems for the Backup Power and Material Handling Equipment Markets

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NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

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August 2012

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Executive Summary

In 2008, the National Renewable Energy Laboratory (NREL), under contract to the U.S. Department of Energy (DOE), conducted a manufacturing readiness assessment (MRA) of fuel cell systems and fuel cell stacks for backup power and material handling equipment (MHE) applications.[1] To facilitate the MRA, manufacturing readiness levels (MRLs) were defined that were based on the technology readiness levels (TRLs) previously established by DOE.[2] NREL assessed the extensive hierarchy of MRLs developed by U.S. Department of Defense (DOD)[3] and other federal entities, and developed an MRL scale adapted to the needs of the Fuel Cell Technologies Program (FCTP) and to the status of the fuel cell industry. The MRL ranking of a fuel cell manufacturing facility increases as the manufacturing capability transitions from laboratory prototype development through low rate initial production (LRIP) to full rate production (FRP). DOE can use MRLs to address the economic and institutional risks associated with a ramp-up in polymer electrolyte membrane (PEM) fuel cell production.

NREL's approach for the DOE MRLs is distinguished from the DOD definition of MRLs by its incorporation of market data, focus on near-term pre-automotive PEM fuel cell manufacturing, and use of industry self-assessment to establish the MRL. As a result, *the DOE MRA process addresses development of a PEM manufacturing base; the DOD MRA process focuses on procurement.* Data from the FCTP market analyses conducted by Battelle[4,5] defined 2008 commercial production rates for backup power and MHE applications at 1,700 and 5,000 units per year, respectively. These commercial production rates were taken to represent FRP. An LRIP was defined to represent production levels for the transition from laboratory-scale assembly through pilot plant manufacturing. This level of production was intended to be indicative of a market-entry level of volume. Based on fuel cell industry interviews and the 2008 market information generated by Battelle, NREL defined LRIP as 1,000 units per year for both applications.

2010 Manufacturing Readiness Assessment: Backup Power Systems, Material Handling Equipment Systems, Fuel Cell Stacks

Business opportunities and market objectives for fuel cell manufacturers have evolved during the two years since the 2008 MRA Report. Expanding backup power opportunities in India, Asia, and South America introduced new specifications for the backup power systems. These include extended operation, often on a daily basis, to compensate for long periods when the electrical grid is not functioning. In many areas where this opportunity is strong, the hydrogen infrastructure has not developed sufficiently to support hydrogen-fueled backup power fuel cell systems. Thus, fuel cell systems that operate on several fuels such as methanol, liquefied petroleum gas, natural gas, and potentially diesel fuel are preferred. This new market is referred to as *supplemental power*.

MHE fuel cell applications also continued to grow, with some dramatic changes. In 2008, the fuel cell was a "drop-in" replacement for the forklift battery. Hydrogen fuel storage was an add-on for the modified battery-powered forklift design. In 2010, Crown Equipment Corporation introduced the industry's first pallet truck to be designed specifically for fuel cells. Continued federal support through DOE, DOD, and the American Recovery and Reinvestment Act (ARRA) has increased the demand and the opportunity to assess performance of fuel cell systems in commercial environments.

NREL updated the 2008 MRA Report to provide the FCTP with up-to-date information about the readiness of fuel cell manufacturers to address these and new markets. We include additional companies to reflect the changing landscape of the industry and to account for companies that could not be included in the first report. In addition to Hydrogenics, Nuvera, and Plug Power, which were evaluated in the 2008 MRA, Altergy Systems, ReliOn, Ballard Power Systems, and IdaTech, Inc. were interviewed. Protonex Technology Systems was not included in this update because of a change in their business plan away from PEM systems as a main focus.

Update of Manufacturing Readiness Assessment Data

Telephone interviews were held with Nuvera, Plug Power, and Hydrogenics to review the status of their manufacturing capabilities. The discussion with Plug Power was restricted to fuel cell manufacturing readiness for MHE systems based on its current business approach. The facilities of Altergy and Ballard were visited and their production capabilities discussed. Telephone interviews were held with IdaTech and ReliOn. In all cases, the assessment questionnaire used for the 2008 MRA was used again for the 2010 interviews. NREL reviewed the self-assessments with each company, provided guidance as necessary, and conducted an independent assessment of the MRA data for each.

Design Modifications

The most insightful and impactful learning from the 2010 MRA was that most participants reported recent upgrades in the designs of their fuel cell systems or fuel cell stacks. Cost and manufacturability were cited as reasons; however, functional changes were clearly necessitated by lessons learned in the marketplace. This suggested a review of the 2008 MRA data was needed. In that report, the Design risk element was given a very high rating: as high as MRL-8 for backup power and MHE applications. The Design risk element for fuel cell stacks was even higher: MRL-9. However, given the information gained during the 2010 MRA, the 2008 Design risk element results were apparently overstated. The Technical Maturity and Materials risk elements could likewise be considered overstated. NREL suggests two possible explanations:

- The fuel cell manufacturers did not fully understand the limitations of their designs. This could be the result of insufficient testing of the designs in environments representative of the intended applications before entering the marketplace.
- The specifications for the fuel cell application from either the telecommunications companies or the MHE companies were incorrect or incomplete. The fuel cell manufacturer designed, fabricated, and tested a fuel cell system that met operational and performance specifications; these were based on replacing a battery system with a fuel cell system. However, given that the fuel cell system does not have the same operating and performance characteristics, mismatches between the design and the actual commercial requirements may have resulted.

Designs that embodied the technologies and materials used did not always meet the requirements of the market. Thus, the underlying TRLs, which precede MRLs, must have been overstated, as the MRL for a manufactured product cannot be higher than the TRL for the enabling technology.

Low Rate Initial Production

Given the churn in system and stack design observed since the 2008 MRA Report, it follows that no fuel cell system manufacturer has achieved LRIP year-on-year (though one manufacturer reports this production rate over one 16-month period). Annual production volumes were generally a few hundred. For some manufacturers, this is still the case. Others report volumes of 500 or more. The LRIP production rate of 1,000 units per year used in the 2008 MRA report was based on market analyses by Battelle[4,5] and was supported by the manufacturers.

Low Rate Initial Production and Manufacturing Readiness Assessment Results for Backup Power Systems

The projected annual demand in the initial years of the backup power market is 1,699 units.[4] This value would represent an annual demand for each manufacturer, assuming four manufacturers with equal market share, of more than 400 units per year. This is reasonably close to the current production information gathered for this report, and indicates that an LRIP value closer to 400–500 units per year (per manufacturer) may be appropriate for backup power fuel cell systems.

Further review of the Battelle methodology is useful for probing the trend in design changes. Battelle found that potential end users chose three factors that would most influence the decision to purchase a backup power system: (1) reliability, (2) capital cost, and (3) lifetime of the unit. The first and third factors directly relate to design, technical, and materials considerations – thus TRLs and the first three MRL risk elements – and provide a basis for understanding the need for design changes in backup power systems. On the other hand, capital cost reduction has been the subject of continuous efforts by industry and DOE,[6,7] in the form of R&D and tax credits of up to $3,000/kW. DOE used net present value (NPV) analyses from Battelle to identify that PEM fuel cells offer considerable cost advantages over battery/generator systems and battery-only systems for backup power.[8] NPV calculations that included a $1,000/kW incentive had a distinct advantage over the battery/generator systems. The incentive that was available in 2009 and 2010 was $3,000/kW, yielding an even greater NPV advantage for fuel cell systems.

Figure ES-1 shows the 2010 MRA results in the aggregate format in and compares them to the 2008 results. An improvement in MRLs in 2010 compared to the 2008 peak values is seen in five of the nine risk elements. The range of individual risk elements has also decreased for all but three, suggesting that company-to-company variability in manufacturing capability is decreasing. Seven of the nine 2010 risk elements have high values of MRL-9, which either supports or requires the demonstration of LRIP. However, this seems to be contraindicated in discussions with the companies. Indeed, because we cannot provide average MRL values in our agreed-upon data aggregation scheme, the lower end values may be more indicative of the industry status.

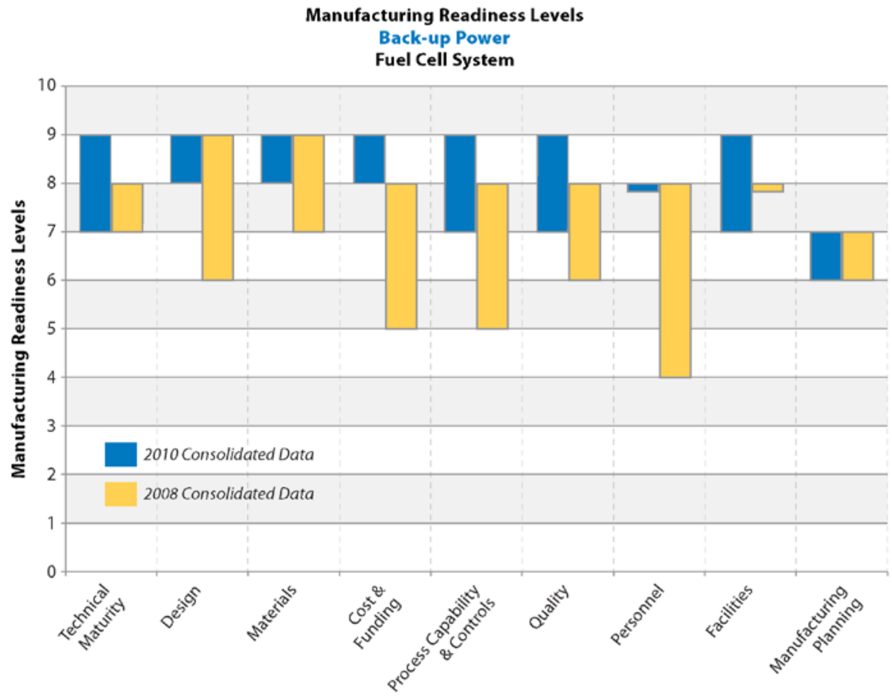

Figure ES-1. Aggregate consensus MRLs for backup power fuel cell systems for 2008 and 2010

Low Rate Initial Production and Manufacturing Readiness Assessment Results for Material Handling Equipment Systems

Battelle determined the replacement market for MHE PEM fuel cell systems to be approximately 5,000 units in the initial years, with an annual replacement market at 108,000. In the 2010 MRA, the three fuel cell manufacturers report production rates of a few hundred to 500 units per year. This lower value is representative of the current market share for multiple manufacturers and is clearly less than Battelle anticipated. As was the case for backup power systems, DOE compared the life cycle cost of two configurations of PEM fuel cell and battery-powered forklifts.[9] The smaller (power) PEM fuel cell configuration had a cost advantage over the battery system, with or without the incentive; the larger system did not show a cost advantage.

Figure ES-2 shows the aggregate MHE system results of the 2010 MRA and compares them to the 2008 data. The risk elements more closely associated with TRLs: Design, Technical Maturity, and Materials are, at their maximum levels, consistent with LRIP. These maximum values are the same as the 2008 data, even though the companies all reported design and technical maturity improvements between 2008 and 2010. Based on conversations with the fuel cell manufacturers, a greater understanding of MHE operational requirements has led to improved fuel cell system designs. The MRL range of two of these three risk elements has also narrowed, indicating that all three companies are reaching a common level of capability. The risk elements Cost & Funding, Process Capability & Controls, and Facilities all show significant improvements as a result of increased manufacturing and commercial experience. These risk elements have all improved to the LRIP capability for at least one manufacturer (although not necessarily the same manufacturer). The risk elements Quality, Personnel, and Manufacturing Planning & Scheduling have demonstrated the least improvement.

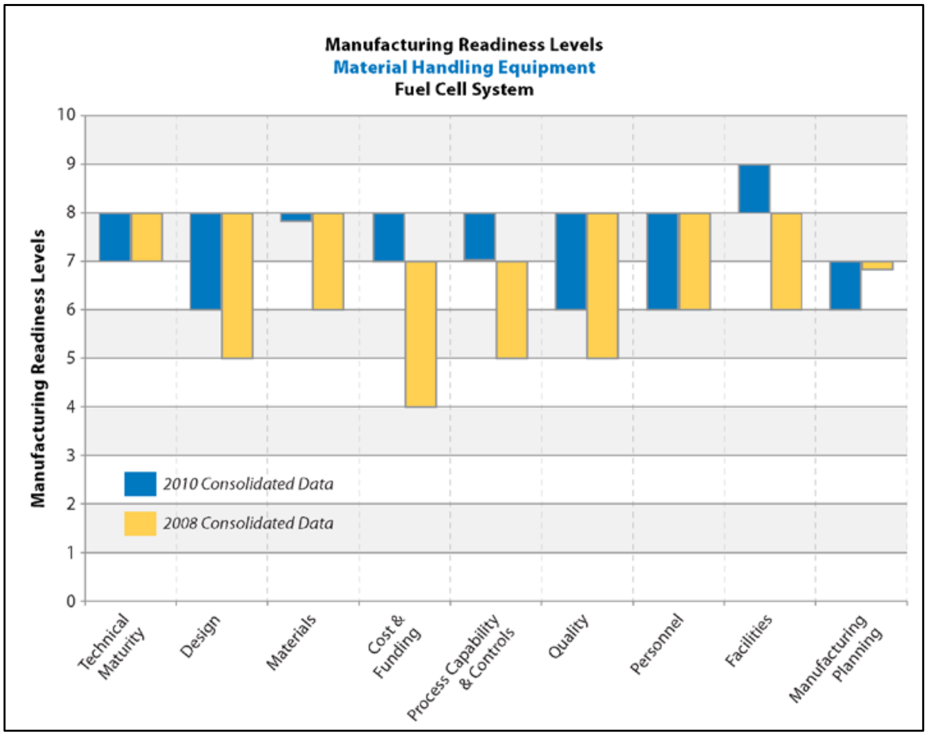

Figure ES-2. Aggregate consensus MRLs for MHE fuel cell systems for 2008 and 2010

Low Rate Initial Production and Manufacturing Readiness Assessment Results for Fuel Cell Stacks

The manufacturing status of fuel cell stacks changed since the 2008 MRA Report. The companies now participating in the MRA of fuel cell stacks are Altergy Systems, Ballard Power Systems, Hydrogenics, Inc., Nuvera Fuel Cells, and ReliOn. The designs vary significantly from company to company, each often being specific to an application. Thus, stack manufacturing processes for these companies may be quite dissimilar.

Figure ES-3 shows the results of the MRA for fuel cell stack manufacturing and compares them to the 2008 data. The variation within each risk element has increased for six of the nine elements. This variation reflects the different levels of maturity for stack designs and the changes in manufacturing processes that are precipitated by the design changes. The MRL range for the Materials risk element has doubled, and the ranges for Technical Maturity and Design show a fourfold increase. Some manufacturers report very mature designs and materials for the fuel cell stacks. Other emerging designs for the fuel cell stack will, according to the manufacturers, provide superior performance; however, these have been built as laboratory prototypes and the specific manufacturing and business processes have not yet been fully integrated into the company's manufacturing enterprise.

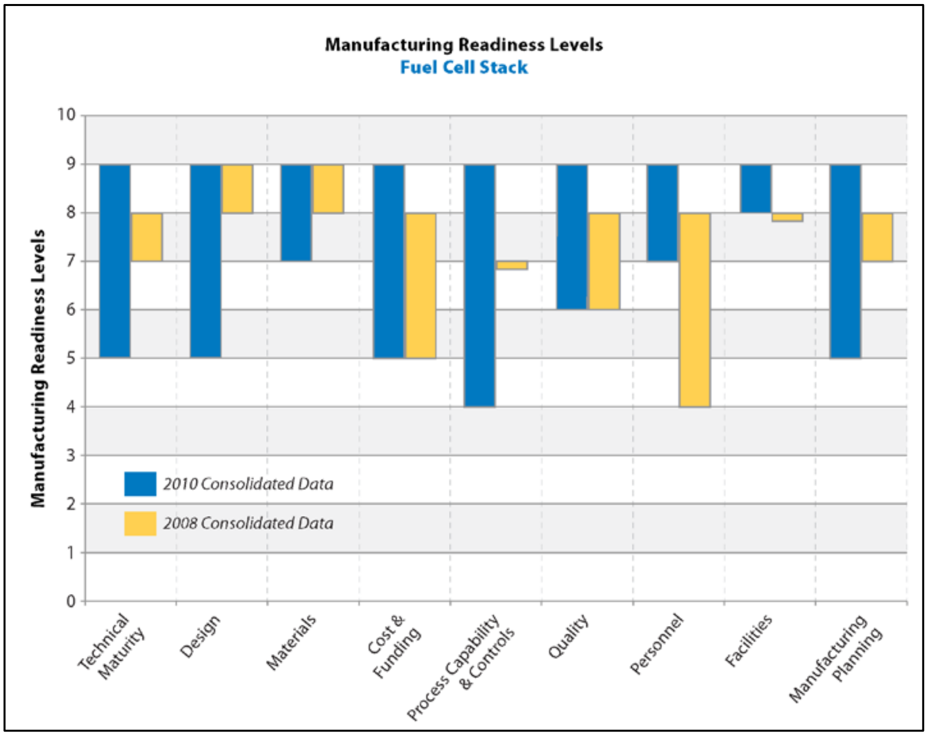

Figure ES-3. Aggregate consensus MRLs for MHE and backup power fuel cell stacks for 2008 and 2010

Conclusions

- Fuel cell manufacturers in the MHE and backup power markets have undertaken design modifications that were originally fielded into these markets, based on lessons learned from deployments to date. Although cost and manufacturability were stated as objectives, the manufacturers indicated that changes were made because initial designs were not fully meeting the operational requirements of the markets. This situation indicates that the Design, Technical Maturity, and Materials risk elements in the 2008 MRA may have been overstated.
- For fuel cell systems, with one short-term exception, manufacturers have still not reached the LRIP defined in the 2008 MRA Report as 1,000 units per year (per manufacturer).
- For fuel cell stacks, some manufacturers report demonstrations of LRIP; others are still below LRIP.
- In general, MRL ranges for MHE and backup power fuel cell systems and stacks have shifted upward from the 2008 MRA to the 2010 MRA, indicating a higher level of manufacturing readiness in the industry. However, in some cases, the lower value of MRL ranges decreased, which is indicative of manufacturing processes and systems supporting new designs that are not yet fully integrated into the manufacturing enterprise.
- The 2010 MRA results are representative of the differences between the demonstration and deployment approaches to assisting early markets. A demonstration approach intends to identify issues with a current system design before market launch. However, this approach is generally slow and does not typically provide significant funding to the industry. The deployment approach typically enables faster market penetration and

increased funding to the industry. The risk is that system designs are not fully vetted at market entry, and may need to be modified during the market launch.

- The federal tax incentive program has, to some extent, compensated for the initial high cost of fuel cell systems, as indicated by improvements in the Cost & Funding risk element, in some cases to < 110% of the cost target.

Recommendations

- This MRA activity, similar to its predecessor, provides a critical linkage to the activities of the PEM fuel cell manufacturers as they react to the developing nature of the MHE and backup power markets. As we have seen over the past year and a half, manufacturing capabilities have advanced, and yet *manufacturing readiness* may actually have regressed because new designs are being brought online and are still being integrated into the manufacturing enterprise. **Thus, support for an ongoing MRA activity continues to be critical, and participation should be required for cost-shared demonstration and deployment activities, so unbiased, comparative assessments can be made.**
- The emergence of the supplemental power market highlights the **need for regularly updated market analyses.**
- **The current incentive program must be sustained at least through 2016 to enable the manufacturers to deploy systems that are fully vetted during the ongoing DOE, DOD, and ARRA deployments and establish the value proposition of these systems against incumbents.**
- Finally, the MHE and backup power markets have undergone a paradigm of support from the FCTP and other federal agencies, wherein market transformation support and a formal technical validation effort have occurred essentially in parallel. This simultaneity has helped speed the readiness of the technology for these markets, and yet, as shown, it has resulted in a situation where PEM fuel cell products have had to undergo design changes during the early stages of maturation of these two markets. This means that not only are MRLs changing, but TRLs are also in flux. Moreover, as new functionality is brought to bear to improve the fuel cell system performance relative to the application needs and relative to incumbent technologies, the FCTP must be armed with a method to understand how technology and manufacturing are advancing in tandem, how these advances are resulting in value propositions that will (or will not) establish a business case for the fuel cell systems in these applications, and how, ultimately, these advances affect sales and the broader market. The FCTP would benefit from **an activity that:**
    - **Links the technical, safety, and reliability data being gathered from these markets and the understandings provided by the MRA activity**
    - **Assesses the actual technical performance of these systems, as indicated by MRLs and TRLs and compared to incumbent technologies**
    - **Uses this corroborated information to assess the ultimate market impact of demonstration activities supporting the MHE and backup power markets.**

Acronyms

APU	auxiliary power unit
ARRA	American Recovery and Reinvestment Act
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
FCTP	Fuel Cell Technologies Program
FRP	full rate production
LPG	liquefied petroleum gas
LRIP	low rate initial production
MHE	material handling equipment
MRA	manufacturing readiness assessment
MRL	manufacturing readiness level
NPV	net present value
NREL	National Renewable Energy Laboratory
PEM	polymer electrolyte membrane
R&D	research and development
TRL	technology readiness level

Contents

Figures

Tables

Background

In 2008, the National Renewable Energy Laboratory (NREL), under contract to the U.S. Department of Energy (DOE), conducted a manufacturing readiness assessment (MRA) of fuel cell systems and fuel cell stacks for backup power and material handling equipment (MHE) applications.[1] To facilitate the MRA, manufacturing readiness levels (MRLs) were defined that were based on the technology readiness levels (TRLs) previously established by DOE.[2] NREL assessed the extensive hierarchy of MRLs developed by U.S. Department of Defense (DOD)[3] and other federal entities, and developed an MRL scale adapted to the needs of the Fuel Cell Technologies Program (FCTP) and to the status of the fuel cell industry. The 10 MRLs defined by NREL are given in that report[1] and, for completeness, are included in Appendix A of this report. The MRL ranking of a fuel cell manufacturing facility increases as the manufacturing capability transitions from laboratory prototype development through low rate initial production (LRIP) to full rate production (FRP). DOE can use MRLs to address the economic and institutional risks associated with a ramp-up in polymer electrolyte membrane (PEM) fuel cell production.

Within its DOE-focused MRL methodology, NREL used nine specific risk elements that address manufacturing status across all elements of the manufacturing enterprise. For transition to the next higher MRL, the requirements of all nine must be satisfied. The risk elements follow:

- Technology & the Industrial Base
- Design
- Materials
- Cost & Funding
- Process Capability and Control
- Quality Management
- Manufacturing Personnel
- Facilities
- Manufacturing Planning, Scheduling, and Control

A family of MRL assessment questions was defined for each risk element. Successive assessment questions for each risk element test the increasing maturity of the manufacturing process and lead to an assessment of readiness. Advancement to a higher MRL requires a more sophisticated manufacturing capability.

NREL's approach for the DOE MRLs is distinguished from the DOD definition of MRLs by its incorporation of market data, focus on near-term pre-automotive PEM fuel cell manufacturing, and use of industry self-assessment to establish the MRL. As a result, *the DOE MRA process addresses development of a PEM manufacturing base; the DOD MRA process focuses on procurement*. The incorporation of marketing data from the FCTP market analyses conducted by Battelle[4,5] defined 2008 commercial production rates for backup power and MHE applications at 1,700 and 5,000 units per year, respectively. These rates were taken to represent FRP. A lower initial production rate, or LRIP, was defined to represent production levels for the transition from laboratory-scale assembly through pilot plant manufacturing. This level of production was intended to be indicative of a market-entry level of volume. Based on fuel cell industry interviews and the 2008 market information generated by Battelle, NREL defined LRIP as 1,000 units per year for both applications.

The Battelle analysis for Federal Aviation Administration tower emergency backup power assumed an instantaneous 75% penetration into the replacement market. This was considered by industry to be high based on industry input. Industry anticipates the year one market entry to be several hundred units growing to 1,000 units per year over a two-year period, growing to the LRIP value.

For the forklift truck applications, Battelle identified the Defense Logistics Agency and the U.S. Postal Service as early adoptors of this technology with initial replacement purchases of 472 units per year. Penetration into the forklift truck replacement market was 20% for all but the Class 2, narrow-aisle, high-reach forklifts, which have a 5% penetration into the replacement market. The market entry of 1,000 units per year for LRIP was confirmed during interviews with forklift PEM power systems manufacturers.

The Self-Assessment Process

To facilitate the self-assignment of MRLs by industry, NREL supplied the assessment questionnaire to the companies for their self-assessment process. (The questionnaire is included in Appendix B.) As part of the self-assessment process, NREL reviewed with each company its self-assessment results to better understand that company's appraisal of its manufacturing capability. In most cases, NREL also toured the company's manufacturing facility to independently verify the self-assessment. The company reviews facilitated a direct comparison by NREL of the companies' self-assessments procedures and results.

Review of the 2008 Fuel Cell Manufacturing Readiness Assessment Results

The NREL 2008 MRA measured the status of the North American fuel cell manufacturers for the transition of PEM fuel cell system manufacture from prototype production to high rate commercial production. The MRA covered three manufacturing categories: Backup Power and Auxiliary Power Units (APUs); MHE (fork lift truck PEM power systems); and PEM fuel cell stack manufacture. Four companies participated in the MRA: Hydrogenics, Inc., Plug Power, Inc., Nuvera Fuel Cells, and Protonex Technology Corporation. Table 1 identifies the companies and their respective fuel cell manufacturing categories.

Table 1. Companies Participating in 2008 Fuel Cell MRA of Backup and APUs, Fuel Cell MHE Systems, and Fuel Cell Stacks

PEM Manufacture Category	Hydrogenics, Inc.	Nuvera Fuel Cells	Plug Power, Inc.	Protonex Technology Corporation
Backup Power and APUs	Yes	No	Yes	Yes
MHE Systems	Yes	Yes	Yes	No
Fuel Cell Stack	Yes	Yes	Yes	Yes

Two of the companies—Hydrogenics and Plug Power—had active manufacturing processes in all three categories. Nuvera did not manufacture PEM backup power and APU systems and Protonex did not manufacture PEM systems for MHE applications.

In 2008, none of the PEM fuel cell manufacturers reached LRIP for these three categories; i.e., no company was manufacturing 1,000 units per year. The primary reason identified by all the companies was lack of market demand that limited the investment of resources in the manufacturing processes and personnel. Table 2 shows the results of the 2008 MRAs for fuel cell Emergency Backup Power & APUs, fuel cell MHE systems, and fuel cell stacks. The data are aggregated to protect the intellectual property of the companies.

Table 2. Compilation of 2008 Fuel Cell MRA Data of Backup and APU Systems, MHE Systems, and Fuel Cell Stacks

PEM Manufacture Category	Highest Rated Manufacturing Maturity Risk Element	Lowest Rated Manufacturing Maturity Risk Element
Backup Power and APUs	Design Materials @ MRL-9	Personnel @MRL-4
MHE	Technical maturity design Materials quality Personnel Facilities @ MRL-8	Cost & Funding @ MRL-4
Fuel Cell Stack	Design Materials @ MRL-9	Personnel @ MRL-4

Common threads in the 2008 MRAs for the three fuel cell categories are the designs and the materials used to manufacture the fuel cell systems. The fuel cell stacks had the greatest manufacturing maturity. The MRL-8 definition for the Design risk element, as noted in Appendix A is:

> ***"All critical product and process technologies and their status are defined; and design is stable, with few or no design change."***

The MRL-9 definition for the Design risk element is:

> ***"Design changes eliminated or minimized."***

The MRL-8 definition for the Materials risk element is

> ***"Make / Buy decisions and Bill of Materials complete and support LRIP."***

The MRL-9 definition for the Materials risk element is

> ***"All materials meet planned LRIP schedules: i.e. FRP material needs are identified."***

The very high MRL ratings for the Design and Materials elements require these factors in the manufacture of fuel cell systems and fuel cell stacks to be stable. Thus, in the best case, the results in *2008 for fuel cell systems and fuel cell stacks indicated that only minor changes in the design and materials were occurring and would not impact the manufacturing process*.

The Personnel element had the lowest MRL rating for the categories Backup Power & APUs and Fuel Cell Stacks at MRL-4. The low rating reflects the emphasis on development and demonstration of a prototype system. Manufacturing had not made the transition from fabrication by highly skilled laboratory personnel to production line personnel. The MRL-4 definition for the Personnel risk element is:

> ***"Training programs necessary for specialty skills are identified and training programs are identified for process control and quality."***

Thus, in the worst case, the 2008 results indicated that implementation of manufacturing training programs had not been initiated for Backup Power & APU systems and Fuel Cell Stacks.

The risk element Cost & Funding for MHE systems had the lowest manufacturing maturity. The Cost & Funding element was the second-lowest rating for Backup Power & APUs and Fuel Cell Stacks at MRL-5. The companies with the lower rating for the Cost & Funding element emphasized the development and demonstration of the prototype designs and were only beginning to implement cost reduction programs. The MRL-4 definition for the Cost & Funding risk element is:

> ***"The total system cost goals are available to the Integrated Product Team and are used to guide the system design. The manufacturing cost drivers were identified but not implemented."***

Thus, in the worst case, the 2008 results indicated that MHE manufacturers had only begun to initiate Cost & Funding controls.

Review of the 2008 Fuel Cell Manufacturing Readiness Assessment Conclusions

The NREL-developed 2008 MRAs brought into focus the manufacturing risks associated with achieving LRIP of 1,000 PEM systems per year. LRIP was not achieved for any applications because, according to industry, the demand for fuel cell systems and fuel cell stacks was insufficient to warrant investment in the manufacturing process. The companies accepted increased risk in the areas of Personnel and Cost & Funding of the fuel cell systems and stacks. They emphasized the development of a fuel cell system or stack that fulfills the application requirements; i.e., development and demonstration were their highest priorities. All other manufacturing elements, including quality, were subservient to the development of a functioning fuel cell system and fuel cell stack.

The above review of the 2008 aggregate data highlights the maximum and minimum MRL ratings determined in the MRAs for fuel cell systems and fuel cell stacks across all risk elements. The status of fuel cell manufacturing issues is understood more comprehensively by evaluating the aggregate data for all nine risk elements. As an example, fuel cell stacks had the greatest overall manufacturing readiness of the three categories assessed; eight of the nine risk elements had a rating of MRL-8 or higher. Thus, as an aggregate, the manufacturing capacity for fuel cell stacks is at LRIP capability for 89% of the manufacturing risks. Importantly (for discussion later in this report), if the fuel cell system or stack is Technically Mature for LRIP production (MRL-8 or higher), the Design and Materials risk elements would also be expected to have high MRL ratings, as these three elements are closely related to the technology.

Additional insight can be gleaned by considering the range of MRL ratings for each risk element. Using the MHE fuel cell system aggregate data as an example, the range for the Design risk element is MRL-5 to MRL-8. This means that at least one company is making significant design and engineering changes, whereas another company has a stable design, with few or no design changes.

Review of 2008 Fuel Cell Manufacturing Readiness Assessment Recommendations

The 2008 MRA report on fuel cell manufacturing[1] recommends the federal government increase market demand through market transformation programs that assist in the purchase and deployment of fuel cell systems and fuel cell stacks. The recommendation remains valid. The MRL rating of the risk elements Personnel and Cost & Funding would be increased with increased market demand. The fuel cell manufacturers' emphasis would shift from development and demonstration to establishing high rate manufacturing facilities, necessitating an increase in the ratings of the Personnel, Cost & Funding, and Quality risk elements.

The recommendation to increase the breadth of the MRAs to include Ballard Power Systems in the fuel cell stack MRA remains valid and is addressed in the next section of this report. Ballard has become a large supplier of fuel cell stacks, and in 2010 supplies fuel cell stacks to Plug Power, Inc. and others.

Support of an ongoing MRA activity for the manufacture of fuel cell components, as well as systems and stacks, continues to be an important recommendation. The present cost of PEM fuel cell systems remains high because of high material costs (e.g., platinum) and high manufacturing costs (carbon-based bipolar plates). High rate manufacturing of fuel cell components, at throughputs much greater than those for stack or system manufacturing (greater than six sigma quality control) will be needed to meet FRP of tens or hundreds of thousands of units.

Market Summary

Business opportunities and market objectives for all fuel cell manufacturers have evolved over the two years since the last MRA. Expanding backup power opportunities in India, Asia, and South America introduced new specifications for these systems. These specifications include extended operation, often on a daily basis, to compensate for long periods when the electrical grid is not functioning. Extended interruption of grid power in many parts of India, Asia, and South America is a persistent problem for the telecommunications industry and is not readily resolved by using batteries for backup power. This new market is referred to as *supplemental power*.

The MHE fuel cell applications continued to grow with some dramatic changes. In 2008, the fuel cell was a "drop-in" replacement for the forklift battery. Its configuration was constrained to match the dimensions of the battery system. Hydrogen fuel storage was an add-on for the modified battery powered forklift design. In 2010, Crown Equipment Corporation [10] introduced the industry's first pallet truck to be designed specifically for fuel cells in an effort to ensure there are no negative impacts on safety, efficiency, and performance. In support of its emerging fuel cell-powered MHE, Crown established a state-of-the-art Fuel Cell Test Center in Huber Heights, Ohio.

As a result of these market developments, additional companies were included in the 2010 industry-wide MRA of fuel cell-powered MHE, fuel cell stacks, and fuel cell-powered backup power; they are Altergy Systems, ReliOn, Ballard Power Systems, and IdaTech Inc. IdaTech, ReliOn, and Altergy manufacture backup power systems. IdaTech was added to the MRA process because supplemental power was added to the backup power category. Altergy Systems and ReliOn are included in this round of MRAs and should have been included in the 2008 study. Ballard Power Systems manufactures fuel cell stacks that IdaTech uses for the supplemental power market and Plug Power uses for the MHE market.

Plug Power, Inc. restructured its business approach to focus on MHE applications and no longer manufactures backup power systems or fuel cell stacks. Thus, this MRA considers only the manufacture of its MHE fuel cell systems. Plug Power purchases its stack from Ballard Power Systems.

Protonex Technology Systems no longer focuses on the manufacture of PEM fuel cell systems for commercial APU applications. Protonex has redirected the bulk of its fuel cell development efforts to solid oxide fuel cells for APU applications, though some activities still remain on PEM systems for military applications. As a result, Protonex was not included in this MRA update.

Emergence of the Supplemental Backup Power Market

Since the 2008 MRA on fuel cell systems for backup power, fuel cell applications have expanded and evolved to include backup power fuel cell systems operating on reformed hydrocarbon fuels. Important advantages for these systems are extended operation and operation on a "logistic" fuel. In many areas of the world the hydrogen infrastructure has not developed sufficiently to support hydrogen-fueled backup power fuel cell systems. These systems operate on methanol, liquefied petroleum gas (LPG), natural gas, and potentially diesel fuel, and are designed to operate continuously and power telecommunication systems from several hours to several days. These systems have their greatest applications in countries that have a weak power grid structure and regularly have extended power outages that interrupt telecommunication service. IdaTech, Inc.[11]

and Nuvera Fuel Cells[12] report business opportunities for backup power operating with on-site reforming of hydrocarbon fuels.

Plug Power, Inc.[13] initially developed and sold supplemental backup power fuel cell systems. However, Plug Power appears to have decreased its activities in the supplemental power arena to focus on MHE fuel cell systems, as evidenced by the sale of its GenSys assets to IdaTech.[14] IdaTech was added to the MRA analyses for backup power.

Backup Power

ReliOn and Altergy Systems manufacture backup power fuel cell systems that are fueled by hydrogen. ReliOn developed a modular, cartridge-based PEM fuel cell system that provides ease of maintenance and scalability of design. Altergy Systems has developed a PEM fuel cell system that has the hallmarks of Design for Manufacturing with robotic assembly of individual cells. Altergy emphasizes cost reduction in the manufacturing processes through automation and quality control.

IdaTech was included as part of the backup power fuel cell system MRA, even though its system operates on reformed hydrocarbon fuels. The IdaTech fuel processing system includes a steam reformer followed by a palladium membrane hydrogen purification system.[15,16] The purified hydrogen fuel is delivered to the backup power fuel cell system.

Fuel Cell Stacks

Hydrogenics manufactures its own stack, as does Nuvera. Both were evaluated in 2008. Ballard Power Systems was included as a stack manufacturer in this study and supplies fuel cell stacks to Plug Power and IdaTech. ReliOn manufactures the fuel cells and assembles them into modular units. The ReliOn fuel cell system[17] does not have a fuel stack in the classical definition of a stack, but has an assembly of fuel cell modules connected to an electronic circuit network. Altergy manufactures its own cell stack that has integrated air cooling and metal bipolar separator plates.

All stacks considered in this report operate on hydrogen and air. Operating parameters vary with application and fuel cell stack design. Continuous operation is not a factor for many backup power fuel cell systems. The fuel cell system may remain in a standby or near off condition for as much as 80% of the time. The supplementary power application may be the exception. For backup power fuel cell systems, humidifying the fuel cell is not an issue for at least one supplier, as it is periodically operated to generate water to humidify the cell. Other backup power fuel cell manufacturers will have a humidifier as part of the fuel cell system balance-of-plant.

The MHE fuel cell stacks have stringent operating requirements and, in some cases, the MHE fuel stack operates continuously. For organizations operating three shifts, the need for a robust design is accentuated. Mechanical shock and vibration resistance is a specification for the mobile MHE fuel cell stack; backup power fuel cell systems have a less stringent mechanical shock resistance specification.

Manufacturing Readiness Assessment: Industry Status

The business objectives for Nuvera, Plug Power, and Hydrogenics were discussed briefly in the 2008 study[1] and will not be repeated here. Altergy Systems, ReliOn, IdaTech, and Ballard were asked to participate in this MRA. Altergy and Ballard were visited; tours of their production facilities greatly assisted the MRA process. The MRAs for IdaTech and ReliOn were conducted via conference call. In all cases, a condition for the MRA for all companies was that the individual MRLs generated by the self-assessment and NREL's assessment would remain confidential. This was also the case for the 2008 report. The data would be reported in an aggregated format with no specification of an individual company's manufacturing readiness. The fuel cell business activities of each newly addressed company are briefly described here:

Altergy Systems

Altergy Systems designs and manufactures PEM fuel cell systems for telecommunication, data centers, and other mission-critical applications. Altergy's fuel cells are used by telecommunications companies to provide backup power at cell sites as an alternative to battery systems or diesel generators, and in some cases the grid. Altergy's design includes metallic bipolar plates and air cooling of the individual cells in the fuel cell stack. The metallic bipolar plate concept makes rapid assembly and welding of the individual cells a reality. The Altergy Design for Manufacturing facilitates the use of standard automated assembly equipment.

Altergy has a worldwide approach to marketing its fuel cell systems. It recently formed Clean Energy Investment[18] in South Africa to manufacture and market Altergy fuel cell systems. Clean Energy is jointly owned by Altergy, Anglo Platinum's Platinum Growth Metals Development Fund, and the government of the Republic of South Africa.

Ballard Power Systems

Ballard Power Systems develops, designs, manufactures, and markets fuel cell stacks for several fuel cell systems. In many cases, the design is unique for a specific application. The applications include backup power, supplemental power, distributed generation, MHE, and bus (though the bus stack information was not included in this report) applications. Ballard manufactures the fuel cell stack for IdaTech that is used in supplemental power applications, and the stack used by Plug Power in the MHE fuel cell system. The market for warehouses, distribution facilities, and industry is a growth market for Ballard and Plug Power.

Ballard has established three production lines, each representing different levels of production maturity. The oldest production facility is the least mature and requires considerable hand labor to produce the fuel cell stack. The second has partial automation with a pick-and-place assembly of the membrane electrode assemblies and then hand placement of the bipolar plates. The final line, which is currently in development, is for continuous roll production of membrane electrode assemblies.

IdaTech, Inc.

IdaTech designs and manufactures fuel cell systems for telecommunications applications, including supplemental power. IdaTech's fuel cell market includes Indonesia, India, Europe, and North America, and has established its production facilities in Tijuana, Mexico. IdaTech continues to invest in this production facility, which includes production of the IdaTech ElectraGen H2. This provides backup power for telecommunication applications. The ElectraGen H2 is fueled by hydrogen. This manufacturing center is also positioned to produce the ElectraGen ME, which operates on reformed methanol. The ElectraGen ME is an extended-run backup power fuel cell system for supplemental power applications. The Tijuana production facility has its ISO 9001 certification. In addition to backup power, IdaTech is also developing prime power systems to provide the primary source of energy for off-grid sites.

ReliOn

ReliOn designs and manufactures modular fuel cell systems for customer applications in the United States and 21 other countries. Its T-series fuel cells include its patented hot-swappable Modular Cartridge Technology, which enables removal and replacement of a faulted cartridge while the rest of the unit continues to create power. T-series products include the T-1000 and T-2000 for power needs between 300 W and 12 kW. The architecture of ReliOn's newer E-series fuel cells continues to include self-hydration, air cooling, and low-pressure operation. This line of products includes the E-200, E-1100, and E-2500, and addresses power requirements between 50 W and 20 kW.

Updated Manufacturing Readiness Assessment Data

Telephone interviews were held with Nuvera, Plug Power, and Hydrogenics to review the status of their manufacturing capabilities. These companies participated in Manufacturing Readiness Assessment of Fuel Cells,[1] and the authors visited and inspected their production facilities in 2008. The discussion with Plug Power was restricted to fuel cell manufacturing readiness for MHE systems based on its current business approach. The facilities of Altergy and Ballard were visited and their production capabilities discussed. The on-site interviews at Altergy and Ballard addressed the implementation of automation in their fuel cell manufacturing and were followed by conference calls to conduct the MRA. Telephone interviews were held with IdaTech and ReliOn.

The assessment questionnaire used in 2008 was used for the 2010 interviews. It was emailed to the interviewees for companies to complete the self-assessment. NREL reviewed the self-assessments with each company and provided guidance as necessary. NREL conducted independent MRAs for each fuel cell manufacturer. Extended discussions with IdaTech and ReliOn helped NREL with its MRA, because these two companies had not been visited.

Design Modifications

The most insightful and impactful learning from the 2010 MRA was that most participants reported recent upgrades in the design of their fuel cell systems or fuel cell stacks. This single observation drives most of the remaining discussion. Cost and manufacturability were cited as reasons for these design changes, clear indications of the developmental stage of the industry. However, there were also clear indications that functional changes were necessitated by lessons learned in the marketplace. This suggested a review of the 2008 MRA data was needed.

In that report, the Design risk element was given a very high rating: as high as MRL-8 for backup power and MHE applications. The Design risk element for fuel cell stacks was even higher: MRL-9. The fuel cell manufacturers were confident in their designs, and as the 2008 fuel cell MRA report concludes:

> The risk elements Cost & Funding, Personnel, and Quality had lower rankings for forklift truck and emergency backup power & APU applications. NREL considers these low ranking risk elements to be representative of the transition from PEM prototype development to a stable, commercial PEM system design. The establishment of a stable PEM design changes the emphasis from demonstration to high rate quality production of a cost competitive PEM system by trained personnel.

The information obtained during the 2010 MRA indicates that the 2008 Design risk element results were overstated. The Technical Maturity and Materials risk elements could likewise be overstated. NREL suggests two possible explanations:

- The fuel cell manufacturers did not fully understand the limitations of their designs. This could be the result of insufficient testing in environments representative of the intended applications before entering the marketplace.
- The specifications for the fuel cell application from either the telecommunications companies or the MHE companies were incorrect or incomplete. The fuel cell manufacturer designed, fabricated, and tested a fuel cell system that met operational and performance specifications; these were based on the replacement of a battery system by the fuel cell. However, given that the fuel cell system does not have the same operating and performance characteristics of a battery system, mismatches between the design and the actual commercial requirements may have resulted.

In either case, the Design, Technical Maturity, and Materials risk elements are the elements most closely related to TRLs. Designs that embodied the technologies and materials used did not always meet the requirements of the market. Thus, the underlying TRLs, which precede the MRLs, must also have been overstated.

Low Rate Initial Production

Given the churn in system and stack design observed since the 2008 MRA Report, no fuel cell system manufacturer has achieved the LRIP year-on-year (though one manufacturer reports this production rate over one 16-month period). As noted in the 2008 report, production volumes were generally a few hundred per year. For some manufacturers, this is still the case. Others report volumes of 500 or more. The LRIP of 1,000 units per year used in the 2008 MRA report was based on market analyses by Battelle[4,5] and was supported by the manufacturers. The projections from these analyses are given in Table 3.

Table 3. Battelle Market Analyses Data for Emergency Backup Power and Forklift Trucks

Market	Market Size	Total Annual Replacement Market in Initial Years	Replacement Market for PEM Fuel Cells in Initial Years
Emergency backup power	19,900	2,265	1,699
Forklift trucks*	628,629	108,606	~5,000
Defense Logistic Agency U.S. Postal Service forklift trucks	14,175	2,435	472

* 2006 estimate based on Scenario 3 of Battelle Report; see references 4 & 5

Low Rate Initial Production and Market Readiness Assessment Results for Backup Power Systems

The projected annual demand in the initial years of the backup power market is 1,699 units. This value would represent an annual demand for each manufacturer, assuming four manufacturers with equal market share, of more than 400 units per year. This is reasonably close to the information gathered for this 2010 report, and indicates that an LRIP value closer to 400–500 units per year may be appropriate.

Further review of the Battelle methodology is useful in probing the trend in design changes observed and previously discussed. Battelle found that potential end users chose three factors that would most influence the decision to purchase a backup power system: (1) reliability, (2) capital cost, and (3) lifetime of the unit (see Figure 1). The first and third factors directly relate to design, technical, and materials considerations – thus TRLs and the first three MRL risk elements. These data are perhaps prophetic relative to the aforementioned design changes. Also, Fuel Availability ranked seventh on the purchase decision ranking. Revisiting this ranking with current end users may be a useful undertaking.

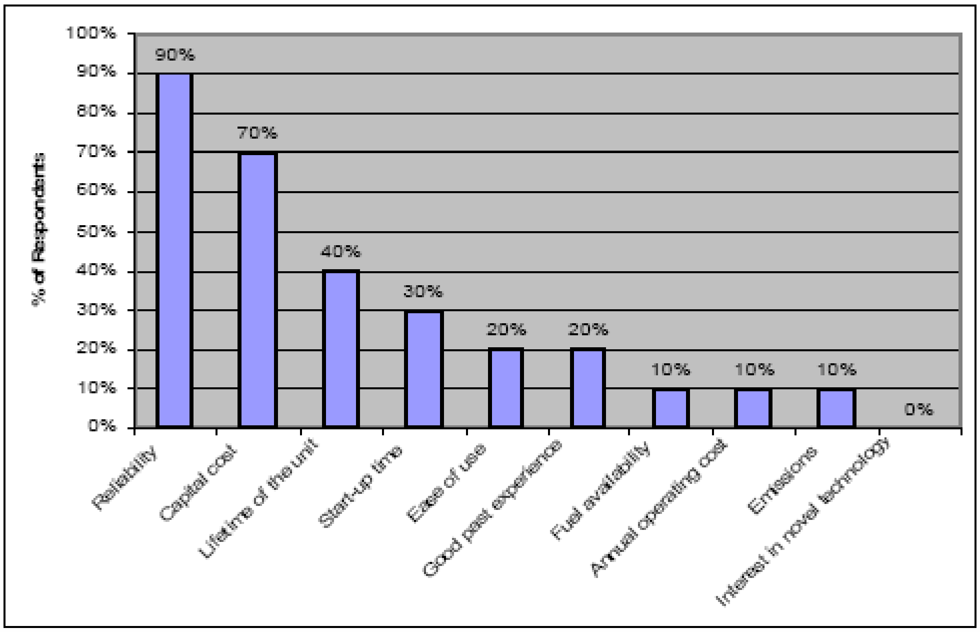

Figure 1. Factors that most influence backup power system purchase decisions[5]

Capital cost, meanwhile, is not a new issue for the fuel cell manufacturer. Reduction of capital cost has been the subject of continuous R&D efforts supported by industry and DOE.[6,7] The federal government has supported R&D and initial market competitiveness of these systems with tax credits of up to $3,000/kW, which continue until 2016.

DOE identified that PEM fuel cells offer considerable cost advantages over battery/generator systems and battery-only systems for backup power.[8] The net present value (NPV) of total cost of backup power systems was established based on Battelle data (see Table 4). The NPV analysis favored backup power fuel cell systems with run times of 8, 52, and 72 hours. NPV calculations that included a $1,000/kW incentive had a distinct advantage over the battery/generator systems. The incentive available in 2009 and 2010 is $3,000/kW, yielding an even greater NPV advantage for fuel cell systems.

Table 4. NPV of Total Cost of Backup Power Systems

Net Present Value of Total Cost of Backup Power Systems for Emergency Response Radio Towers

	Outdoor Installations			Indoor Installations		
	Battery/ Generator	PEM Fuel Cell with no tax incentive	PEM Fuel Cell with $1K/kW incentive	Battery Only	PEM Fuel Cell with no tax incentive	PEM Fuel Cell with $1K/kW tax incentive
8-hour run time				$19,037	$14,023	$12,136
52-hour run time	$61,082	$61,326	$56,609			
72-hour run time	$47,318	$33,901	$32,014			
176-hour run time	$75,575	$100,209	$95,491			

Source: *Identification and Characterization of Near-term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets*, Battelle Memorial Institute (April 2007).
Notes:
1. Total cost includes capital costs and operations and maintenance costs.
2. As of October 2008, fuel cells are eligible for a tax credit of up to $3,000/kW. As shown here, however, fuel cells can be cost-competitive with the previous tax credit of $1,000/kW.Calculations assume a 5-year battery replacement schedule.
3. Analysis of 3-year replacement schedules (for cold or harsh environments) indicates PEM fuel cells compare more favorably to traditional technologies.

NREL applied the MRA methodology to understand the manufacturing status of the backup power fuel cell manufacturers and to shed light on why the LRIP of 1,000 units per year could not be achieved for backup power fuel cell systems even when purchase incentives drive the cost of fuel cell systems to competitive levels and life cycle costs are comparable to batteries. Figure 2 shows the 2010 MRA results in the aggregate format and compares them to the results from 2008. An improvement in MRLs in 2010 compared to the 2008 peak values is seen in five of the nine risk elements. The range has decreased for all but three risk elements, suggesting that company-to-company variability in manufacturing capability is decreasing.

Seven of the nine 2010 risk elements have high values of MRL-9, which either supports or requires the demonstration of LRIP. However, in general, this seems to be contraindicated by discussions with the companies. Indeed, because we cannot provide average MRL values in our agreed-upon data aggregation scheme, the lower end values may be more indicative of the status of the industry. The low values of the 2010 MRA data for backup power systems are, with the exception of the Manufacturing Planning risk element, indicative of manufacturing systems that are supporting, or are ready to support, LRIP. The Manufacturing Planning risk element includes scheduling. The lower values here indicate that although other manufacturing systems and processes are ready for LRIP, the scheduling activity does not currently support actual LRIPs.

Finally, discussions with fuel cell system manufacturers identified that changes in design and technical maturity were needed to move backup power fuel cell systems forward. NREL concluded that the manufacturers overrated the Technical Maturity and Design risk elements in 2008. Thus, even though the Design and Technical Maturity (and Materials) risk elements are again rated highly in the 2010 MRA, NREL believes that the new design systems and stacks have not been demonstrated long enough in the market to prove that operational performance shortfalls have been addressed. The business case, according to the Battelle and DOE analyses can be made, but the value proposition relative to battery systems that is required to create self-sustaining demand—even with the benefit of purchase incentives and positive life cycle cost comparisons—has not yet been proven. Further, even with the incentive, costs may still be too high for a strong business case.

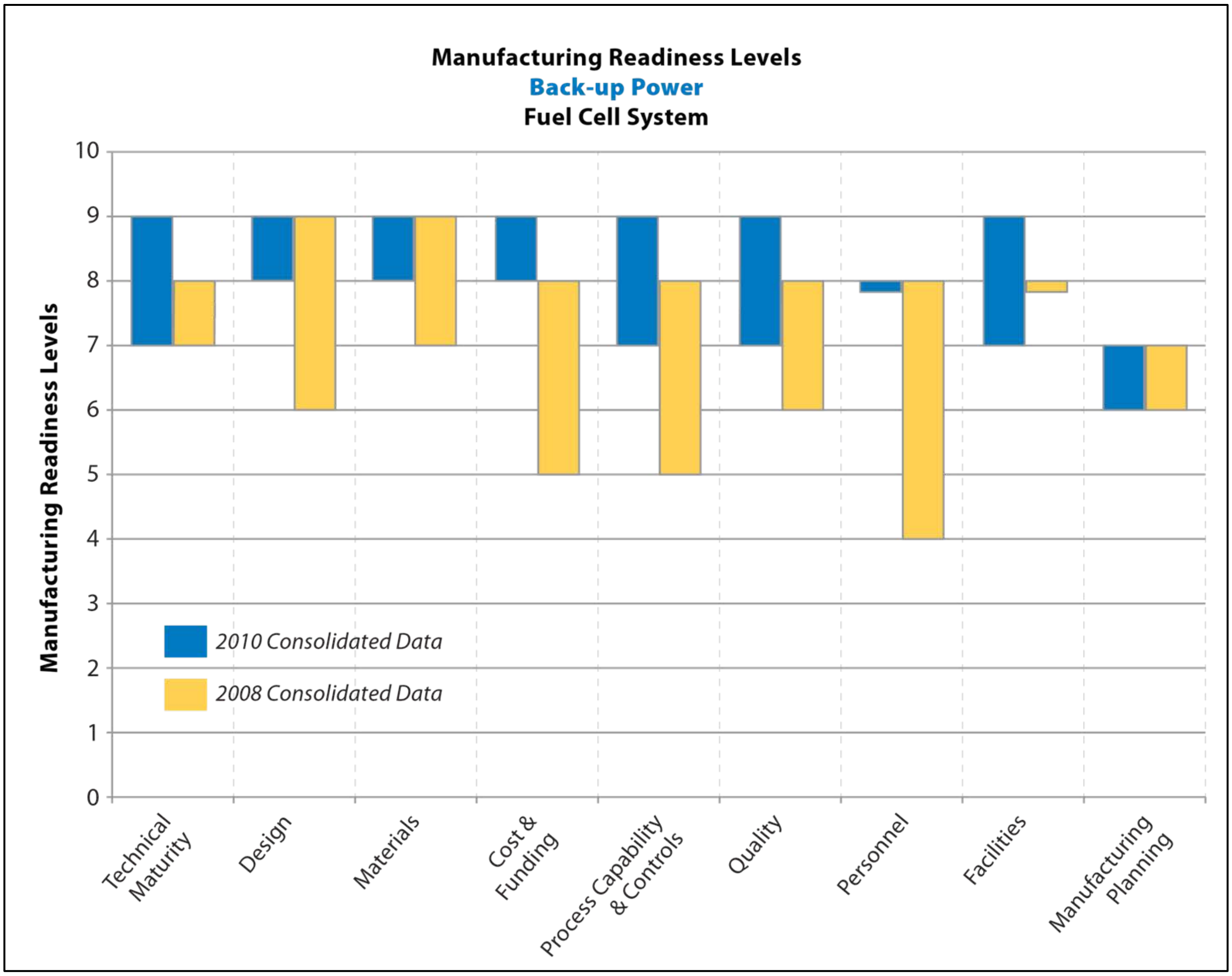

Figure 2. Comparison of 2010 MRA data to 2008 MRA data for backup power

Low Rate Initial Production and Manufacturing Readiness Assessment Results for Materials Handling Equipment Systems

Battelle determined that the replacement market for MHE PEM fuel cell systems was approximately 5,000 units in the initial years (see Figure 3, which assumes a federal government subsidy of approximately $3,000) with the annual replacement market at 108,000 (see Table 3). The fuel cell manufacturers agreed with an LRIP of 1,000 units per year in the 2008 MRA conducted by NREL. In the 2010 MRA, the three fuel cell manufacturers report production rates on the order of a few hundred to 500 units per year. This lower value is representative of the current market share for multiple manufacturers and is clearly fewer than the 5,000 units annual production anticipated by the Battelle report. As was the case for backup power systems, the DOE compared the lifecycle cost of PEM fuel cell and battery-powered forklifts[9] (see Table 5). The PEM fuel cell system was rated at 3 kW and paired with a nickel metal hydride battery system for the pallet truck case and an 8-kW PEM fuel cell paired with an ultracapacitor for the Class 1 trucks. The tax incentive for the DOE analyses was $1,000/kW. Without a tax incentive, the 3-kW PEM had almost a twofold NPV advantage over the battery system. On the other hand, the 8-kW PEM system did not demonstrate an NPV advantage for either the no tax incentive or the tax incentive case. However, given the present tax incentive of $3,000/kW, a more positive economic comparison is expected.

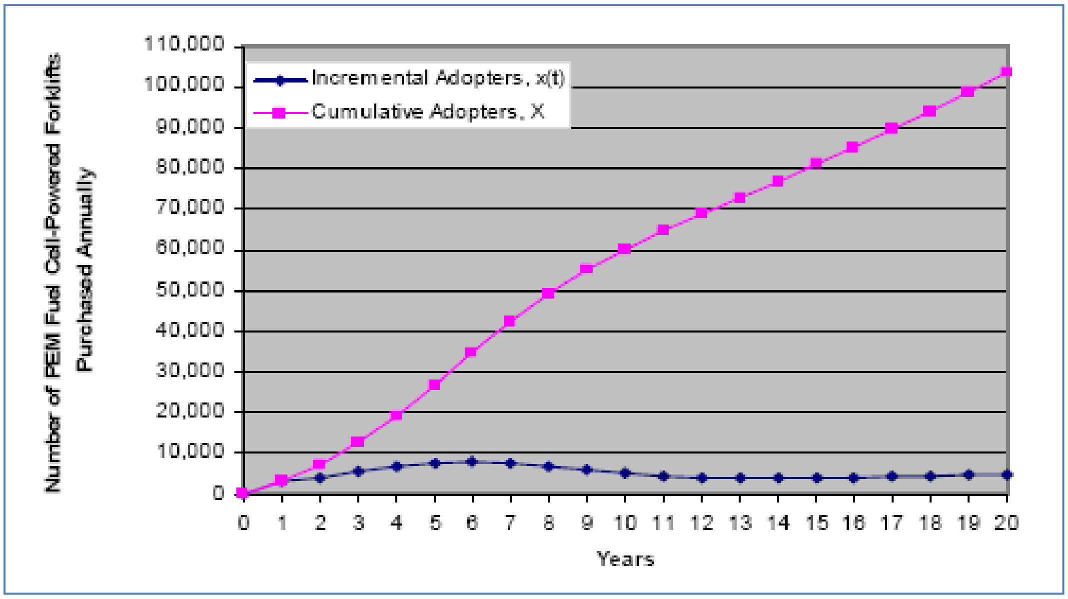

Figure 3. Battelle market projections for forklift trucks – scenario 3[5]

Table 5. NPV of Total Cost: Comparison of PEM Fuel Cell Forklifts to Battery-Powered Forklifts

Lifecycle Cost Comparison of PEM Fuel Cell- and Battery-Powered Forklifts

	3kW PEM Fuel Cell Paired with Integral NiMH Battery, for Pallet Trucks*			8kW Fuel Cell Paired with Integral Ultracapacitor, for Sit-down Rider Trucks**		
	Battery-Powered (2 batteries per truck)	PEM Fuel Cell-Powered with no tax incentive***	PEM Fuel Cell-Powered with $1K/kW tax incentive***	Battery-Powered (2 batteries per truck)	PEM Fuel Cell-Powered with no tax incentive***	PEM Fuel Cell-Powered with $1K/kW tax incentive***
Net Present Value of Capital Costs	$17,654	$23,835	$21,004	$43,271	$63,988	$56,440
Net Present Value of O&M Costs (including the cost of fuel)	$127,539	$52,241	$52,241	$76,135	$65,344	$65,344
Net Present Value of Total Costs of System	**$145,193**	**$76,075**	**$73,245**	**$119,405**	**$129,332**	**$121,784**

Figure 4 shows the aggregate results of the 2010 MRA and compares them to the 2008 data. The risk elements more closely associated with TRLs, Design, Technical Maturity, and Materials are, at their maximum levels, consistent with LRIP; i.e., there has been a demonstrated capability to manufacture at LRIP. These maximums values are the same as the 2008 data, even though the companies all reported design and technical maturity improvements between 2008 and 2010. Based on conversations with the fuel cell manufacturers, the understanding of the PEM fuel cell specifications for MHE improved considerably as a result of the recent deployments, which enabled improved fuel cell system designs to be developed. As with backup power systems, the lesson learned is that experience with near-commercial applications is critical to the development of fuel cell systems.

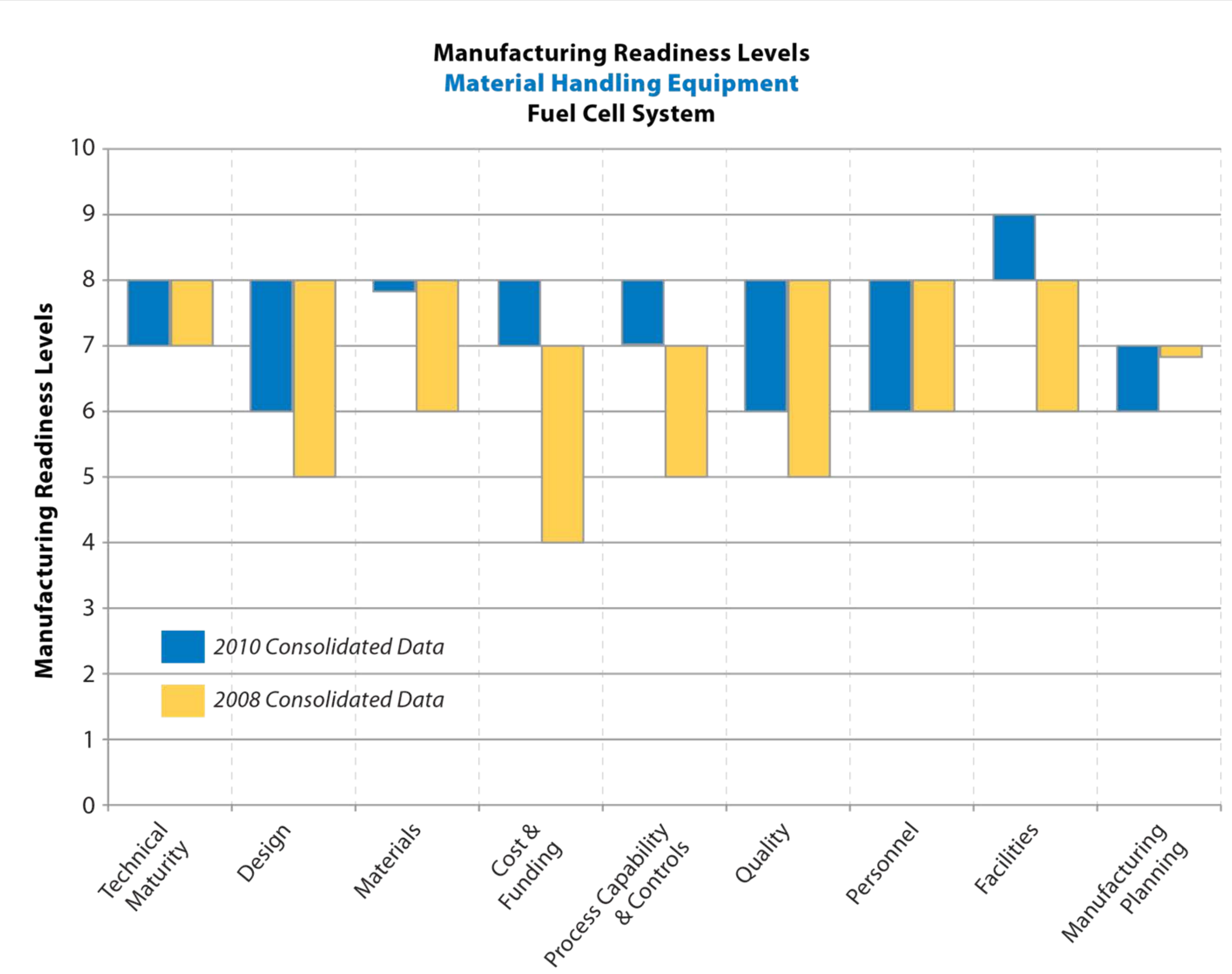

Figure 4. Comparison of 2010 MRA data to 2008 MRA data for MHE fuel cell systems

The ranges of two of these three TRL associated risk elements have narrowed, which is indicative of manufacturing readiness of all three companies reaching a common level of capability. The Design risk element has the lowest MRL (a value of 6), which suggests at least one company is making frequent design changes.

The risk elements Cost & Funding, Process Capability & Controls, and Facilities all show significant improvements as a result of increased manufacturing and commercial experience. These risk elements have all improved to the LRIP capability for at least one manufacturer (although not necessarily the same one). The minimum level for these three 2010 risk elements is equivalent to the maximum of the 2008 risk element levels.

The Quality, Personnel, and Manufacturing Planning & Scheduling risk elements have demonstrated the least improvement. Although there is some level of improvement in the MRL range for Quality, the Personnel and Manufacturing Planning & Scheduling risk elements show no improvement in maximum level or range. Moreover, 2010 minimum MRL for the Manufacturing Planning & Scheduling risk element is reported at a lower capability than in 2008.

Low Rate Initial Production and Market Readiness Assessment Results for Fuel Cell Stacks

The manufacturing status of fuel cell stacks changed since the 2008 MRA. Plug Power, Inc. stopped manufacturing fuel cell stacks to focus on manufacturing of fuel cell systems. Plug Power purchases its fuel cell stacks from Ballard Power Systems. IdaTech, who was not evaluated in 2008, also purchases its fuel cell stacks from Ballard. ReliOn and Altergy Systems were also added to the MRA for 2010 – both companies manufacture their own fuel cell stacks. Protonex is not included in the 2010 MRA.

The companies participating in the MRA of fuel cell stacks are Altergy Systems, Ballard Power Systems, Hydrogenics, Inc., Nuvera Fuel Cells, and ReliOn. The designs of the fuel cell stacks vary significantly from company to company. Ballard has developed more than one fuel cell stack design, and the stack use varies with application. As an example, Ballard has an air-cooled stack and liquid-cooled stack. The Ballard stack uses graphite or Grafoil bipolar plates. Altergy Systems has a stack design that is air cooled and uses metallic bipolar plates. Nuvera Fuel Cells also uses metallic current collectors and flow distributors. Hydrogenics reportedly has developed fuel cell stacks with carbon-based bipolar plates and fuel cell stacks with metallic bipolar plates. ReliOn uses carbon-based bipolar plates but with a distinct modular stack design. Consequently, the fuel cell manufacturing processes for these companies are dissimilar.

Figure 5 shows the results of the MRA for fuel cell stack manufacturing and compares them to the 2008 data. The variation within each risk element has increased for six of the nine elements. This reflects the different levels of maturity for fuel cell stack designs and the changes in manufacturing processes that are precipitated by the design changes. The MRL range for the Materials risk element has doubled, and the ranges for Technical Maturity and Design show a fourfold increase. The maximum for these three risk elements is MRL-9; a system that is at LRIP. The minimum for Technical Maturity and Design is MRL-5; prototype components are being manufactured, with significant design changes. Some manufacturers report very mature designs and materials. Other emerging designs will, according to the manufacturers, provide superior performance; however, these were built as laboratory prototypes and the specific manufacturing and business processes have not yet been fully integrated into the company's manufacturing enterprise.

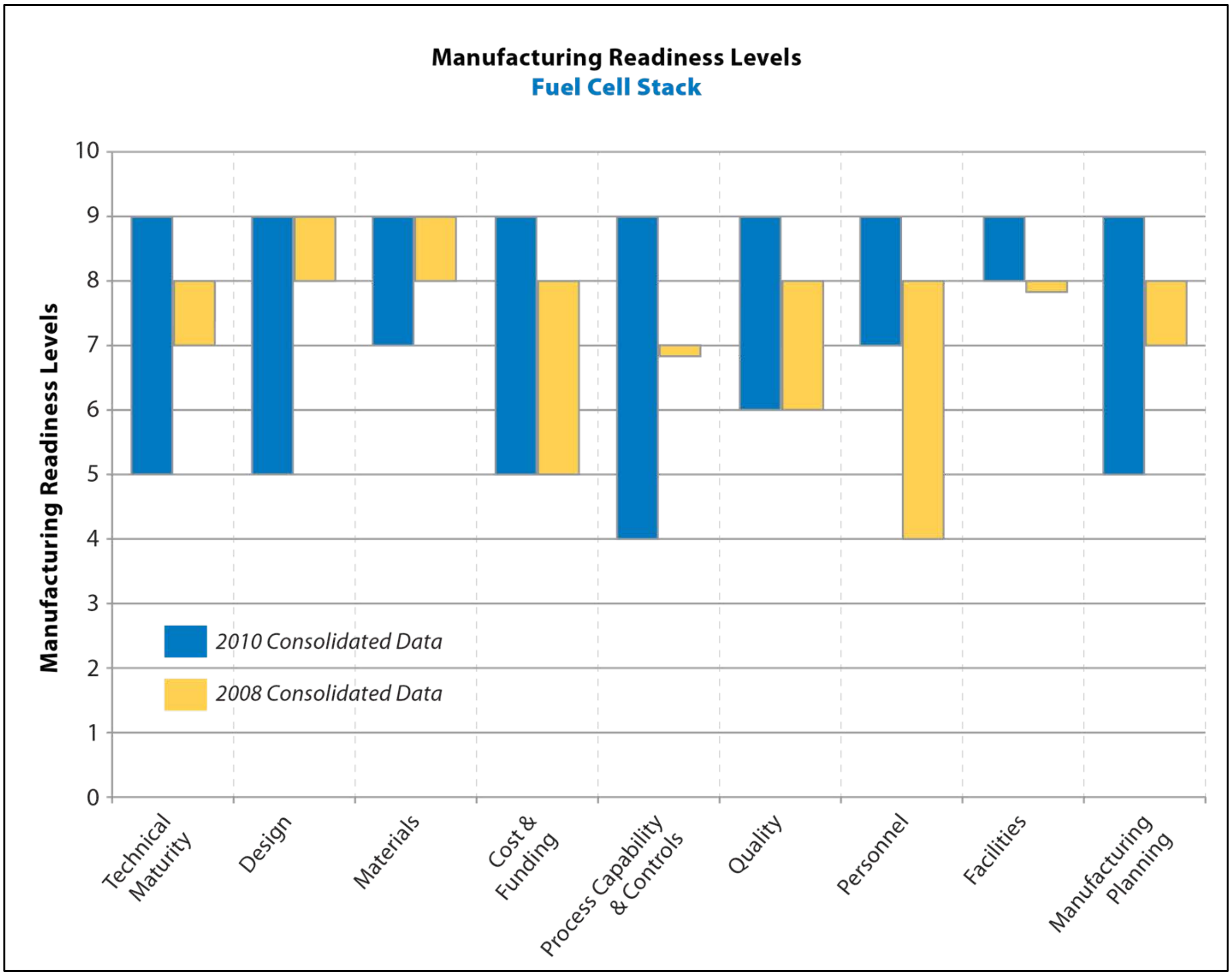

Figure 5. Comparison of 2010 MRA data to 2008 MRA data for fuel cell stacks

The Cost & Funding, Process Capability & Controls, and Manufacturing Planning & Scheduling risk elements give further credibility to mature fuel cell stacks and emerging fuel cell stack designs. All three have large MRL ranges and maximums of MRL-9; a very mature manufacturing level with LRIP demonstrated by at least one manufacturer. The minimum values for Cost & Funding and Manufacturing Planning & Scheduling are at MRL-5; cost controls have been defined and are being initiated and manufacturing plans and flow have been defined. The Process Capability risk element has a minimum at MRL-4; concepts for manufacturing are being identified. The data demonstrate that at least one manufacturer's fuel cell stack manufacturing processes are mature, and at least one other is in the beginning stages of development. From these data, the fuel cell stack manufacturers with more mature manufacturing capabilities may have a market advantage in driving down cost and high rate production; whereas the fuel cell manufacturers with lower MRLs may anticipate that their design improvements will eventually give them a market advantage. Stack manufacturing capabilities with currently low MRLs will likely be able to move up the MRL scale faster than they could in the past, as systems are quickly integrated for the new designs, rather than developed anew.

Three risk elements improved their maximum MRL and did not decrease their minimum MRL: Quality, Personnel, and Facilities. The improvement in Quality resulted from experience and lessons learned since the 2008 MRA. The fuel cell stack manufacturers developed quality control procedures for their manufacturing processes, at current volumes, and that will be easily translated to new fuel cell stack designs. The Personnel and Facilities risk elements similarly benefited from the manufacturing lessons learned since 2008. The fuel cell manufacturers report they have developed, or are developing, standard practices and between 2008 and 2010 improved training procedures. The Facilities risk element benefits from the experience obtained designing fuel cell manufacturing production lines, or the integration of lines for new stack designs.

Demonstration Versus Deployment

Many fuel cell manufacturers consider the demonstration approach, as exemplified by the DOE- and automobile industry-supported fuel cell vehicle technical validation activity, to be an R&D activity. The approach does not produce significant sales, which can be a great risk to the manufacturer. The manufacturer further risks missing a market opportunity while waiting for the fuel cell system design to stabilize. However, the demonstration approach emphasizes developing an understanding of the performance and durability issues associated with designs prior to entering the commercial market.

The FCTP Market Transformation activity has aggressively deployed fuel cell systems into the MHE and backup power markets. This approach is consistent with the interests of the fuel cell manufacturers, which continually push for increased government support through either direct purchase or rebate and tax credit programs. The deployment approach benefits the fuel cell manufacturers because they show product sales to their owners or shareholders. The downside is that the product may not fully meet expectations and the manufacturers risk discouraging the customers. Also, the manufacturer may have high warranty risk with the deployment approach. This happened, in some cases, with both markets. Market penetration appears to be expanding, but design churn is occurring midstream, affecting the agility of the manufacturers. This situation, and the inherent tradeoffs in the two approaches, should be important considerations for market transformation decision makers as they evaluate how to address emerging fuel cell markets.

Conclusions

Based on the inputs received during the interviews and visits for the 2010 MRA, NREL draws the following conclusions:

- Fuel cell manufacturers in the MHE and backup power markets have undertaken design modifications to the systems that were originally fielded into these markets, based on lessons learned from deployments. Cost, manufacturability, and improved performance or functionality were stated as objectives of these design changes. In particular, the manufacturers indicated that changes were made because initial designs were not fully meeting the operational requirements of the markets. This situation indicates that the Design, Technical Maturity, and Materials risk elements in the 2008 MRA may have been overstated. This may be because the manufacturers did not fully recognize the limitations of their 2008 designs, perhaps because of a lack of demonstration testing in a representative operating environment. Or, operational specifications for these markets may have been incomplete or incorrect, owing to the differences in operational and performance characteristics between fuel cells and the battery systems they were intended to replace.
- For fuel cell systems, with one short-term exception, manufacturers have still not reached the LRIP defined in the 2008 MRA Report as 1,000 units per year (per manufacturer). Whereas most manufacturers interviewed for the 2008 MRA Report were producing at the 200–300 units per year level, some now have consistent production levels above 500 units per year.
- For fuel cell stacks, some manufacturers report demonstration of LRIPs ; others are still below LRIPs.
- In general, MRL ranges for MHE and backup power fuel cell systems and stacks have shifted upward from the 2008 MRA to the 2010 MRA, indicating a higher level of manufacturing readiness in the industry.
    - Comparison of the MRL ranges for MHE and backup power fuel cell systems shows that, for most risk elements, the maximum MRL value is higher for backup power than for MHE. This may be for one of several reasons:
        - More maturity in the manufacturing capability for backup power systems.
        - Differences in the operational requirements and environments of these two applications.
        - New manufacturers being added to the MRA activity
        - There is currently very little standardization of processes and materials between manufacturers. Thus, one manufacturer with improved capabilities may singularly impact the ranges, given that we report only high and low values (not averages).
    - For fuel cell systems, relatively tight MRL ranges were observed. This is consistent with the data from the 2008 MRA Report. However, the lower end of the MRL range for certain risk elements decreased relative to the 2008 data. This is indicative of the situation wherein new designs have recently been or are soon to be released, and certain aspects of the entire manufacturing enterprise, for

example Facilities and Manufacturing Planning, Scheduling & Control, have not yet been integrated for the new design.

- For fuel cell stacks, the high ends of the MRL ranges in all cases were at least as high as the 2008 data, but in many cases the low end of the range was lower than the 2008 data. This again is indicative of new designs where support structures are not yet fully integrated. In some cases, new manufacturing capabilities are being brought into operation that are designed for higher volumes, but which may not be fully integrated into the entire manufacturing enterprise.

- Modifying stack and system designs in the midst of market launch provides improved functionality and value, but poses risks to the industry. This situation highlights the differences between the demonstration and deployment approaches to assisting early markets. A demonstration approach intends to identify issues with a current system design before market launch. This approach is generally slow and does not typically provide significant funding to the industry. The deployment approach typically enables faster market penetration and increased funding to the industry. Thus, it allows the risk that system designs are not fully vetted at market entry, and may need to be modified during the market launch.
- The federal tax incentive program has opened the commercial market for backup power and MHE fuel cell systems by compensating for the initial high cost of fuel cell systems. The fuel cell manufacturers report improvements in the Cost & Funding risk elements and in some cases have reduced cost to < 110% of target.

Recommendations

Based on the MRAs performed, and the information gathered about the status of the MHE and backup power emerging markets for PEM fuel cells and the activities of the manufacturers in addressing the development of these markets, both in manufacturing capability and product design, NREL provides the following recommendations:

- This MRA activity, similar to its predecessor, provides a critical linkage to the activities of the PEM fuel cell manufacturers as they react to the developing nature of the MHE and backup power markets. Assessment of sales alone does not provide a complete picture of the development of the domestic manufacturing base. As we have seen over the past year and a half, manufacturing capabilities have advanced, and yet *manufacturing readiness* may actually have regressed because new designs are being brought online and are still being integrated into the manufacturing enterprise. This detailed insight can be invaluable to the FCTP as it evaluates and prioritizes the need for fuel cell market transformation funding of emerging markets. **Thus, support for an ongoing MRA activity continues to be critical, and participation in this activity should be required for cost-shared demonstration and deployment activities so unbiased, comparative assessments can be made.**
- The emergence of the supplemental power market highlights the **need for regularly updated market analyses**. As manufacturers develop and participate in these new markets, some of which may be greatly aided by FCTP and other federal agency funding and acquisition, additional design changes will occur, necessitating further modification and advancement of the manufacturing enterprise.
- The MHE and backup power markets have received support from the FCTP and other federal agencies wherein market transformation support and a formal technical validation effort have occurred essentially in parallel. This is opposed to the case of automotive fuel cells. This simultaneity has helped speed the readiness of the technology for these markets, and yet, as shown, it has resulted in a situation where PEM fuel cell products have had to undergo design changes during the early stages of maturation of these two markets. Although considerable effort during these design changes has been spent on decreasing cost and improving manufacturability, changes in the functionality of the systems have also been made to address lessons learned during these market transformation supported deployments. This means that not only are MRLs changing, but TRLs are also in flux. Moreover, as new functionality is brought to bear to improve the fuel cell system performance relative to the application needs (and relative to incumbent technologies), the FCTP must be armed with a method to understand how technology and manufacturing are advancing in tandem, how these advances are resulting in value propositions that will (or will not) establish a business case for the fuel cell systems in these applications, and how, ultimately, these advances affect sales and the broader market. The FCTP would benefit from **an activity that:**
    - **Links the technical, safety, and reliability data being gathered from these markets and the understandings provided by the MRA activity**
    - **Assesses the actual technical performance of these systems, as indicated by MRLs and TRLs and compared to incumbent technologies**
    - **Uses this corroborated information to assess the ultimate market impact of demonstration activities supporting the MHE and backup power markets.**

- Based in part on the federal tax incentive program for fuel cell systems, manufacturers report improvements in the Cost & Funding risk elements and in some cases have reduced cost to < 110% of target. However, recent design changes made in order to better address the operational requirements of the backup power and MHE markets are just now arriving into these markets. **The current incentive program must be sustained at least through 2016 to enable the manufacturers to deploy systems fully vetted during the ongoing DOE, DOD, and ARRA deployments and establish the value proposition of these systems against incumbents.**

Appendix A

Table A-1. Manufacturing Readiness Levels

MRL	Definitions
1	**Manufacturing Feasibility Assessed –** Top level assessment of feasibility based on technical concept and laboratory data.
2	**Manufacturing Concepts Defined** – Initiate demonstration of feasibility of producing a prototype system or component.
3	**Manufacturing Concepts Developed –** Manufacturing concepts identified and based on laboratory studies.
4	**Laboratory Manufacturing Process Demonstration**. Manufacturing processes identified and assessed in lab. Mitigation strategies identified to address manufacturing/producibility shortfalls. Targets set for cost as an independent variable, and initial cost drivers identified.
5	**Manufacturing Process Development:** Trade studies and laboratory experiments result in development of key manufacturing processes and initial sigma levels. Preliminary manufacturing assembly sequences identified. Process, tooling, inspection, and test equipment in development. Significant engineering and design changes. Quality and reliability levels not yet established. Tooling and machines demonstrated in the laboratory. Physical and functional interfaces have not been completely defined.
6	**Critical Manufacturing Process Prototyped:** Critical manufacturing processes prototyped, targets for improved yield established. Process and tooling mature. Frequent design changes still occur. Investment in machining and tooling identified. Quality and reliability levels identified. Design to cost goals identified. Pilot line operation demonstrated.
7	**Prototype Manufacturing System.** Prototype system built on soft tooling, initial sigma levels established. Ready for low rate initial production (LRIP). Design changes decrease significantly. Process tooling and inspection and test equipment demonstrated in production environment. Manufacturing processes generally well understood. Machines and tooling proven. Materials initially demonstrated in production. Manufacturing process and procedures initially demonstrated. Design to cost goals validated.
8	**Manufacturing Process Maturity Demonstration**. Manufacturing processes demonstrate acceptable yield and producibility levels for pilot line. All design requirements satisfied. Manufacturing process well understood and controlled to 3-sigma or appropriate quality level. Minimal investment in machine and tooling - machines and tooling should have completed demonstration in production environment. All materials are in production and readily available. Cost estimates <125% cost goals (e.g., design to cost goals met for LRIP).
9	**Manufacturing Processes Proven.** Manufacturing line operating at desired initial sigma level. Stable production. Design stable, few or no design changes. All manufacturing processes controlled to 6-sigma or appropriate quality level. Affordability issues built into initial production and evolutionary acquisition milestones. Cost estimates <110% cost goals or meet cost goals (e.g., design to cost goals met). Actual cost model developed for FRP environment, with impact of continuous improvement. Full rate process control concepts under development. Training and budget plans in place for transition to full rate production.

MRL	Definitions
10	**Full Rate Production demonstrated and lean production practices in place** The system, component or item is in full rate production. Technologies have matured to at least TRL 9. This level of manufacturing is normally associated with the Production or Sustainment phases of the acquisition life cycle. System, components, or items are in full rate production and meet all engineering, performance, quality, and reliability requirements. All materials, manufacturing processes and procedures, inspection and test equipment are in production and controlled to six-sigma or some other appropriate quality level. Rate production unit costs meet goals, and funding is sufficient for production at required rates. Lean practices are well established and continuous process improvements are ongoing.

Appendix B

Industry Interview Questions

Technical Maturity

4. Scalable technology prototypes have been produced in laboratory
5. Prototype materials, prototype components, tooling and test equipment in development for pilot line production, but manufacturing process still in development
    a. Trade studies and laboratory experiments under way to define critical manufacturing processes
    b. Subcontractors are identified
6. Trade studies and laboratory experiments to define critical manufacturing processes complete
    a. Critical manufacturing processes prototyped
    b. Successful system manufacture on pilot line demonstrated
7. Components are representative of production components; and materials, manufacturing processes, and manufacturing procedures initially demonstrated on pilot line
8. Manufacturing processes demonstrated at low rate initial production (LRIP) on pilot line
    a. Components are form, fit and function compatible with operational system
9. Stable LRIP production and meeting LRIP cost targets
    a. Actual system fully demonstrated
    b. Full scale production decision made
10. Stable full rate production (FRP); and meeting FRP cost targets

Design

4. Integrated Product Team (IPT) been formed that includes manufacturing and engineering
    a. IPT is guided by "Design to Cost" criteria
    b. The component and hardware requirements are established
5. There are significant design and engineering changes
    a. IPT has established design and manufacturing approach
    b. Configuration management process is tracking subcontractors
6. IPT integrates manufacturing needs into overall product plan
    a. "Design to Cost" criteria maintained
    b. Frequent design changes still occur
7. Configuration management and engineering change process are in place for production and subcontractors
    a. System design is low risk for manufacturing
    b. Design changes decrease significantly
8. All critical product and process technologies and their status are defined; and design is stable, with few or no design changes
9. Design changes eliminated or minimized
10. Design changes eliminated and "Design to Cost" criteria met

Materials

4. Exotic / high cost materials identified and this issue is being addressed
5. Material standardization plan developed

6. Material control and inventory control processes in place
    a. Environmental issues with materials addressed
7. Procurement plan in place and materials available in "production quantities"
    a. Pre-production system hardware is available, although quantities may be limited
8. Make / Buy decisions and Bill of Materials complete and support LRIP
9. All materials meet planned LRIP schedules
    a. FRP material needs are identified
10. Full scale manufacturing materials needs are met

Cost and Funding

4. The total system cost goals are available to the IPT and are used to guide the system design
    a. Manufacturing cost drivers identified
5. Investment needs for process and tooling are determined; and Make / Buy program initiated
    a. Cost reduction plan is operational and contributing to reducing cost
    b. Cost model is developed
    c. Subcontractors and suppliers cost control identified
6. Cost center accumulates cost data and reports results on regular basis
    a. Costs are traceable to manufacturing process steps
    b. Cost model is contributing to cost reduction program
7. Analyses of non-recurring engineering and capital costs for LRIP are completed
    a. Cost mitigation plans are developed
    b. Program continues to make progress to cost goals
8. Cost estimates < 125% of cost goals
    a. Cost mitigation incorporated in cost reduction plan
    b. Initiate analysis for non-recurring capital and engineering costs for FRP
    c. Cost model is mature, no changes to model and model is contributing to cost reduction program
9. LRIP cost goals and production goals met or at < 110% of cost
    a. Cost to achieve FRP including non-recurring costs are identified and funds are requested
    b. Cost model developed for FRP
10. FRP cost goals and production goals met
    a. FRP meets cost model target
    b. Full rate cost model includes continuous improvement and lean practices

Process Capability and Controls

4. Manufacturing State-of-the-Art identified
    a. Key manufacturing processes are identified and assessed in the laboratory
    b. Manufacturing processes that need to be developed are identified
5. Key manufacturing processes assessed for pilot line
    a. Processes that require major production-scale related changes are identified
6. Production issues identified and major issues resolved
    a. Prototype process demonstrations are complete
    b. Analysis of production throughput completed using pilot line

    c. Yield issues understood and major issues resolved
7. Process tooling and inspection / test equipment demonstrated on pilot line for LRIP
    a. Manufacturing processes generally well understood
    b. Process equipment enables pre-production quality of system prototype
    c. Maintainability, reliability, and supportability data for manufacturing processes is above 60% of total needed
8. Manufacturing processes demonstrate acceptable yield
    a. LRIP production levels achieved; and maintainability, reliability, and supportability data collection for manufacturing processes has been completed
    b. Manufacturing process controlled to appropriate quality level
    c. Quality trend and failure analysis operational for continuous process control
9. All LRIP manufacturing processes controlled to 6-sigma or appropriate quality level
    a. Machines and tooling for FRP under evaluation
10. Machines and tooling for FRP installed and operational
    a. All manufacturing processes controlled to 6-sigma or appropriate quality level

Quality

5. Continuous process improvement program in place and working
    a. Metrology program in place
6. Quality and reliability levels established
    a. Quality and reliability requirements flowed down to subcontractors
7. Quality organization operating to established quality goals
    a. Metrology program is in place for production equipment, tooling and testing calibration
    b. Statistical process control capability in place
        i. Subcontractor and suppliers quality programs reviewed and accepted / changed
8. Quality and reliability levels established
    a. Quality program part of continuous process improvement program
9. Machines, tooling, and inspection and test equipment deliver appropriate quality level at LRIP
    a. Quality strategy under evaluation for FRP
10. Machines, tooling, and inspection and test equipment deliver appropriate quality level at FRP
    a. Metrology program in place for production equipment, tooling and testing calibration
    b. Quality strategy in place for FRP

Personnel

4. Training programs necessary for specialty skills identified
    a. Training programs identified for process control and quality
6. Funding for training is in place
    a. Training program necessary for specialty skills and for process control and quality in place
7. All training programs in place and operational
8. Specialty skills verified on pilot line

    a. Training part of continuous improvement program
9. Plans in place for FRP training
10. FRP training completed

Facilities

4. Non-recurring costs associated with facility requirements are documented
    a. Facility resource requirements are documented
5. Facility changes initiated that are consistent with proposed LRIP production levels
6. Facility changes underway that are consistent with proposed LRIP production levels
7. Facility changes near completion that are consistent with proposed LRIP production levels
8. Facilities in place for LRIP production; and facilities certification for LRIP is completed
    a. All non-recurring costs associated with facilities documented
9. Identified non-recurring cost associated with facility requirements for FRP
    a. Facility upgrades to full rate production initiated
    b. Facilities certification for FRP initiated
10. Facility upgrades for FRP in place; and facilities certification for FRP in place

Manufacturing Planning, Scheduling, Control

4. Manufacturing strategy developed
    a. A manufacturing control hierarchy is in place
5. Manufacturing plan is developed, working, and being reviewed; and manufacturing flow chart completed
6. Manufacturing plan updated and evaluated with risk plan; and critical schedule paths are identified
7. Production planning is complete; ready for LRIP
    a. Delivery schedules meet program needs
8. Operating at LRIP rate production
    a. Initiate analysis for FRP planning and control
9. FRP planning and control measures under development; and initiate analysis of FRP throughput
10. Operating at FRP; and FRP planning and control measures in place

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