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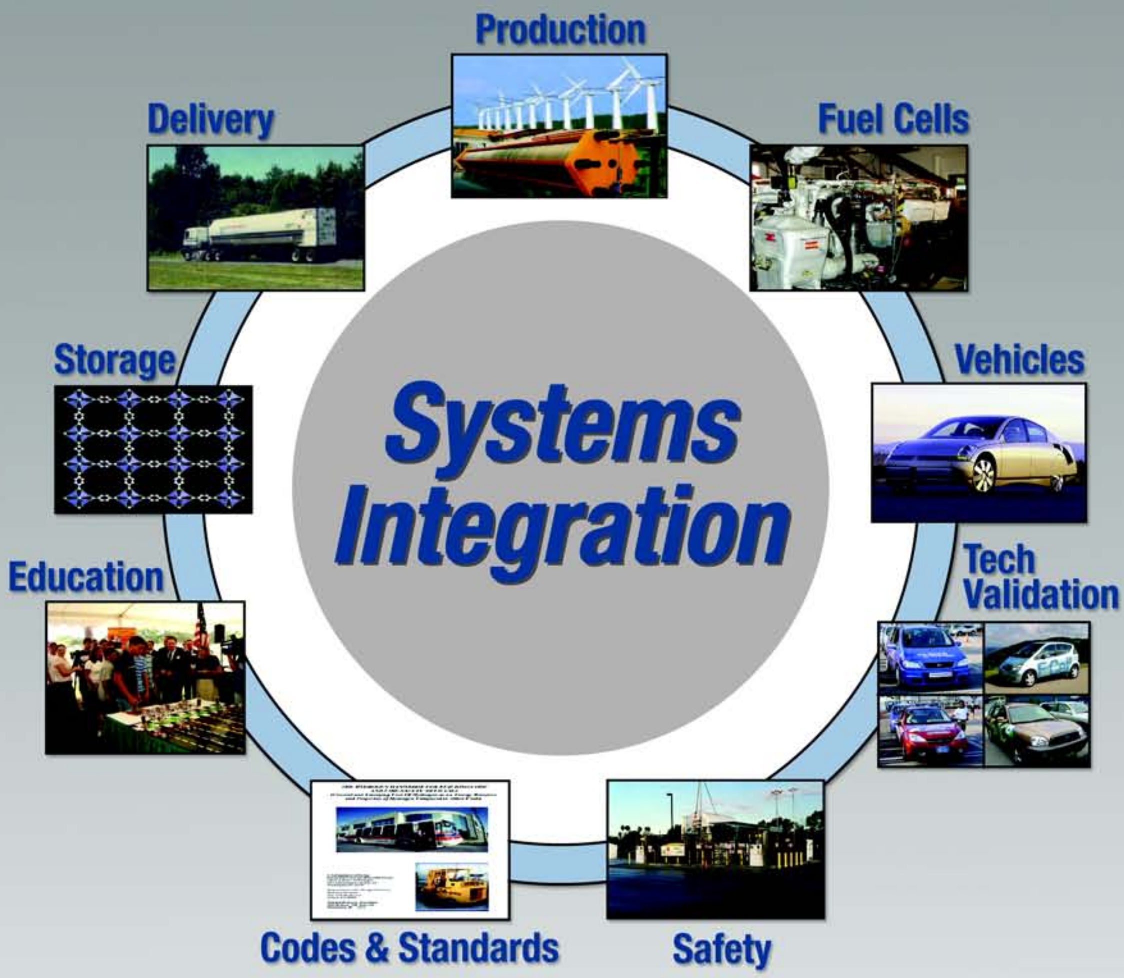
1–10 kW Stationary Combined Heat and Power Systems Status and Technical Potential



Independent Review

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Independent Review Panel Executive Summary

May 28, 2010

From: Independent Review Panel for 1–10 kW Stationary Combined Heat and Power Systems Status and Technical Potential

To: Mr. Mark Ruth, NREL, Alliance for Sustainable Energy, LLC

Subject: Independent Review Panel Report

As per the tasks and criteria of the Independent Review Charter of November 13, 2009, this document represents the Independent Review Panel's unanimous technical conclusion, arrived at from data collection, document reviews, stakeholder interviews, and deliberations between February 2010 and May 2010.

Conclusions

The Independent Review Panel was commissioned by the National Renewable Energy Laboratory's Systems Integrator to review the status of 1–10 kW CHP stationary fuel cell systems and to comment on the achievability of cost, efficiency, and durability targets. The Independent Review Panel evaluated the three independent fuel cell technologies that are being developed to address the market needs of 1–10 kW CHP stationary systems: low-temperature proton exchange membrane (LT-PEM) fuel cell systems operating, for the most part, in a temperature range of 60°–90°C; high temperature PEM (HT-PEM) fuel cell systems operating in a temperature range of 130°–180°C; and solid oxide fuel cell (SOFC) systems operating in a temperature range of 550°–1,000°C.

Stakeholder claims regarding the current status for efficiency, cost, and durability varied widely within each of these three technologies. DOE reports the 2008 status of electrical efficiency, CHP efficiency, and durability at 34%, 80%, and 6,000 hours, respectively (see Table 2). Those values are representative of or even on the low end of demonstrated results. On the other hand, the stakeholders claimed that the reported 2008 status for factory cost ($750/kW) is low, especially for the low end of the 1–10 kW range.

In Table 1, the Panel provides its own perspectives on the cost and performance technical potential in 2012, 2015, and 2020 for each fuel cell technology. This information is based on the collective fuel cell experience of the panel members and is arrived at independently from the inputs of the stakeholders. While there is some correspondence between the Panel's perspective and the inputs from the stakeholders, in some cases the Panel does not agree with the stakeholders. For example, an operating lifetime of 60,000 h may be feasible but will likely be at cost and efficiency levels that will be unacceptable to end users.

In analyzing the achievability of the DOE cost, efficiency, and durability targets, the Panel concludes the following:

- The electrical efficiency target of 45% is likely to be achievable with HT-PEM and SOFC fuel cells but is unlikely to be achieved by LT-PEM fuel cells.

- Only SOFC fuel cells are likely to achieve the targeted CHP efficiency of 90% at the required electrical efficiency.
- Based on anticipated technical advances and improvements in manufacturing capability of the fuel cell industry, the factory cost target of $450/kW will be extremely challenging for all of the technologies.

The durability target of 40,000 h is deemed achievable but 60,000 h is a significant challenge, especially in conjunction with factory costs near the $450/kW target.

Table 1. Panel Perspective on Cost and Technical Potential for 1–10 kW CHP Stationary Fuel Cell Systems Operating on Natural Gas[a]

	2012			2015			2020		
	LT PEM	HT PEM	SOFC	LT PEM	HT PEM	SOFC	LT PEM	HT PEM	SOFC
Electrical efficiency at rated power,[b] %	38	42	40	40	42	45	40	45	60
CHP energy efficiency,%	85	85	85	87	87	90	87	87	90
Factory cost,[c] $/kW	1,000–1,500	1,000–2,000	1,300–4,500	750–1,200	550–1,500	1,000–3,000	450–750	450–750	1,000–2,000
Transient response (10%–90% rated power), min	< 1	<1	5	< 1	< 1	3	< 1	< 1	2
Start-up time from 20°C ambient temperature, min	30	30	60	20	20	45	15	15	30
Degradation with cycling, %/1,000 h	<0.3	<0.3	<0.7	<0.3	<0.2	<0.5	<0.2	<0.2	<0.3
Operating lifetime,[d] h	30,000	30,000	30,000	40,000	40,000	35,000	40,000	40,000	40,000
System availability, %	97	97	97	98	98	98	99	99	99

[a] Standard utility natural gas delivered at typical residential distribution line pressures.
[b] Regulated AC net/lower heating value of fuel.
[c] Cost defined at 50,000 unit/year production (250 MW in 5-kW modules). The basic unit includes all processing necessary for conversion of natural gas to unregulated DC power; i.e., the basic unit does not include power conditioning.
[d] Time until > 20% net power degradation.

The Panel's conclusions and R&D priorities for individual fuel cell technologies are summarized below and discussed further in the recommendations section of this report (see section 10).

LT-PEM Fuel Cell Systems

- The majority of LT-PEM fuel cell systems produced today are at the low end of the 1–10 kW range.
- More R&D investment for the fuel processing, air management, and power conditioning subsystems is needed to meet the DOE 2015–2020 targets.
- The 2020 target of 45% electrical efficiency will be a stretch goal unless catalyst systems can be improved and operating temperature increased to at least 90°C.
- At present, the low quality of heat available from LT-PEM fuel cell systems may limit their use beyond residential cogeneration.

HT-PEM Fuel Cell Systems

- HT-PEM fuel cell systems are an emerging 1–10 kW CHP stationary application, but their cost of $1000/kW–$2000/kW is greater than the factory cost proposed by the DOE status and targets.
- HT-PEM fuel cell systems have demonstrated the 2012 and 2015 electrical efficiency targets at beginning-of-life (BOL), and the 2020 target of 45% electrical efficiency is considered feasible.
- One stakeholder has reported a CHP efficiency of 88%, and CHP efficiencies in the range of 85% to 90% are considered reasonable.
- R&D investments in system demonstration, fuel processing cost reduction, and power conditioning subsystems are necessary. Additional fuel cell component R&D is needed to advance the HT-PEM systems.

SOFC Systems

- SOFC systems either already achieve or are capable of achieving DOE targets for electrical and CHP efficiencies, but the start-up time and factory cost targets are challenging.
- An insufficient number of SOFC prototype units have been installed, so information on the current status and future investment needs is limited. Further investment in prototype units would increase the understanding of durability and costs.
- R&D investment is needed to lower the cell, interconnect, and power conditioning costs.

Discussion of Conclusions

The Panel believes that each of the three technologies is at a different level of maturity and has its own pros and cons relative to the cost and technical targets identified by DOE. Depending on end-user requirements for product attributes such as life cycle cost, reliability, operational characteristics, or quality of heat, one particular technology may possess an inherent advantage over its competitors. For example, the low operating temperature of LT-PEM fuel cell systems requires that a multi-component gas reforming subsystem be included to ensure the levels of carbon monoxide do not significantly reduce efficiency, whereas an SOFC system can provide *in situ* reforming of natural gas.

The Panel and stakeholders recognize that the cost of a 1 kW unit will not be one-tenth of the cost of a 10 kW unit. While the stack subsystem may scale proportionately, the cost of the balance-of-plant components will be significantly more per kW for the lower power systems, especially at the 1–2 kW range. As such, it may be more representative to split the power range into two and define the technical potential of each range.

It is the Panel's belief that the lack of stakeholder consensus on cost and technical potential in later years is as much a factor of limited information as it is a reflection of the capability of the technologies to meet the technical potential. An insufficient number of fuel cells for 1–10 kW CHP stationary applications have been manufactured to permit a credible prediction of the cost at a production volume of 50,000 units per year; therefore, the panel recommends a rigorous, bottom-up, manufactured cost evaluation of each technology.

Achieving an operating lifetime of 60,000 h (2020 target) with original installed capital was seen by the majority of stakeholders as either an enormous challenge or in some cases as an unnecessary requirement. The Panel agrees with the majority of stakeholders who recommended a 40,000 h technical goal for operating life in 2015 and 2020. Many assumed that such lifetimes would be most practically achieved through a replacement and maintenance strategy. Following 40,000 h of operating lifetime, it seems reasonable to include cell/stack change-out as part of a maintenance program to extend the life of the system.

A common thread from the stakeholder inputs is the need to develop the commercial market. Identifying and taking advantage of early market opportunities is one way to build commercial momentum for 1–10 kW CHP stationary fuel cells. These opportunities can be found in specific geographic regions where the cost of grid electricity is high and there is a use for the produced heat or where operations are in remote locations. Early adopters who are less cost sensitive provide another market opportunity. Federal and state governments can play a pivotal role in many ways such as directed R&D funding, manufacturing process optimization and quality controls development, demonstration programs, manufacturer and end-user incentives, component specification, and codes and standards development.

Dr. Hans Maru

Dr. Subhash C. Singhal

Dr. Charles Stone

Mr. Douglas Wheeler

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1 Introduction

The U.S. Department of Energy (DOE) Fuel Cell Technologies (FCT) Program Manager requested the DOE Fuel Cell Technologies Program's Systems Integrator at the National Renewable Energy Laboratory (NREL) to commission an independent review of combined heat and power (CHP) stationary systems status and potential, with specific reference to the 2010 published preliminary cost and technical targets for 1–10 kW CHP fuel cell systems (see Table 2).

1.1 Technical and Cost Targets

Preliminary technical and cost targets for fuel cells used in CHP and auxiliary power applications were released by DOE in 2009. These targets are based on Request for Information responses from fuel cell developers and the broader R&D community working in technology areas related to the intended applications. Table 2 summarizes these preliminary targets and lists the 2008 status. Final targets will be published in the next revision of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan, to be released in 2010.

Table 2. Preliminary Cost and Technical Targets: 1–10 kWe Residential Combined Heat and Power Fuel Cells Operating on Natural Gas[a] [1]

	2008 Status	2012	2015	2020
Electrical efficiency at rated power[b]	34%	40%	42.5%	45%
CHP energy efficiency[c]	80%	85%	87.5%	90%
Factory cost[d]	$750/kW	$650/kW	$550/kW	$450/kw
Transient response (10%–90% rated power)	5 min	4 min	3 min	2 min
Start-up time from 20°C ambient temperature	60 min	45 min	30 min	20 min
Degradation with cycling[e]	< 2%/1,000 h	0.7%/1,000 h	0.5%/1,000 h	0.3%/1,000 h
Operating lifetime[f]	6,000 h	30,000 h	40,000 h	60,000 h
System availability	97%	97.5%	98%	99%

[a] Standard utility natural gas delivered at typical residential distribution line pressures.
[b] Regulated AC net/lower heating value of fuel.
[c] Only heat available at 80°C or higher is included in CHP energy efficiency calculation.
[d] Cost includes materials and labor costs to produce stack, plus any balance of plant necessary for stack operation. Cost defined at 50,000 unit/year production (250 MW in 5-kW modules).
[e] Based on operating cycle to be released in 2010.
[f] Time until > 20% net power degradation.

Following the publication of these targets, NREL commissioned an Independent Review Panel of industry experts (see Appendix A) to evaluate the reasonableness of the preliminary cost and technical targets in relation to 2008 fuel cell status estimates and projections out to 2020.

The Independent Review Panel posed a common series of specific questions (see section 3) to a collection of industry experts, fuel cell system developers, and fuel cell component developers.

The responses from stakeholders were then collated and analyzed. These data were supplemented by primary and secondary reference sources in combination with more than 110 years of collective expertise of the Panel in all areas of fuel cell technology.

Defining a single set of representative cost and technical targets for 1–10 kW CHP stationary fuel cell systems is complicated because there are at least three independent fuel cell technologies that can be used to address the market needs. There are two proton exchange membrane (PEM) fuel cell technologies, low temperature PEM (LT-PEM) and high temperature PEM (HT-PEM), which operate at around 60°–90°C and 130°–180°C, respectively. Efforts to increase the LT-PEM fuel cell system's operating temperature above 90°C are underway. In addition, solid oxide fuel cell (SOFC) technology, operating at 550°–1,000°C, is being developed for this market. While liquid phosphoric acid fuel cells (PAFC), direct methanol fuel cells (DMFC), and theoretically molten carbonate fuel cells (MCFC) could address 1–10 kW CHP stationary fuel cell systems, the Panel is not aware of any significant efforts in these areas, and as such, the Panel has focused its analysis on LT-PEM, HT-PEM, and SOFC systems. Section 4 outlines the constraints and assumptions used to analyze the data and structure recommendations.

Using data derived predominantly from stakeholders, the current status of each of the three key technologies relative to the existing DOE status and future potential for the CHP stationary application is outlined in sections 5–7. Section 8 includes a comparison of each technology, indicating the various pros and cons associated with the technology and relative to product requirements. Section 9 includes a discussion of the supplier network.

Based on its analyses, the Panel has proposed a series of recommendations, which are described in section 10. These recommendations may provide the process by which the next iterations of cost and technical potential are compiled and reported. In addition, the Panel has highlighted potential areas where the development toward meeting 2015 and 2020 targets might be facilitated.

The report ends with acknowledgments to various key contributors and to the many stakeholders who gave their valuable time and inputs, without which this report could not have been written.

2 Panel Mandate and Objective

The NREL Systems Integrator is responsible for conducting independent reviews of progress toward meeting the FCT Program's technical targets. An important technical target of the FCT Program is a distributed generation fuel cell system operating on natural gas, propane, or similar fuel that achieves the following 2020 targets for 1–10 kW CHP applications: 45% electrical efficiency and 60,000 h durability at $450/kW (assuming a production rate that meets commercialization requirements and does not include integrated auxiliaries, battery, and power regulation necessary for unassisted start). At this time, no manufacturer is producing fuel cell systems in the quantities needed for market introduction of small scale CHP products; as such, these estimates are necessary for DOE to gauge progress toward meeting its targets.

An Independent Review Panel (see Appendix A) was formed to review the status and probability of achieving the preliminary cost and technical potential related to the 2008 fuel cell status estimates and the projected targets out to 2020. The Panel members were selected for their expertise in each of the three technologies that have the potential to meet the DOE targets for the stated applications: LT-PEM fuel cell systems; HT-PEM fuel cell systems; and SOFC systems.

3 Methodology

The primary sources of information for the Panel's independent review were technical- and business-related interviews of key stakeholders in the identified technology areas. These stakeholders are listed in Appendix B. The stakeholders were asked about their businesses and their fuel cell technology type(s) and were asked the following introductory questions to obtain information on technology and commercialization status, potential improvements, and R&D needs for the technologies:

<u>Question 1.</u> The U.S. Department of Energy (DOE) has published technical and cost targets for 1–10 kW CHP systems and is seeking confirmation that these targets represent the acceptable industry targets. Your thoughtful comments on the validity of these targets or recommended changes will help DOE in their planning for future R&D programs. As part of your recommendations, would you prefer the emphasis of the DOE effort be on cell stack development, system component and balance-of-plant development, or all of the above? For the three areas, what are the main technology barriers to achieving the performance targets you have established and how do these targets compare to the DOE targets? Keeping in mind that all budgets would be limited, where do you recommend the DOE emphasize their R&D programs?

<u>Question 2.</u> The objective of the market transformation programs operated by DOE and the Defense Logistics Agency is to accelerate market development. Examples are the PEM forklift truck and PEM backup power programs. Please suggest market transformation programs for stationary 1–10 kW CHP systems that would accelerate product development.

<u>Question 3</u>. The high initial capital cost for stationary fuel cell systems is often cited as a barrier to commercialization. What are the stationary applications for which the initial cost will not be a major hindrance? Which R&D programs or market transformation programs would accelerate cost reduction for 1–10 kW CHP applications?

<u>Question 4</u>. The establishment of a mature supplier network can be a pathway to cost reduction. At the present stage of development, what aspects of a supplier network should become a high priority?

<u>Question 5</u>. Durability is a significant barrier for commercial viability of fuel cell-based CHP systems. Beyond the development of robust materials and designs, what other strategies are you considering to achieve and provide customer satisfaction in this area?

The information obtained from the interviews was summarized by the Panel and, in most cases, edited and approved by the respective stakeholder. The Panel conducted its interviews and evaluation between February and April 2010. In producing this final report, the Panel used these discussions with stakeholders, some information from stakeholder Web sites, and its own collective fuel cell experience and expertise.

Informative presentations were also provided by the Acting DOE-Fossil Energy Solid State Energy Conversion Alliance (SECA) Program Manager, DOE-FCT Program, NREL, and Battelle. Information from these presentations was considered by the Panel in writing this final report.

4 Constraints and Assumptions

The DOE stationary fuel cell system preliminary targets given in Table 2 were to be used as a reference for the industry stakeholders, who were asked questions about their system status and future design characteristics in relation to the 2008 status and future target data. The targets in Table 2 are constrained by the following:

- Stationary power systems should be rated in the range of 1–10 kW, operating on natural gas at typical residential pressures.
- Stationary power efficiency is based on AC net power / "lower heating value of fuel".
- Only heat available at 80°C or higher is considered for CHP.
    - This constraint could eliminate consideration of many of the LT-PEM fuel cell systems and possibly some HT-PEM fuel cell systems. For the purpose of this report, the Independent Review Panel collected and reports CHP information for all LT-PEM and HT-PEM fuel cell systems.
- The cost target should consider only the cell stack and the balance-of-plant (BOP) components necessary for the operation of the cell stack.
    - Industry practice breaks out the cost of the fuel cell system into three categories: 1) fuel processing system, 2) cell stack, and 3) power conditioning with balance-of-plant components associated with each of the respective categories. For the LT-PEM fuel cell systems, HT-PEM fuel cell systems, and low temperature SOFC systems, the overall fuel cell system cost would include the fuel processor as an additional cost component. The high temperature SOFC system does not have a fuel processor cost component; hence, the high temperature SOFC system cost should be lower relative to the other fuel cell systems reviewed here. All of the fuel cell systems require a desulfurization process to pre-treat the natural gas. The differences in system designs based on operating temperature should influence overall fuel cell system cost. Cost should be estimated based on production of 50,000 units per year.
- DOE reports the factory cost status for 2008 based on performance and on low volume production extrapolated to a 50,000-unit annual production cost.
- The DOE factory cost targets for 2012, 2015, and 2020 are guided by the perceived cost the market will accept and not by actual fuel cell system costs.

4.1 Independent Review Panel Assumption

The Independent Review Panel, along with DOE and the Fuel Cell Technologies Program's Systems Integrator, reviewed this group of assumptions and constraints, which formed the framework for the Independent Review Panel's analysis and interviews with the fuel cell industry.

The Independent Review Panel defined a high level fuel cell system block diagram, shown in Figure 1, which is generic and represents LT-PEM and HT-PEM fuel cell systems as well as SOFC systems.

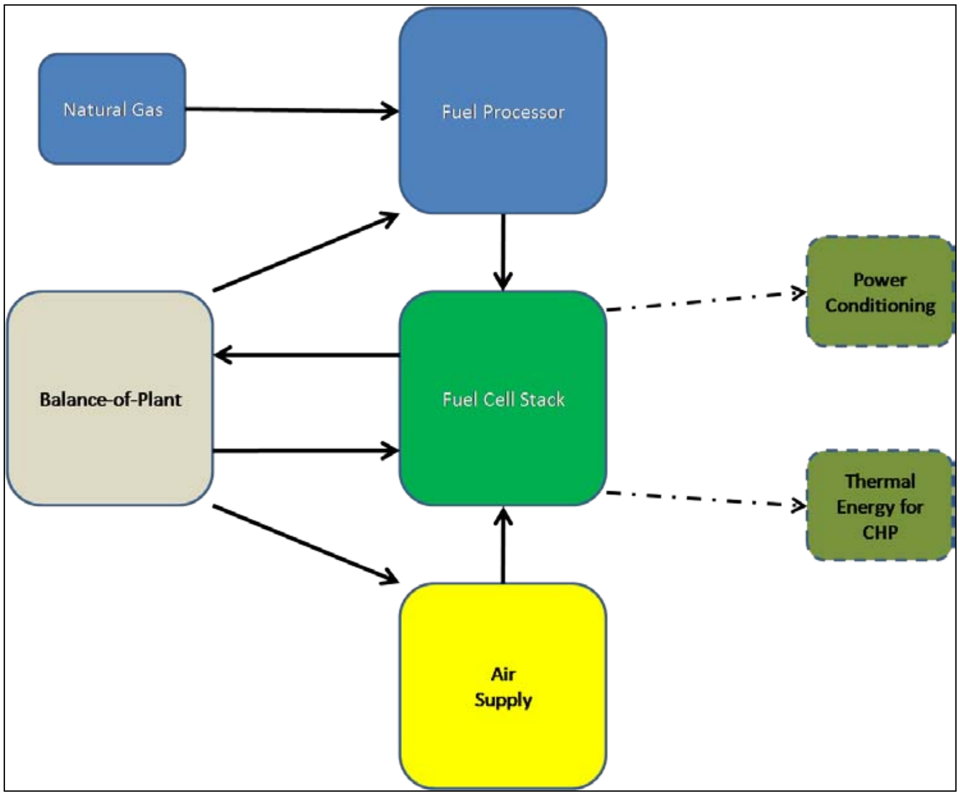

Figure 1. Block diagram of generic fuel cell system

The analysis and data collection focused on evaluating the major components and not on the sub-component detail; i.e., the focus would not be on catalysts, membranes, interconnects, the steam generator, or other stack and BOP components. The hardware requirements related to CHP thermal management and power conditioning subsystems were not addressed.

5 Evaluation of Cost and Technical Potential based on LT-PEM Technology

LT-PEM fuel cell systems have been used in applications in the low end of the 1–10 kW power range for more than 10 years. The majority of the development and product demonstration has been in Japan, with significant activities in South Korea and in Europe over the last 5–7 years. In all cases, the advances in technology and deployment have been assisted by government incentives to component suppliers, fuel cell development companies, and end users. To date, more than 11,000 LT-PEM fuel cell systems have been deployed in Japan [2], with electrical efficiencies as high as 38% based on LHV of natural gas and CHP efficiencies of up to 85%.

Most of the LT-PEM fuel cell systems deployed in stationary power applications operate at around 60°–65°C and at up to 3 psig, but some developers are using systems that operate at higher temperatures. These systems are fueled using reformate from natural gas, liquefied petroleum gas (LPG), and even kerosene in some demonstrations being conducted in Japan.

LT-PEM fuel cell systems represent the most mature technology today in the low end of the 1–10 kW power range. This technology has benefited from the greatest level of sustained development and broad-based demonstration in residential CHP stationary applications. However, there are some concerns that the low quality of heat produced could limit its application in areas beyond residential cogeneration where high heat quality is a requirement.

An additional operational issue related to LT-PEM fuel cell systems is the relative complexity of the reformer gas clean-up subsystem. At temperatures below 120°C, the stack's platinum-based catalysts are susceptible to performance losses at carbon monoxide (CO) levels in excess of 100 ppm. In general, these LT-PEM fuel cells require less than 10 ppm CO during regular operation, thereby increasing the cost and complexity of the gas reforming process.

5.1 Electrical and CHP Efficiency

The LT-PEM stakeholders confirmed that DOE's 2008 electrical efficiency status was well within the demonstrated capability of their systems. There was a consensus among stakeholders that achieving 40% to 45% electrical efficiency will be a stretch for LT-PEM fuel cell systems operating on reformed fuels, including natural gas. The CHP efficiency was reported to be as high as 85% with current product designs. However, the ability to achieve 90% efficiency, the 2020 DOE target, is a significant stretch unless the operating temperature can be increased beyond 60°–65°C, the operating temperature stated by most stakeholders, to offer the end user a higher quality of heat.

5.2 Factory Cost

The majority of LT-PEM fuel cell systems produced today are at a power level of 1 kW or less. While these systems were initially developed to meet the needs of the Japanese market, they have now been adopted in other countries in Asia and in Europe. The majority of stakeholders believe that the DOE cost targets are unnecessarily aggressive for this power level and that the technology is capable of reaching an end product (including water tank) selling price to the utilities of $5,000–7,000/kW by 2012–2015. As expected, system costs are very sensitive to production volume. Most stakeholders agree that while the DOE targets may be achievable at 50,000 units, at volumes closer to 5,000 units per year, costs could be double those cited in DOE's preliminary targets (Table 2).

As with all fuel cell applications, stack materials and BOP components are candidates for cost reduction, and improvements in manufacturing processes, such as the deployment of roll-to-roll processing and equipment, and quality control measures can increase yields and reduce costs. Leveraging the use of costly components developed for non-fuel cell applications, such as air management subsystems and power conditioning devices, is desirable.

When questioned about validation of factory costs, most stakeholders indicated that manufacturers have not yet completed sufficiently detailed analyses to a high level of confidence in their cost results. For the stack subsystem, one manufacturer identified cost potential for the

2012–2015 timeframe to be within the $1,000–$1,200/kW range, with an emphasis on producing products within the lower power levels of the 1–10 kW range in volumes in the low 10,000s. Catalyst cost remains an issue, given the requirements for high efficiency and greater than 40,000 h of durability. Gas diffusion media, bipolar plates, and sealing materials are cell components for which incremental cost reduction, without detriment to durability or efficiency, is desirable.

The cost of the reformer and its related components, including reformate clean-up, was not specifically addressed by the majority of stakeholders as a cost issue per se, but challenges associated with sulfur as a fuel contaminant and the development of a cost effective desulfurizer were noted by many to be worthy of further investment.

As with all fuel cell technologies being developed for stationary power applications, cost reductions related to air management subsystems and power conditioning devices were noted as areas for additional investment.

5.3 Transient Response Characteristics

The DOE targets for transient response are well within the performance levels already demonstrated for the LT-PEM fuel cell systems. While the reformer is the slowest responding subsystem on the order of 100s of seconds, it is assumed for transient response that the reformer is already at operating temperature. The response times for the rest of the LT-PEM systems are very fast, on the order of < 10 seconds.

For LT-PEM fuel systems operating in the grid-parallel mode, the grid would deliver supplementary power during the transient operation and effectively provide backup to the fuel cell. For systems functioning in a grid-independent mode, batteries or supercapacitors could be used to provide the power required during the transient.

5.4 Start-up Time

The start-up time for LT-PEM fuel cell systems depends on the reforming process used, e.g., steam reforming, partial oxidation, or autothermal reforming. For steam reforming, the start-up times from ambient temperature can be less than 30 minutes; this is projected to decrease to less than 10 minutes by 2015. For the lower power units in the 1–10 kW range, the smaller thermal mass of the reformer will ensure that start-up from ambient conditions, as defined by the DOE targets, is not a commercialization issue for LT-PEM systems.

5.5 Operating Lifetime

The majority of stakeholders responded that the DOE durability targets of up to 30,000 h are not a significant commercialization issue, while some stakeholders believe that a durability of 40,000 h is already achievable with today's technology, at least for the stack components. To go beyond this level of durability, a number of different strategies could be employed, depending on the cost of components. Stakeholders noted that existing residential heat and electrical systems require regular maintenance and replacement of parts due to failure and wear out. A similar approach could be employed for fuel cell systems, depending on the replacement cost of components, the ease of serviceability, and the frequency of repair. Most stakeholders said that a minimum of 10,000–20,000 h of operating lifetime would be required for commercial viability.

A majority of stakeholders noted that the components that suffered from the most frequent failures and required replacement most often were actually related to the balance-of-plant. However, the systems under evaluation today do not contain the components that meet the ultimate commercial cost targets, and there may be some tradeoffs between durability and cost as lower cost materials and components are utilized in system designs.

Almost all of the stakeholders challenged the target beyond 40,000 h, suggesting that this is not required to achieve commercial success. If such lifetimes were to be required beyond 2020, the objective would be best addressed through servicing and component replacement, rather than incurring the huge cost and timeline associated with developing the materials and designs to meet a 60,000 h operating life.

Some stakeholders suggested that operating lifetime alone is not the best indicator of value to the end users; using a metric of cost per kWh, while taking the complete cost of ownership into account, would be more useful. This metric would also have to take into account the variances between grid-connected and grid-independent systems. Some countries are providing incentive tariffs to end users for energy feedback to the grid, and in some cases for avoidance of use of grid energy, thereby freeing capacity for other uses.

5.5.1 Degradation with Cycling

The operational characteristics and design of LT-PEM fuel cell systems allow for rapid and frequent response to load cycling without significant detriment to performance and durability. One stakeholder noted that existing demonstration units have shown more than 2,000 ON/OFF real time cycles in an ongoing test with negligible loss in performance and an overall system operating life in excess of 30,000 h.

Through experience in developing automotive stacks, many stakeholders have gained fundamental understanding of the degradation process resulting from ON/OFF cycling as well as rapid load following behavior. This has led to improvements in materials and designs that have significantly reduced performance degradation during cycling for LT-PEM fuel cell systems in CHP applications.

Overall, most stakeholders were not able or willing to address this technical target in significant detail.

5.6 System Availability

A majority of stakeholders consider 97% availability to be a reasonable value for the current status of technology. Future systems will be optimized to meet the DOE availability targets for 2015 and 2020.

5.7 Capital Cost Reduction Through Manufacturing Capability

Existing LT-PEM fuel cell systems have demonstrated sufficient capability that they are ready for use in applications where the grid electricity price is high and in remote areas where the grid is either not available or is less reliable than in large urban areas. This capability will facilitate larger demonstration programs and early commercial growth, allowing for investment in manufacturing process optimization and deployment of higher levels of automation, which will in turn reduce capital cost. Increased confidence in the technology will generate the necessary in-field data to accelerate design improvements, drive down cost, and create the necessary sales volume to enhance the capability of the supplier network while building manufacturing understanding and efficiencies. While LT-PEM fuel cell systems are the most advanced and commercially viable in the low end of the 1–10 kW power range, these systems still require further cost reduction and enhancements in stack design and BOP components to become competitive with the cost and reliability of grid electricity. The low quality of heat currently produced from these systems will likely limit their adoption in certain applications. Opportunities to increase operating temperature without detriment to cost and reliability are being pursued.

6 Evaluation of Cost and Technical Potential based on HT-PEM Technology

HT-PEM fuel cell system development is ongoing in the United States, Europe, and Asia, with several product demonstrations, mostly in the United States, initiated in the last several years. HT-PEM fuel cell systems operate in the temperature range of 130°–180°C and are commonly reported to operate at 160°C. The operating pressure is atmospheric to ~2 atmospheres, depending on the manufacturer's cell stack and system design. HT-PEM fuel cell systems operating on reformed natural gas have electrical efficiencies of 40% to 45% at BOL. At operating temperature, the HT-PEM fuel cell system is tolerant to relatively high carbon monoxide concentrations of 1% to 2%, and as such does not require the more complex and expensive reformate clean-up systems seen in LT-PEM fuel cell systems.

The CHP efficiency of HT-PEM fuel cell systems benefits from the moderate fuel cell operating temperature and the quality waste heat from the fuel cell anode and cathode exhaust. The waste heat can be used to generate steam for the fuel processing system. The integration of the waste heat from the fuel cell exhaust is an important contributor to reaching 40% to 45% BOL electrical efficiency.

HT-PEM fuel cell systems perform similarly to liquid electrolyte PAFC systems and, for the HT-PEM fuel cell systems reported here, the membrane contains phosphoric acid as a component of the electrolyte. The HT-PEM fuel cell system fabricators report that the vapor pressure of phosphoric acid is reduced when the acid is bound in the membrane and acid loss degradation is reduced or possibly eliminated, dependent on the mole ratio of acid used to produce the final membrane. In the PAFC system, the design of the cell components significantly reduces the phosphoric acid loss.

6.1 Electrical and CHP Efficiency

The HT-PEM fuel cell system stakeholders stated that the 2012 and 2015 electrical efficiency targets are well within their capability, with some stakeholders reporting 2010 electrical efficiencies at 43%. There is a consensus among stakeholders that 45% electrical efficiency would be a difficult but feasible target to achieve in 2020.

All of the HT-PEM fuel cell system stakeholders agree that CHP efficiency of 85% is possible and in some cases has already been demonstrated. One stakeholder has demonstrated (in 2010) 88% CHP efficiency under laboratory conditions. The 2020 CHP efficiency target of 90% is a reachable goal based on stakeholder feedback. For these CHP efficiencies, the HT-PEM fuel cell system will deliver hot water at 60°C to 80°C.

One stakeholder, UTC Power, addressed the heat quality issue with a "high-grade heat option" for their commercial PAFC. This option uses some of the thermal energy (almost 50%) to increase the quality of the heat and deliver 125°C steam; however, the overall CHP energy efficiency for the high quality heat option is 60%–70%.

6.2 Factory Cost

Some of the stakeholders believe that factory costs higher than the DOE 2008 status by a factor of 2 or more are acceptable to some end users today. In some cases, present factory costs are 3 times the DOE 2008 status. Future cost potential identified by some of the stakeholders was greater than the DOE cost targets for 2015 and 2020.

One stakeholder suggested that the DOE targets are perhaps too stack-centric. Other subsystems, such as the inverter, will drive up the fuel cell system cost. Several HT-PEM fuel cell system stakeholders identified the high cost of power conditioning for fuel cell systems as a potential problem.

The validity of the potential factory costs responses may be questioned, because some of the respondents indicated that their answers were not based on a detailed analysis, but rather on estimates of where a fuel cell cost could be in 2012, 2015, and 2020.

Cost reductions based on manufacturing improvements such as high roll-to-roll processing for the cell components and improvements in material stability are important advancements necessary to approach the DOE factory costs, according to the stakeholders.

One manufacturer believes it can maintain high quality and achieve the target factory cost by keeping all production capability in-house; i.e., vertical integration of the manufacturing process. On the opposite extreme, another manufacturer proposes to outsource all of the stack component production to limit capital investment in manufacturing equipment and thereby achieve the factory cost targets.

6.3 Transient Response Characteristics

Stakeholders did not consider the transient response targets to be important for the 1 kW HT-PEM fuel cell systems in residential applications. These stakeholders consider the grid to provide backup power to the 1 kW HT-PEM fuel cell system; i.e., the system operates in a grid-parallel mode.

Rapid transient response times are < 10 seconds with battery or supercapacitor assist. The rate-limiting component for the rapid transient response is the reformer response. To achieve rapid response, the system needs to be designed with a surplus of hydrogen available to operate the fuel cell and compensate for the slow reformer response, in addition to the battery and supercapacitor assist. Without battery buffering, and once the stack/reformer is hot, a 5 minute transient response time is achievable with a 2 minute transient time possible in the future.

6.4 Start-up Time

A start-up time of 30 minutes in 2010 is presently feasible for one stakeholder. This stakeholder also stated that an improvement in start-up time was not needed. While asked, other stakeholders did not address start-up time for the HT-PEM fuel cell system. One stakeholder suggested that regular maintenance could be done "on the fly" without turning off the HT-PEM fuel cell system and that the only time the system would be turned off is for change-out of the cell stack, or every 40,000 h.

6.5 Operating Lifetime

The operating lifetime status for 2008 (6,000 h) and targets for 2012 (30,000 h), 2015 (40,000 h), and 2020 (60,000 h) are valid according to the HT-PEM fuel cell system stakeholders. The stakeholders' 2020 (60,000 h) operating life target is greater than the Panel's perspective in Table 1. Change-out of the cell stack at less than 40,000 h (5 years) was considered restrictive and too expensive by more than one stakeholder. The acceptance of these operating lifetimes by the HT-PEM fuel cell system stakeholders is strongly influenced by the similarities in the operating conditions of the HT-PEM fuel cell systems to the PAFC systems and the success of UTC Power in meeting the 60,000 h life for a commercial phosphoric acid fuel cell.

Some stakeholders expressed concern over acid loss, because this limits operational life. The acid loss problem was resolved by UTC Power for their larger (200 kW and 400 kW) models through continuous recycling of the acid within each individual cell. Similar technology could resolve acid loss issues for HT-PEM fuel cell systems. Other approaches include development of improved membrane materials that bind the acid within the membrane and significantly reduce its vapor pressure; advances in this area have been claimed by at least one stakeholder.

A critical issue for several stakeholders is the operating life of the BOP components, such as blowers and valves. For stationary applications, the lifetime of the furnace or boiler is a suggested measure of durability. However, thermal systems are not operated continuously, while power demand for a residential or commercial facility in many cases is continuous at some load level. The stakeholders recommended a minimum operating life of 40,000 h.

Stakeholders proposed that operating life should be qualified to mean operating life at rated power. Lowering the operating point of the fuel cell system to less than rated power can increase the operating life of the system; however, this effectively increases the purchase price per kW of the fuel cell system and increases the energy production costs. For commercial applications, stakeholders suggested that operating life be expressed in kWh. Operating life alone is not a good indicator of performance because commercial and residential users are concerned with $/kWh. This view is consistent with the LT-PEM fuel cell system stakeholder inputs on operating life.

6.5.1 Degradation with Cycling

One stakeholder reported degradation at 0.3%/1,000 h for 2008, which is considerably less than the < 2%/1,000 h status reported by DOE for 2008. The same stakeholder has set their 2015 degradation goal at 0.25%/1,000 h for 2015, which is less than half of the 2015 DOE target. It is unclear whether such low degradation rates are obtainable over 40,000 h, because these are early results. Other stakeholders did not directly address degradation but rather discussed durability of the cell stack as a critical issue.

Given the close association of HT-PEM fuel cell systems with PAFC systems through the phosphoric acid in the electrolyte, HT-PEM fuel cell system stakeholders anticipate similar degradation rates as the technology matures.

6.6 System Availability

The target for one stakeholder is 100% availability, but most stakeholders did not discuss system availability. HT-PEM fuel cell systems operating in the grid-parallel mode use the grid as backup and the availability target is readily met. The grid-independent mode is a more difficult problem to address. One stakeholder suggested Mean Time Between Forced Outages (MTBFO) as an additional target that may more appropriately define system availability.

6.7 Capital Cost Reduction Through Manufacturing Capability

Driving down stack cost components will be governed by manufacturing advances and increased yields. The big issue is how to bridge the gap between pilot scale and full scale continuous production. For many organizations, the present manufacturing approach is the "pick-and-place" manufacturing technology. Research and development on manufacturing automation and adaptation of appliance manufacturing technologies, e.g., manufacture of air conditioners, would drive down the cost of HT-PEM fuel cell systems.

High-cost components for the HT-PEM fuel cell system are the MEA catalysts and the bipolar plates. R&D efforts can drive down the material cost and result in capital cost reductions. The introduction of continuous, roll-to-roll processing for MEA manufacturing is an important step that needs to be completed to increase manufacturing rates with a concomitant reduction in cost.

Many stakeholders identified power conditioning as a prime area for cost reduction. Some stakeholders recommended that the cost of the fuel processor be addressed by manufacturing R&D. Mass production of reformers would greatly assist in the reduction of first cost for the HT-PEM fuel cell system. Another potential route to cost reduction is standardization of these BOP subsystems; commonality of BOP components would increase market volume and drive down costs.

7 Evaluation of Cost and Technical Potential based on SOFC Technology

Solid oxide fuel cells (SOFC) operate in three temperature ranges and use different electrolytes for each: low temperature from about 550°C to 600°C, usually consisting of ceria-based electrolyte; intermediate temperature from 700°C to 850°C, consisting of a thin zirconia- or lanthanum gallate-based electrolyte; and high temperature from 900°C to 1,000°C, consisting of a thicker zirconia-based electrolyte.

All of these SOFC systems are capable of generating power using hydrogen or carbon monoxide as the fuel. The lower temperature systems require an external fuel processing system to convert natural gas to reformate (hydrogen, carbon monoxide, carbon dioxide, and steam); however, the external fuel processor does not require a shift reactor to convert carbon monoxide and steam to hydrogen because the SOFC can use the carbon monoxide as fuel. The higher temperature units process the natural gas fuel to hydrogen and carbon monoxide internally in the stack or in the anode chamber of the fuel cell. Strict control of the carbon-to-steam ratio of the anode fuel feed gas prevents the formation of carbon deposits (coking) in the anode chamber during internal reforming.

SOFC systems operating on natural gas have a wide range of electrical efficiencies, from 35% to 60%, depending upon the operating conditions. The CHP efficiency of SOFC systems benefits from the high fuel cell operating temperature, and waste heat from the fuel cell can be used for thermal applications. The heat from the fuel and air exhaust is used to pre-heat the incoming reactants.

7.1 Electrical and CHP Efficiency

The SOFC stakeholders identified the 2012, 2015, and 2020 electrical efficiency targets to be well within their capability, with one stakeholder reporting 2010 electrical efficiency at 60%. These electrical efficiencies represent BOL values. The SOFC stakeholders report that performance degradation of the SOFC systems (discussed below) will reduce the electrical efficiency to 35%–40% at end-of-life (EOL).

One stakeholder suggested that operating at 60% electrical efficiency does not provide the optimum ratio of electrical efficiency and thermal efficiency and that lower electrical efficiency in the range of 35%, achieved by operating at higher current density, may better fulfill customer requirements for CHP.

Present CHP efficiency is 85%, and all of the SOFC stakeholders agree that the CHP efficiency target of 90% is possible and in some cases already demonstrated. The high quality of the SOFC heat readily satisfies the CHP targets.

7.2 Factory Cost

The SOFC stakeholders stated that the DOE factory cost targets were very aggressive. Some of the stakeholders report 2008 and current factory costs for the systems to be ~ $9,000/kW at low production volume. Some stakeholders suggested a factory cost of ~$4,500/kW at a production rate of 50,000 units per year. These system costs may reflect the high cost for SOFC balance-of-plant subsystems, such as heat exchangers for pre-heating the reactants, which are more exotic and costly at higher temperatures.

The SOFC stakeholders stated that the $/kW cost for a 10 kW system would be less than the $/kW cost of a 1 kW system. While the number, size, and cost of the cell stack repeat parts (anode-ceramic membrane-cathode, interconnects, and seals) would scale with the kW rating, the reduction in cost of the fuel processor, power conditioning unit, and other BOP components would not be proportional to the kW rating of a fuel cell system. The SOFC stakeholders' higher $/kW cost for 1 kW systems than for 10 kW systems is consistent with the stakeholder inputs for the LT-PEM and the HT-PEM fuel cell systems.

The high cost of SOFC systems is somewhat unexpected because they do not use a platinum catalyst. Instead, the high cost is due to expensive high temperature materials for interconnects, heat exchangers, manifolding, and power conditioning system. The minimum requirements for SOFC system cost [3] set by the Solid State Energy Conversion Alliance (SECA) are lower than the DOE 1–10 kW targets considered by the stakeholders. The discrepancy is due to differences in power rating; the SECA program considers multi-megawatt SOFC systems, while 1–10 kW SOFC systems are considered in this independent review.

7.3 Transient Response Characteristics

The transient response targets for 2015 and 2020 were reasonable according to most of the stakeholders for the 1 kW SOFC stationary residential applications. One stakeholder reported a present transient response time of 15 minutes; however, this was not considered an issue because the system operates in a grid-parallel mode and the electrical grid supplies backup power.

SOFC system stakeholders reported that rapid transient response (< 2 sec) is not possible when operating in the grid-independent mode, even with battery or supercapacitor assist.

7.4 Start-up Time

Start-up times for the SOFC stakeholders varied from 2.5 h to 20 h, well beyond the DOE 2008 status of 60 min. The SOFC stakeholders operate their systems continuously. Shut-down (with thermal cycling) degrades the performance of the SOFC systems. The longer start-up times represent SOFC systems designed for continuous operation, and modification of the system design to facilitate faster start-up times is considered an unwarranted cost by some stakeholders.

7.5 Operating Lifetime

The operating lifetime status for 2008 (6,000 h) is reasonable and has been demonstrated by more than one SOFC system stakeholder. A couple of stakeholders report operating lifetime at 10,000 h under well-defined conditions and control. Longer operating lifetimes in the range of 30,000 h (2012), 40,000 h (2015), and 60,000 h (2020) will be challenging, according to SOFC system stakeholders.

Some stakeholders consider change-out of the cell stack to be a solution to the operating lifetime issue. Other stakeholders consider stack change-out to be an unacceptable, expensive process. No stakeholders claimed that BOP life is an issue.

7.5.1 Degradation with Cycling

The degradation targets set by DOE are reasonable for SOFC systems, although there is a large variance in the degradation data. Some stakeholders report present degradation rates at 1%–2% per 1,000 h, while other stakeholders report degradation rates at 0.1%–0.3% per 1,000 h. Thermal cycles impact degradation considerably more than load cycles do. One manufacturer expects 200 thermal cycles to be achievable over the life of the stack with degradation at 2% per 1,000 h within a few years.

7.6 System Availability

The 97% availability status is reasonable for systems using today's technology. Future systems will meet the DOE availability targets of 98% and 99% by 2015 and 2020, respectively. One stakeholder considered reliability a more important issue than availability.

7.7 Capital Cost Reduction Through Manufacturing Capability

To date, fewer than 200 SOFC CHP systems have been deployed globally based on the Independent Review Panel's knowledge and as indicated by Fuel Cell Today [4]. These systems have been used to demonstrate different cell and BOP materials and designs. Very few companies have been able to gain significant manufacturing experience with these systems. As materials and designs for the SOFC CHP systems that meet the early commercialization targets and volumes for cost, lifetime, reliability, and overall functionality emerge, it appears appropriate that more efforts be directed toward manufacturing to reach the final cost target. Significant cost reduction and increased reliability can be achieved with investments in manufacturing process development, equipment design, on-line quality control procedures, and factory acceptance testing methodologies.

High-cost components for the SOFC CHP system are the cells and the interconnects. R&D efforts can drive down the material costs and result in capital cost reductions. Many stakeholders identified power conditioning as a prime area for cost reduction. Another potential route to cost reduction is standardization of BOP subsystems; commonality of BOP components would increase market volume and drive down costs.

8 Comparative Analysis of Key Fuel Cell Technologies

The three candidate fuel cell systems, LT-PEM, HT-PEM, and SOFC, have been discussed individually in sections 5–7. This section provides a comparative analysis of these three fuel cell systems.

8.1 Key Component Breakdown

A fuel cell system can be described in terms of cells (electrolyte membrane, anode, cathode, diffusion layers, bipolar plates) stacked in series to generate practical DC voltage. Sealing and thermal management are two critical aspects of a stack design. Proper sealing of cell edges and gas manifolds throughout different operating conditions is required for efficient operation over the life of the stack. Proper thermal management design is essential to maintain uniform temperatures in planar as well as in stacking directions. Steam required for reformer reaction is also generated in the thermal management subsystem.

A fuel cell system can be complicated. A fuel such as natural gas has to be converted to a H_2-rich feed with minimal sulfur; ambient air has to be cleaned up to remove any particulate and chemical impurities; and DC power generated by the fuel cell has to be converted to AC using a power conditioning system (PCS). Detailed evaluations of the individual systems were given in sections 5–7. An R&D effort is required to simplify the overall system, thereby reducing the cost while increasing reliability. Each of the fuel cell systems discussed here operates in different ways, depending on the technology, application, and end-user requirements.

Table 3 compares various components, subsystems, and other parameters for the three fuel cell technologies discussed in this report [5]. In sections 8.2 and 8.3, the major end-user requirements are examined from the perspective of typical characteristics of a given system.

Table 3. Comparison of Various Components, Subsystems, and Other Parameters for Three Candidate Fuel Cell Types [5]

Fuel Cell Type	Electrolyte	Operating Temperature	Electrodes	Bipolar Plate	Fuel Processor	Cooling	System Output	Advantages	Disadvantages
Low Temperature Proton Exchange Membrane (LT-PEM)	Solid organic polymer poly-perfluorosulfonic acid	60°–90°C	Noble metal	Graphite/carbon composite or metallic	External reformer, shift reactor, and selective oxidizer	Water cooling	< 1–250 kW	-Solid electrolyte with no electrolyte loss issues -Low temperature -Quick start-up	-Low temperature waste heat
High Temperature PEM (HT-PEM)	PBI or alternate polymer system, both with phosphoric acid	130°–180°C	Noble metal	Graphite composite or metallic	External reformer and shift reactors	Water/steam cooling	< 1–250 kW	-Higher overall efficiency with CHP -Increased tolerance to impurities in hydrogen	-Poor cathode performance due to anion adsorption
Solid Oxide (SOFC)	Stabilized zirconia or ceria	550°–1,000°C	Ceramic or cermet	Ceramic or metallic	Internal or external reformer	Air cooling and internal reforming	< 1 kW – multi-MW	-High efficiency -Fuel flexibility -Solid electrolyte reduces electrolyte management problems	-May not tolerate thermal cycling

8.2 Major Differences

8.2.1 Electrolyte and Operating Temperature

Solid polymer electrolyte membranes with high proton conductivity are utilized in LT-PEM and HT-PEM fuel cell systems. The LT-PEM fuel cell system uses perfluorosulfonic acid ionomers with a Teflon-like structure, in which all ion-exchange functionalities are chemically bound into the polymer. HT-PEM fuel cell systems use a different chemistry that is based on a polybenzimidazole (PBI) containing phosphoric acid. PBI is commercially available and used in many non-fuel cell applications. Because of a strong bond between phosphoric acid and PBI, phosphoric acid loss is minimized when the two compounds are used at equivalent molar ratios. However, acid loss remains a concern for performance and durability when excess phosphoric acid is used. Researchers are evaluating chemistries other than PBI to try to address the acid loss issue, as are the developers of the PBI-based membranes. A PBI-free electrolyte has been developed that incorporates phosphoric acid. This membrane is specifically synthesized for fuel cell applications and is claimed to be less susceptible to acid loss than PBI membranes are.

The fuel cell operating temperature dictates the quality of byproduct heat available for CHP applications. The LT-PEM fuel cell systems can operate at 60°–90°C, but most of the systems providing long life (30,000 h) were operated at 65°C. HT-PEM fuel cells operate at 130°–180°C and are therefore tolerant to higher levels of CO, on the order of 2%, in the fuel. At certain temperatures, SOFC systems can actually use CO as a fuel and therefore are tolerant to all CO levels, obviating the need for a shift converter and, in the case of LT-PEM fuel cell systems, a selective oxidizer.

Operating temperatures of 550°–1,000°C for SOFC systems imply longer start-up time, which has a strong influence on cyclic degradation rates. Byproduct heat from SOFC systems can produce high pressure steam and high quality hot water. Many SOFC system developers propose that because the system is capable of delivering high electrical efficiencies, it can be designed to operate continuously, thereby reducing the cyclic degradation rate.

8.2.2 Cell Design

The membrane-electrode assembly (MEA) is the heart of power production in PEM fuel cell systems. Heat released in the fuel cell reaction has to be removed for steady state operation. An effective cooling approach is critical for a simple, cost effective cell/stack design and therefore is a subject of many patents. Loading of a noble metal catalyst (mg/cm^2) is a major cost contributor. The loading also influences degradation rate and operating lifetime.

Electrochemically, SOFC systems operate differently from PEM fuel cell systems. In SOFC systems, oxygen ions are produced at a cathode and travel through a ceramic electrolyte to the anode. The cell construction for SOFC may be planar or tubular. The electrolyte layer is very thin to minimize resistive losses across the electrolyte. SOFC uses non-noble metal catalysts and therefore offers a cost saving in this regard.

8.2.3 Fuel Cell Stack

Two types of stacking approaches are used in candidate fuel cell systems: axial in-series and tube bundles. All PEM stacks use planar cell construction. SOFC stacks use planar or tubular designs. MEAs are placed on a bipolar plate in a planar cell construction. The cell temperature profile and bipolar plate material strongly influence the stability and cost of the bipolar plate. An MEA may provide sealing at the edges; otherwise a separate gasket is used. A gas diffusion layer (GDL) is used to maximize utilization of electrode surface area and assist in heat and water management for the stack. To assist in water management, the PEM GDL is made hydrophobic using Teflon. Some developers propose as many as seven layers and claim a negligible cost differential between five-layer and seven-layer MEA construction. The design of optimum cell size and number of cells in a stack is dependent on the operating voltage and current, cost of materials, stack components, and PCS as a function of DC input voltage.

The reactant gases have to be delivered uniformly for optimum utilization of cell area, especially in larger stacks. Strict quality control in manufactured parts is essential. External manifolding, internal manifolding, and hybrid manifolding approaches have been reported to provide adequate sealing and separation of fuel, oxidant, and coolant.

For SOFC systems, tubular cell and stack construction is expected to yield better gas sealing and thermal cycling capability, but it may be more expensive than planar construction, especially for stacks in the 1–10 kW power range.

8.2.4 Fuel Processor

Natural gas is assumed to be the fuel of choice for baseline residential or stationary CHP applications. Hydrogen is extracted from natural gas via steam reforming at 700°–800°C in an "external" reformer for PEM systems; autothermal reforming provides for a faster start-up, but it is more expensive. Waste heat from PEM is not available at reforming temperatures, so supplemental heat is provided by burning fuel, which penalizes electrical efficiency. For high temperature fuel cells such as MCFC and SOFC systems, waste heat is available at the reforming temperatures, so there is no electrical efficiency penalty. It is also advantageous to perform at least a part of the reaction in an "internal" reformer within the stack, which helps provide stack cooling and cell temperature uniformity.

A common comment by stakeholders was the need to develop a desulfurization subsystem. Odorants are added by pipeline gas companies for leak detection, but they are poisonous for PEM fuel cell and SOFC systems. Removal of these odorants requires expensive equipment and sorbents. Stakeholders suggested that these odorants should be standardized so that the same equipment can be utilized by different fuel cell systems and in different countries in Europe and North America. Some research into non-sulfur based odorants is being conducted in Japan. The results from the study may be used to recommend preferred odorants from a fuel cell viewpoint.

Different strategies are employed for recycle of exhaust fuel and for operating pressure, resulting in different impacts on cost and durability.

8.2.5 Air Handling

Large quantities of air are required for reactant air and for cooling. An industrial blower is generally inefficient and can consume significant amounts of power, taxing the system's electrical efficiency. A more efficient, cost-effective blower is desirable for all fuel cell technologies. Low-cost heat exchangers are desirable for heating or cooling various gas streams.

8.2.6 Power Conditioning System (PCS)
As mentioned before, DC power produced by the fuel cell is converted to AC power in a power conditioning system (PCS). The efficiency of this equipment is inversely proportional to the cost. The input operating voltage range also affects the cost of PCS. If the design can be standardized, order volume can be high, leading to cost reduction. The control system for fuel cell, fuel processing, and PCS can be integrated, reducing the total system cost.

8.3 Meeting End-User Requirements
The end user in residential applications is an individual home-owner, a multiple housing management company, a utility company, or an independent power producer. Power requirements may range from 3–5 kW for a single family home in the United States. Multiple fuel cell units may be sited to match the customer demand. The end user desires the following important characteristics from the on-site fuel cell unit:

- High electrical efficiency
- High thermal (CHP) efficiency
- 3–4 year return on investment (ROI)
- High reliability and durability.

These requirements were translated into quantitative technology and cost targets by DOE (see Table 2). Each of the three fuel cell systems meets some of the requirements; however, some trade-offs are needed for selecting one particular type.

8.3.1 Cost
A 2020 target of $450/kW is provided as a "factory cost" objective by DOE. The Independent Review Panel's interviewees indicated that this target is challenging for all three fuel cell types. Rather than a single value, the Panel estimated an experienced based range of "achievable" cost values for each technology given in Table 1.

Net end-user installed cost will be higher than the factory cost target. If any site engineering and site preparation is required, these costs should be accounted for in the overall economic analysis. For 1 kW units, both internal and external installations have been used; external installations were used in Japan to minimize regulatory issues. Larger fuel cell units, say 10 kW, could be skid-mounted, requiring minimal work at the site. Some assembly cost should be assumed for skid mounting at the manufacturing plant. Installation costs in the United States have been very high for small numbers of units; however, this is believed to be an infancy issue that will be resolved as regulatory bodies become more familiar with fuel cell technology and as volume grows.

The return on investment (ROI) for the end user will depend on fuel cell usage, spark-spread, electric versus thermal control, over- or under-sizing of the unit with respect to site demand, grid-connect versus grid-independence, thermal cycling profile and frequency, stack replacement frequency and cost, frequency of repair, and down time. A separate study is needed to quantify the cost related to fuel cell product capabilities. The 1–3 kW systems will be more expensive ($/kW) than 10 kW systems.

8.3.2 Technical Targets

Technical targets for the three fuel cell systems were deemed feasible by the interviewees, although some targets were characterized as "aggressive." Several interviewees stated that SOFC systems can easily exceed the DOE 2020 electrical efficiency target of 45%, but this may be at a small sacrifice to CHP efficiency. The SOFC system may require longer start-up time than the HT-PEM or LT-PEM fuel cell systems. One interviewee stated that start-up time was irrelevant for residential applications, especially where grid connection was included.

8.3.3 Manufacturing Status

Manufacturing capacity and experience reflect the level of technology and reliability of the fuel cell power plant. Significant global manufacturing capacity exists for LT-PEM fuel cell systems. The existing capacity for HT-PEM and SOFC power plants is not so mature.

Factory cost of a fuel cell system is governed by capacity factor and production volume. The manufacturer designs its manufacturing plant based on anticipated demand and demand growth. Manufacturing efficiencies that come with greater levels of automation cannot be effectively used at low production rates. When the sales volume is initially ramping up, the manufacturer's unit cost is higher than the projected cost.

8.3.4 External Factors

Sometimes external factors such as utility support and interest, national and state government policies, and strength of industry players influence the technical progress and future implementation of a fuel cell system. If the utility companies are willing to accommodate new technology on their grid and are willing to back up the power interruptions, infancy-related fuel cell failures will become less significant. A utility company may also own the stationary fuel cell unit and simply charge the end user for electricity and heat usage. The latter approach would make the financing and maintenance of the unit an easier task. National and state government policies have helped fuel cell development in Japan. Environmental-related initiatives have helped the growth of installed fuel cell capacity in Europe and California. All three fuel cell systems have benefitted from the support of the U.S. Department of Energy and Department of Defense.

Stakeholders commented that the technology, as well as developers and suppliers, will benefit if a strong industry player participates in the development process. On the other hand, the technology development decelerates if a large industrial player drops out.

9 Supplier Network

Fuel cell stack components as well as BOP components can be procured from suppliers outside the fuel cell company to minimize a developer's investment in working capital and manufacturing infrastructure. The manufacturer can then focus attention on the development and commercialization of proprietary fuel cell technology. For the LT-PEM and HT-PEM fuel cell systems, cell component supplier networks were encouraged by the fuel cell system manufacturers and integrators. As a result, several companies have established themselves as suppliers of catalysts, membranes, MEAs, and bipolar plates. On the other hand, the SOFC and MCFC system manufacturers have vertically integrated the manufacture of cell components for the assembly of these high temperature fuel cell systems.

Based on fuel cell system type, the cell stack generally includes the following components:

- Electrolyte layer (SOFC systems) or membrane layer (LT-PEM and HT-PEM fuel cell systems)
- Anode and cathode layers
- Gas diffusion layers (GDL) for some systems including a microporous layer (LT-PEM and HT-PEM fuel cell systems)
- Gas flow and current collection layers with specific geometry: bipolar plates (LT-PEM and HT-PEM fuel cell systems) or interconnects (SOFC systems)
- Gas seals, gas manifolds, and stacking hardware.

The supplier network is the source of BOP components, or subsystems other than the stack itself, and includes:

- Fuel clean-up and fuel processing to extract H_2 from pipeline natural gas
- Water treatment and water/steam management
- Air supply subsystem, air blower, and heat exchangers
- Power conditioning system (PCS).

Other subsystems and components manufactured by the supplier network include:

- Controls, sensors, electric grid interface, and heat recovery system.

BOP components can easily make up 50% or more of the fuel cell system cost. Sometimes their availability is unreliable. As such, a mature supplier network is important for overall cost reduction.

9.1 Status of Supplier Network

The principal fuel cell manufacturers often keep their fuel cell design proprietary and tend to keep the manufacturing of fuel cell and stack components under their direct control. This approach is often slow and too costly. On the other hand, the fuel cell manufacturers are not experts in BOP components, and therefore they need industrial vendors to design, develop, and manufacture these components to their specifications. The cost to do this depends on such factors as total volume of the order and commonality of components. Using commercial suppliers is therefore a pathway to overall system cost reduction.

Cell components for SOFC and HT-PEM systems are presently available only in small quantities. The supply network for cell components is more developed for LT-PEM. Bipolar plate design and stack hardware are generally considered proprietary and are procured on a special order basis. In many cases, a completely assembled stack is available for system integrators. BOP subsystem components that are made to provide specified output are produced a few systems at a time and are being further developed. Power conditioning subsystems (PCS) are considered by most stakeholders as "very expensive," even though similar systems are available in the wind and solar industries. Therefore, further work on PCS would be welcome. The development effort on other subsystems and components has been limited. Section 9.2 summarizes specific feedback from stakeholders in regard to the priority aspects of supplier network development.

9.2 Establishing a Mature Supplier Network

Stakeholders suggested the following strategies and actions as high priority:

- Involve suppliers from the design phase through the development and manufacturing stages. Form an academia, industry, and supplier collaboration for cost-effective development and commercialization of specific components.
- For sustained involvement of the supplier and for low-cost components, DOE should consider facilitating orders with large volume and density. (For example, 1–10 kW units may require volume orders of 1,000 to 10,000 systems per year.) It should be noted that suppliers need to earn profits across all scales of manufacture if they are to survive financially. This comment was made by many of the stakeholders.
- To create large-volume orders for an individual component, standards and specifications should be established. Key components are the power conditioning system, fuel processor, high efficiency blower, and air handling systems. Stakeholders recommended that DOE should participate proactively in establishing standards and specifications. The Japanese government example was often mentioned as a model of successful development of suppliers. The Japanese government actively engaged the suppliers, helped develop standards and specifications, and supported installations of a large number of 1 kW systems. DOE should formulate a long term (5-year) plan for research and development, scale-up, and field testing. To initially generate large order volume, the fuel cell units could be installed at national laboratories and government buildings.
- The selected supplier should have adequate quality control systems and resources for large-volume manufacturing. If these requirements are not met, the supplier may not be successful or reliability may suffer.
- Additional strategies may include the use of commercially available parts for existing product lines. Manufacturers may find similar components in the automobile, aerospace, solar, and wind industries. Components from other power generation technologies may also be more cost effective. Offshore procurement of materials and parts as well as offshore manufacturing should be considered.

10 Recommendations

The following recommendations were arrived at using a combination of feedback and interactions with DOE and NREL staff, interviews with key stakeholders and experts in each of the three key technology areas, as listed in Appendix B, and the Independent Review Panel's significant industry experience.

Cost and Technical Targets

- The factory cost definition should be revisited to provide a clearer position on which components are included and which are excluded. This definition should take into account the fact that some technologies require different components, especially those related to natural gas reforming. Key technical criteria should be specified separately for each fuel cell technology to reflect the inherent differences in maturity, design, and operational strategy.
- Mean Time Between Forced Outages (MTBFO) should be adopted as a more accurate and meaningful measure of system availability. For example, a MTBFO of 2,920 h represents a 99% availability based on a yearly scale and would clearly state the time period between interruptions.
- Factory cost and certain technical requirements (e.g., start-up time) do not scale linearly with power level. As such, it may be useful to split the targets into two power ranges, to be defined with the assistance of a more detailed market study.

Areas for Further Development

- A rigorous, bottom-up, manufactured cost evaluation for each technology is critical to ascertain investment focus in areas that will provide the earliest and highest returns.
- Technology and supplier development support directed toward power conditioning, air management, and desulfurization subsystems will bring value to all fuel cell technologies.
- There is a direct link between electrical efficiency and thermal efficiency. Given this linkage, we recommend a market study be done to clarify the optimum balance between electrical and thermal efficiency from an end-user perspective.
- A more detailed analysis of the required operational lifetime, including how it can be most cost-effectively achieved, would be beneficial, especially for the 2020 target of 60,000 h.
- Early investments in manufacturing process optimization, quality control, codes and standards development, and service and maintenance strategies will help drive cost reduction and customer acceptance.

Path to Commercialization

- Government support programs, such as direct rebates that reduce the high cost of capital, feed-in tariffs and credits for off-grid electricity generation, or market transformation programs that purchase stationary fuel cell systems, should be considered as positive methods to accelerate volume production, reduce cost, and increase commercialization of stationary CHP fuel cell systems.
- Partnerships should be fostered between utility companies and fuel cell developers to encourage the development and deployment of grid-connected products. Coupled with

incentives for end-user sale of surplus electricity back to the grid, these efforts will provide a greater value proposition for fuel cell adoption.

- To reflect the differing levels of maturity and to facilitate further development in meeting commercialization targets, a different approach will have to be pursued for each fuel cell technology, especially for the stack components. Technology and components from other applications can be leveraged; e.g., PAFC materials are likely viable for use in HT-PEM fuel cell systems.

General Recommendations

- Broadening the focus beyond residential cogeneration, the most cost-sensitive application, will provide opportunities for early markets that are less cost sensitive while assisting in the transition to this higher-volume application.
- Supporting activities that help grow effective supplier networks from raw materials to final systems and encouraging supplier involvement and cooperation in the early design phase of a new system can reduce product development cost and cycle times.
- Defining a "cost-of-use metric," such as $/kWh, that would take into account incentives like feed-in tariffs associated with grid connection and avoidance of grid electricity use could help offset end-user concerns regarding initial high capital cost and payback.

11 References

1. U.S. Department of Energy. "DOE Releases Preliminary Fuel Cell Cost and Technical Targets for Combined Heat and Power and Auxiliary Power." Washington, DC: U.S. Department of Energy; November 17, 2009. http://www1.eere.energy.gov/hydrogenandfuelcells/news_detail.html?news_id=15626.
2. Hisao, W. "Commercialization of Residential Fuel Cell Systems at Tokyo Gas." Presented at the 20th World Energy Congress, Rome, Italy, 2007. http://www.worldenergy.org/documents/p001503.pdf.
3. 2009 SECA/Fuel Cells Accomplishments Summary. Pittsburgh, PA: U.S. Department of Energy National Energy Technology Laboratory. http://www.netl.doe.gov/technologies/coalpower/fuelcells/publications/SECA_FC_Accomp_Summary_2009.pdf.
4. Fuel Cell Today. "Semi-Annual Legislation Review: April 2010." Fuel Cell Today Web site; July 22, 2010. Available at http://www.fuelcelltoday.com/media/pdf/surveys/2010-April-Half-Yearly-Legislation-Review.pdf.
5. Adapted from DOE/EERE fuel cell comparison chart: U.S. Department of Energy, DOE Hydrogen Program, "Comparison of Fuel Cell Technologies." Washington, DC: U.S. Department of Energy; December 2008. http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf.

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- Darlene M. Steward, NREL, for fuel cell power model for CHP and CHHP economics and performance analysis.
- Kathyayani Mahadevan, Battelle, for evaluation of the market opportunity and techno-economic potential of fuel cell micro-CHP products.

Appendix A. Independent Review Team

The National Renewable Energy Laboratory identified and contracted with the following four fuel cell industry experts, who have combined experience of more than 60 years in R&D and manufacturing and more than 110 years specifically in fuel cells.

Dr. Hansraj C. Maru is internationally recognized as an expert in fuel cell technology. After earning his bachelor's degree in chemical engineering from the Indian Institute of Technology, he earned both his master's degree ('70) and his Ph.D. ('75) in chemical engineering at Illinois Institute of Technology. He is best known for his pioneering contributions in developing and commercially introducing ultra-clean, high-efficiency, stationary fuel cell power plants using fuel cells (Direct Fuel Cells) that create virtually no air pollution. Maru has overseen the growth of these power plants, which are currently installed in many countries and on the verge of large-scale deployment. Dr. Maru has total of 40 years of experience in fuel cells, including 29 years at FuelCell Energy (FCE). FCE, which produces Direct Fuel Cells, began with only three employees in 1970 and currently consists of 500 employees. Maru, who has a talent for solving multidisciplinary technical problems in the energy industry, has been an integral part of the company's immense growth, holding a number of technical and management positions in the 29 years since joining the firm in 1977. Over the years, he has served as vice president of research and development, executive vice president, and chief technology officer of FuelCell Energy, Inc. In addition to carbonate fuel cells, Dr. Maru guided research in phosphoric acid, polymeric electrolyte membrane (PEM), and solid oxide fuel cells (SOFC). Dr. Maru retired as CTO, but he continues to serve as a consultant in fuel cells. Prior to FCE (previously known as Energy Research Corporation), Dr. Maru worked for 8 years at Institute of Gas Technology in the fields of fuel cells, hydrogen, and energy storage. Maru holds 13 patents, and he has authored more than 160 publications. He has edited four symposia volumes and contributed chapters in two books. Maru's work has been recognized with the 2004 F.T. Bacon Medal Award, which is given to those exhibiting leadership and accomplishment in fuel cell technology. He was also honored with the 2003 Mass High Tech All Star Award for his contributions to fuel cell technology. Dr. Maru was awarded IIT Alumni Professional Achievement Award in 2008. He was awarded Electrochemical Society's New Electrochemical Technology (NET) Award and Fuel Cell Seminar Award in 2009.

Dr. Subhash C. Singhal is a Battelle Fellow and Director, Fuel Cells at Pacific Northwest National Laboratory (PNNL). He obtained a Ph.D. in Materials Science & Engineering from the University of Pennsylvania and an M.B.A. from the University of Pittsburgh. Dr. Singhal joined PNNL in April 2000 after having worked at Siemens Power Generation (formerly Westinghouse Electric Corporation) for more than 29 years. At PNNL, Dr. Singhal provides senior technical, managerial, and commercialization leadership to the laboratory's extensive fuel cell and clean energy programs. At Siemens/Westinghouse, he conducted and/or managed major research, development, and demonstration programs in the field of advanced materials for various energy conversion systems including steam and gas turbines, coal gasification, and fuel cells. From 1984 to 2000, he was manager of Fuel Cell Technology there and was responsible for the development of high temperature solid oxide fuel cells (SOFCs) for stationary power generation. In this role, he led an internationally recognized group in the SOFC technology and brought this technology from a few-watt laboratory curiosity to fully-integrated 200-kW size power generation systems. He has authored more than 85 scientific publications, edited 14 books, received 13 patents, and given almost 300 plenary, keynote, and other invited presentations worldwide. Dr. Singhal is a member of the U.S. National Academy of Engineering and the Washington State Academy of Sciences; a Fellow of four professional societies (American Ceramic Society, The Electrochemical Society, ASM International, and American Association for the Advancement of Science); and a senior member of the Mineral, Metals & Materials Society (TMS). He served on the Electrochemical Society's Board of Directors during 1992–1994, received its Outstanding Achievement Award in High Temperature Materials in 1994, and continues to serve as the Chairman of its International Symposium on Solid Oxide Fuel Cells, held biennially since 1989. He served as President of the International Society for Solid State Ionics during 2003–2005. He received the American Ceramic Society's Edward Orton Jr. Memorial Award in 2001; an Invited Professorship Award from the Japan Ministry of Science, Education and Culture in 2002; the Christian Friedrich Schoenbein Gold Medal from the European Fuel Cell Forum in 2006; the Fuel Cell Seminar Award for outstanding leadership and innovation in the promotion and advancement of fuel cell technology in 2007; and the prestigious Grove Medal in 2008 for sustained advances in fuel cell technology.

Dr. Charles Stone, sole proprietor of EON Consultants Ltd., specializes in fuel cell technologies and provides strategic business and technical consulting services in various fields of green energy. Dr. Stone began his career with Ballard Power Systems in 1990 as a research scientist after completing his Ph.D. at the University of British Columbia. He took on increasingly senior roles at Ballard, becoming vice president of research and development in 2002. In this role, Dr. Stone had overall responsibility for fuel cell stack technology development, in addition to executive responsibility for intellectual property. During his tenure at Ballard, he developed significant expertise in establishing and managing key strategic supplier and end-user partner relationships. Dr. Stone left Ballard in March 2007 to start his own consulting firm in the area of green energy. Dr. Stone completed a double M.B.A with the University of California at Los Angeles and the National University of Singapore in 2008. In these studies, he received the C.H. Wee Gold Medal of accomplishment as the top ranking student in his graduating year. He has advised various government and private entities on technology and product development strategy, supplier and end-user development activities, and technology and product portfolio management.

Mr. Douglas Wheeler, sole proprietor of DJW TECHNOLOGY, LLC, provides complete services in the areas of manufacturing, cost analysis, and market analysis for fuel cell systems, hydrogen production technology, and hydrogen purification technology. Mr. Wheeler was manager of technology and government contracts at UTC Fuel Cells (now UTC Power) for 18 years. At UTC Fuel Cells, he managed the Advanced Technology team during UTC Fuel Cells' transition from phosphoric acid fuel cells to PEM fuel cells. DJW TECHNOLOGY's expertise in proton exchange membrane fuel cells, phosphoric acid fuel cells, and reforming of hydrocarbons to fuel cell grade hydrogen provides the basis for contracts with the U.S. Department of Energy through the National Renewable Energy Laboratory, the U.S. Department of Defense, the University of Hawaii, and private industry. Research and development programs support the Office of Naval Research and the Naval Research Laboratory. DJW TECHNOLOGY's technical expertise in stationary, portable, and transportation fuel cells is complemented by expertise in renewable energy and energy efficiency. Management experience and communications skills allow DJW TECHNOLOGY to provide a full range of services.

Appendix B. List of Stakeholders Contacted

Companies

- Acumentrics
- Advent
- Ballard
- BASF
- Baxi Innotech
- Ceres Power
- ERDC/CERL
- Ceramic Fuel Cells Limited (CFCL)
- ClearEdge Power
- Delphi
- e4tech
- FuelCell Energy
- Fuji Electric
- Hydrogenics
- IdaTech
- Intelligent Energy
- Kyocera Ceramics
- Logan Energy
- Nuvera
- Plug Power
- Samsung
- Siemens Stationary Fuel Cell Systems
- Tokyo Gas
- Topsoe Fuel Cells
- Toshiba
- UTC Power
- Versa Power Systems
- Zentrum für BrennstoffzellenTechnik (ZBT GmbH)

Organizations

- DOE-Fossil Energy Solid State Energy Conversion Alliance (SECA)
- Battelle

National Laboratories

- National Renewable Energy Laboratory (NREL)

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