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FUEL CELL AND DISTRIBUTED GENERATION RESEARCH, DEVELOPMENT, AND DEMONSTRATION PLAN

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

- PIER funding efforts are focused on the following RD&D program areas:
- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Fuel Cell and Distributed Generation Research, Development, and Demonstration Plan is the final report for the Research, Development, and Demonstration Plan for Fuel Cells project (Contract Number 500-02-004, work authorization number UC WA MR-068) conducted by the National Fuel Cell Research Center. The information from this project contributes to PIER's Environmentally Preferred Advanced Generation Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

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Abstract

Barriers to fuel cell commercialization are regularly introduced as general challenges, such as cost and durability, but without a description of what is meant by the terms and without prioritizing the degree to which the perceived barriers hinder the development of fuel cell technology. This work acts to objectively delineate the importance of technology barriers to fuel cell commercialization in California and to suggest actions to overcome these barriers.

The foundation of the research was an exhaustive review of prior studies directed at determining technical hurdles for fuel cell technology. Working with stakeholders through the design and implementation of unique surveys, technical hurdles were identified, and projects to address the technical hurdles were developed. To prioritize the information, a unique blend of personal communications, workshops, and Web-based surveys were used. This method resulted in a wide and comprehensive scope of the technical challenges hindering the commercialization of fuel cells in an effort to provide value to the technical community, the California Energy Commission in the scoping of research priorities, and those responsible for policy.

Keywords: Fuel cell, commercialization, barriers, benchmarks, milestones, surveys, roadmap, action plan, technology gap, technology issues

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Executive Summary

The work presented herein represents a multi-year collaborative effort between the California Energy Commission (Energy Commission), the National Fuel Cell Research Center, and the fuel cell community. Major deliverables resulting from this work include identification and classification of fuel cell technology status and the development of a technology roadmap and action plan for use by the Energy Commission's Public Interest Energy Research (PIER) Program. Results will be integrated into its five-year fuel cell technology research, development and deployment plan. The goal of this five-year plan, like the roadmap and action plan from this work, is to develop a strategy to drive the development and market acceptance of fuel cell technology in the most cost- and time-effective manner possible.

Advancing the development and marketability of fuel cells requires that the barriers hindering this development be addressed. Understanding the current technology status (benchmarks), the desired technology status (milestones), and the commercialization barriers hindering further development is required to achieve the desired status for fuel cell technology. Using previous roadmaps and action plans along with extensive feedback from the fuel cell community, a list of benchmarks, milestones, and commercialization barriers for fuel cell technology are developed. The barriers or technology gaps represent issues that if addressed will enhance the market feasibility and acceptance of fuel cell technologies. It was determined that the best technique to bridge the gap between benchmarks and milestones is to develop a detailed list of projects in which each project addresses a collection of the commercialization barriers. This technique allows for a high resolution of issues while presenting the material in a form that will be conducive for the Energy Commission's PIER Program or any other interested group to pursue or solicit proposals for one or more of the prioritized projects.

Prioritization of the collected list of projects was accomplished using the response of the fuel cell community to several surveys, fuel cell workshops and additional stakeholder feedback. Information about the projected cost, duration and overall value for each project (score) resulted from the survey and workshop feedback. These parameters are the main elements used to develop the fuel cell technology roadmap and action plan. Key findings are listed below.

An analysis of the commercialization barriers concluded that the c*ost/value to customer* barrier is the most important parameter when determining the value of a project to bridge the gap between fuel cell technology benchmarks and milestones. The second highest ranking barrier is s*ystem integration*. These two are followed in order by c*ustomer requirements*, r*eliability*, c*ontrol*, e*missions*, e*fficiency*, and *cost reduction*. The least important barriers hindering fuel cell commercialization are *transient operation*, *safety*, *power and energy density*, *size and weight*, and *decommissioning / recycling*.

Researches determined that the most important technology category to pursue is the *Grid-Distributed Generation (Grid-DG) Connectivity* category. That means if the projects within this category are pursued, they are the most likely to provide the greatest benefit to the fuel cell industry and fuel cell users. The *Grid-Distributed Generation Connectivity* category encompasses equipment interconnection and interaction with the electrical distribution network, ancillary services and service agreements between the fuel cell installer and the utility. Ancillary services refer to those services that are necessary to support the transmission and distribution of electric power from the seller or power generator to purchaser or loads while maintaining reliable operation. The second highest ranking category was the *Opportunity Fuels* category. This category includes the production and use of renewable fuels like digester gas and landfill gas, waste fuel streams and other opportunity fuels. The third highest ranking category is the *Transportation* category followed by *Fuel Cell – Gas Turbine Hybrid*, *Episodic*, *Grid Support*, *Distributed Generation/Combined Cooling, Heating and Power (DG/CCHP)*, *Energy Storage*, *Fuel Cell Cross-Cutting*, and *Materials Handling* categories. The 10 lowest ranking projects include *Materials Handling*, *Hydrogen Fuel*, *Portable*, *Solid Oxide Fuel Cell (SOFC)*, *Balance of Plant*, *Market Cross-Cutting*, *Molten Carbonate Fuel Cell (MCFC)*, *Proton Exchange Membrane Fuel Cell* (*PEMFC)*, *Phosphoric Acid Fuel Cell* (*PAFC)* and *Direct Methanol Fuel Cell* (*DMFC)* categories. A low ranking does not mean that there are not important and worthy technology development aspects to any one of the 19 technology categories that is ranked lower than others; however, a low ranking indicates that the fuel cell community believes there is more benefit in pursuing topics in the higher ranking categories.

Another analysis conducted for the work is a keyword analysis study of projects grouped by similar types. Some of the types of projects included: hybrid systems, carbon sequestration, material and fuel impurities, demonstration and deployment projects, manufacturing, environmental issues, fuel reforming, grid-related issues, and performance characteristics. Thus, the scores for all of the projects relating to improving performance characteristics or the projects that consider demonstration and deployment activities are averaged to determine if any specific groups of projects will provide additional benefit. From this analysis it was determined that projects relating to demonstration or deployment of fuel cell technology are of higher importance than the typical project. This was corroborated by a 13 percentage point increase in the average score of demonstration and deployment projects over the average of all the projects. Similarly, environmental and grid-related issues are 11 percentage points above the average with a significant natural break between these two groups of projects and the next project group. None of the project groups that were below the average score are far enough from the average to be definitively less important than the others. A summary of the highest ranked items from each analysis is presented in the figure below (Figure 1).

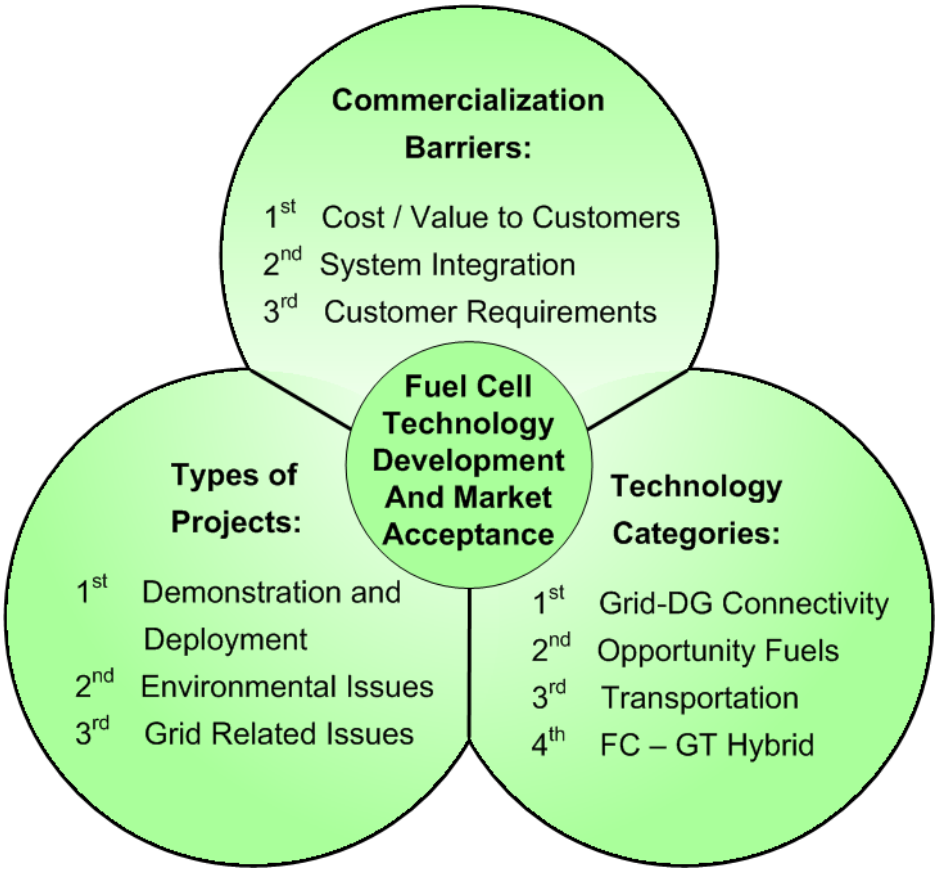

Figure 1: Summary of the Major Findings
Source: National Fuel Cell Research Center.

While the roadmap is meant to be like a compass, pointing technology research efforts in the direction of where the fuel cell community believes the research can provide the most benefits, the action plan is like a map used to chart the specific coordinates that should be taken to further develop and commercialize fuel cell technology. Using these definitions, the roadmap contains information about which general technologies are of particular interest and includes some insights into the duration and appropriate timing for each technology. This establishes the areas the fuel cell community believes to be the most critical areas to pursue to address the identified barriers. The action plan completes the fuel cell technology analysis by taking the highest ranking projects along with the expected cost and duration values for each project and organizing them based upon their importance. Additionally, the commercialization barriers that each of the highest ranking projects will potentially address is presented in the action plan, thereby establishing a detailed strategy to bridge the gap between fuel cell technology benchmarks and milestones. The overall technique employed for this work provides insights into not only which fuel cell commercialization barriers pose the most significant challenges to fuel cell development but also presents a strategy, validated with fuel cell community input, to address those barriers and further technological

development and market acceptance of fuel cells. The major recommendations resulting from this work are presented below.

- There is a great need to pursue grid-connected fuel cell research, development, and demonstration (RD&D) that addresses fuel cell **electrical distribution network issues** as they relate to fuel cells. This sentiment was echoed by the high average score and rank for the *Grid-DG Connectivity* category and the keyword analysis. For instance, deploying and demonstrating more grid-connected fuel cell systems that can test the methods and equipment for connection, requirements for transmission and distribution of power, and interconnection processes are the types of projects that were considered to be the most important to pursue. Issues associated with providing grid support (for example, at utility substations with very large fuel cell systems) were identified as the third most important type of project to pursue. Addressing fuel cell grid-connected installations and grid related issues also was determined to have a notable impact on fuel cell commercialization barriers facing California and more broadly the world.

- The importance of **demonstration and deployment activities** was a recurring theme throughout the analyses. Survey participants typically ranked these types of projects higher and, as a result, many of the highest rated projects within each category include demonstration or deployment of a specific technology. This is especially true for the *Market Applications* categories. Demonstration and deployment projects have the potential to address many commercialization barriers within the context of a single project. That is to say, a single demonstration project can address multiple barriers like performance, cost, market and other issues while it might take several more fundamental research projects to address the same number of barriers.

- The **development and commercialization** of fuel cell technology is often associated with a time frame. Fuel cells are penetrating distributed generation, materials handling, and backup power markets, but with limited numbers and for limited applications. It is recommended that the concept of *time to commercialization* be replaced with, *remaining barriers to commercialization*. Thus, instead of speculating upon the number of years required for widespread market penetration, the cost-competitiveness of a set of technology and the policy barriers should be used to better express the status of the technology. This will provide a more tangible understanding of the needs for fuel cell technology development and can be used to establish a more detailed and explicit time estimate.

- The **Opportunity Fuels** category was the second most important technology category. Furthermore, two projects under this category ranked highest and third highest. The importance of this area was explicitly noted in the comments from fuel cell stakeholders and should not go without notice. Opportunity fuels have

the potential to increase the sustainability of power generation while addressing climate concerns and should be pursued accordingly.

- The **Fuel Cell – Gas Turbine (FC-GT) Hybrid** category should be considered for further research and development. This category was ranked fourth out of all of the nineteen technologies categories and within that category has the second highest ranking project. The fuel cell community feedback highlighted not only the current challenges facing this area, but also the potential that further development of this technology could have. FC-GT Hybrid system development includes all three of the most important types of projects found in this work (that is, demonstration and deployment, environmental issues, and grid related issues). This technology has the potential to affect the large-scale stationary power sector as well as the distributed power sector and presents the hybridization of two distinct technologies that can provide unique synergistic benefits.

Benefits to California

The project addresses the PIER goal of reducing the environmental impacts of electricity generation, distribution, and use, and enhancing California's economy through the potential increased use of fuel cell technology. Fuel cells have tremendous potential, being the most environmentally benign of the distributed generation technologies that consume either natural gas or alternative fuels. Fuel cells also offer remarkable opportunity to increase energy efficiency and lower electricity costs in the future. However, the fuel cell technology is significantly different from other power generation technologies and faces significant barriers to its widespread adoption to provide clean and efficient heat and power in California. This project identified and analyzed these barriers and developed a pathway to help overcome those barriers. The roadmap and action plan developed by the project were comprehensive and contained inputs from various stakeholders. The action plan contained specific recommendations on RD&D and expected benefits to California ratepayers, while the roadmap overlays the scientific and technology hurdles, milestones, and RD&D projects to show how actions can hasten the acceptance of fuel cell systems. Full benefits can be realized with the implementation of the research, development and demonstration plan for fuel cell. Implementing this plan can help achieve cost-effective, clean, environmentally benign, and high efficiency fossil and alternative fuel-based distributed generation in California. The information generated by the project can be used to benefit the political community that is working to address legislative and regulatory challenges for fuel cells as well as the technical community of engineers and scientists that are laboring to solve the technical challenges facing fuel cells.

1.0 Introduction

1.1. Goal

Fuel cells have tremendous potential but face significant barriers in providing clean and efficient heat and power to California. The State of California has limited resources that it can invest to advance energy efficient and environmentally sensitive energy technologies. With limited resources, it is important that California ratepayer funding be wisely used. It is also important that California ratepayer funding be focused on technological advances that can best meet the needs that are particular to California and the technology advancements that have the potential to significantly leverage the investments of others (e.g., industry, federal government, academia) to make a contribution to technology advancement. To accomplish this, a thoroughly developed plan is needed that (1) considers an applicable subset of scientific and technology hurdles together with the current energy technology landscape, competitive technologies, and distribution grid needs, and (2) coordinates California investments and research and development strategies with those of the U.S. Department of Energy, other states and local jurisdictions, industry, and others.

This project meets the Public Interest Energy Research (PIER) goal of reducing the environmental impacts of electricity generation, distribution and use and enhancing California's economy through the potential increased use of fuel cell technology. The goal of the project is to develop a strategy to drive the development and market acceptance of fuel cell technology in the most cost and time effective manner possible. This is part of a long term goal to achieve cost effective, clean, environmentally benign, and high efficiency fossil and alternative fuel-based distributed generation in California.

1.2. Objectives

The overall objective of this project is to develop a Research, Development, and Demonstration Plan (hereinafter called *The Plan*) that defines an integrated set of research, development and deployment (RD&D) and technology transfer activities to be taken by the PIER Program to improve the performance and cost effectiveness of fuel cell systems. To aid in achieving the goal of this work, a set of specific objectives was generated. Addressing each of these objectives provides insight into the status, needs and recommendations to further enhance the development and market acceptance of fuel cell technology. These objectives are listed below. The main focus of each item is presented in bold font style.

- **Conduct a literature review** of fuel cell roadmaps, action plans and other relevant literature.
- **Establish target and stretch goals** for fuel cell system cost, performance and other parameters based on current technology status and the desired technology status.

- **Develop a set of commercialization barriers** identified as hindering the technology development and market acceptance of fuel cell technology.
- **Generate a list of projects** for fuel cells and related fuel cell technologies that are capable of addressing the commercialization barriers.
- **Obtain and integrate comments and suggestions** for the methodology of the work and for the prioritization of the previous items.
- **Develop a Roadmap** that overlays scientific and technology hurdles, milestones, and RD&D projects and advances in science and technology to show how California actions can hasten the acceptance of fuel cell systems.
- **Prepare an Action Plan** with specific recommendations of the RD&D to be funded, the amount of funding required, and the expected benefits to California ratepayers.
- **Disseminate the findings** through appropriate and approved presentations, publications, and/or website postings in conjunction with the California Energy Commission Project Manager.

This report is a culmination of the work done to collect, characterize and prioritize commercialization barriers that are hindering the development of fuel cell technology. A general description of the method used to isolate and analyze each fuel cell barrier is presented first. The results from several surveys and workshops are presented next. The results section is followed by the *Fuel Cell Technology Roadmap* and *Fuel Cell Action Plan* sections which provide a concise interpretation of the results. The fuel cell technology roadmap contains general recommendations for the fuel cell community as to the technologies and types of projects that, if pursued, can elicit the most benefit as well as identification of the most important commercialization barriers, as determined by a cross-section of the community. In contrast, the action plan presents a detailed analysis of the specific areas to pursue within each technology. Projected duration and cost values are supplied for each of the actions that are recommended by the action plan.

1.3. Motivation

Many different entities have developed planning documents to guide the research, development and demonstration investments in the fuel cell sector. In addition to development of roadmap and action plan documents in the United States, there has been international efforts as well, with documents developed for Europe, the United Kingdom, Canada, and Japan; however, these plans provide a relatively narrow perspective of the status and barriers hindering fuel cell development and oftentimes focus heavily on the political aspects of fuel cell development. This work is unique in that, information from all of the relevant fuel cell literature and the fuel cell community is drawn together to develop a more complete perspective of the status and technical needs for fuel cells in California and more generally, the world. This information can be used to benefit the political community that is working to address legislative and

regulatory challenges for fuel cells as well as the technical community of engineers and scientists that are laboring to solve the technical challenges facing fuel cells.

While the previous plans typically provide information for one particular area of fuel cell technology, this work collects information concerning all of the technical barriers that are identified from the literature and are important to stakeholders for all different types and markets for fuel cells. This method relies on a unique blend of personal communication, workshops and Web-based surveys to collect and prioritize the information. Due to the level of technical information discussed in this work, it is essential that the author has an intimate understanding of fuel cells from a scientific and engineering perspective as well as familiarity with fuel cells from a political perspective. The method of surveying the community is unique in that with sufficient participation this strategy allows for the objective review of technical needs for fuel cells. Also, since the results reflect the sentiment of the fuel cell community, every stakeholder in the community can benefit from understanding what other stakeholders believe are the major barriers hindering further development and market acceptance of fuel cell technology. Thus, the completion of this work has the potential to produce great benefit and provide guidance for the technical community as well as the political community to help drive further technology development and market acceptance of fuel cell technology.

2.0 Approach

The first step in developing *The Plan* was to establish the best method to formulate a fuel cell roadmap and action plan that can be used by stakeholders in California's fuel cell future to guide the development of fuel cell technology. In an effort to meet these objectives, a literature review of all pertinent fuel cell roadmaps and other planning documents was conducted. Based on the information gained, it was determined that the best general methodology to accomplish the objectives of characterizing commercialization barriers and establishing the needs to address those barriers and hasten further fuel cell market acceptance is as follows:

Task 1: Conduct a literature review of fuel cell roadmaps, action plans and other relevant literature. In an effort to meet the first objective, a literature review of all pertinent fuel cell roadmap and other planning documents was conducted. The literature review included all relevant documents from international sources as well as domestic sources. Particular attention was focused to documents developed for use in California. Thorough collection of this information represented an essential step toward identifying the status and needs for fuel cell technology.

Task 2: Establish targets and stretch goals for fuel cell system cost, performance and other parameters based on current technology status and the desired technology status. Based on the fuel cell literature and stakeholder feedback the current status of fuel cell technology (benchmark) and the desired status and goals of the fuel cell community (milestones) was developed. The goal of identifying these benchmarks and milestones was to objectively determine the significance of each and to develop a method for effectively addressing the technology development needs to achieve the performance goals (milestones).

Task 3: Develop a set of commercialization barriers identified as hindering the technology development and market acceptance of fuel cell technology. In order to bridge the gap between the current status of the technology (benchmarks) and the desired status of the technology (milestones), barriers or technology gaps that precluded this process were identified and explored. Collecting and prioritizing a list of the barriers precluding further fuel cell commercialization provided the fuel cell community insight into the areas of technology that need to be specifically addressed.

Task 4: Generate a list of projects for fuel cells and related fuel cell technologies that are capable of addressing the commercialization barriers. Building upon information generated from the aforementioned tasks, a list of specific technology development issues was developed. These issues included those that address every aspect of fuel cell development needs that the community identified, ranging from materials issues, to marketing and policy issues, to installation and cooperation issues. The issues were used to formulate a list of projects that can be pursued to achieve the technology milestones while addressing fuel cell commercialization barriers. Each of these projects was

reviewed by the fuel cell community through several survey tools and workshops administered by the National Fuel Cell Research Center.

Task 5: Obtain and integrate comments and suggestions for the methodology of the work and for the prioritization of the previous items. Public and expert review played an integral role in the formulation of this work, ensuring that the voice of the fuel cell community was well represented in the results of this work. Review mechanisms were used during every part of this work. All of the established information was subjected to review on several occasions. Inputs from stakeholders were used to evaluate and prioritize all of the information gathered in the previous tasks. The evaluation and prioritization process proceeded, predominantly, through the use of surveying tools and public workshops.

Proper survey development and delivery was essential to achieving the objectives of this work. It was through this process that the majority of prioritization information was obtained. To expose a wider audience and garner additional revisions to this work, in addition to the survey tools, several workshops were organized. Workshops were held to discuss and evaluate the results; however, these were not the only events from which information was gathered. Material from other conferences and workshops were integrated into this report as well. Some examples include the Fuel Cell Seminar, the solid state energy conversion alliance industry and core technology program meetings and the U.S. Department of Energy modeling meeting. The material introduced at these meetings along with discussions at those meetings provided additional insight for this work.

Task 6: Develop a Roadmap that overlays scientific and technology hurdles, milestones, and RD&D projects and advances in science and technology to show how California actions can hasten the acceptance of fuel cell systems. Based on the response of the fuel cell community to the surveys and workshops a formal roadmap was generated. This roadmap presented the technology areas that are especially important to address. The roadmap succinctly stated the general results of this work and provided a quick evaluation of the status and goals established for fuel cell technology.

Task 7: Prepare an Action Plan with specific recommendations of the RD&D to be funded, the amount of funding required, and the expected benefits to California ratepayers. Following the roadmap, an action plan was generated. This document supplemented the roadmap by providing more detailed information regarding the specific actions that should be taken to elicit the most beneficial results. This document relied on the survey and workshop feedback to provide its structure and content.

Task 8: Disseminate the findings through appropriate and approved presentations, publications, and/or website postings in conjunction with the Energy Commission Project Manager.

The first step toward achieving these objectives was to establish the current status of fuel cell technology (benchmark) and the desired status and goals of the fuel cell community

(milestones). Based on the fuel cell literature and stakeholder feedback, a list of fuel cell technology benchmarks and milestones was developed. The goal of identifying these benchmarks and milestones was to objectively determine the significance of each of them and to develop a method for effectively addressing them. In order to bridge the gap between the current status of the technology and the desired status of the technology, barriers or technology gaps that preclude this process must be identified and explored. In light of this, the next step was to identify, in detail, barriers to fuel cell commercialization. Using all of this information, a list of specific technology issues was developed. These issues included every aspect of fuel cells that the community could identify, ranging from materials issues, to marketing and policy issues, to installation and cooperation issues. Those issues were in turn used to formulate a list of projects that can be pursued to achieve the technology milestones while addressing fuel cell commercialization barriers. Each of these projects was reviewed by the fuel cell community through several survey tools and workshops administered by the National Fuel Cell Research Center. Lastly, the results of these reviews were used to determine which projects would provide the most benefit in addressing fuel cell commercialization barriers and achieving the desired goals and milestones. The use of *projects* as the medium to address the technology barriers had two major advantages. This technique allowed for (1) a high resolution of issues and (2) presentation of the material in a form that is conducive for the Energy Commission, the PIER program or any other interested group to pursue research or solicit proposals for one or more of the projects. An illustration of the general methodology used in developing *The Plan* is illustrated in Figure 2.

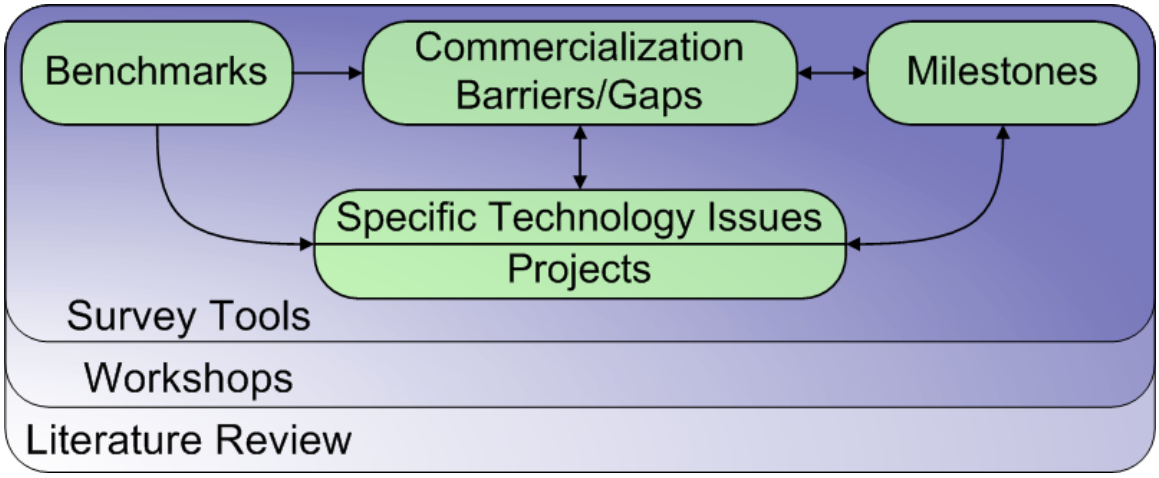

Figure 2: Overall Approach and Methodology for Bridging the Technology Gaps
Source: National Fuel Cell Research Center.

Several things are important to notice regarding the methodology used in this work. The benchmarks are not affected by the barriers or projects; however, the milestones both have an effect on the barriers and project selection and are affected by the barriers and projects selected. That means, based on the outcome of this work, discrepancies may

arise between the previously perceived milestones and the practical or optimal milestones. Simply stated, the selection of milestones may be affected by the realized importance or insignificance of certain barriers or projects. Additionally, the list of projects directly reflects the needs to address commercialization barriers for fuel cell technology, and most of the projects are derived from the barriers while the fuel cell technology benchmarks and milestones are used to augment the list of projects.

Public review plays an integral role in the formulation of *The Plan*, ensuring that the voice of the fuel cell community is well represented in the results of this work. Review mechanisms were used during every part of this work. All of the established information was subjected to review on several occasions including through surveys and workshops. With the general methodology of *The Plan* established, the following table contains the specific implementation strategy for *The Plan.* Each action item has an associated description column, where a more detailed description of the activities undertaken is described and a date of completion column that contains when each activity was completed.

Table 1: Implementation Strategy

Action	Description	Completion Date (08-09)
Develop review criteria	Formulated criteria used to evaluate fuel cell and fuel cell related technology barriers.	March 31
Conduct initial literature review	Collected and summarized information from current fuel cell roadmaps, action plans and other relevant literature, used to develop the benchmarks, milestones, and commercialization barriers.	April 30
Initial technology review documents	Developed technology specific documents that can be used to aid in that technologies commercialization	April 30
Develop survey strategy	Established a technique to administer a survey that will evaluate different fuel cell technology projects.	May 15
Initial stakeholder survey	Reviewed project methodology and list of technology projects with fuel cell stakeholders	June 30
Complete literature review	Completed collecting and summarizing information from current fuel cell roadmaps, action plans and other relevant literature	August 1
Complete technology review documents	Completed all 19 technology documents thereby completing the list of potential projects to be surveyed	August 18
Second stakeholder survey	Reviewed the refined project methodology and technology projects with fuel cell stakeholders to further develop their content and scope	August 25
Public workshop	Held a meeting at the NFCRC to expose a larger group of the fuel cell community to *The Plan* and elicit comments and suggestions	August 27
Web-based stakeholder survey tool	Web-based survey tool administered to a wider spectrum of the fuel cell community	September 5
Roadmap and action plan development	Used results from multiple surveys and workshops to develop a fuel cell roadmap and action plan for California	January 30

3.0 Analyses

3.1. Literature Review

In order to gain a complete understanding of the technology status and needs within the community, all of the relevant roadmaps and program plans must be reviewed. The literature review will allow for the development of a more complete draft list of the barriers to fuel cell commercialization. All of the relevant previously developed roadmaps and program plans must be reviewed to allow for the development of a more complete draft list of the barriers to fuel cell commercialization. Table 2 contains a breakdown of the roadmaps and program plans that were reviewed in the current effort while Table 4 contains the list of additional literature reviewed for *The Plan*. These documents were used to gather much of the information that was used to develop the benchmarks, milestones, commercialization barriers and in-turn the technology projects used for this analysis.

3.1.1. Referenced Literature

Table 2: Fuel Cell Roadmap and Action Plan References

Year	Title	Contributing Groups
1995	Report of the DOE Advanced Fuel-Cell Commercialization Working Group	DOE
1998	Draft Plan for Fuel Cell Technology Research, Development and Demonstration for Public Interest Energy Research	NFCRC
2001	Hybrid Fuel Cell Technology Overview	NETL
2001	Hybrid Program Plan	DOE
2002	National Hydrogen Energy Roadmap	Energetics
2002	A National Vision of America's Transition to a Hydrogen Economy — To 2030 and Beyond	DOE
2003	Canadian Fuel Cell: Commercialization Roadmap	Government of Canada, Pricewaterhouse Coopers, Fuel Cells Canada
2003	Energy Action Plan	CPA, CEC, CPUC
2003	Fuel Cell Development in Japan; An Outline of Public and Private Sector Activities	British Embassy, Japan
2003	Fuel Cell Report to Congress	DOE
2003	Fuel Cells and Hydrogen: The Path Forward	Breakthrough Technologies Institute Inc.
2003	Hydrogen and Fuel Cells: A Vision of Our Future	European Commission
2005	Energy Action Plan II: Implementation Roadmap for Energy Policies	CEC, CPUC
2005	European Hydrogen and Fuel Cell Technology Platform: Strategic Research Agenda	HFP
2005	Roadmap on Manufacturing R&D for the Hydrogen Economy	DOE
2005	Technology Review and Assessment of Distributed Energy Resources: 2005 Benchmarking Study	EPRI
2005	UK Fuel Cell Development And Deployment Roadmap	Synnogy Ltd.
2006	Hydrogen Posture Plan: An Integrated Research, Development and Demonstration Plan	DOE, DOT
2006	Independent Review of CALIFORNIA ENERGY COMMISSION PIER-EPAG Fuel Cell Program: Final Report	CFCC, Mike Binder and Associates, DOE, SCE
2007	Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan	EERE
2007	Identification and Characterization of Near-Term Direct Hydrogen PEM Fuel Cell Markets	Battelle
2007	Office of Fossil Energy Fuel Cell Program Annual Report	DOE
2007	Outline of NEDO: Fuel Cell and Hydrogen Technologies	NEDO

This set of documents represents all of the significant and relevant previously developed roadmaps and actions plans that were identified and includes a broad cross-section of contributing organizations. Most of the documents were developed in the United States and, among that group, a small subset was developed particularly for California. Documents from Japan, Canada, United Kingdom and the European community were reviewed as well. Reviewing such a wide spectrum of documents was done to ensure that as many fuel cell and fuel cell related technology issues were identified in the development of the roadmap and action plan. Table 3 contains information describing from where the review documents were collected.

Table 3: Fuel Cell Roadmap and Action Plan Breakdown

Contributing Group	Number of Reviewed Documents
United States	**17**
U.S. DOE	12
California Specific	5
Japan	**2**
Canada	**1**
United Kingdom	**1**
Europe	**2**

In addition to the roadmaps and other plans reviewed, a collection of other technology specific documents were reviewed. In comparison to the previous reports these documents were referenced only a few times regarding specific topics like absorption chilling and combined heat and power (CHP). The bibliographic information for these additional documents can be found in Table 4.

Table 4: Additional Fuel Cell Literature Review References

Year	Title	Contributing Groups
1998	Absorption Chillers: Advanced Design Guideline Series	SCGC, NBI
1999	Distributed Generation: System Interfaces	A. D. Little
2001	National CHP Roadmap	USCHPA, DOE, EPA
2004	Combined Heat and Power Market Potential for Opportunity Fuels	RDC, DOE
2004	Honda Fuel Cell Power: Press Release	Honda
2004	The Development of an Air-cooled Absorption Chiller Concept and its Integration in CHP Systems, Liao X.	University of Maryland
2005	SOFC Development at Pacific Northwest National Laboratory. Fuel Cell Seminar, Stevenson J. W., et al.	PNNL
2006	Phosphoric Acid Fuel Cells. California Energy Commission Fuel Cell Workshop, Binder M. J.	Mike Binder and Associates
2006	Fuel Cell Barriers. California Energy Commission Fuel Cell Workshop, Garland N.	DOE
2006	SCE Fuel Cell Activities. California Energy Commission Fuel Cell Workshop, Hamilton S.	SCE
2006	Marketing and Commercialization: Challenges for PEM Fuel Cells. California Energy Commission Fuel Cell Workshop, Harris K.	Hydrogenics
2006	Fuel Cell Bus Programs. California Energy Commission Fuel Cell Workshop, Koyama K.	PIER
2006	Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities, Lopes J., et al.	Electric Power Systems Research
2006	Status of Molten Carbonate Fuel Cells. California Energy Commission Fuel Cell Workshop, Remick R.	CFCC
2006	Solid Oxide Fuel Cells: Challenges and Opportunities. California Energy Commission Fuel Cell Workshop, Simon G.	Acumentrics
2006	Fuel Cell Technology Update. California Energy Commission Fuel Cell Workshop, Stone C.	Ballard
2006	Building Fuel Cell Companies – Challenges & Opportunities. California Energy Commission Fuel Cell Workshop, Wu M.	Morh Davidow Ventures
2006	Feasibility analysis of fuel cells for combined heat and power systems in the tertiary sector, Zabalzaa I., et al.	IJHE
2007	A dynamic simulation model for transient absorption chiller performance, Kohlenbach P., et al	International Journal of Refrigeration

3.1.2. Method of Categorizing Findings

Given the large amount of information that resulted from review of all of the documents in Table 2 and Table 4, a method was developed to quickly identify which document(s) the information was drawn from and where similar information can be found. The

solution chosen was to use two reference metrics for each piece of information: first, a category reference(s) and second, a source reference(s).

The category reference divides the information into unique technology categories that span the fuel cell sector. Table 5 contains the established categories for discriminating between all of the information that is collected (e.g., benchmark, milestone and technology issues). There are four main categories (e.g., market applications, fuels) and 19 sub-categories used throughout this report. Each category was selected so as to contain a similar magnitude of data as other categories and prevent overlap between categories. Following Table 5 are brief descriptions for each category, including some background and the potential benefits from pursuing that technology.

Source references represent the second categorizing metric used to cite a particular piece of literature. The sources that are used often are assigned a Greek symbol as shown in Table 6, while others that are not used as often are designated by the author or document title as found in Table 4. Multiple sources can be referenced for a single piece of information. The use of several source references for a single item signals agreement between the sources.

Category Referencing

Table 5: Category Reference Key

1. Market applications
    a. Stationary
        1. Grid support
            a. Integrated gasification technology
            b. Carbon capture and sequestration
            c. Integration into transmission level grid support
        2. Distributed generation including co-generation and CCHP
            a. Chilling
        3. Fuel cell – gas turbine hybrid
    b. Transportation
        1. On-road light duty support
        2. On-road heavy duty support
        3. Fueling stations
    c. Materials handling
        1. Lifts
        2. Ships Auxiliary Power Unit (APU)
        3. Tractor trailers APU
        4. Locomotive
    d. Episodic
        1. Peak shaving
        2. Back-up power
    e. Portable
        1. Remote areas
    f. Market Cross-Cutting
2. Fuel cell technology specific development
    a. Solid Oxide Fuel Cell
    b. Molten Carbonate Fuel Cell
    c. Proton Exchange Membrane Fuel Cell
    d. Phosphoric Acid Fuel Cell
    e. Direct Methanol Fuel Cell
    f. Fuel Cell Cross-Cutting
3. Technology integration development
    a. Balance of plant
    b. Energy storage
    c. Grid-DG connectivity
4. Fuels
    a. Hydrogen
        1. Delivery
        2. Education and Outreach
        3. Production
        4. Storage
5. Opportunity fuels

It is essential for the understanding of this document to know the scope of the technology categories presented in Table 5. The following 19 sections contain a brief description of each technology category including background and a description of

some of the benefits of that category. Exploring the projects that are included within each category provides additional understanding for how each category is unique.

Market Applications

Market Cross-Cutting

The technology barriers for fuel cell market development include many issues that are specific to a single or only a few markets; however, there are also many issues that are similar amongst most or all of fuel cell markets. The fuel cell market cross-cutting development category represents the barriers to fuel cell development that are similar between many of the fuel cell markets.

Projects selected from the cross-cutting category have the potential of addressing multiple or all of the fuel cell markets which will typically have a wider effect than addressing an issue for a single market. Examples of the broad effects of addressing cross-cutting issues is evident from projects like providing support the fuel cell market supply chain, introducing codes, standards, incentives, mandates to aid in fuel cell market development and product deployment.

Grid Support

Fuel cell systems in grid supporting applications will act to supplement, support and/or replace current power generation, transmission and distribution equipment. Direct competition with the current grid mix that is already installed and can reliably produce power with average efficiencies including generation and transmission in excess of 35% is difficult for many fuel cell technologies. These efficiencies in large part stem from the size of the plants that are included. Fuel cells can achieve very high efficiencies even for significantly smaller systems, between 40% and 60% efficiency without even utilizing the waste heat. For central generation, some degree of fuel flexibility must be established as well. As competition for limited fossil fuel reserves increases, the need for operation on renewable fuels and higher efficiencies become essential. Fuel cells offer a solution to both of these issues.

Fuel cells in grid supporting applications can offer high efficiencies, with very low criteria pollutant emissions. When compared to other generation devices, fuel cells output very little noise pollution and can operate on many different fuels, which result in more flexible operation and siting opportunities. Lastly, the scalability and modularity of fuel cells contributes to adaptable system design. The generation demand and capacity can be better matched to the installed equipment with the opportunity for expansion on account of the modularity of fuel cells.

Distributed Generation and Combined Cooling, Heating, and Power

The current energy distribution paradigm involves predominantly central generation, transmission, distribution, and final sale to the customer. Distributed generation with cogenerating systems represents a transition away from central generation to the generation of power near the point of use. Distributed generation (DG) units are much

smaller than central plants (less than tens of megawatts) and are typically used to power local loads. Co-generation and combined cooling, heat and power (CCHP) opportunities offer an additional efficiency benefit by converting waste energy into useful product(s). Some examples for the use of waste streams for CCHP and co-generation applications include generating hot water for domestic uses, secondary power generation cycles, absorption chiller cycles and generating hydrogen.

The use of DG/CCHP fuel cell technology could result in efficiency improvements over current technologies and the potential for economic benefit. Electrical distribution networks powered using DG technologies offer potential for grid stabilization, premium power and electricity availability during power outages. Fuel cells also offer low pollutant and noise emissions and can provide system scalability to allow for appropriate mating with the load. In addition, the use of co-generation can introduce many options for using the waste products.

Fuel Cell – Gas Turbine Hybrid

Hybrid systems rely on the synergy of integrating constituent components to achieve better performance and efficiency than either system could provide separately. There are many technologies that can benefit from hybridization with fuel cells. Some of these examples include a fuel cell with thermoelectric devices, photovoltaic devices, steam turbines, other fuel cells, and turbo machinery. The integration of fuel cells with gas turbines is particularly promising.

Fuel cell – gas turbine hybrid systems typically operate with the gas turbine providing the balance of plant for the fuel cell, while the fuel cell produces electricity and heat in the stead of the combustor in the gas turbine cycle. There are many possible hybrid system configurations that include pressurized and unpressurized fuel cell operation and placement of the fuel cell either upstream or downstream of the turbine. A 2001 Department of Energy document reviewing hybrid fuel cell technology, concluded that a hybrid fuel cell – gas turbine system can achieve efficiencies in excess of 70% on a lower heating value (LHV) basis for large systems (between 10 and 100MW).

Gas turbines with their proven track record, high availability and ability to provide balance of plant services to a fuel cell, complement the low pollutant emissions, and high efficiency of fuel cells. When integrated, these two systems can achieve efficiencies greater than 70% with lower criteria pollutant emissions than a gas turbine. Also, with the proper integration and fuel cell cost reduction, fuel cell – gas turbine hybrid systems could ultimately provide a lower cost alternative for electricity generation than the current technologies. These capabilities illustrate the need for research, design and development for both distributed and centralized-scale hybrid systems.

Transportation

On-road transportation is dominated by gasoline and diesel fueled vehicles. The United States Department of Transportation estimates that in 2006 there were over 250 million registered highway vehicles. With the vast majority of these vehicles operating on fossil

fuels, there is a tremendous opportunity to provide cleaner, more efficient, fuel flexible transportation solutions using fuel cells. Different types of fuel cells and fuel cell hybrid systems can be used to power vehicles each with their own advantages and disadvantages. The transition from combustion vehicles to fuel cell vehicles will require that many technical challenges be addressed in both fuel cell specific areas as well as related areas. Some examples of areas that require development include fuel cell operation and manufacturing, fueling infrastructure, fuel storage and fuel production.

With over 250 million registered highway vehicles in 2006 operating on fossil-fuels, the transition to fuel cell powered vehicles can provide the transportation sector with energy security and independence that is not possible under the current scenario. Also, fuel cells used in transportation devices can operate more efficiently and cleaner than the current combustion technology. Thus, the introduction of fuel cell vehicles has the potential to reduce criteria pollutant emissions leading to better air quality and less environmental impact.

Materials Handling

The materials handling area includes equipment that is used to lift, transport and otherwise manipulate materials. Examples include, but are not limited to, forklifts, other lifts, tractor trailers, ships and locomotives. Current materials handling technology typically relies on fossil-based combustion devices or batteries for power. Fuel cells are being considered for materials handling applications to overcome several of the shortcomings of the current technology options. Combustion powered materials handling products typically have low efficiencies and poor pollutant and greenhouse gas emissions. Also, for the battery powered materials handling equipment, there are many logistical issues associated with the recharging, replacement and life cycle costs of using batteries. These shortcomings warrant the exploration of alternative methods to power materials handling equipment. One of the most promising technologies for use in this field is fuel cell technology.

When compared with combustion technologies, fuel cells offer much cleaner, quiet and more efficient energy generation for materials handling applications. In addition, fuel cells can offer better fuel flexibility and the capability to operate on renewable fuels. When compared to battery technology, fuel cells offer quicker refueling since they do not require hours to recharge but just need to have their fuel storage tank refilled. Fuel cells are also very modular in nature and offer greater flexibility for system power requirements.

Episodic

A power generation system that is designed to be used periodically under particular conditions is considered episodic. The goal of episodic power equipment is to compensate for grid or primary power intermittency and/or demand changes. The two main examples of episodic power applications are for backup power, used under the condition that the primary power source is unavailable and peak power shaving, used under the condition that the base loading power plants cannot support the maximum

daily load demand on the electrical distribution network. Currently, battery banks or combustion devices are commonly used for episodic power. Combustion devices often include diesel generator sets, which are particularly known for their poor emissions signature, especially following startup. Independent of the technology chosen, all episodic power generation equipment requires extensive maintenance and operation actions to maintain good system performance and very high availability.

Fuel cells exhibit favorable properties that are particularly amenable to episodic power generation. One key benefit for fuel cells is their ability to generate premium power while maintaining low criteria pollutant emissions and high efficiencies. Fuel cells also have the potential to contribute to the episodic power area with potentially quick startup and response times (load following). Another benefit of using fuel cells in episodic applications is their ability to operate on a wide range of fuels.

Portable

The portable power market category encompasses the cross-section of equipment that acts as the primary energy generation device and typically does not have a connection to the electrical grid. Consumer demands and resulting technical challenges for portable power are uniquely different from grid support and distributed generation, but for portable fuel cells to achieve commercialization, just as with the grid support and distributed generation, the technical challenges must be identified and addressed. The current techniques used to generate power portably are combustion devices for large, continuous systems and batteries for smaller systems. Some examples of portable power applications include many electronic devices (ex. laptops, cell phones), and remote area power generation.

Fuel cell have the ability to revolutionize the portable market by giving devices previously powered by batteries indefinite operation time with short refuel periods. Also, for devices powered by combustion engines, fuel cells offer fuel flexibility and reduced criteria pollutant and noise emissions. More generally, portable fuel cell power generation can provide very high operating efficiencies and modular and scalable power capacity. The modularity and scalability are critical issues when considering the wide range of power requirements for portable devices.

Fuel Cell Technology Specific Development

Fuel Cell Cross-Cutting

Though all fuel cell types are based on the same principles of electrochemistry, typically the method and type of ions that are conducted, the materials used to construct them, their performance, operating conditions are different for each fuel cell type. Fuel cells are typically named by the type of electrolyte that they use to conduct ions from one electrode to the other electrode. The technology barriers for fuel cell development include many issues that are specific to a few types of fuel cells; however, there are also many issues that are similar between most or all of the types of fuel cells. The cross-cutting development category represents the barriers to fuel cell development that are

similar between many types of fuel cells. Knowing that for many of those types fuel cells offer high efficiencies, fuel flexibility, design modularity, have the potential to reduce criteria pollutants and greenhouse gas emissions and can operate with low noise pollution, the cross-cutting category is especially important.

Solid Oxide Fuel Cell

Solid Oxide Fuel Cells (SOFC) are noted for their thin solid electrolyte and typically operate at temperatures ranging from 600-1000ºC. The charge carrier for SOFCs is the oxygen ion (O^{2-}). Typical fuels used for SOFCs include hydrogen (H_2), methane (CH_4) and carbon monoxide (CO).

Molten Carbonate Fuel Cell

Molten Carbonate Fuel Cells (MCFC) are noted for their liquid carbonate electrolyte and typically operate at temperatures around 650ºC. The charge carrier for MCFCs is the carbonate ion (CO_3^{2-}). Typical fuels used for MCFCs include hydrogen (H_2) and methane (CH_4).

Proton Exchange Membrane Fuel Cell

Proton Exchange Membrane Fuel Cells (PEMFC) are noted for their solid polymer electrolyte and typically operate at temperatures around 80ºC. The charge carrier for PEMFCs is the hydrogen ion (H^+) and PEMFCs typically operate on hydrogen (H_2).

Phosphoric Acid Fuel Cell

Phosphoric Acid Fuel Cells (PAFC) are noted for their molten phosphoric acid electrolyte and typically operate at temperatures around 200ºC. The charge carrier for PAFCs is the hydrogen ion (H^+) and PAFCs operate on hydrogen gas.

Direct Methanol Fuel Cell

Direct Methanol Fuel Cells (DMFCs) are noted for their solid polymer electrolyte and typically operate at temperatures around 90ºC. The charge carrier for DMFCs is the hydrogen ion (H^+) and DMFCs typically operate on methanol.

Technology Integration Development

Balance of Plant

In addition to the fuel cell stack, there are many components in a fuel cell system that is required for the system to operate efficiently and effectively. *Balance of plant* (BOP) is the term used to describe the components not included in the fuel cell stack and stack components. BOP components include items like pumps, and blowers, hoses and valves, seals, heat exchangers and basically anything that supports the operation of the fuel cell stack.

Balance of plant components present a unique and potentially rewarding challenge for their optimization and integration. Due to the distributed nature of the components, it can more beneficial to advance a single BOP component than it is to work on increasing the performance or reducing the cost of the fuel cell stack. In addition, many of the

components used for fuel cell BOP can be used on other equipment which can dramatically affect the cost and versatility of high-volume BOP components.

Energy Storage

Energy storage technology includes typical forms of energy storage like batteries and capacitors, but also includes less prevalent forms of energy storage like thermal storage using salts and phase change materials and hydrogen storage as well as how they interact with fuel cells. One major category for energy storage technology is the use of reversible fuel cells to generate electrical power at some times and consume electrical power at other times and store that energy in the form of a fuel (e.g., hydrogen).

Providing energy storage for fuel cell technology widens the available markets and applications for which fuel cells can be used. In addition, energy storage can have a profound effect on the hybridization of fuel cells with non-dispatchable or intermittent power sources leading to increased economic and environmental value.

Grid Level Distributed Generation Connectivity

It is not enough to develop technology that can generate high efficiency and ultra low emission electricity generation like fuel cells without also exploring where and how that power generator can be connected to the electricity distribution network. There are many grid related issues that augment the attractiveness of fuel cell implementation for both the consumer and the utility.

Allowing fuel cells to be connected to the distribution network would provide the customers with increased power reliability, even during grid loss situations, more control over their power signature and CHP opportunities. At the same time, grid connected fuel cells would provide the utility with reduced consumer loads, peaking flexibility and the ability to defer or prevent the installation of additional infrastructure.

Fuels

Hydrogen

Given the price volatility, resource availability and the growing environmental concerns over the current energy carriers that are mostly petroleum-based, it is critical for economic and environmental stability that the United States and California transition toward a more sustainable, hopefully renewable, domestically produced and cheaper fuel source for energy carriers. Current energy carriers like natural gas, coal and oil are experiencing rising demand, which creates increased competition over limited resources. Hydrogen has the potential to address many of the current energy issues because it is one of only a couple of options that produces zero greenhouse gas emissions and criteria pollutants at point of use while offering features of high energy density and rapid refueling. But the widespread use of hydrogen as an energy carrier will require a significant amount of research, development and deployment activities to introduce infrastructure and technologies that can compete with the current technologies.

To address the research, development and deployment needs for hydrogen as an energy carrier, the field will be separated into four categories. These categories include delivery, education and outreach, production and storage.

- Delivery explores the transportation and distribution aspects of using hydrogen as an energy carrier.
- Education and outreach explores the requirements to provide understanding about issues relating to hydrogen to everyone from scientists, to policy makers, to the general public.
- Production involves the method and feedstock from which hydrogen is generated.
- Storage bridges the gap between pre-conversion hydrogen production and delivery. Storage explores different methods for achieving containment of hydrogen.

As a replacement for conventional energy carriers, hydrogen has many benefits in comparison. Hydrogen can be made and consumed using a variety of methods and can be produced from a variety of feedstocks. Using a fuel that does not include carbon makes hydrogen powered technologies emit no carbon products, while having the potential to reduce or completely remove criteria pollutant production even in blended configurations. Also, hydrogen production allows for domestic fuel production and can increase energy security and stability.

Opportunity Fuels

Opportunity fuels represent the fuels that result as a by-product of another activity (e.g., landfill gas, digester gas, bio-derived fuels). Oftentimes these fuels are vented or used in devices less efficient than fuel cells.

The use of opportunity fuels with fuel cells provides a unique opportunity to increase energy independence while using a fuel that would previously have been wasted or used inefficiently. Due to the high electrical to heat product ratio of fuel cells, they can be used in applications where the heat energy from opportunity fuels is less valuable than electrical energy.

Source Referencing

Table 6: Source Reference Key

Source Reference	Sources	Year
α	National Hydrogen Energy Roadmap	2002
β	Fuel Cell Report to Congress	2003
γ	Draft Fuel Cell RD&D Plan for PEIR	1998
δ	Expert communication, Shane Stephens-Romero, 3/17/08	2008
ε	Hybrid Fuel Cell Technology Overview	2001
ζ	Expert communication, James Maclay, 2/22/08	2008
η	Hybrid Program Plan	2001
θ	Additional expert communications (e.g., Samuelsen, Brouwer)	2008
κ	Expert communication, Pere Margalef, 7/8/07	2007
λ	Expert communication, Allie Auld, 7/27/07	2007
μ	Technology Review and Assessment of DER	2005
ν	UC Irvine, MAE 214 Lectures	2007
ξ	Fuel Cells and Hydrogen: The Path Forward	2003
π	Hydrogen Posture Plan	2006
ρ	Fuel Cell Program Annual Report (SECA)	2007
σ	Canadian Fuel Cell Roadmap	2003
τ	A National Vision of America's Transition to a Hydrogen Economy	2002
υ	Fuel Cell Development in Japan; An Outline of Public and Private Sector Activities	2003
φ	Roadmap on Manufacturing R&D for the Hydrogen Economy	2005
χ	UK Fuel Cell Development And Deployment Roadmap	2005
ψ	Identification and Characterization of Near-Term Direct Hydrogen PEMFC Markets	2007
ω	Outline of NEDO: Fuel Cell and Hydrogen Technologies	2008
Γ	Hydrogen, Fuel Cells and Infrastructure Multi-year RD&D Plan	2007
Δ	Hydrogen Energy and Fuel Cells: A Vision of the Future	2005
Θ	European Hydrogen and Fuel Cell Technology Platform: Strategic Research Agenda	2003
Λ	CEC PIER-EPAG Fuel Cell Program	2006
Ξ	Initial Fuel Cell RD&D Survey	2008
Π	Fuel Cell RD&D Plan Workshop at the NFCRC	2008
Σ	ASME Fuel Cell Science Engineering and Technology Conference	2008

A bracket is used to indicate a reference entry followed by one or more category references separated by commas. Next, a semicolon is used to signify the transition to the source reference, where one or more source references are separated by commas. Finally, a closed bracket ends the reference (e.g., [1a1; π, β] represents the Grid Support category from the Hydrogen Posture Plan and the Fuel Cell Report to Congress).

In addition to the information obtained from outside sources, the surveys and workshops administered for this project have been integrated into the findings. Notice in Table 6 the Greek symbols Ξ and Π denote comments from the initial survey and comments from the workshop, which occurred in August of 2008 and was held at the National Fuel Cell Research Center at the University of California, Irvine. Proceedings from the August 2008 workshop are presented in Appendix A.

3.2. Benchmarks and Milestones

Developing the benchmarks and milestones for fuel cell technology is an essential first step in the development of a roadmap and action plan. This effort will greatly aid in the selection and timing of appropriate markets and tasks to pursue. In addition, determining the status of fuel cell technology puts the need for particular projects into perspective. This process is complicated for two major reasons: (1) the values for benchmarks and milestones are very dependent on the assumptions that go into their formulation, which vary heavily between sources, and (2) many sources containing values must be searched through, each search being time consuming and often resulting in only a few values.

Benchmarks represent proven status of the technology while milestones represent the future or desired status of the technology. Benchmarks have an associated date when that data was determined. Further review of the reference documents can supply additional information about the context for each item. Benchmarks and milestones are drawn from fuel cell roadmaps and plans and are separated into groups based on different performance measures (e.g., availability, and capacity factor).

3.2.1. Benchmarks

The benchmarks for fuel cell performance are obtained from the reference documents, insights from fuel cell manufacturers, academic, national laboratory, and agency experts and members of the fuel cell community are summarized below. All of the benchmarks are listed in Appendix B. Benchmarks have been established for many specific types of fuel cell technology including SOFCs and PEMFCs as well as performance of sensors, component lifetime and cost issues. Each of the major headings contains a performance measure for which a benchmark has been established. Each subcategory (alphabetically delineated) contains a specific benchmark performance value. Some sections do not contain any benchmarks, but are left in this section for consistency with the milestones section.

From all of the benchmarks collected, the following list was used to organize the major categories of benchmarks and milestones: availability, capacity factor, cost, degradation, efficiency, emissions, energy density, incentives, life, noise, power, sales volume, sensors, size and weight, transient response and other. Every benchmark is classified into one of the above listed categories.

3.2.2. Milestones

Similar to the benchmarks, milestones for fuel cell performance are obtained from the reference documents, insights from fuel cell manufacturers, academic, national laboratory, and agency experts and members of the fuel cell community. The complete list of milestones is located in Appendix B, where each of the major headings contains the measure of performance for which a milestone has been established. Each subcategory (alphabetically numbered) contains a specific milestone performance value and a reference from where the material was drawn.

Every milestone is classified into a category consisting of the same list of topics as those used for the benchmarks (e.g., availability, capacity factor). There were significantly more milestones than benchmarks identified from the literature. The milestones cover a broad spectrum of technologies and topics. For example, there are milestones for specific types of fuel cells, as well as components for specific fuel cells (e.g., MEAs, bipolar plates). Additionally, there are several milestones for market related technologies like distributed generation and grid support.

Formalizing a list of benchmarks and milestones is useful for putting into perspective the growth of certain technologies and requirements. The collection of these technology evaluation metrics is essential to moving to the next step in *The Plan* and developing a list of commercialization barriers.

3.3. Commercialization Barriers

The fuel cell industry is currently comprised of technology, companies and applications that are in various stages of commercialization depending upon the type of technology and application that is being examined. Some technologies are in the research and development stage while other technologies are pressing towards different levels of market penetration. Fuel cell technology commercialization can be separated into four distinct stages: early research and development stage; demonstration stage; deployment stage and full commercialization stage.

Research and development occurs at every stage of commercialization, but technologies in the early research and development stage do not have any products. The research and development stage is characterized by promising technology that needs further development to determine the potential and best uses. The demonstration stage is characterized by alpha or beta testing one or more fuel cell products. Information learned from the demonstrations is used to further develop the product. Concurrent research and development is expected during this and every other stage of commercialization. The deployment stage is the following step, after the demonstration stage, where the production scale is dramatically increased. Increasing market acceptance and penetration are strongly associated with this stage. Subsidies, buy-down and other forms of incentives can be used to move into this stage; however, will likely taper off after sufficient product cost and penetration milestones are met. The final stage is full commercialization. Full commercialization is characterized by independence from

incentives for market stability and significant market presence. A graphical representation of the four stages of commercialization is presented in Figure 3. Features that most define each stage are presented to the left of the figure.

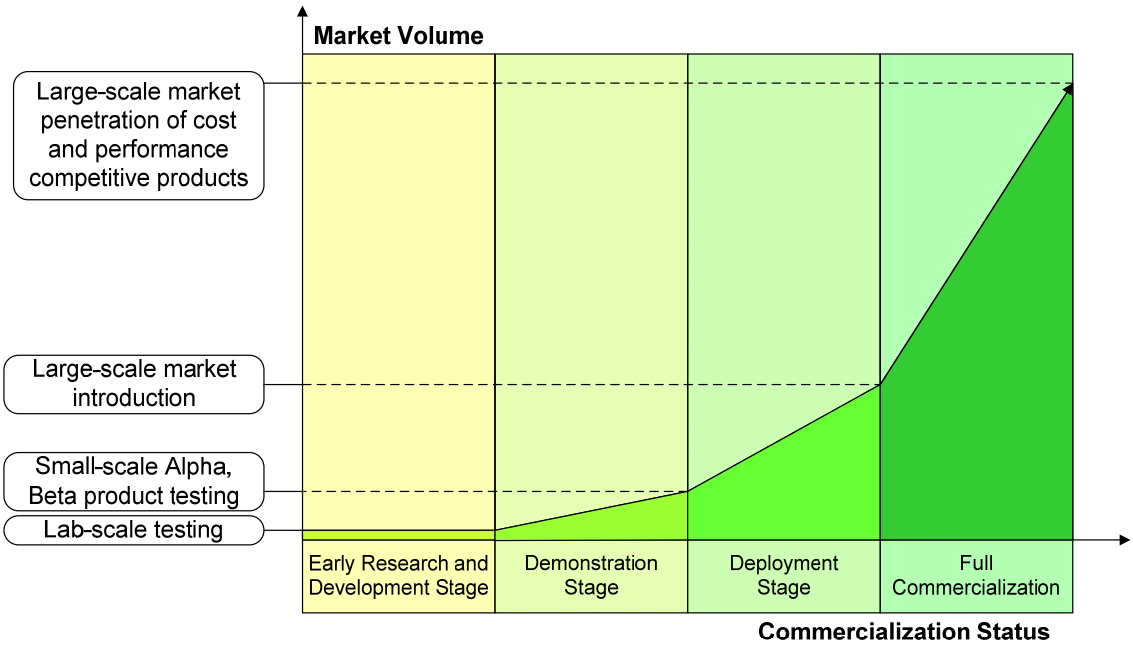

Figure 3: Graphical Depiction of Technology Commercialization Progression
Source: National Fuel Cell Research Center.

Using the understanding of technology and product commercialization described above, the list of barriers is presented in Table 7. Included in Table 7 are several examples and a short description of what is meant by each criterion. Understanding of the scope of each barrier is essential to understanding the results of this study.

Criteria are grouped into subsets based upon similar properties. These groups include cost, performance, manufacturing, operation, safety, marketing and other. It is believed that this set of criteria capture the major barriers hindering further commercialization and market acceptance of fuel cell technology. Additionally, each of the barriers is assigned a letter designation (e.g., A, B, etc.) that will be used for identification. All of the highest ranking projects are evaluated for their ability to address each barrier. An analysis of the type and quantity of letters assigned to the highest ranking projects shows the relative significance of each barrier and to what extent the projects will address specific commercialization barriers.

Table 7: Fuel Cell Commercialization Barriers

	Criteria	Example	Description	Designation
Cost	Cost Reduction	Reduce component cost	Direct reduction in the cost of the system or its components.	A
	Cost / Value to Customer	Incentives, cost of electricity, CHP	Increase the value of the technology by methods other than direct system or component cost reductions	B
Performance	Durability	Degradation and life	A measure of degradation and lifetime of a system	C
	Reliability	Availability, capacity factor	A measure of the availability and capacity factor of a system	D
	Efficiency	Thermal, electrical	Performance measure of system or component efficiency	E
	Transient Operation	Startup, shutdown, load shed, load following	Performance measure of the ability to perform dynamic operations	F
	Power and Energy Density		Performance measure of system or component power, power density, and energy density	G
	Control	System, sub-component, control of integrated systems	A measure of the ability to control a system to desired customer specifications with minimal additional equipment	H
	Size and Weight	Shape, volume, mass	A measure of the volume, shape, mass and weight of a system	I
Manufacturing	Manufacturing	Tooling, processes	Relating to how systems or components are manufactured	J
Operation	Maintenance	Preventative, routine, emergency	How often and how extensively a system requires maintenance	K
	Installation / Commissioning	Site preparation, initial startup	Includes what is required to prepare a system for installation and for its initial startup	L
	Decommissioning / Recycling	Recycling, removal, restoration, final shutdown	Includes what is required to shutdown, remove and recycle a system	M
	Certification	Inspection, application and development of codes and standards	Includes what is required for the system to pass various inspections and receive approval for installation	N
	System Integration	Compatibility	Concerns how and the extent to which a systems can be combined and integrated	O
Safety	Safety		Encompasses issues where safety is of particular concern	P
Marketing	Public Awareness / Acceptance		Concerns public interaction and knowledge of the technology and any implications stemming from the introduction of new technologies	Q
	Customer Requirements		Regarding specifications unique to the customer that must be considered	R
	Market size	Sales volume, product demand	Directly cause an increase in the size of a particular market by increasing volume or increasing demand	S
	Number of markets		Directly introduce fuel cell technology to new markets not previously pursued	T
Other	Energy Independence	Oil and natural gas imports	Concerns sovereignty and independence of energy supply	U
	Energy security	Grid stability, energy reserves	Concerns the safety and stability of generation equipment and fuel supply. Includes daily energy supply and more long-term supply and system integrity	V
	Environmental Impact	Aesthetics, noise, footprint and water and ecological management	The effect of non-greenhouse gas and criteria pollutant emissions on the environment	W
	Emissions	GHGs, criteria pollutants	Relating predominantly to greenhouse gas and criteria pollutant emissions	X

3.4. Development of Fuel Cell Projects

Using all of the information gathered thus far including benchmarks, milestones, commercialization barriers and insights from fuel cell manufacturers, academic, national laboratory, and agency experts and members of the fuel cell community, an outline of specific issues that are hindering fuel cell technology development is generated. This outline acts to organize the issues and serves as an intermediate step to formulating the list of projects. The following section is an abridged list of the development issues for fuel cell technology that is used in-part to generate the list of projects. The complete list of fuel cell technology issues is listed in Appendix C.

3.4.1. Specific Fuel Cell Technology Issues

Capital Cost Barriers

1. Primary materials cost barriers
    a. Platinum for PEMFC
    b. Nickel for SOFC
    c. Carbon for PEMFC
    d. PEMFC electrolyte material
    e. Electrodes, interconnects, electrolyte, Gas Diffusion Layer (GDL), catalyst, bipolar plates [2; α]
    f. Hydrogen storage devices raw material costs [4a4; α]
2. Lack of high-volume manufacturing capabilities and techniques
    g. Barriers to fuel cell thin film manufacturing methods [2; θ]
    h. High-temperature fuel cell material processing and assembly methods [2a; Simon 2006, Xinyu Lu ICEPAG 2008]
    i. Fuel cell manufacturing consistency and quality control [2; α, γ, θ, ξ]
    j. Fuel cell coating techniques and materials [2; π]
    k. Low cost, non-invasive product testing and evaluation [1; ξ]
    l. Profitable fuel cell operations during pre-large-scale manufacturing [2; α]
    m. Large-scale hydrogen storage media production process [4a4; α]
    n. Low alternative fuel demand inhibits large production capacity [4; β]
    o. Manufacturing barriers for balance of plant components [3; ϕ, ξ, χ]
3. Lack of designs prepared for high-volume manufacturing
    p. Design for high volume manufacturing of solid oxide fuel cells [2a; γ]
    q. Stack orientation constraints (PEMFC, PAFC, MCFC) [2; θ]
    r. Flow and electrical connection design barriers [2; θ]
    a. Development of PAFC and PEMFC with lower operation temperatures to reduce capital investment [2; μ]
    s. Fuel and oxidant flow manifolding design barriers [2; θ, γ]
4. Optimization of fuel cell system components
    t. Need to optimize BOP for lower cost manufacturing [1; ξ, μ, α, β]
    u. Need to incorporate advanced components into balance of plant at lower cost [1; ξ, μ, α, β]

v. Power plant packaging [2; β]
w. Component standardization [2; β]

Operating Cost Barriers

1. High fuel costs
    a. Parasitic losses from fuel crossover and leakage [2; θ]
    b. Relatively high cost of removing fuel and oxidant impurities [2; θ, α, β]
    c. Hydrogen-natural gas fuel blend performance [4a; α]
    d. High cost of hydrogen production [4a3; β, α]
    e. Need to develop renewable fuel clean-up technologies for use in fuel cells [3; θ]
    f. Need to develop fuel cell systems capable of alternative fuel use [3; θ]
2. Relatively high operation and maintenance costs
    a. High-temperature operation material constraints [2; Stevenson 2005, μ]
    b. High-temperature fuel cell sealing [2a-b; Stevenson 2005, Simon 2006, μ]
    c. Fuel cell materials susceptibility to degradation and stress [2a; AVD MS thesis]
    d. Material recycling issues [5; ξ, θ]
    e. Inconsistent maintenance on DG equipment [1a2, 3d; DG DOE 1999]
    f. Remote monitoring capabilities [2; θ]
    g. Stack lifetime and replacement requirements [2; μ, θ]
3. System management
    a. Minimize heat loss through system integration and thermal management [2; γ]
    b. Additional cost of water/coolant management [2; θ]
    c. Need to develop advanced fuel cell sensors and instrumentation [2; Garland1 2006]

Integration With Current Infrastructure

1. Fuel processing and transport barriers
    a. High-purity hydrogen stream from fuel reforming [4; θ, ξ]
    b. Carbon formation (coking) prevention for fuel reforming [4; θ]
    c. Improvements in reformer response times and efficiency [3f; α]
    d. Development of fuel producing, processing and reforming methods [4; θ, δ, π, α, γ]
    e. Accommodation for fuel variations (i.e., long-term and short-term fuel flexibility) [4; γ, χ, Θ, π, Π]
    f. Fuel infrastructure for transportation applications [1b-c, 4a1; Wu 2006]
    g. Cost and convenience for dispensing system designs [1b-c, 4a1; α]
    h. Fuel delivery system right-of-way [4; π]
    i. Establish fuel quality specifications [4; ξ]
2. Electrical transmission/distribution barriers
    a. Need fully integrated power conditioning devices [1a3; η, ε, ξ]
    b. Ancillary grid service barriers (power factor, phase angle, etc.) [3d; λ]

   c. Electricity transmission system integration [3d; λ]
   d. Fuel cell system islanding, safety and reliability barriers [3d; DG DOE 1999]
   e. Interaction of fuel cell and fuel cell-gas turbine systems with one another and the grid [1a3; ε]
3. Hydrogen storage and transport barriers
   a. Hydrogen storage media performance and safety [4a4; β, δ, π]
   b. Experience with hydrogen dispensing for self-service refueling facilities [1b-c, 4a1; α]
   c. Experience and knowledge for maintenance and operation of fuel cell technologies [4a; α]
   d. Need advanced hydrogen storage solutions [4a1, 1b-c; α]
      i. High-pressure hydrogen storage technology (5,000-10,000 psi) [4a4; α]
      ii. Filling and discharging limitations of hydrogen storage devices [4a4; α, Π]
   e. Need for a life-cycle analysis for fuel production and delivery alternatives [4a; α, δ]
   f. High cost of hydrogen and alternative fuel technologies when compared to current technologies [4a; α]
4. Hybrid system barriers
   a. Performance and cost implications for FC hybridization [1a3; ε, θ]
   b. Fuel cell hybrid system integration requirements [1a3; ε]
   c. Optimized chilling system hybridization for improved CHP performance [1a2a; θ]

Research and Development Barriers

1. Materials science advancements needed
   a. Understanding of material impurity effects on fuel cell fabrication and performance [2; γ]
   b. Achieving material purity levels [2c; α]
2. Performance understanding/insights
   a. Understanding performance under diverse climactic conditions and locations [2; α]
   b. Understanding fuel cell interaction with the grid [3d; λ, γ]
   c. Understanding thermal and electric load profiles for CHP [1a2; θ]
   d. Understanding building load fluctuation effects on CHP equipment [1a2; θ]
   e. Externality evaluation and valuation (ex. carbon tax) [1, 4; α]
      i. Determination of the social cost of alternative fuels [4a; α]
   f. Establishing a strategy for progression from current fuel to an alternative fuel future (ex. hydrogen) [1, 4a; α]
3. System modeling needs
   a. Modeling fuel cell and absorption chiller systems [1a2a; κ]
   b. Modeling of gas turbine and fuel cell operation [1a3; γ]

c. Electrochemistry modeling techniques [2; θ]
d. Thermodynamic fuel cell systems analyses [2; θ, ϱ]
e. Modeling of integrated fuel cell and energy storage systems [3b; θ, ϱ]
f. Electric utility grid network modeling [3d; λ]

Equipment Performance Compared to Existing Technology

1. Efficiency improvements
   a. Material processing challenges [2a; γ]
   b. Relative low power density of tubular SOFC technology [2a; μ]
   c. Optimum distribution of heat, cooling, electricity, hydrogen, etc. from multi-generation systems [1a2; Binder 2006]
   d. Relative high ohmic polarization of tubular SOFC technology [2a; θ, μ]
2. Exploration of lifetime issues
   a. Meeting dynamic operation requirements for fuel cell and fuel cell hybrid systems (e.g., startup, shutdown, load following) [1a3, 2; ε, ζ, η, θ]
   b. High fuel cell system and stack degradation rates [2; ν, μ, α, ξ, Stone 2006]
   c. Need to increase material resistance to thermal cycling [2; Simon 2006]
   d. Fuel cell fuel or oxidant contamination prevention requirements [2; α]
      i. Sulfur contamination and degradation [4; ξ]
      ii. Carbon monoxide degradation of low-temperature fuel cells [2c-d; α, ν, β]
3. Demonstration efforts
   a. Lack of hydrogen conversion technology demonstrations [4a; α, Harris 2006, ξ]
   b. Lack of data available from demonstration sites [1; α]
   c. Lack of hydrogen production technology demonstrations [4a3; α]

Policy Barriers

1. Interconnection with grid
   a. DG-grid interconnection process barriers [3d; DG DOE 1999]
   b. Implementation of novel metering technology (e.g., net metering) [3d; λ]
   c. Need policies for DG integration and sale of electricity on the distribution network [1a2, 3d; Lopes 2007]
2. Codes and standards
   a. Equipment siting process barriers [1a2; γ]
   b. Need for hydrogen testing, validation and certification organization [4a; α]
   c. Need for consistent and harmonized national and international codes [1; α, π]
   d. Need for hydrogen codes and standards to ensure safety [4; α]
   e. Nationwide interconnection agreements to allow connection to grid without punitive costs; policies or actions [1; θ]

    f. Creation and enforcement of permitting code, standards and regulations for DG [1a2; γ]
    g. Adjustments to intellectual property provisions [1; ξ]
3. Education
    a. Need for long-term resource and education commitment for all levels [4a2; α]
    b. Ensuring sufficient training on hydrogen for emergency responders and code officials [4a2; π]

3.4.2. Summary of Projects

Following the specific technology issues, projects to address both those issues and the commercialization barriers are generated. Projects are formulated for each technology category (e.g., DG/CCHP, grid support). Figure 4 contains a graphical representation of the number of projects included in each category. The inner ring presents the four major technology category groups and the percentage of projects that are included in that group. The outer ring presents each technology category and the number or projects included within that category. Table 8 contains the number of projects included in each category. The complete list of projects is located in Appendix D. These projects are separated by their technology category and each table includes the associated score, projected cost and duration, and project title for each project. Additionally, a longer description of the project title and any comments that were introduced specifically for that project or that category during the survey process are included.

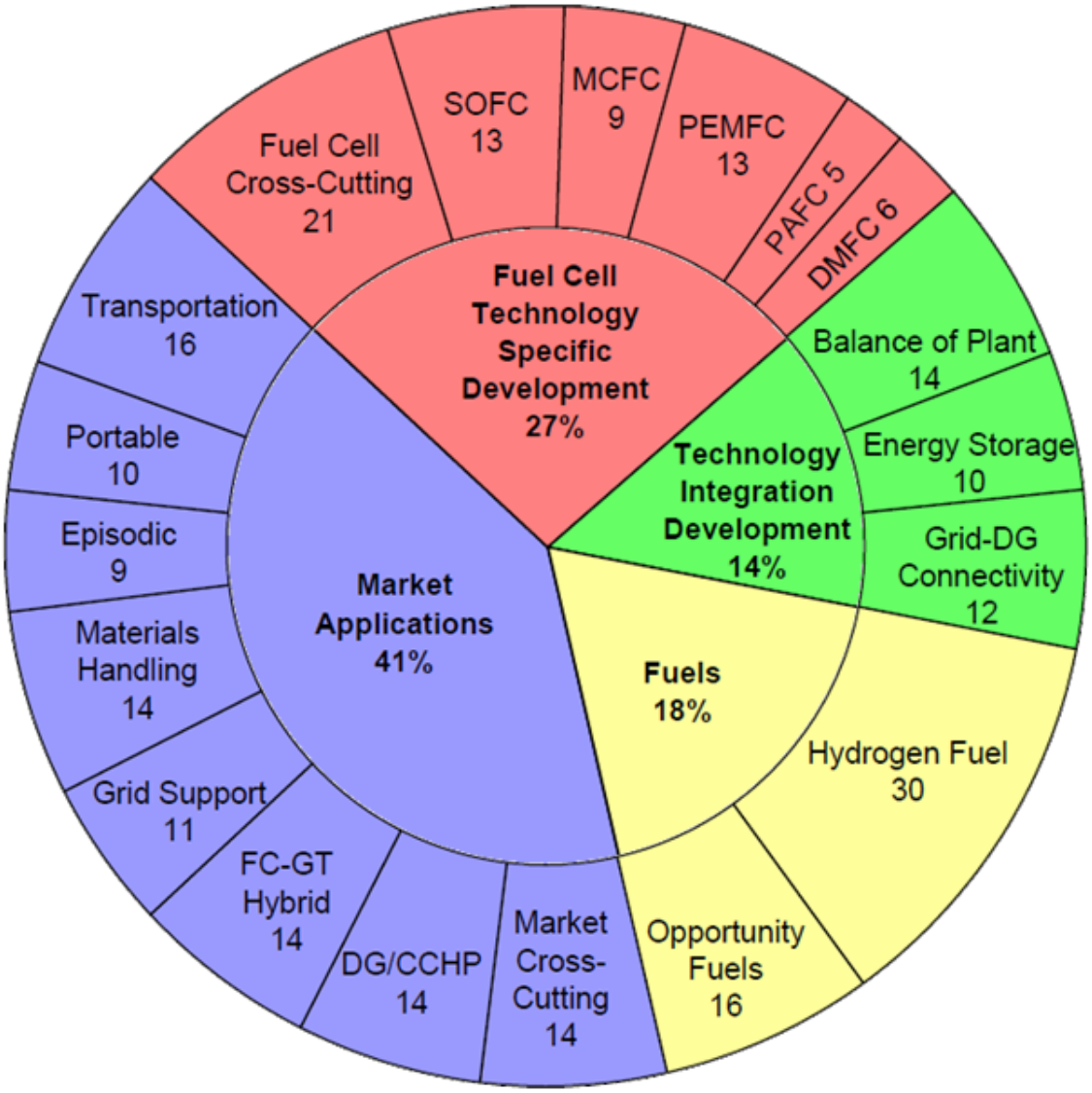

Figure 4: Project Distribution Amongst All Technology Categories

Source: National Fuel Cell Research Center.

Table 8: Project Distribution Amongst All Technology Categories

Technology Categories	Identified Projects
Market Applications	
Stationary power	
Grid support	11
DG/CCHP	14
FC-GT hybrid	14
Transportation	16
Materials handling	14
Episodic	9
Portable	10
Market cross-cutting	14
Fuel Cell Technology Specific Development	
SOFC	13
MCFC	9
PEMFC	13
PAFC	5
DMFC	6
Fuel cell cross-cutting	21
Technology Integration Development	
Balance of plant	14
Energy storage	10
Grid-DG connectivity	12
Fuels	
Hydrogen	30
Opportunity fuels	16
TOTAL	251

3.5. Stakeholder Surveys and Feedback

Once the list of projects is created, it must be refined and reviewed by stakeholders in the fuel cell community. This was a multi-stage process and began with the first refinement occurring on April 3, 2008, with a workshop in Sacramento. This was quickly followed by the request for participants in that group to complete the *initial* survey, which contained only projects from the market application categories. Following the first survey, a second survey was developed based on the feedback from the *initial* survey. The second survey was administered online to a larger group of the fuel cell community and included a subset of the market application projects from the *initial* survey. A second workshop occurred on August 27, 2008 where the results from the initial and online surveys were disseminated, all the while any additional feedback was collected.

All of this feedback was gathered and used to develop the *final* survey. This survey was administered online to a very broad spectrum of the fuel cell community including the United States Fuel Cell Council (USFCC) members, California Hydrogen Business Council (CHBC), California Stationary Fuel Cell Collaborative (CaSFCC) and more.

Because of the highly technical nature of the material being surveyed, it is difficult to both survey a large number of individuals and survey a knowledgeable set of individuals. This is again complicated because of the size of the fuel cell sector. Thus, for the first survey, specific industry professionals were asked to review the survey. Following their responses, the survey was refined and distributed to a wider set of participants. The final survey consisted of the largest set of participants and the most refined set of criteria. In this way, confidence in the response for the initial surveys is bolstered by the perceived experience and knowledge of the participants, while confidence in the final survey, which was distributed to a significantly more diverse spectrum of the community, is bolstered more by the sample size. Information about the participation for each survey is included briefly in the following sub-sections and more completely in the following section.

Data from all three surveys were collected and combined to develop the final list and parameters for each project in this study. The following sections describe each of the three surveys in detail. They include information about the scope and format for each survey as well as participation information. Each section introduces evaluation criteria used to evaluate the projects. It is from these criteria that the primary project parameters (score, cost and duration) are derived.

3.5.1. Initial Survey

Distribution of the initial survey occurred on May 22, 2008 with a requested submission date of April 25, 2008. The first survey was sent to a relatively small group of participants on account of the detail required to complete the survey. Table 9 shows the final list of participants in the initial survey. The high degree of detail was used to establish which survey properties are the most beneficial, thus allowing for simplification. Table 10 presents the format for the initial survey.

Table 9: Initial Survey Participants

Fuel Cell Area	Initial Survey Participants	Related Organization
Large Unit Manufacturers	Christian Forbes Mike Brown, Ram Ramaswamy	Siemens UTC Power
Small Unit Manufacturers	Katrina Fritz-Intwala Kevin Harris	Plug Power Hydrogenics
Agency and Other	Lori Schell Steve Ambrose Jonathan Foster	Empowered Energy DGS ARB

Table 10: Initial Survey Format

Category	Description
Project Duration	Expected duration of California Energy Commission funded project
Funding Required	Expected total funding required to fully address project/concept
Co-Funding Source	Existing state, DOE, PIER, Industry, or match funding
Project type	1. Basic Research 2. Applied Research 3. Development 4. Deployment
RD&D Category	1. Materials 2. Cell and stack 3. Operation 4. Integration 5. Application 6. Cross-cutting 7. Market, policy and education

Criteria	Description	Value	Criteria Weight
Funding	Anticipated need for state funding	Low, Medium, High	8
	Anticipated match funding	Low, Medium, High	5
Goals	Satisfaction of state energy policies and policy goals	Low, Medium, High	10
	Satisfaction of state environmental policies and goals	Low, Medium, High	5
	Ability to meet fuel cell targets and milestones	Low, Medium, High	9
Benefits	Societal benefits	Low, Medium, High	6
	California business (investor) benefits	Low, Medium, High	8
	California ratepayer benefits	Low, Medium, High	10
	Environmental benefits	Low, Medium, High	6
	Significance to related industry/field(s)	Low, Medium, High	3
Status	Distinctness from existing programs/funding	Low, Medium, High	4
	Correspondence to projected significant fuel cell market applications	Low, Medium, High	9
Time to Payoff	Time required for technology to become fully developed and to result in		
	Societal Benefits	Low, Medium, High	-2
	California business (investor) benefits	Low, Medium, High	-3
	California ratepayer benefits	Low, Medium, High	-7
	Environmental benefits	Low, Medium, High	-3
	Time when initial benefits will be achieved	Low, Medium, High	-3
Risk	Likelihood that investment will not lead to expected outcome(s)	Low, Medium, High	-4
	Dependence on uncompleted programs	Low, Medium, High	-2
	Likelihood that required special resources (equipment, personnel, etc.) are unavailable	Low, Medium, High	-1
	Instability of match funding sources	Low, Medium, High	-2

The first table contains general information about each project including the project duration, funding required, co-funding source, project type, and RD&D category while ranking of each project is achieved using the second table. The groups of weighted evaluation criteria presented in the second table were developed to encompass all of the aspects of importance for each project. The value for each criterion is multiplied by its corresponding *Criteria Weight* and the sum of all of the *Weighted Scores* represents the

significance of that particular project concept. Once all of the project concepts are evaluated, the results should provide guidance for prioritizing RD&D topics. The categories in the first table are described below.

Category Definition

Project duration:

The project duration category represents the expected time required to complete this project. This time will typically span between 1 and 5 years to be considered by the California Energy Commission. It is acceptable to enter a value over 5 years, and non-integer year values are also acceptable (e.g., 1.5 years).

Funding required:

The funding required category represents the projected amount of funding needed to address the project including equipment, personnel, etc. The exact dollar number or the number (1-5) for the range (given below) can be inserted into the project description table.

1. <$100,000
2. ≥$100,000 and <$200,000
3. ≥$200,000 and <$500,000
4. ≥$500,000 and <$1,000,000
5. ≥$1,000,000

Co-funding source

The co-funding source category represents the amount of additional funding that will be contributed. The exact dollar number or the number (1-5) for the range (given below) can be inserted into the project description table.

1. <$100,000
2. ≥$100,000 and <$200,000
3. ≥$200,000 and <$500,000
4. ≥$500,000 and <$1,000,000
5. ≥$1,000,000

Project type

The project type category represents the general type of work that will be addressed. Sub-categories include basic research, applied research, development and deployment. Basic research seeks to solve or explain issues that occur on the most fundamental level. Applied research builds on the discoveries from basic research by broadening the scope and end goals of the research. Development refers to component or system advances, optimization and integration. Deployment includes opportunities for system installation and operation.

RD&D category

The last category reflects the kind of information that will be examined during each project. Sub-categories include materials, cell and stack, operation, integration, application, cross-cutting and market, policy and education.

Criteria Definition

Funding:

Anticipated need for state funding

- Represents a measure of the importance of funding from the state of California for the completion of a particular project, relative to the other projects
- A project that needs state funding more than another project is of more value

Anticipated match funding

- Represents the anticipated portion of funding that will be provided by other groups for the completion of a particular project, relative to the other funding provided
- A project that receives more match funding than another project is of more value

Goals:

Satisfaction of state energy polices and goals

- Represents the extent to which a particular project addresses California's energy policies
- A project that addresses more or better addresses energy policies or energy goals is of more value

Satisfaction of state environmental polices and goals

- Represents the extent to which a particular project addresses California's environmental policies
- A project that addresses more or better addresses environmental policies or environmental goals is of more value

Ability to meet fuel cell technology targets and milestones

- Represents the extent to which a particular project will coincide with established targets and milestones for achieving fuel cell commercialization
    - Benchmarks and milestones are listed in the Research Outline document under the *Cross-cutting technology development and analyses* category.
- A project that addresses more or better addresses fuel cell technology targets and milestones than another project is of more value

Benefits:

Societal benefits

- Represents the effect that the completion of a particular project will have on society

- A project that provides more benefits for society than another project is of more value

California business (investor) benefits

- Represents the effect that the completion of a particular project will have on related California businesses
- A project that provides more benefits for California businesses than another project is of more value

California ratepayer benefits

- Represents the effect that the completion of a particular project will have on California ratepayer
- A project that provides more benefits for a ratepayer than another project is of more value

Environmental benefits

- Represents the effect that the completion of a particular project will have on the environment
- A project that provides more benefits to the environment than another project is of more value

Significance to related industry/field(s)

- Represents the effect that the completion of a particular project will have on the related fields or industries
- A project that is more significant or has a larger effect than another project on the direction and speed of a field or industry towards product development, refinement or commercialization is of more value

Status:

Extent addressed by current programs

- Represents the extent to which the goals and implementation of a project have been or are already being explored in existing projects
- A project that has not and is not currently being addressed is of more value

Correspondence to expected significant fuel cell market applications

- Represents how well a particular project fits into the anticipated market structure for fuel cells
    - Projected fuel cell market structure
        - Large Units (100kWs to MWs)
            - Grid support
            - Renewable continuous power
            - Distributed generation with CCHP
            - Cogeneration of hydrogen
            - Advanced fuel cell-gas turbine hybrids
        - Small Units (1kW to 10kWs)
            - Real-time mission critical back-up
            - Back-up for peak power shaving
            - Backload power for distributed generation

        - Specialty vehicle applications
    - A project that coincides with the projected market structure more than another project is of more value

Time to Payoff:

Time required for technology to become fully developed and to result in:

Societal benefits

- Represents when the value from the results of a project will be realized or become useful to society
- A project that provides benefits to society sooner than another project is of more value

Investor benefits

- Represents when the value from the results of a project will be realized or become beneficial to its investor(s)
- A project that provides benefits to its investor(s) sooner than another project is of more value

California ratepayer benefits

- Represents when the value from the results of a project will be realized or become useful to California and its ratepayers
- A project that provides benefits to California and its ratepayers sooner than another project is of more value

Environmental benefits

- Represents when the value from the results of a project will be realized or become beneficial to the environment
- A project that benefits the environment sooner than another project is of more value

Time when initial benefits will be achieved

- Represents the distribution of value over the lifetime of a project
    - Example, are the most significant results likely to be realized early or late in the project?
- A project that provides significant benefits during the beginning is of more value than a project that provides significant benefits toward the end

Risk:

Likelihood that investment will not lead to expected outcome(s)

- Represents the chance that a project will deviate from the established project description.
    - Example, more expensive, requires additional time, inconclusive or incomplete results
- A project that is likely to be more coincident with its project description than another project is of more value

Dependence on uncompleted programs

- Represents whether the completion of a project requires data, legislation, equipment, etc. from another program or project yet to be completed.

- A project that is less dependant on other programs than another project is of more value

Likelihood that required special resources are unavailable

- Represents the extent to which and the difficulty of acquiring certain resources required to complete a particular project
  - Example, equipment, personnel, location, etc.
- A project that is more independent of special resources than another project is of more value

Instability of match funding sources

- Represents a measure of the security of the funding for a particular project over its lifetime
- A project that has more secure funding sources than another project is of more value

Initial Survey Comments

The most significant comment was that the survey was too long and that the criteria were so detailed for each project that either there needs to be fewer projects or fewer criteria. Other feedback received is listed below.

- Simplify scoring criteria
  - Clear confusion over the meaning of the funding criteria
  - Difficult to complete the project description table
- Modify list of projects
  - Reduce the number of evaluated projects
  - Suggestions of several additional projects
    - Regenerative systems
    - Electrolyzers
    - Hybrid systems
  - Combine several projects into one

3.5.2. Second Survey (Web-Based)

The second survey made use of the feedback and results from the first survey to shorten and focus the scope of future surveys. A larger group of participants was targeted for participation and the resulting list of participants is shown in Table 11. The modifications to the format are quite recognizable when comparing the initial survey format (Table 10) to the second survey format (Table 12). Following the initial survey, the second survey was distributed on August 1, 2008 and the requested date of submission was August 15, 2008.

Table 11: Second Survey Participants

Name	Affiliation
Mike Binder	Binder and Associates
Yaofan Yi	Chevron
Mark Williams	Consultant
Franklin Holcomb	ERDC-CERL
Chuck Sishtla	Gas Technology Institute
Wolfgang Winkler	Hamburg University of Applied Sciences
Joongmyeon Bae	KAIST
Josh Freeh	NASA
William Ernst	Plug Power
Matt Miyasato	SCQAMD
Randy Brown	Southern California Gas Company (Sempra Energy Utility)
C.C. Lee	United States EPA
Daniel Mumm	University of California, Irvine
Martha Mecartney	University of California, Irvine
Faryar Jabbari	University of California, Irvine
Keyue Smedley	University of California, Irvine
Ram Ramaswamy	UTC Fuel Cells

Table 12: Second Survey Format

Criteria	Description	Value	Criteria Weight
Funding	How much funding is needed to complete this project? (low is <$100,000, high is >$1,000,000)	Low, Med-low, Medium, Med-High, High	13
Goals	To what extent are national or state goals met by pursuing this project?	Low, Med-low, Medium, Med-High, High	24
Benefits	How significant are the benefits from this project? (for society, California ratepayer, business/investors)	Low, Med-low, Medium, Med-High, High	33
Status	How much work has been and is being done related to this project?	Low, Med-low, Medium, Med-High, High	12
Time to Payoff	How long until this project enhances the economic viability of this technology? (Low is <1 year, High is >5 years)	Low, Med-low, Medium, Med-High, High	18
Risk	What is the level of risk for pursuing this project? (Low is very likely to achieve desired outcomes and high is very unlikely to achieve desired outcomes)	Low, Med-low, Medium, Med-High, High	9

The criteria used in the second survey are a condensed version of the initial survey criteria. One of the major comments from the first survey was that the criteria list was

too extensive to complete in a reasonable amount of time. Thus, for the second survey, the number of criteria was reduced while maintaining the same types of groups that were used in the first survey and the criteria weight was modified based on feedback from the first survey. Additionally, the participants made several comments about the content and scope of the second survey, which are listed below:

- Low estimate in funding criteria (recommends <$1million to >$10 million).
- Explore which entities are pursuing or have already pursued selected projects.
- What is the responsibility of the state to fund and what should the return on investment expectations be for DG/CCHP projects?
- Focus more on industrial CHP and less on residential CHP.
- Include fundamental fuel cell projects (e.g., performance, manufacturing, lifetime).
- Additional Projects
    - Address on-board reforming of transportation fuels.
    - Fuel Cell-Gas Turbine (FC-GT) constituent materials analysis and the impacts of those materials.
    - Fuel cell development in aviation and space applications.
    - Interconnection with renewable energy sources (e.g., wind, solar).
    - Public education concerning the benefits and safety of fuel cell technology.
    - Develop effective fuel processing schemes (e.g., syngas, internal reforming).
    - Explore fuel cell and electric storage hybrid (e.g., batteries, supercaps).
    - Stability and performance of fuel cell materials sets in FC-GT hybrids.
    - Co-production of hydrogen and electricity using SOFCs.
    - Develop low-cost BOP components.
    - Explore value proposition and additional opportunities for Portable fuel cell applications.
    - Refine and optimize emissions regulation framework.

3.5.3. Final Survey (Web-Based)

The final survey made use of feedback from the previous two surveys, the workshops and additional stakeholder feedback. All of the categories and all of the projects were

included in this survey, which resulted in 19 sub-surveys. The participants were asked to complete as many of the surveys as they could. Participation in the final survey represented the broadest cross-section and more participants than any other survey. Table 13 contains a list of those who participated in the final online survey process, while Table 14 presents the format used for the final survey. The final survey first opened on September 17, 2008 and October 10, 2008 was the requested date of submission.

Table 13: Final Survey Participants

Name	Affiliation
Allie Auld	APEP, UC Irvine
Andrew Martinez	NFCRC
Anh-Tuan Do	NFCRC
Brendan Shaffer	NFCRC
Brian B. Bonner	Air Products and Chemicals, Inc.
Chris	Marketing
Edward C. Heydorn	Air Products
Eric Simpkins	IdaTech, LLC
Erik Turner	NFCRC
Fabian Mueller	APEP, UC Irvine
Jack Brouwer	NFCRC
Jeff Cox	FuelCell Energy
Jonathan Foster	Air Resources Board
Joseph McMenamin	Direct Methanol Fuel Cell Corp
Josh Eichman	NFCRC
Ken Schultz	General Atomics
Kevin Harris	Hydrogenics
Larry Watkin	SCAQMD
Li Zhao	NFCRC
Michael Hicks	IdaTech, LLC
Mu Li	APEP, UC Irvine
Nicole Barber	Chevron
P.J. Buehler	Plug Power Inc.
Pere Margalef	APEP, UC Irvine
Randall Gemmen	NETL
Richard Kriete	FuelCell Energy
Rick Cooper	Polyfuel
Robert Wichert	Technical Director, USFCC
Rosario Berretta	Daimler
Shane Stephens-Romero	APEP, UC Irvine
Stan Foster	Sales and Marketing Mgr NA
Tim Brown	University of California, Irvine
Tom Pine	NFCRC

Table 14: Final Survey Format

Question	Description	Value	Criteria Weight
Initial Evaluation	Do you feel this project is valuable for the commercialization of fuel cells in California?	Yes, No	
Funding Value Required	What is this projects need for funding?	< $1, $1-2, $2-5, $5-10, >$10M	
Cost Sharing Potential	What is the potential for cost-sharing on this project?	Low, Med-low, Medium, Med-High, High	15
Need for State Funding	Considering previous related technology developments, and current and expected support (funding) for this work, how significant or important is state funding for this project?	Low, Med-low, Medium, Med-High, High	23
Benefits	How significant are the benefits for this project? (for society, California ratepayer, business/investors)	Low, Med-low, Medium, Med-High, High	15
Benefit to Cost Ratio	What is the benefit to cost ratio for this project? (low score represents either high costs and/or low benefits and a high score represents either low costs and/or high benefits	Low, Med-low, Medium, Med-High, High	22
Goals	To what extent are national or state goals met by pursuing this project?	Low, Med-low, Medium, Med-High, High	10
Time to Payoff	How long until this project enhances the economic viability of this technology?	< 1, 1-2, 2-3, 3-5, >5 years	10
Risk	What is the level of risk for pursuing this project? (Low is very likely to achieve desired outcomes and high is very unlikely to achieve desired outcomes)	Low, Med-low, Medium, Med-High, High	5

The participants in the second survey, again, noted that the survey was long and that better participation would result if the survey was shortened. Given the scope of projects reviewed in the final survey, achieving high participation for each project is essential to developing valuable results. The first question of the final survey was used to shorten the survey. There are three possible responses: (1) yes, and I will complete the evaluation (continue below), (2) yes, but I will not complete the evaluation (skip to the next project), and (3) no, this project is not worthy of consideration (reject this project and skip to the next project). If response (1) was indicated, the participant completed the ranking table for that project and their values were included in that project's average parameters. If response (2) was indicated, no information about that project could be determined so that participant's response was not applicable to the overall project parameters. Lastly, if response (3) was indicated, the project was given the lowest score

possible signifying that the participant did not consider this project to be valuable compared to the other projects.

The *Funding Value Required* questions was used to determine a projected cost value for that project. Similarly, the *Time to Payoff* question was used to establish projected project duration values. The *Criteria Weight* values were selected based on the response from the previous two surveys and the sentiment of those participating in the workshops.

Once all of the criteria were evaluated for each project, the response for each survey was averaged. These average project scores were adjusted for similarity between the three surveys and the values from the three surveys were averaged. The resulting values were used to determine the final project parameters (e.g., participation, score, cost and duration). The score value is a function of the cost, duration and all of the other criteria evaluated in the surveys making it the most important for classification and prioritization. These parameters and their use are described in greater detail in the following chapters.

3.5.4. Survey Revisions and Feedback

Stakeholder review and revision plays an integral role in the development of this work. For every survey, the participants submitted their critical reviews of *The Plan* then the appropriate revisions were made to address key concerns and identified errors. Feedback for the initial and second surveys is listed in the sections above, while the feedback from the final survey is predominantly related to the projects and is included in Appendix D with the projects. Some of the areas that the stakeholders were requested to review include:

- Completion of project evaluation tables.
- Adjustments to the technology categories.
- Adjustments to the criteria weight and evaluation technique and format for the surveys.
- Comments and justification for project selection and scoring.
- Identification of additional projects to pursue.
- Separation of a single, general project into more specific projects.
- Removal of selected projects.
- Combining of related projects.
- Anything else that the participants deemed important for determining and prioritizing fuel cell technology challenges.

4.0 Results

By collecting the results and feedback from each survey, the final score, cost and duration values from the surveys can be generated. Technology roadmaps and action plans can be very subjective; however, confidence in the resulting parameters for this work relies on the consistency of the respondents' evaluations as well as a large sample size, as discussed in greater detail in the following sub-sections.

Optimally, several dozen or even hundreds of individuals are surveyed, but due to the technical nature of this material, this level of participation is not possible for every project, thus even though this method generates precise values to several significant digits caution must still be used when attempting to compare project parameters that are very similar. For projects with fewer survey participants, the uncertainty in the statistical parameters will rise. Some of the uncertainty is alleviated because, of all of the projects, only the highest ranking projects are used in the roadmap. This concept is discussed in the following sub-sections.

This section contains the list of the highest ranking projects followed by information concerning participation and uncertainties within the survey. Lastly, a summary of the survey results for all of the projects is presented. The highest ranking projects were selected first by taking at least five projects for each project category and second by including additional projects based upon their overall rank among all projects. This ensures that categories with significantly more projects than another category have the potential to include more projects. Similarly, categories with few projects benefit from the inclusion of at minimum five projects. Based on this schema, the projects are separated into four groups. The most important group of projects is the *Critical* project group, followed by the *High* and *Medium* priority groups. Projects not included in the high ranking projects list are placed in the last group, the *Low* priority group. Though the projects in this group are still important and should be considered for pursuit, the projects within the other groups were identified as potentially more beneficial (see Appendix D for complete list of projects and see Appendix E for the complete prioritized list of projects organized by score, cost and duration).

4.1. Participation

Knowing the sample size is essential to establishing confidence in the results of a survey style analysis like that contained herein. A summary of the participation results are presented in Table 15 and a breakdown of the distribution of individuals contributing to the surveys is presented in Figure 5. For Figure 5, all of the participants were separated into five different groups including: university, government, industry, consulting, and anonymous and the resulting distribution is presented.

Table 15: Summary of Survey Participation Results

Technology Categories		Identified Projects	Participation	
			Average	Total
Market Applications	Market Cross-Cutting	14	14.5	203
	DG/CCHP	14	20.1	282
	FC-GT Hybrid	14	15.3	214
	Grid support	11	14.4	158
	Materials Handling	14	13.1	183
	Episodic	9	10.7	96
	Portable	10	10.1	101
	Transportation	16	12.9	207
Fuel Cell Technology Specific Development	Fuel Cell Cross-Cutting	21	7.7	161
	SOFC	13	7.4	96
	MCFC	9	5.2	47
	PEMFC	13	6.2	81
	PAFC	5	2.2	11
	DMFC	6	3.3	20
Technology Integration Development	Balance of Plant	14	4.9	69
	Energy Storage	10	8.9	89
	Grid-DG Connectivity	12	10.6	127
Fuels	Hydrogen Fuel	30	10.3	310
	Opportunity Fuels	16	8.2	132
Total		**251**	**10.3**	**2587**

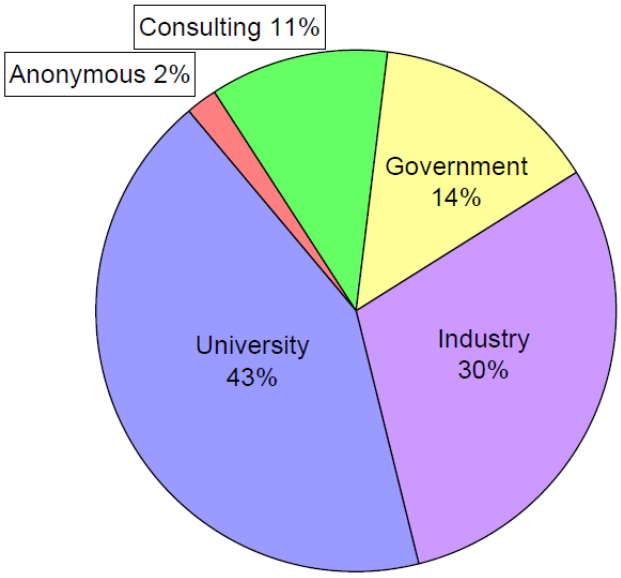

Figure 5: Survey Participant Distribution

Source: National Fuel Cell Research Center.

Combined participation in all surveys is presented in Table 16. These values represent the number of individuals that completed a survey for that specific project. Caution is recommended when considering the implications of the values presented. Cost, duration and overall score values are the result of the opinions of the participants in the survey. Though the results indicate the parameters for a particular project, the absolute values are subject to some degree of uncertainty. Due to the nature of the analysis, intra-category comparisons can be made with more confidence than cross-category comparisons. That is because not all participants completed all surveys; however, most participants completed every project within the categories that they reviewed.

In Table 16 all of the projects surveyed are included and the priority of each project is denoted by the background color of each cell. The *critical*, *high*, and *medium* priority projects have dark green, light green and yellow background colors, respectively. The *low* priority group has a white background color. Additionally, there are two average values included at the bottom of the table. The first are the average values for the total participation within each category while the second contains the average values for only the highest ranking projects within each category (*critical*, *high*, and *medium* priority projects). The average participation in the scoring of the highest ranking projects is higher than compared to the average participation for all projects. An average of 11.6 participants completed the surveys for the highest ranking projects compared to an average of 10.3 participants for all of the projects. This shows that an average of greater than 10 people submitted individual scores for each project with even more participation for the highest ranking projects, which is why, as stated previously, the use of the highest ranking projects reduces some of the uncertainty while focusing upon a smaller set of projects to be analyzed.

Table 16: Fuel Cell Technology Survey Participation

Project Number	Marketing Applications								Fuel Cell Technology Specific Types						Tech. Integration			Fuels		Project Number
	MK-CC	DG/C CHP	FC-GT Hybrid	Grid Support	Materials Handling	Episodic	Portable	Transpor tation	FC-CC	SOFC	MCFC	PEMFC	PAFC	DMFC	BOP	Energy Storage	Grid-DG	Hydrogen Fuel	Op-fuels	
1	17	28	21	17	10	6	13	18	5	8	5	6	2	3	5	7	6	8	3	1
2	17	27	21	16	18	15	13	18	6	8	5	7	2	3	4	6	12	20	18	2
3	19	28	20	12	18	16	13	16	5	8	5	7	2	4	5	11	10	9	5	3
4	21	25	9	17	16	15	13	17	6	5	5	6	3	4	4	12	4	18	5	4
5	21	27	21	17	16	9	13	16	10	8	6	5	2	3	5	12	6	8	17	5
6	21	15	10	18	7	8	7	9	20	6	5	6		3	5	7	6	7	5	6
7	10	28	11	18	7	15	13	9	11	8	6	7			6	12	5	8	4	7
8	7	27	10	11	18	3	6	17	5	9	5	7			5	12	24	6	5	8
9	11	11	10	9	9	10	6	17	5	6	5	6			4	5	25	10	7	9
10	7	27	22	11	18		4	17	6	7		6			5	5	6	8	5	10
11	7	12	21	12	18			8	6	7		6			5		17	18	6	11
12	18	7	21		10			9	6	8		6			4		6	21	15	12
13	12	8	6		8			9	6	8		6			6			8	4	13
14	17	12	11		10			17	5						6			18	4	14
15								5	6									10	5	15
16								5	6									11	23	16
17									9									7		17
18									10									9		18
19									9									9		19
20									9									9		20
21									9									8		21
22			Critical Priority															7		22
23			High Priority															9		23
24			Medium Priority															7		24
25			Low Priority															8		25
26																		10		26
27																		11		27
28																		8		28
29																		11		29
30																		9		30
Average	14.5	20.1	15.3	14.4	13.1	10.7	10.1	12.9	7.7	7.4	5.2	6.2	2.2	3.3	4.9	8.9	10.6	10.3	8.2	Average
Average*	16.2	22.2	18.9	16.3	17.3	10.3	11.8	15.2	7.3	7.3	5.2	5.8	2.2	3.4	4.8	9.4	12.6	10.2	9.8	Average*
Total	203	282	214	158	183	96	101	207	161	96	47	81	11	20	69	89	127	310	132	Total
Total*	97	244	132	114	104	52	71	76	58	44	26	29	11	17	29	47	88	102	59	Total*

*Values present results for all of the highest ranking projects

4.2. Summary of All Projects

Now that an understanding of the types of projects selected and a measure of uncertainty within the results is established, this section presents a summary of results from evaluations of all of the projects. Table 17 presents an average score for each of the projects along with statistical parameters at the bottom of the table. Table 18 contains the projected cost of each of the projects with units of millions of dollars. Finally, Table 19 presents the projected duration in years for each of the projects. These tables serve as a condensed version of the tables located in Appendix D and Appendix E. In these three tables the priority (e.g., critical, high, medium and low) is determined by the highest scoring projects within that category and amongst the other technology groups and is explained in more detail in the next section.

A graphical depiction of the scores for every project is included after Table 19. This figure, Figure 6, allows for a quick valuation of project category properties, especially properties like range, rank and deviation. Important characteristics to note when reviewing these figures include: the green bar at the top of the bar for each category is the maximum project value, the red bar at the base of the bar for each category is the minimum project value and the orange bar near the middle of the bar for each category is the average project value (i.e., unlike the green and red bars the orange bar does not represent a project). The orange horizontal line that spans all of the categories is the average value among all of the projects. Each blue rectangle along the bar represents the value for a particular project.

Table 17: Average Project Score

Project Number	Marketing Applications								Fuel Cell Technology Specific Types						Tech. Integration			Fuels		Project Number
	MK-CC	DG/C CHP	FC-GT Hybrid	Grid Support	Materials Handling	Episodic	Portable	Transpor tation	FC-CC	SOFC	MCFC	PEMFC	PAFC	DMFC	BOP	Energy Storage	Grid-DG	Hydrogen Fuel	Op-fuels	
1	48%	70%	61%	84%	36%	27%	73%	45%	52%	71%	57%	48%	36%	57%	37%	61%	83%	54%	28%	1
2	46%	74%	55%	84%	61%	69%	71%	46%	61%	54%	48%	44%	51%	59%	65%	43%	64%	61%	59%	2
3	55%	83%	70%	46%	61%	56%	56%	64%	60%	50%	52%	40%	32%	8%	41%	63%	67%	52%	54%	3
4	62%	85%	35%	60%	56%	52%	48%	51%	34%	52%	41%	35%	24%	16%	64%	62%	51%	52%	54%	4
5	66%	79%	51%	73%	54%	64%	56%	37%	49%	69%	54%	69%	68%	7%	39%	37%	27%	54%	47%	5
6	64%	52%	51%	73%	48%	57%	46%	65%	62%	50%	40%	48%		43%	50%	53%	86%	55%	27%	6
7	43%	71%	46%	76%	49%	59%	51%	51%	43%	48%	46%	37%			38%	52%	84%	37%	42%	7
8	19%	59%	21%	63%	49%	69%	57%	72%	81%	39%	56%	36%			47%	64%	58%	67%	9%	8
9	54%	42%	25%	52%	29%	76%	29%	70%	55%	71%	62%	45%			19%	56%	73%	45%	23%	9
10	33%	72%	91%	46%	68%		49%	34%	45%	65%		41%			29%	41%	15%	38%	0%	10
11	45%	47%	81%	48%	44%			24%	65%	80%		46%			21%		42%	51%	24%	11
12	59%	78%	72%		27%			5%	14%	83%		41%			40%		30%	53%	36%	12
13	55%	58%	82%		37%			23%	59%	51%		46%			41%			67%	100%	13
14	54%	58%	36%		31%			47%	82%						57%			45%	91%	14
15								12%	40%									45%	17%	15
16								24%	48%									33%	83%	16
17									36%									25%		17
18									39%									17%		18
19									44%									52%		19
20									26%									58%		20
21									49%									58%		21
22			Critical Priority															52%		22
23			High Priority															49%		23
24			Medium Priority															66%		24
25			Low Priority															34%		25
26																		42%		26
27																		32%		27
28																		45%		28
29																		38%		29
30																		39%		30
Average	50%	66%	55%	64%	46%	59%	54%	42%	50%	60%	51%	44%	42%	32%	42%	53%	57%	47%	43%	Average
Cat. Avg	54%								49%						50%			46%		Cat. Avg
Count	14	14	14	11	14	9	10	16	21	13	9	13	5	6	14	10	12	30	16	Count
Max	66%	85%	91%	84%	68%	76%	73%	72%	82%	83%	62%	69%	68%	59%	65%	64%	86%	67%	100%	Max
Min	19%	42%	21%	46%	27%	27%	29%	5%	14%	39%	40%	35%	24%	7%	19%	37%	15%	17%	0%	Min
Cat. Rank	10	1	6	2	13	4	7	18	11	3	9	14	16	19	17	8	5	12	15	Cat. Rank

Table 18: Average Project Cost (million $)

Project Number	Marketing Applications								Fuel Cell Technology Specific Types						Tech. Integration			Fuels		Project Number
	MK-CC	DG/C CHP	FC-GT Hybrid	Grid Support	Materials Handling	Episodic	Portable	Transpor tation	FC-CC	SOFC	MCFC	PEMFC	PAFC	DMFC	BOP	Energy Storage	Grid-DG	Hydrogen Fuel	Op-fuels	
1	5.67	2.20	5.98	6.73	1.15	3.67	3.23	6.41	1.75	3.00	3.67	1.41	1.03	4.33	4.33	2.33	1.03	2.81	1.98	1
2	5.67	3.07	5.40	6.82	3.67	4.59	2.79	6.68	2.67	3.67	1.51	2.47	1.51	4.33	3.67	1.51	2.16	5.26	4.44	2
3	1.63	7.79	8.22	1.94	3.33	5.04	1.77	6.77	3.67	4.67	1.98	1.41	0.56	3.67	3.00	3.13	2.23	7.00	1.98	3
4	2.00	7.72	2.73	2.75	5.28	5.79	3.01	6.66	1.98	1.98	0.80	3.67	3.67	3.67	3.67	3.04	1.98	4.25	1.98	4
5	4.27	7.05	4.17	6.02	5.28	5.57	3.99	6.11	3.67	7.67	3.67	5.67	1.03	1.98	3.00	3.13	3.00	3.67	3.70	5
6	4.72	2.43	3.97	6.64	4.67	1.63	1.67	3.27	4.60	1.60	4.33	1.60		1.98	5.67	1.22	3.00	4.87	3.67	6
7	1.95	2.30	4.37	3.11	5.67	1.99	2.11	5.00	3.31	1.79	2.67	1.51			5.67	5.76	3.27	9.67	7.67	7
8	1.67	2.20	5.67	6.07	2.67	1.35	1.98	6.40	7.67	1.60	1.51	4.67			7.00	7.10	2.36	2.47	9.67	8
9	1.54	7.67	3.21	1.51	1.67	6.43	3.11	6.40	2.67	1.60	1.22	2.67			1.98	4.33	2.67	1.98	3.00	9
10	1.35	6.25	7.69	6.60	4.03		1.03	2.89	1.51	6.67		4.67			1.98	1.35	1.98	2.67	9.67	10
11	1.98	6.53	7.40	1.89	1.64			2.84	5.00	1.98		3.67			1.98		1.51	1.84	1.35	11
12	3.60	1.30	6.27		1.47			1.67	1.51	5.00		1.75			1.51		4.33	2.05	5.34	12
13	2.87	1.85	1.03		3.83			1.51	1.60	1.79		1.41			8.33			3.00	6.67	13
14	2.15	1.85	3.93		0.95			2.73	2.47						6.67			5.63	8.67	14
15								1.98	1.27									8.33	5.67	15
16								2.17	4.33									7.67	7.38	16
17									2.97									9.67		17
18									3.81									8.33		18
19									3.31									7.38		19
20									2.47									5.10		20
21									2.26									1.41		21
22			Critical Priority															3.27		22
23			High Priority															8.33		23
24			Medium Priority															9.67		24
25			Low Priority															7.67		25
26																		9.00		26
27																		9.00		27
28																		5.67		28
29																		4.95		29
30																		5.67		30
Average	2.93	4.30	5.00	4.55	3.24	4.01	2.47	4.34	3.07	3.31	2.37	2.81	1.56	3.33	4.18	3.29	2.46	5.61	5.18	Average
Cat. Avg	3.89								2.88						3.36			5.46		Cat. Avg
Count	14	14	14	11	14	9	10	16	21	13	9	13	5	6	14	10	12	30	16	Count
Max	5.67	7.79	8.22	6.82	5.67	6.43	3.99	6.77	7.67	7.67	4.33	5.67	3.67	4.33	8.33	7.10	4.33	9.67	9.67	Max
Min	1.35	1.30	1.03	1.51	0.95	1.35	1.03	1.51	1.27	1.60	0.80	1.41	0.56	1.98	1.51	1.22	1.03	1.41	1.35	Min
Cat. Rank	14	6	3	4	12	8	16	5	13	10	18	15	19	9	7	11	17	1	2	Cat. Rank

Table 19: Average Project Duration (years)

Project Number	Marketing Applications								Fuel Cell Technology Specific Types						Tech. Integration			Fuels		Project Number
	MK-CC	DG/C CHP	FC-GT Hybrid	Grid Support	Materials Handling	Episodic	Portable	Transpor tation	FC-CC	SOFC	MCFC	PEMFC	PAFC	DMFC	BOP	Energy Storage	Grid-DG	Hydrogen Fuel	Op-fuels	
1	3.40	2.43	3.32	3.46	1.50	2.00	2.54	3.77	2.21	3.83	2.58	2.13	3.33	2.83	3.33	1.92	1.83	3.12	1.83	1
2	3.77	2.44	3.71	3.69	2.40	2.61	2.66	4.07	1.51	3.40	2.21	2.73	2.58	1.83	3.33	2.21	2.42	3.32	3.22	2
3	2.76	3.26	3.81	2.47	2.43	2.78	2.45	3.87	2.58	3.63	2.58	3.33	1.03	2.58	2.33	3.14	2.07	4.08	2.96	3
4	2.03	3.32	3.17	2.81	2.72	2.98	2.64	3.91	2.83	3.71	2.21	2.96	1.83	1.83	2.58	3.05	1.35	2.99	2.49	4
5	2.32	3.10	3.31	3.49	2.72	2.85	2.81	4.42	2.60	3.61	2.21	2.96	1.03	2.58	2.33	3.27	2.33	2.08	3.07	5
6	2.23	2.86	3.17	2.99	3.85	1.96	2.60	3.22	3.11	2.43	1.35	1.83		2.83	1.83	2.73	2.33	2.13	4.83	6
7	2.41	2.27	3.47	2.15	3.85	1.91	2.48	3.92	4.23	2.55	2.21	1.51			3.33	4.12	2.73	4.23	4.08	7
8	1.83	2.44	3.42	3.92	2.64	1.35	2.42	4.05	2.43	1.83	1.83	1.83			2.83	4.06	2.23	2.13	4.83	8
9	2.42	3.92	3.29	1.38	2.00	3.37	2.29	4.25	3.63	2.58	1.60	2.21			1.03	2.96	2.32	1.41	4.83	9
10	1.67	3.25	3.83	3.92	2.85		1.03	2.85	1.83	2.43		2.58			1.83	1.83	1.83	2.58	4.83	10
11	2.58	3.79	3.76	2.57	2.41			2.58	3.83	2.33		1.83			1.51		2.80	2.68	2.83	11
12	3.13	1.30	3.71		2.42			2.42	1.51	2.90		1.51			2.58		2.83	2.07	3.65	12
13	2.52	2.69	1.83		3.10			3.33	2.13	1.98		1.60			3.83			1.83	2.83	13
14	2.05	1.82	3.25		1.14			2.55	1.79						3.71			3.60	3.71	14
15								1.03	1.83									4.58	3.33	15
16								0.92	1.67									3.83	3.19	16
17									2.80									4.83		17
18									3.11									3.33		18
19									2.92									4.83		19
20									2.38									3.55		20
21									2.84									1.60		21
22			Critical Priority															3.93		22
23			High Priority															3.58		23
24			Medium Priority															3.33		24
25			Low Priority															3.71		25
26																		4.83		26
27																		4.83		27
28																		3.93		28
29																		3.55		29
30																		3.03		30
Average	2.51	2.78	3.36	2.98	2.58	2.42	2.39	3.20	2.56	2.86	2.09	2.23	1.96	2.42	2.60	2.93	2.26	3.32	3.53	Average
Cat. Avg	2.81								2.44						2.58			3.39		Cat. Avg
Count	14	14	14	11	14	9	10	16	21	13	9	13	5	6	14	10	12	30	16	Count
Max	3.77	3.92	3.83	3.92	3.85	3.37	2.81	4.42	4.23	3.83	2.58	3.33	3.33	2.83	3.83	4.12	2.83	4.83	4.83	Max
Min	1.67	1.30	1.83	1.38	1.14	1.35	1.03	0.92	1.51	1.83	1.35	1.51	1.03	1.83	1.03	1.83	1.35	1.41	1.83	Min
Cat. Rank	12	8	2	5	10	13	15	4	11	7	18	17	19	14	9	6	16	3	1	Cat. Rank

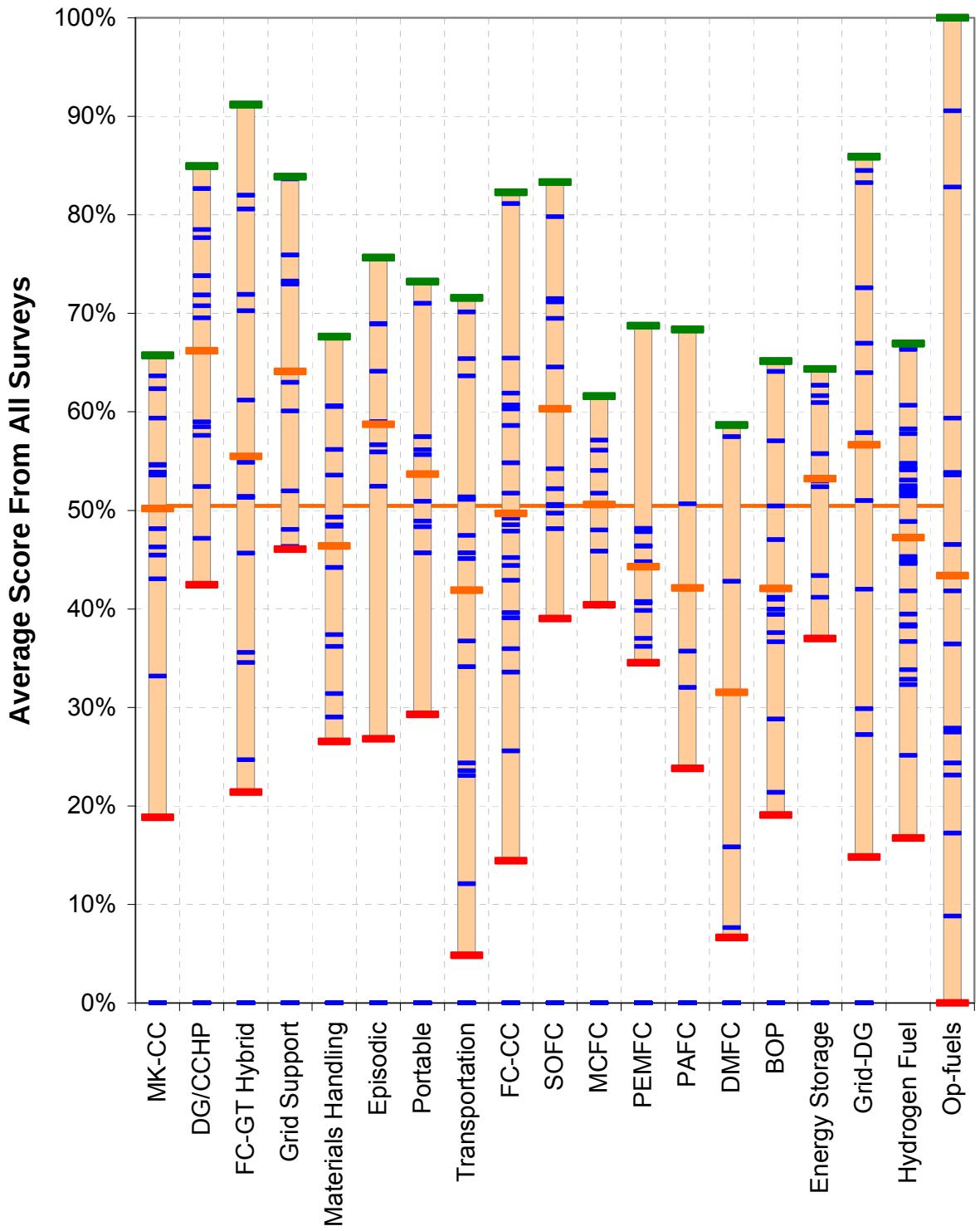

Figure 6: Project Score Distribution

Source: National Fuel Cell Research Center.

4.3. Highest Ranking Projects

All of the projects are separated into four groups (critical, high, medium, and low priority projects). Critical priority projects are the top ranking 21 projects. This grouping was delineated by the natural break in the ranking of the projects as determined by all survey respondents. The *High* priority group includes 47 projects with rank ranging from 22 to 70 and the *medium* priority group includes 53 projects ranging from a rank of 71 to a rank of 248. The *low* priority projects are the remaining projects that are not included in the previous three groups. The highest ranking projects are comprised of projects from the three most important groups (*critical*, *high*, and *medium*). A graphical depiction of the distribution of the highest ranking projects is presented in Figure 7. The inner ring presents the four major technology categories and the percentage of the highest ranking projects that are contained in each of the categories. The outer ring contains each of the specific technology categories and the number of projects that are denoted as the highest ranking projects for each category.

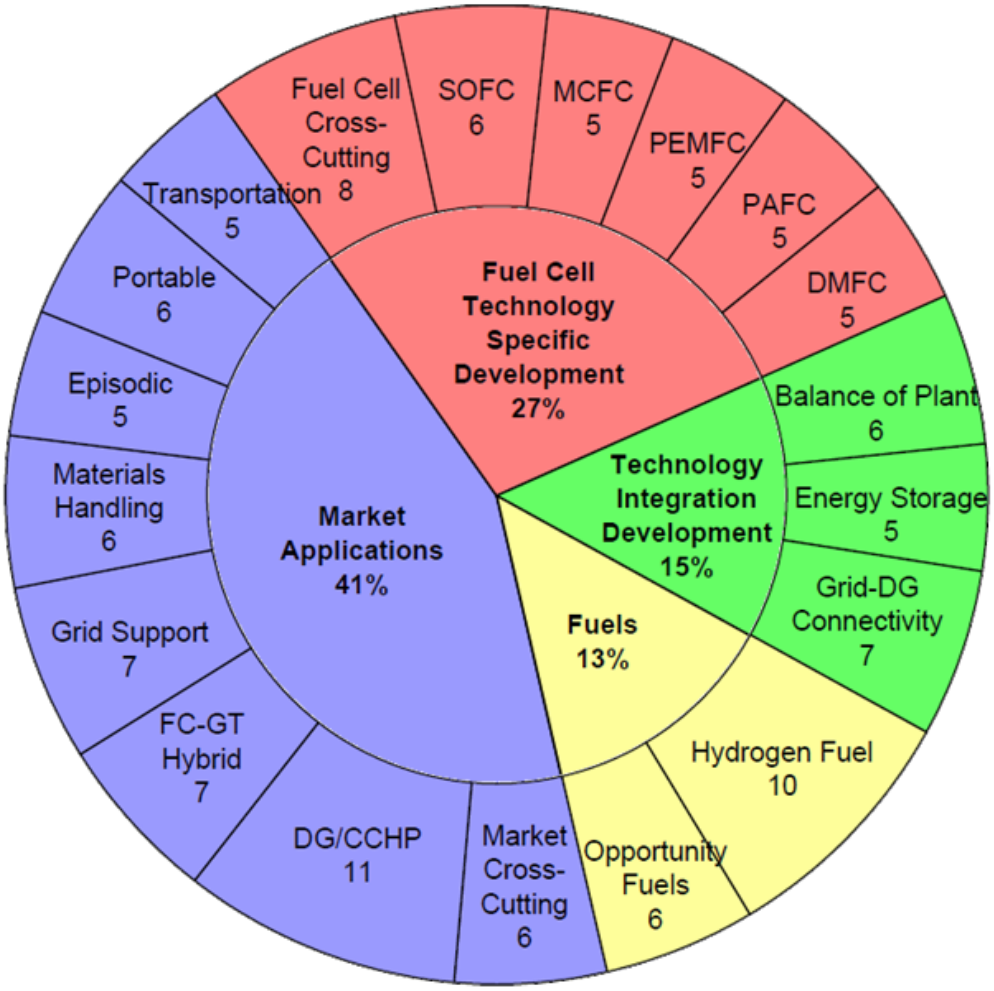

Figure 7: Summary of Highest Ranking Project Distribution

Source: National Fuel Cell Research Center.

Table 20 contains the breakdown of the project groups for each category. These results are followed by Table 21, Table 22 and Table 23, which contain the descriptions for each of projects within the three highest ranking groups. These tables are sorted by decreasing project score and, equivalently, overall project rank. Unique from the full list of projects in Appendix D is the inclusion of the *Barriers Addressed* column. This column contains the set of commercialization barriers that the fuel cell community believes will be addressed by pursuing that particular project. The letters signify one of the commercialization barriers, as presented in Table 7. Further analysis of the highest ranking projects will be presented in the roadmap and action plan sections.

A graphical depiction of the scores for the highest ranking projects based on score, cost and duration are shown below in Figure 8, Figure 9 and Figure 10. Important characteristics to note when reviewing these figures include: the green bar at the top of the bar for each category is the maximum project value, the red bar at the base of the bar for each category is the minimum project value and the orange bar near the middle of the bar for each category is the average project value (i.e., unlike the green and red bars the orange bar does not represent a project). The orange horizontal line that spans all of the categories is the average value among all of the highest ranking projects and the brown horizontal line shows the average value among all of the projects. Each blue rectangle along the bar represents the value for a particular project. Viewing this figure presents a quick view of the deviation between projects within a category, which project categories have the highest average and which have the lowest average.

Table 20: Project Priority Distribution

Project Number	Marketing Applications								Fuel Cell Technology Specific Types						Tech. Integration			Fuels		Project Number
	MK-CC	DG/C CHP	FC-GT Hybrid	Grid Support	Materials Handling	Episodic	Portable	Transpor tation	FC-CC	SOFC	MCFC	PEMFC	PAFC	DMFC	BOP	Energy Storage	Grid-DG	Hydrogen Fuel	Op-fuels	
1	4	2	2	1	4	4	2	4	4	2	3	3	3	3	4	2	1	3	4	1
2	4	2	3	1	2	2	2	4	2	4	4	4	3	3	2	4	2	2	3	2
3	3	1	2	4	2	4	3	2	2	4	3	4	3	3	3	2	2	4	3	3
4	2	1	4	3	3	4	4	3	4	4	4	4	3	3	2	2	4	4	3	4
5	4	1	4	2	3	2	3	4	4	2	3	2	2	4	4	4	4	3	4	5
6	4	4	4	2	4	4	4	2	2	4	4	3		3	3	4	1	3	4	6
7	4	2	4	1	4	3	3	4	4	4	4	4			4	4	1	4	4	7
8	4	3	4	2	3	2	3	2	1	4	3	4			3	2	3	2	4	8
9	3	4	4	4	4	1	4	2	3	2	2	4			4	3	2	4	4	9
10	4	2	1	4	2		4	4	4	2		4			4	4	4	4	4	10
11	4	4	1	4	4			4	2	1		3			4		4	4	4	11
12	3	1	2		4			4	4	1		4			4		4	3	4	12
13	3	3	1		4			4	3	4		3			4			2	1	13
14	3	3	4		4			4	1						3			4	1	14
15								4	4									4	4	15
16								4	4									4	1	16
17									4									4		17
18									4									4		18
19									4									4		19
20									4									3		20
21									4									3		21
22		1	Critical Priority															4		22
23		2	High Priority															4		23
24		3	Medium Priority															2		24
25		4	Low Priority															4		25
26																		4		26
27																		4		27
28																		4		28
29																		4		29
30																		4		30
Critical	0	4	3	3	0	1	0	0	2	2	0	0	0	0	0	0	3	0	3	Critical
High	1	4	3	3	3	3	2	4	4	4	1	1	1	0	2	4	3	4	0	High
Medium	5	3	1	1	3	1	4	1	2	0	4	4	4	5	4	1	1	6	3	Medium
Low	8	3	7	4	8	4	4	11	13	7	4	8	0	1	8	5	5	20	10	Low

4.3.1. Critical Priority Projects

Table 21: Critical Priority Projects

Category	Project Number	Average Project Score	Title (Critical Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
Opportunity fuels	13	100%	Support multiple demonstrations of similar fuel cell technologies applied to opportunity fuels	1	1	216	137	B	CDH		KLNO		QRT	VWXU
FC-GT Hybrid	10	91%	Intensify demonstration efforts for fuel cell - gas turbine hybrid systems	1	2	236	218	B	DEH		KLO			X
Opportunity fuels	14	91%	Support greenhouse gas and emissions reduction through multiple demonstration projects in non-attainment areas that use opportunity fuels	2	3	244	209	B	H		KLNO		QRT	VWXU
Grid-DG connectivity	6	86%	Analyze different control strategies and arrangements for optimum grid connections and interactions between customers and the utilities.	1	4	111	75	A B	CDEFH	J	LNO		QRST	VWXU
DG/CCHP	4	85%	Augment deployment activities for fuel cell CCHP systems	1	5	237	180	A B	D	J	KLNO		QRS	VWX
Grid-DG connectivity	7	84%	Design and develop a smart controller to autonomously connect DG systems to the electricity distribution network and develop corresponding metering technology and controls to interface with DG systems	2	6	128	128	A B	CDEFH	J	LNO		QRST	VWXU
Grid support	2	84%	Augment deployment activities for grid supporting fuel cell systems	1	7	222	206	A B	DH	J	KLNO		RS	VWX
Grid support	1	84%	Intensify demonstration efforts for grid supporting fuel cell systems	2	8	220	195	B	DH		KLO			W
SOFC	12	83%	Establish an understanding for SOFC internal reforming mechanisms and develop technique for effective use of internal reforming	1	9	179	149	A B	EHI		O		R	
Grid-DG connectivity	1	83%	Exploration of contractual ancillary service arrangements between customers and the utility.	3	10	4	27	B	DH		NO	P	QRST	V
Opportunity fuels	16	83%	Increase deployment activities for systems operating on landfill and digester gas	3	11	228	170	A B		J	KLNO		ST	VWXU
DG/CCHP	3	83%	Increase fuel cell CCHP system demonstrations	2	12	238	175				KLO		R	

Category	Project Number	Average Project Score	Title (Critical Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
Fuel cell system cross-cutting	14	82%	Develop dynamic models to aid in improving fuel cell and fuel cell system performance	1	13	92	25	B	CDEFG H		O		R	WX
FC-GT Hybrid	13	82%	Develop a value proposition for fuel cell systems in the FC-GT hybrid market in California	2	14	4	27	A B					QRST	VWX
Fuel cell system cross-cutting	8	81%	Explore fuel cell synergies with other energy conversion equipment and energy storage devices	2	15	230	91	B	DEFGHI		O		QRT	VWX
FC-GT Hybrid	11	81%	Augment deployment activities for FC-GT hybrid systems	3	16	229	213	A B	DEH	J	KLNO		RS	VWX
SOFC	11	80%	Develop and demonstrate SOFC degradation mitigation techniques	2	17	59	75	B	CDH	J	K			
DG/CCHP	5	79%	Intensify validation and demonstration efforts for using DG/CCHP fuel cells at DC data centers	3	18	225	161	A B	DE		KLNO		RT	
DG/CCHP	12	78%	Develop a value proposition for fuel cell systems in the DG/CCHP market in California	4	19	13	8	B					QRST	VWXU
Grid support	7	76%	Explore the effects of and need for reactive power and ancillary service support for grid supporting fuel cell applications	3	20	121	61	B	FH		O		R	V
Episodic	9	76%	Development of regenerative fuel cell systems for episodic power applications	1	21	211	191	B	CDEFH		O		RT	VWXU

4.3.2. High Priority Projects

Table 22: High Priority Projects

Category	Project Number	Average Project Score	Title (High Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
DG/CCHP	2	74%	Grid connectivity of fuel cell CCHP and sale of electricity to the grid	5	22	120	94	B	H		LNO		RS	WX
Grid support	6	73%	Transmission Integrated Grid Energy Resource (TIGER) station development and deployment	4	23	214	156	A B	DFH		KLO		RS	VX
Portable	1	73%	Intensify demonstration efforts for portable power applications	1	24	126	101	B	DFGHI		O	P	QR	
Grid support	5	73%	Develop and demonstrate grid supporting fuel cell power systems that operate on landfill gas	5	25	203	197	B	DH		LO		R	VWXU
Grid-DG connectivity	9	73%	Streamline DG equipment interconnection process set forth by the utility	4	26	101	73	B	D		LMNO	P	QRS	V
FC-GT Hybrid	12	72%	Explore operation of a fuel cell - gas turbine hybrid system on varying fuel compositions	4	27	207	207	B	CDEF H		O		RT	VWXU
DG/CCHP	10	72%	Intensify demonstration efforts for fuel cell and absorption chiller systems	6	28	206	173	B	EH		KLMO		RT	
Transportation	8	72%	Intensify development and demonstration of hydrogen fueling stations	1	29	208	233	A B	DH		KLNO	P	QR	WXU
SOFC	1	71%	Development of SOFC electrocatalysts	3	30	111	219	A B	CEF	J				
SOFC	9	71%	Develop understanding and novel methods for better SOFC electrode and electrode-electrolyte interface performance	4	31	35	105		CE	J				
Portable	2	71%	Augment deployment activities for portable fuel cell power systems	2	32	105	123	A B	D	J	MNO	P	QRST	
DG/CCHP	7	71%	Simplify DG/CCHP system siting processes and requirements	7	33	87	71	B			LN		RST	WX
FC-GT Hybrid	3	70%	Redesign gas turbines to be properly mated with fuel cells	5	34	239	217	A B	CDEG HI		O	P	R	

Category	Project Number	Average Project Score	Title (High Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
Transportation	9	70%	Augment deployment activities highlighting hydrogen fueling stations	2	35	208	241	A B	D	J	KLNO	P	QRS	WXU
DG/CCHP	1	70%	Determination of critical fuel cell DG/CCHP installation locations and corresponding design requirements (e.g., thermal and electrical profiles)	8	36	84	89	B	FH		LO		RT	
SOFC	5	69%	Develop intermediate temperature SOFCs	5	37	230	202	A B	CDE	J	O			
Episodic	8	69%	Develop a value proposition for fuel cell systems in the episodic market in California	2	38	14	9	A B			N		QRST	VWX
Episodic	2	69%	Develop and demonstrate fuel cell systems for backup power applications	3	39	169	120	B	DE		KLNO	P	RT	WX
PEMFC	5	69%	Development and optimization of PEMFC electrocatalysts	1	40	190	151	A B	CEG	J	M			
PAFC	5	68%	Develop and demonstrate PAFC degradation mitigation techniques	1	41	4	2	B	CDH	J	K			
Materials handling	10	68%	Explore available methods and effectiveness of those methods to produce renewable fuel for use in materials handling applications	1	42	156	146	B			N		QR	VWXU
Grid-DG connectivity	3	67%	Explore the practicalities and consequences of supplying reactive power to the electrical distribution network from distributed sources	5	43	85	54	B	DFH		KO	P	RT	VWX
Hydrogen Fuel	8	67%	Explore the flexibility of industrial processes for supplying hydrogen fuel at large volumes	1	44	92	57	B	E	J	NO		RS	VWXU
Hydrogen Fuel	13	67%	Increase public awareness, understanding and acceptance of hydrogen technologies	2	45	111	29	B					QR	
Hydrogen Fuel	24	66%	Design, develop and optimize high-pressure hydrogen gas storage technologies	3	46	247	182	A B	CDGH I	J	NO	P	R	U
Fuel cell system cross-cutting	11	65%	Conduct a study to characterize fuel cell system degradation mechanisms and mitigation strategies	3	48	179	219	B	CD		K		R	
Transportation	6	65%	Engage in demonstrations to highlight hydrogen-fueled vehicles	3	49	127	172	B	CDE	J	KN	P	QR	XU

Category	Project Number	Average Project Score	Title (High Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
Balance of plant	2	65%	Further develop catalyst manufacturing technology (e.g., for use in reformers, fuel cells)	1	50	135	182	A B	CEG	J	M		T	
SOFC	10	65%	Design of high-temperature SOFC cells and stacks for better integration with other system components	6	51	216	91	A B	DEHI	J	KLO		R	
Energy storage	8	64%	Develop improved reversible SOFC technology for energy storage	1	52	226	234	A B	CEGH	J	O		T	VWXU
Episodic	5	64%	Augment deployment activities for fuel cell based peak shaving systems	4	53	188	147	A B	DEF	J	KLNO		RS	VX
Balance of plant	4	64%	Develop BOP components for dynamic operation to support economic dispatch	2	54	135	105	B	FH		O		RT	
Grid-DG connectivity	2	64%	Develop technology to provide ancillary power filtering, line switching, etc. to the electrical distribution network (i.e., power electronics)	6	55	81	84	A B	DFH		O	P	R	V
Transportation	3	64%	Increase demonstration projects for heavy duty on-road fuel cell vehicles	4	57	221	225	B	CDEG HI		KO	P	QRT	XU
Grid support	8	63%	Provide development and deployment opportunities for integrated gasification fuel cell (IGFC) systems for central power generation	6	58	204	227	A	DE		O			VWXU
Energy storage	3	63%	Explore the integration of fuel cells and energy storage systems with intermittent, distributed photovoltaic power systems	2	59	123	167	B	DEFH		O		QT	VWXU
Market cross-cutting	4	62%	Establish a study that evaluates the needs and opportunities for implementing subsidies, buy-downs, other incentives and mandates to support fuel cell development and commercialization	1	60	77	52	B		J	KLNO		QRS	
Fuel cell system cross-cutting	6	62%	Develop strategies for optimization and control of fuel cell performance during dynamic operations	4	61	170	163	B	CDFH		O		R	
Energy storage	4	62%	Explore the integration of fuel cells and energy storage systems with intermittent, centralized wind power systems	3	62	119	159	B	DEFH		O		QT	VWXU
MCFC	9	62%	Examine the purity requirements for inputs into MCFC systems	1	63	10	20	A B	H		LNO			

Category	Project Number	Average Project Score	Title (High Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
FC-GT Hybrid	1	61%	Explore and optimize fuel cell - gas turbine system configurations	6	64	202	181	A B	CDEF HI	J	O			W
Energy storage	1	61%	Explore hybridizing fuel cells with electrical energy storage devices (e.g., batteries, capacitors)	4	65	88	47	B	EFH		O		T	X
Fuel cell system cross-cutting	2	61%	Explore techniques to increase profitable operation during pre-large-scale manufacturing	5	66	95	15	A B		J	KLNO		QRS	
Hydrogen Fuel	2	61%	Support demonstration of renewable hydrogen production and delivery	4	67	183	179	B					QRST	VWXU
Materials handling	2	61%	Intensify fuel cell forklift and other lift demonstration efforts	2	68	135	81	B	D		KLMO	P	QR	WX
Materials handling	3	61%	Augment deployment activities for fuel cell based lift systems (e.g., forklift, scissors lift)	3	69	132	90	A B	D	J	KLMO	P	QRS	WX
Fuel cell system cross-cutting	3	60%	Further develop manufacturability of fuel cells and fuel cell systems	6	70	135	105	A B	D	J	O		RS	

4.3.3. Medium Priority Projects

Table 23: Medium Priority Projects

Category	Project Number	Average Project Score	Title (Medium Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
Grid support	4	60%	Explore the effects of replacing current grid support systems with fuel cells	7	71	104	135	B					QR	VWXU
Opportunity fuels	2	59%	Improve and optimize production methods for methane containing opportunity and renewable fuels	4	72	168	171	A B	E	J	O		RT	VWXU
Market cross-cutting	12	59%	Establish a study that develops a strategy for a California state-wide transition to greater use of alternative fuels in fuel cell power systems	2	73	133	166				O		T	VWXU
Episodic	7	59%	Explore the environmental effects of replacing current episodic systems with fuel cell systems	5	74	76	46	B	E		LM		QR	WX
DG/CCHP	8	59%	Explore the optimum design for fuel cell CCHP and co-production systems in various applications	9	75	83	95	A B	EH		O		RT	VWXU
DMFC	2	59%	Development and optimization of DMFC electrocatalysts	1	76	160	29	A B	CEGI	J	M			
Fuel cell system cross-cutting	13	59%	Develop steady state models to aid in improving fuel cell and fuel cell system performance	7	77	35	57	A B	CDEGI		O		R	WX
DG/CCHP	13	58%	Explore the requirements and the current feasibility of introducing dynamic fuel composition changes	10	78	53	125	B	CDFH		O		R	VWXU
Hydrogen Fuel	20	58%	Improve gas separation and purification technology	5	79	182	198	A B	CDE	J	KN		RT	
Grid-DG connectivity	8	58%	Explore the reliability and safety of connecting DG equipment with the electrical distribution network	7	80	89	69		D		NO	P	QR	V
Hydrogen Fuel	21	58%	Conduct a life-cycle analysis for hydrogen production technologies and distribution methods	6	81	18	20	B	E		N		QR	VWXU
DG/CCHP	14	58%	Modeling and analysis of fuel cell CCHP systems	11	82	54	26	A B	DEFH		O	P	QRT	VWXU
DMFC	1	57%	Address DMFC membrane concerns	2	83	160	137	B	CDEGI	J				

Category	Project Number	Average Project Score	Title (Medium Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
Portable	8	57%	Determine the compatibility of current and future fuel storage techniques for portable fuel cell power applications	3	84	58	84	B	GI	J	MNO	P	QRT	
MCFC	1	57%	Improve high-temperature fuel cell materials processing and assembly	2	85	135	105	A B		J				
Balance of plant	14	57%	Development of advanced hydrogen separation membranes	3	86	216	209	A B	E	J	O			
Materials handling	4	56%	Develop and demonstrate fuel cell systems for auxiliary power units (e.g., ships, tractor trailers, recreational vehicles)	4	88	184	126	B	DEGHI		KLO	P	RT	WX
Portable	3	56%	Further identify and develop markets for portable power	4	89	49	96	B					QRST	
MCFC	8	56%	Establish an understanding for MCFC internal reforming mechanisms and develop techniques for effective use of internal reforming	3	90	25	29	A B	EHI		O		R	
Energy storage	9	56%	Further development of high-performance batteries and ultracapacitors for use in hybrid applications	5	92	160	151	A B	CGHI	J	O	P	R	W
Portable	5	56%	Explore portable power fuel cell systems design for operation on particular fuels	5	93	155	135	B	GH	J	O		RT	
FC-GT Hybrid	2	55%	Explore the compatibility of fuel cell - gas turbine systems with other advanced technologies	7	94	187	207	B			O		QRT	
Fuel cell system cross-cutting	9	55%	Explore the prospects of remanufacturing, recycling, reprocessing and requalifying fuel cell systems	8	95	95	203	A B		J	MN		QR	WX
Hydrogen Fuel	6	55%	Improve design and integration of hydrogen delivery components	7	96	176	57	A B	DEFHI	J	KNO	P	Q	W
Market cross-cutting	3	55%	Develop appropriate fuel cell system standards, policies and codes	3	97	41	131				LMNO	P	R	
Market cross-cutting	13	55%	Conduct a study to determine how fuel cell technology can be used to enable more significant use of intermittent renewable power generation	4	98	108	100	B	FH		O		QST	VWXU
Hydrogen Fuel	1	54%	Determine the effects of fuel variation on conversion technologies	8	99	106	165	B	CDFH		KO		RT	VXU

Category	Project Number	Average Project Score	Title (Medium Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
Hydrogen Fuel	5	54%	Optimize hydrogen combustion and after-treatment strategies for engine and turbine designs	9	101	135	56	A B	DEH				R	WXU
MCFC	5	54%	Optimize MCFC stack for longer lifetime	4	102	135	62	B	CD		K		R	
Market cross-cutting	14	54%	Explore the potential for fuel cell systems to reduce criteria pollutants and greenhouse gas emissions throughout California	5	103	80	53						QT	WX
Opportunity fuels	4	54%	Advance gas cleanup and purification processes for digester gas use in fuel cell systems	5	104	59	99	A B	CDEH		O		R	VWXU
Opportunity fuels	3	54%	Advance gas cleanup and purification processes for landfill and biomass gas use in fuel cell systems	6	105	59	151	A B	CDEH		O		R	VWXU
Market cross-cutting	9	54%	Conduct a socio-economic study of fuel cell technologies to aid in market and policy development	6	106	34	84	B			O	P	QRT	
Materials handling	5	54%	Augment deployment activities for fuel cell powered auxiliary power units	5	107	184	126	A B	DH	J	KLO	P	RS	WX
Hydrogen Fuel	12	53%	Explore the needs and opportunities for governmental mandates and financial incentives for hydrogen production, delivery and storage	10	108	78	55	B		J	KLNO		QRS	XU
MCFC	3	52%	Address MCFC electrode and electrode-electrolyte interface development barriers	5	118	59	105	B	CD	J				
Transportation	4	51%	Increase deployment activities for heavy duty on-road fuel cell vehicles	5	123	215	226	A B	DE	J	KLNO		QRS	WXU
Portable	7	51%	Investigate fuel provision and infrastructure opportunities for portable fuel cell power applications	6	127	79	98	B	H		LMO	P	QRST	VWX
PAFC	2	51%	Development and optimization of PAFC electrocatalysts	2	128	25	105	A B	CEG	J	KM			
Balance of plant	6	50%	Simplify fuel processor system complexity	4	131	190	29	A B	DH	J	KO			
Materials handling	8	49%	Develop a strategy for successful transition from current materials handling systems to fuel cells and fuel infrastructure	6	133	95	121	B			LMO	P	R	WX

Category	Project Number	Average Project Score	Title (Medium Priority Projects)	Category Rank	Overall Rank	Cost Rank	Duration Rank	Barriers Addressed						
								Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
PEMFC	1	48%	Optimize PEMFC gas diffusion layer	2	141	18	57	A B	EF	J				
PEMFC	6	48%	Explore ion transport dependencies to improve PEMFC performance	3	147	35	29	B	CEGH					
Balance of plant	8	47%	Deploy multiple distributed fuel reforming systems	5	150	223	137	A B		J	KLNO		QS	VWU
PEMFC	11	46%	Develop and demonstrate PEMFC degradation mitigation techniques	4	152	135	29	B	CDEF H		O	P	R	
PEMFC	13	46%	Develop control and system management strategies for PEMFC systems	5	152	18	20	B	CDH	J				
DMFC	6	43%	Develop and demonstrate DMFC degradation mitigation techniques	3	175	59	137	B	CDH	J				
Balance of plant	3	41%	Optimize major BOP components and instrumentation (e.g., sensors, controls) to improve performance and economics	6	180	111	75	A B	CDEF HI	J	KO			
PAFC	1	36%	Explore the effects of material properties on PAFC fabrication and performance	3	207	4	182	B	CDEG	J				
PAFC	3	32%	Develop better performing PAFC fuel cell seals	4	217	1	2	B	CD	J	K			
PAFC	4	24%	Design of PAFC cells and stacks for better integration with other system components	5	233	135	29	A B	DEHI	J	O		R	
DMFC	4	16%	Design of DMFC stack with respect to cellular phone system requirements	4	243	135	29	B	GI		O	P	R	
DMFC	3	8%	Design of DMFC stack with respect to laptop system requirements	5	248	135	105	B	GI		O	P	R	

The rank of the categories within Figure 8, Figure 9 and Figure 10 is presented in the previous tables, but is collected and repeated below in Table 24 for convenience. It is apparent from these results that there is no significant correlation between score, cost and duration. This is not to say that the score, cost and duration data should not be used together when considering which projects and technology categories to pursue, but rather, should state that there are no discernable trends within the top ranking project data among score, cost and duration. That means that, among all of the projects, no particular category has higher cost associated with longer duration for example.

Table 24 contains a collection of the most significant results from the surveys. For example, project categories like *FC-GT Hybrid, Transportation* and *Grid Support* have the highest cost and duration values of any category. This is expected as projects relating to these technology categories are very long-term, often requiring extensive infrastructure and large equipment. Similarly, research and development of each specific fuel cell type have relatively low cost and duration as there is not a significant amount of equipment required or time investment necessary to conduct fuel cell materials, performance and degradation tests. The *Grid-DG Connectivity* category ranked very high for score, cost and duration. As will be discussed later, this category was determined to be the most important category to pursue to further fuel cell development and aid in overcoming technology barriers to fuel cell commercialization. On the opposite end of the category rankings were the *Materials Handling* and the *Balance of Plant,* which had very low rankings meaning that the projects within those categories were scored lower, the project costs were generally higher and the project durations were generally longer than projects in other categories. Again, Table 24 presents the average values for the overall score, cost and duration. That means that every project does not follow this trend, but that a typical project will rank as prescribed by Table 24.

Table 24: Average Category Values and Rank for Highest Ranking Projects

Categories		Average Category Score		Average Category Cost		Average Category Duration	
		Value	Rank	Value	Rank	Value	Rank
Market Applications	Market Cross-Cutting	56%	14	2.30	2	2.48	7
	DG/CCHP	71%	6	3.96	9	2.57	10
	FC-GT Hybrid	73%	5	6.00	19	3.42	18
	Grid Support	73%	4	5.45	17	3.21	17
	Materials Handling	58%	13	4.04	13	2.63	12
	Episodic	67%	7	3.99	11	2.42	6
	Portable	61%	11	2.65	5	2.56	9
	Transportation	64%	9	5.90	18	3.86	19
Fuel Cell Type Specific	Fuel Cell Cross-Cutting	66%	8	3.79	8	2.63	11
	SOFC	73%	3	4.32	14	2.95	14
	MCFC	56%	15	2.41	4	2.16	3
	PEMFC	51%	17	2.75	6	2.07	2
	PAFC	42%	18	1.56	1	1.96	1
	DMFC	36%	19	3.60	7	2.38	5
Technology Integration	BOP	54%	16	4.94	15	2.77	13
	Energy Storage	61%	10	3.99	10	3.03	15
	Grid-DG Connectivity	74%	1	2.39	3	2.27	4
Fuels	Hydrogen Fuel	59%	12	4.03	12	2.52	8
	Op-fuels	73%	2	5.19	16	3.07	16

Because there is little correlation between the project score, cost and duration, as expected due to the varied nature of the project parameters contained in each category, no analysis will be conducted among these features, but an analysis has been done on each of the parameters individually (i.e., score, cost and duration). Figure 8 presents an increase in the average score for top ranking projects over the average score for all projects. This means, as expected, that the average of the top ranking projects within each category will have a higher average than all projects. Additionally, this figure allows for a quick valuation of project category characteristics. For example, the *DMFC* and *PAFC* categories have very low average score values whereas categories like *Grid-*DG and *Opportunity Fuels* have very high average scores. The figure provides a measure of the variation between projects as well as their score with respect to other categories. The project cost figure, Figure 9, shows a slight increase in the cost of the highest ranking projects over the average cost of all of the projects. Figure 10 presents the projected project duration for each of the highest ranking projects. This figure shows a notable decrease in the duration for the highest ranking projects over the average duration of all of the projects.

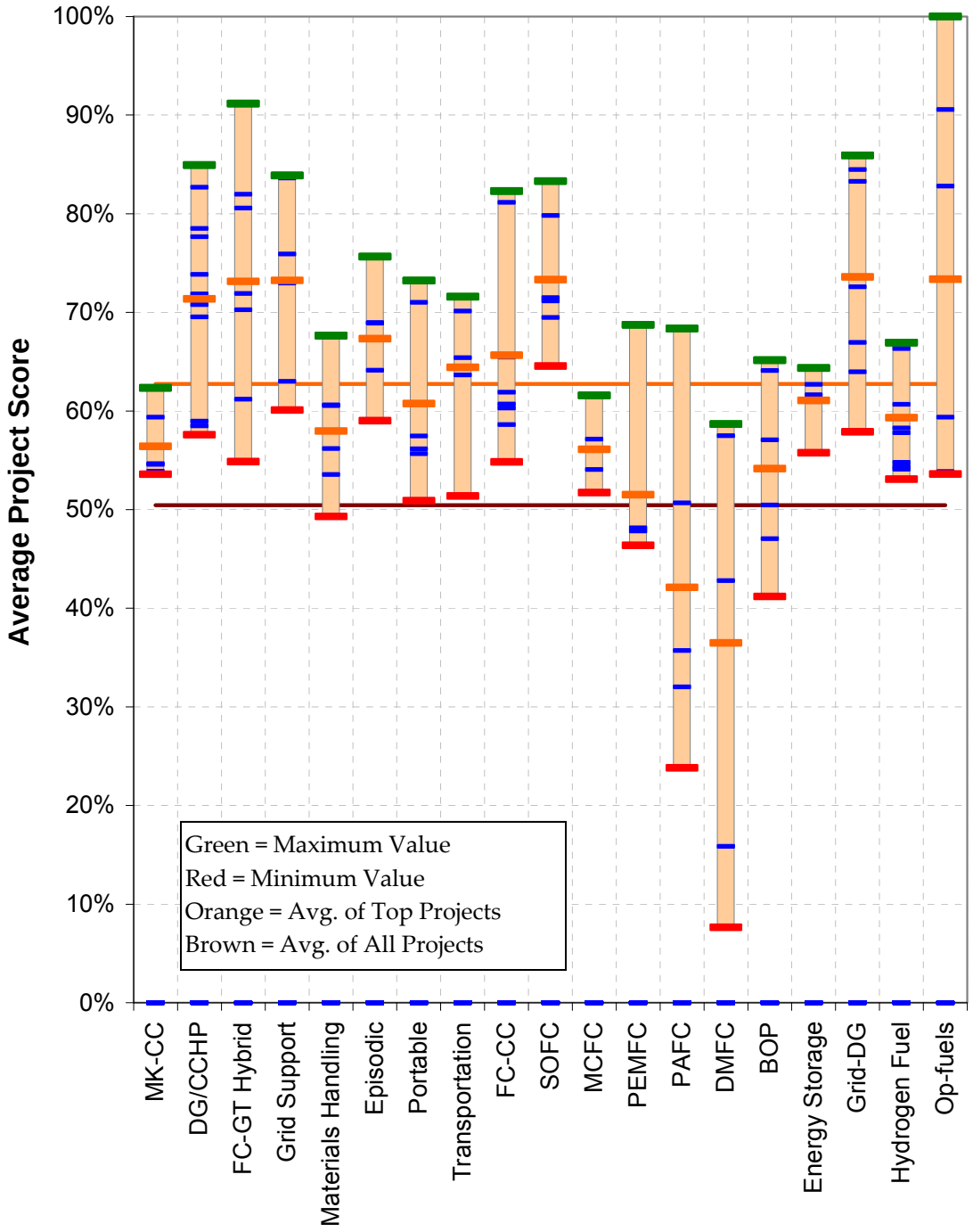

Figure 8: Project Score Distribution for Highest Ranking Projects

Source: National Fuel Cell Research Center.

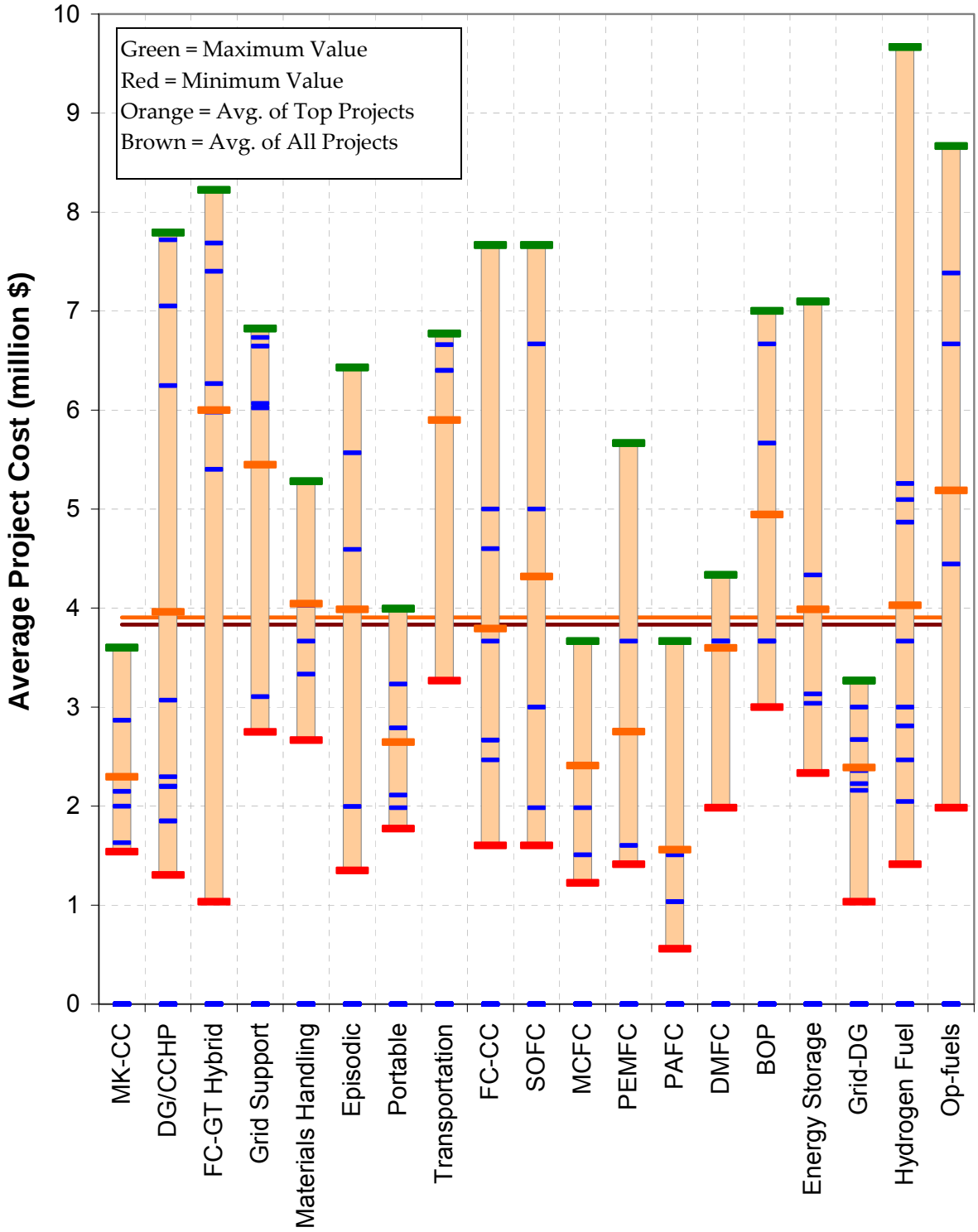

Figure 9: Project Cost Distribution for Highest Ranking Projects

Source: National Fuel Cell Research Center.

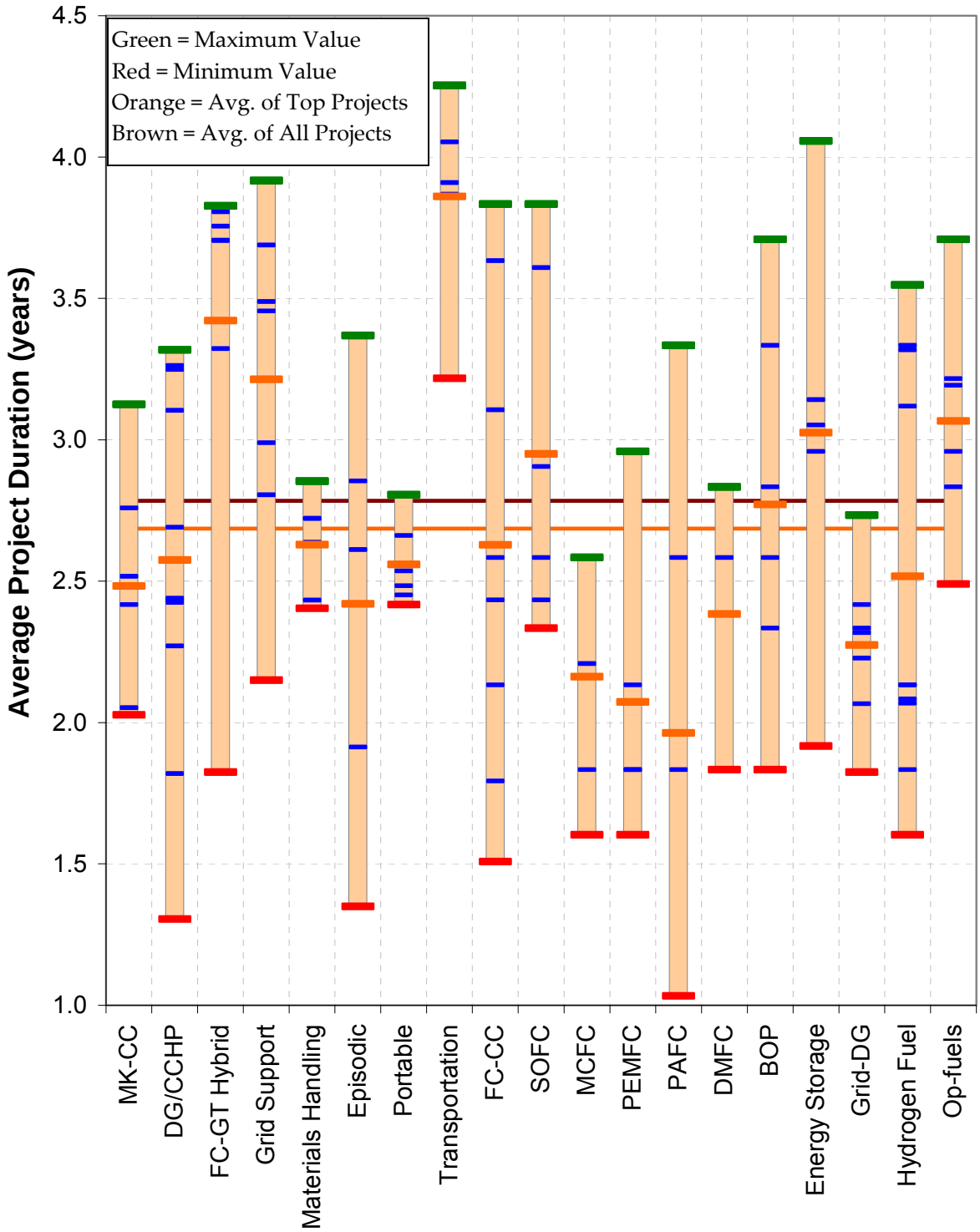

Figure 10: Project Duration Distribution for Highest Ranking Projects

Source: National Fuel Cell Research Center.

4.4. Technology Category Rank

Based on the scores of each of the highest ranking projects and the extent to which commercialization barriers are addressed, one can determine which technology categories are the most promising. Two columns are presented in Table 25 to convey this information. The first column depicts the rank of each category when the score and extent to which commercialization barriers are addressed is included while the second shows the rank of technology categories when only the average project score is considered. This analysis presents an interesting contrast. The result is that the first column conveys the technologies that the surveyed group of fuel cell stakeholders thinks will provide the most benefit to addressing energy concerns and commercialization in California and the second column outlines the technology categories that the same group saw as the most promising to pursue to further fuel cell technology development.

The most influential set of category rankings for this study is the analysis using both project score and commercialization barriers. This analysis reflects the importance that each technology category and similarly each project have to fuel cell development and acceptance in California. As a result, the first column of Table 25 will be used when developing the technology roadmap for California. Additionally, reasoning for the rank of each project is presented in the roadmap section.

Table 25: Technology Category Rank Based on Score and Barriers Addressed

Rank	Considering Project Score and Commercialization Barriers	Considering only Project Score
1	Grid-DG Connectivity	Grid-DG Connectivity
2	Opportunity Fuels	Opportunity Fuels
3	Transportation	Solid Oxide Fuel Cells
4	FC-GT Hybrid	Grid Support
5	Episodic	Fuel Cell – Gas Turbine Hybrid
6	Grid Support	DG/CCHP
7	DG/CCHP	Episodic
8	Energy Storage	Fuel Cell Cross-Cutting
9	Fuel Cell Cross-cutting	Transportation
10	Materials Handling	Energy Storage
11	Hydrogen Fuel	Portable
12	Portable	Hydrogen Fuel
13	Solid Oxide Fuel Cells	Materials Handling
14	Balance of Plant	Market Cross-Cutting
15	Market Cross-cutting	Molten Carbonate Fuel Cells
16	Molten Carbonate Fuel Cells	Balance of Plant
17	Proton Exchange Membrane Fuel Cells	Proton Exchange Membrane Fuel Cells
18	Phosphoric Acid Fuel Cells	Phosphoric Acid Fuel Cells
19	Direct Methanol Fuel Cells	Direct Methanol Fuel Cells

4.5. Keyword Analysis to Identify Important Types of Projects

In addition to reviewing the results, just based on score, several keyword analyses were pursued for determining the areas that should be pursued to further develop fuel cell technology. Each project type contained several keywords in the project description and then the results were collected. Table 26 shows the results in order of descending average score. The first column (#) is used for indexing. The *Project Type Description* column is used to convey the scope of the projects included in that study. Keywords used to collect the projects into groups are listed in the third column. To accommodate different tenses of the keywords, shortened words were used (i.e., demonstra for demonstration and demonstrate). The last three columns contain statistical information resulting from the analysis. *Count* is the number of projects included in the analysis. *Average* is the resulting average score of all of the included projects. Finally, the *StDev* column presents the standard deviation of the resulting scores. The baseline analysis is

one where all of the projects are included and is represented in bold font in the twelfth row position of the table and can be used as a comparison for all of the resulting values.

Table 26: Keyword Analysis Results

#	Keyword Description	Search Input	Count	Average	StDev
1	Technology demonstration and deployment projects	demonstra, deploy	48	63%	0.16
2	Environmental issues (i.e., criteria pollutants, GHGs)	pollutant, environment, greenhouse	5	61%	0.17
3	Grid related issues	grid, distribution netw, utility, transmission	24	61%	0.19
4	Electrode and electrolyte related issues	electrocatalyst, electrolyt, electrode	8	56%	0.13
5	Technology modeling and analysis projects	model, analysis, study	14	55%	0.12
6	Fuel Reforming technologies (e.g., internal reforming, SMR)	reform, fuel processor	8	54%	0.14
7	Manufacturing related issues	manuf	5	54%	0.15
8	Renewable energies and alternative fuels	renewab, alternativ	10	54%	0.10
9	Value propositions	proposition	7	53%	0.25
10	Hybrid systems	hybrid, synerg	13	52%	0.15
11	Codes, policies, standards issues	code, polic, standards	5	51%	0.05
12	**Baseline analysis including all projects**		**251**	**50%**	**0.18**
13	General technology optimization issues	optim	24	50%	0.14
14	Performance characteristics	performance, lifetime, reliabil	17	49%	0.15
15	Electricity and fuel storage issues	storage, batter	23	47%	0.15
16	Carbon sequestration	sequestrat	3	47%	0.04
17	Market issues (e.g., studies, integration, valuation)	market	15	46%	0.22
18	Fuel production and use issues	fuel, production, renewable	44	45%	0.18
19	Explore material and fuel impurity requirements	purit	6	44%	0.10
20	Component design, development and performance	componen, OEMs, seals	40	43%	0.15

Several unique findings result from this analysis. Since the average score for all of the projects is 50%, there is no appreciable conclusion for those projects that are near 50%. It was determined that the top three and bottom three project types are selected for further review. An explanation of why these were selected and their significance follows.

As a result of markedly higher scores than the fourth project type and reasonable standard deviation values, when compared with the baseline value, the top three project types are considered significant and should be pursued above other project types if possible. With an average score of 63%, deployment and demonstration projects are on average more significant than any other project. Having 48 projects analyzed for this type adds to the confidence in this conclusion. Tied for second with scores of 61% are projects related to environmental issues and projects related to the development of the

grid and grid related technologies. For projects relatively close to the baseline score of 50%, there is no significant conclusion that can be drawn about whether that project type more important than another. The break in scores for the lowest projects is not as distinctive as that of the highest projects. The lowest ranking project types are those related to fuel production and use issues, material and fuel impurities, and component related issues. The fuel production and use project type had a higher standard deviation than the other two project types meaning that there was more disagreement between the scores, while the material and fuel impurity project type had an exceptionally low standard deviation. One should think twice before supporting projects in the lowest scoring type categories. On the other hand, the importance of actively pursuing technology demonstration and deployment projects, and projects that address environmental issues and grid related issues (the highest ranking types of projects) should be emphasized.

4.6. General Fuel Cell Commercialization Barrier Analysis

The list of fuel cell commercialization barrier criteria (Table 7) was applied to each of the highest ranking projects to determine the extent to which each project could address the criteria. Once each project was assigned the appropriate criteria as shown in the *Barriers Addressed* column in Table 21, Table 22 and Table 23; then the values can be ranked to determine which commercialization barriers are the most important among all projects and among each technology category. The complete table from which the data were drawn is in Appendix F.

Table 27 contains an example of the pertinent commercialization barrier data available for each of the high-ranking projects. This table is not presented for every project but rather serves as an example of what information was derived from the analysis. The *Raw Criteria Score* column represents the direct input of criteria values for this project. A "0, 1 or 2" is given to each criteria based on how significantly that criterion is affected by this project. For example a project with a "0" for the reliability criterion, a "1" for the cost reduction criterion and a "2" for the manufacturing criterion denotes that the particular project predominantly addresses, or is concerned with manufacturing. Furthermore, that project is less concerned with or to a lesser extent addresses the cost reduction criterion and does not significantly address reliability issues. The *Criteria Score* column weights the criteria based on the average score. The next column, *Criteria Rank: Market Cross-Cutting,* shows the ranking of the criteria within the Market cross-cutting technology category. Not every technology category was identified as being able to address every commercialization barrier. As a result, the category specific criteria rank column has several blank values, signifying that the particular technology category will not significantly address the commercialization barrier for which cells are blank. Finally, the last column, *Criteria Rank: All Projects*, presents the resulting rank of the criteria among all projects.

This analysis provides a second level of specification to include in the fuel cell roadmap. Now it is possible to determine not only which technology areas should be pursued and

the type of projects that are the most important but also the barriers that will be addressed for each project. Determining the barriers that will be overcome by pursuing certain projects or technology areas is the mechanism used to associate each project with its ability to achieve certain technology goals.

Table 27: Project Information Example

Direct Technology Issues Addressed (Proj. 4 Market Cross-cutting)	Raw Criteria Score	Criteria Score*	Criteria Rank: Market cross-cutting*	Criteria Rank: All Projects*
Cost Reduction	0	0		8
Cost / Value to Customer	2	12.5	3	1
Durability	0	0		12
Reliability	0	0		4
Efficiency	0	0		7
Transient Operation	0	0	13	20
Power and Energy Density	0	0		22
Control	0	0	13	5
Size and Weight	0	0		23
Manufacturing	1	6.2	16	11
Maintenance	1	6.2	16	19
Installation / Commissioning	1	6.2	11	16
Decommissioning / Recycling	0	0	18	24
Certification	1	6.2	8	18
System Integration	1	6.2	1	2
Safety	0	0	15	21
Public Awareness / Acceptance	1	6.2	2	10
Customer requirements	1	6.2	9	3
Market size	2	12.5	6	17
Number of markets	0	0	5	14
Energy independence	0	0	7	15
Energy security	0	0	12	13
Environmental impact	0	0	10	9
Emissions	0	0	4	6
TOTAL	**11**	**69**		

*Weighted by project score

This technique is used to determine which technology barrier criteria are the most important. The barrier criteria for each project are weighted based on the score for that project. This step effectively integrates the importance of different projects into the criteria ranking process. Finally by averaging the responses for each criterion, the technology barrier criteria that are most important can be found. Thus, the measure of criteria importance is based not only upon the number of criteria selected, but also upon the score and the distribution of criteria for each project. Table 28 shows the resulting

rank of each criterion among all technology categories and projects and is followed by a description of the reasoning and validation for the results. Additionally, each of the groups of commercialization barriers can be analyzed to present a more general evaluation of the barriers. This information is shown in Table 29 and is followed by a graphical summary of this information presented in Figure 11.

The reason for this analysis is to provide a detailed description and validation for the claims that cost, performance, marketing, etc. are the major barriers to fuel cell commercialization. Far too often these general terms are used with little to no further description of their meaning. This analysis provides a description for why certain barriers are more significant than others.

Table 28: Prioritized Commercialization Barriers for all Projects

Ranking Criteria For All Projects (Weighted by project score)	
1	Cost / Value to Customer
2	System Integration
3	Customer requirements
4	Reliability
5	Control
6	Emissions
7	Efficiency
8	Cost Reduction
9	Environmental impact
10	Public Awareness / Acceptance
11	Manufacturing
12	Durability
13	Energy security
14	Number of markets
15	Energy independence
16	Installation / Commissioning
17	Market size
18	Certification
19	Maintenance
20	Transient Operation
21	Safety
22	Power and Energy Density
23	Size and Weight
24	Decommissioning / Recycling

From this analysis the *Cost / Value to Customer* is the most important criteria to consider when determining what results will be achieved if the aforementioned projects are

pursued. *System Integration* ranks second while satisfying unique *Customer Requirements* ranks third.

Two cost terms are included in the list of barriers/gaps. Discrimination between these two cost terms results in *Cost Reduction* term being ranked eighth. This is a unique finding in that when the term *Cost* is used the value to the customer is considered more important than a cost reduction.

Similarly when considering performance characteristics the highest ranking criteria are *Reliability, Control, Efficiency, Durability* with ranks of fourth, fifth, seventh and twelfth, respectively. Following *Durability,* there is a large discontinuity to the last performance criteria. *Transient Operation*, *Power and Energy Density,* and *Size and Weight* are the lowest ranking performance criteria with ranks of twentieth, twenty-second and twenty-third, respectively.

Manufacturing was ranked near the middle at eleventh, while *Safety* was ranked near the bottom at twenty-first. A rank of tenth for *Manufacturing* means that of all of the high ranking projects, manufacturing improvements were slightly more beneficial than average at addressing fuel cell technology barriers. The rank for *Safety* seems reasonable as many fuel cell technologies are regarded as safe and very few high ranking projects would focus or have a significant impact on the safety of fuel cell technologies.

Most of the *Operation* criteria were ranked low including I*nstallation* / *Commissioning, Certification, Maintenance,* and *Decommissioning* / *Recycling* with ranks of sixteenth, eighteenth, nineteenth and twenty-fourth, respectively. The final *Operation* criterion was *System Integration* ranked second.

The highest ranking for the *Marketing* group was the *Customer Requirements* criterion with a rank of third. *Public Awareness* / *Acceptance* and *Number of Markets* ranked tenth and fourteenth, respectively. There was some surprise with the *Market Size* criterion with a rank of seventeenth. This result is caused by the fact that very few high ranking projects directly address market size. The majority of high ranking projects that addressed market size were product deployment projects.

Finally, within the *Other* criteria set, *Emissions* and *Environmental Impact* ranked the highest with sixth and ninth, respectively. *Energy Security* and *Energy Independence* were ranked thirteenth and fifteenth out of twenty-four. As a practical example of the implications of these criteria rank for California, in light of statewide legislation like Assembly Bill 32 and California's Renewable Portfolio Standard, *Emissions* and *Environmental Impact* are ranked reasonably high. This means that by pursuing the projects outlined in this report, it is likely that these two technology barrier criteria will be addressed thereby increasing the marketability of fuel cells while also addressing California legislation requirements.

Table 29: General Commercialization Barrier Evaluation

Commercialization Barriers	Barrier Groups	Rank of Barriers
Cost Reduction	Cost	1st
Cost / Value to Customer		
Durability	Performance	6th
Reliability		
Efficiency		
Transient Operation		
Power and Energy Density		
Control		
Size and Weight		
Manufacturing	Manufacturing	4th
Maintenance	Operation	5th
Installation / Commissioning		
Decommissioning / Recycling		
Certification		
System Integration		
Safety	Safety	7th
Public Awareness / Acceptance	Markets	2nd
Customer Requirements		
Market Size		
Number of Markets		
Energy Independence	Other	3rd
Energy Security		
Environmental Impact		
Emissions		

By way of a summary of the results of the commercialization barrier analysis, Figure 11 is presented on the following page. This figure contains all of the commercialization barrier groups on the inner ring, including a percentage value showing each group's relative importance. The outer ring is populated with the 24 commercialization barriers. The size of each slice represents the importance of that particular barrier. The rank for each barrier is presented at the interface between the inner and outer circle.

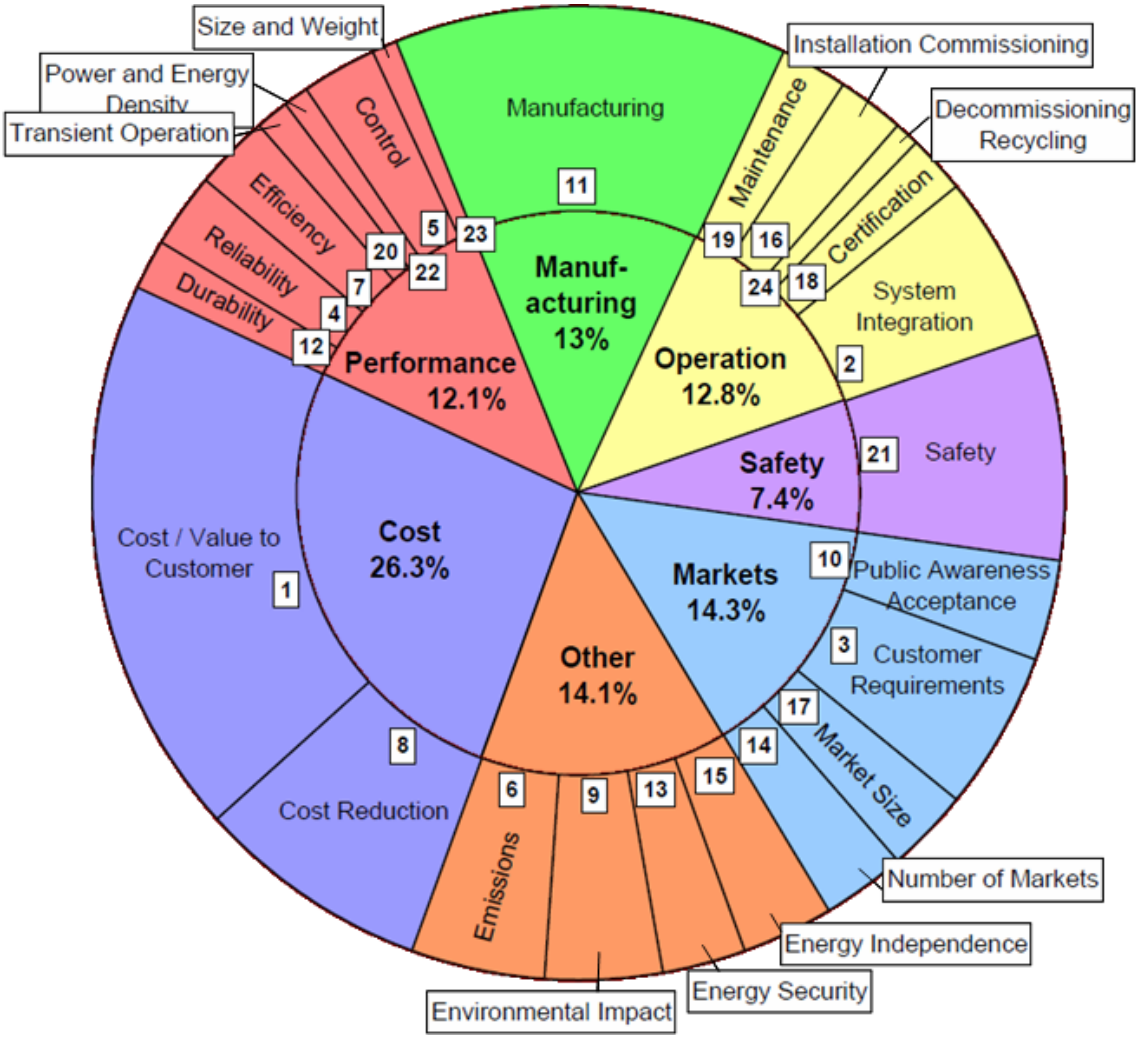

Figure 11: Summary of Commercialization Barrier Analysis
Source: National Fuel Cell Research Center.

4.7. Technology-Specific Commercialization Barrier Analysis

In addition to a general commercialization barrier analysis, a similar analysis is performed for each technology category. Each category has specific barriers that it addresses better than others. Table 30, Table 31, Table 32 and Table 33 contain the technology category analyses. The tables are separated by the technology categories of each and the ranks of the top 8 barriers are highlighted with increasingly light shades of green for lower ranking projects. Cells that are left blank signify that the particular technology category was not identified as addressing that barrier.

This analysis gives insight into the ability of different technology types to address each of the commercialization barriers. The general order of the barriers for each of the four main technology categories is similar to that of the same analysis for all of the projects as

expected (as seen in Table 28). *Cost / Value to Customer* is clearly the highest ranked barrier receiving the highest rank for all four of the main technology categories.

Two examples are presented to validate the results. When considering manufacturing, the *Market Applications* category should have a significantly lower rank for manufacturing than the *Fuel Cell Technology Specific* category. As expected, the former is ranked 20 while the latter is ranked 5. Similarly, the *Market Applications* and the *Fuels* category intuitively should receive higher rank for the *Public Awareness and Acceptance* categories than the *Fuel Cell Technology Specific* and the *Technology Integration* categories. The former two categories receive more public attention and scrutiny with regard to the public's acceptance and awareness of new products, while the latter two categories do not receive the same degree of scrutiny. These results are corroborated by the former two categories ranked seventh and tenth, while the latter two categories ranked eighteenth and nineteenth.

It is envisioned that the results for this section will provide those with additional interest in a specific technology category insights into which commercialization barriers are most likely to be addressed and the area that could use additional focus. Also, these results can be compared to the barrier analysis for all of the projects to see how each particular technology category differs from the others.

Table 30: Rank of Market Application Commercialization Barriers

	Criteria	Market cross-cutting	DG/CCHP	FC-GT Hybrid	Grid support	Materials handling	Episodic	Portable	Transportation
1	Cost / Value to Customer	3	1	2	2	2	1	2	6
2	System Integration	1	2	1	1	6	6	1	10
3	Customer requirements	9	3	6	7	3	3	3	1
4	Emissions	4	6	7	9	1	3	17	4
5	Reliability		16	5	6	8	7	9	3
6	Environmental impact	10	6	8	8	3	5	17	12
7	Public Awareness / Acceptance	2	14	12	15	11	12	6	2
8	Installation / Commissioning	11	4	15	3	5	13	17	12
9	Market size	6	9	10	13	13	11	8	11
10	Number of markets	5	5	13		19	8	4	19
11	Control	13	8	4	5	16	17	12	17
12	Efficiency		11	3	18	19	2		16
13	Energy security	12	12	11	4	17	9	17	
14	Maintenance	16	13	15	11	8	16		6
15	Energy independence	7	17	21	10	12	17		4
16	Certification	8	10	20	16	17	10	14	9
17	Cost Reduction		15	9	12	13	15	16	12
18	Safety	15	22	22		6	20	5	8
19	Transient Operation	13	18	18	14		14	15	
20	Manufacturing	16	19	17	16	13	21	11	15
21	Size and Weight			19		19		7	19
22	Decommissioning / Recycling	18	20			10	22	13	
23	Durability		21	14			17		18
24	Power and Energy Density			22		19		10	19

Table 31: Rank of Fuel Cell Technology Specific Commercialization Barriers

	Criteria	Fuel cell system cross-cutting	SOFC	MCFC	PEMFC	PAFC	DMFC
1	Cost / Value to Customer	2	3	1	2	3	2
2	Durability	6	2	3	3	1	3
3	Efficiency	8	1	7	1	6	6
4	Cost Reduction	9	4	2	4	7	8
5	Manufacturing	12	5	4	7	2	5
6	Control	5	7	5	5	8	10
7	Reliability	4	8	9	9	4	7
8	Power and Energy Density	13			6	9	1
9	System Integration	1	6	5	11	11	11
10	Customer requirements	2	9	8	11	12	11
11	Transient Operation	7	12		8		
12	Emissions	10					
13	Environmental impact	10					
14	Size and Weight	15	9	12		12	4
15	Safety				11		11
16	Maintenance	16	11	13		5	
17	Decommissioning / Recycling	19			10	10	8
18	Certification	18		10			
19	Public Awareness / Acceptance	14					
20	Installation / Commissioning	22	13	10			
21	Market size	17					
22	Number of markets	20					
23	Energy security	20					
24	Energy independence						

Table 32: Rank of Technology Integration Commercialization Barriers

	Criteria	Balance of plant	Energy storage	Grid-DG connectivity
1	Cost / Value to Customer	3	4	1
2	Control	7	1	4
3	System Integration	4	4	6
4	Transient Operation	5	2	12
5	Reliability	12	8	2
6	Efficiency	6	3	17
7	Number of markets	9	6	11
8	Energy security	16	10	2
9	Market size	11		8
10	Emissions		6	14
11	Certification	16		5
12	Cost Reduction	1	15	16
13	Manufacturing	2	15	17
14	Customer requirements	15	18	6
15	Environmental impact	16	9	14
16	Durability	10	12	17
17	Power and Energy Density	13	13	
18	Public Awareness / Acceptance	16	14	10
19	Safety		18	9
20	Energy independence	16	10	17
21	Installation / Commissioning	16		13
22	Maintenance	8		22
23	Decommissioning / Recycling	13		21
24	Size and Weight	22	17	

Table 33: Rank of Fuel Commercialization Barriers

Criteria		Hydrogen Fuel	Opportunity fuels
1	Cost / Value to Customer	1	1
2	Emissions	3	3
3	Energy independence	4	2
4	Customer requirements	2	7
5	Environmental impact	7	3
6	System Integration	10	5
7	Certification	6	10
8	Energy security	13	5
9	Cost Reduction	8	13
10	Public Awareness / Acceptance	5	16
11	Control	15	9
12	Reliability	12	14
13	Maintenance	16	10
14	Manufacturing	9	18
15	Efficiency	11	17
16	Number of markets	20	8
17	Durability	19	14
18	Market size	14	19
19	Installation / Commissioning	23	10
20	Safety	17	
21	Size and Weight	17	
22	Transient Operation	21	
23	Power and Energy Density	22	
24	Decommissioning / Recycling		

4.8. Market Transforming Projects

Also resulting from the survey completion and stakeholder feedback is a list of the *Market Transforming* projects. *Market Transforming* projects are selected independent of the score or other parameters for a given project. These projects have the potential to radically accelerate fuel cell development and the development of the entire energy sector. Transforming the market most oftentimes requires that a significant breakthrough must occur. For the selected projects, it is believed that a breakthrough or a sufficient solution to the related issues will result in extreme benefit.

Twenty-one projects were selected from the list of 251 total projects. The *Market Transforming* projects are distributed among the technology categories with *Market Cross-Cutting, DG/CCHP* and *Hydrogen fuel* containing three projects each. *Episodic*, *Fuel Cell System Cross-Cutting*, *PEMFC*, and *Grid-DG Connectivity* all contain two *Market Transforming* projects each. The categories that contain one transforming project include: *Transportation*, *SOFC*, *Balance of Plant*, and *Energy Storage*, while all of the remaining categories have zero *Market Transforming* projects. Figure 12 illustrates the distribution of projects that are identified as Market Transforming amongst all of the technology categories while Table 34 contains all of the Market Transforming projects sorted with the highest scoring project at the top. The inner ring in Figure 12 contains the four major technology categories and the percentage of Market Transforming projects that are included within that category, while the outer ring provides more detail on the distribution of Market Transforming within each of the 19 technology categories. Many of the projects selected as transforming projects have similar themes. For instance, several of the projects on the list in Table 34 regard the installation and interconnection of fuel cell systems to the electrical distribution network. Additionally, there are several deployment projects that are viewed as an integral part of accelerating fuel cell commercialization. Lastly, several of the transforming projects include design, development and manufacturing of fuel cell systems and fuel cell components.

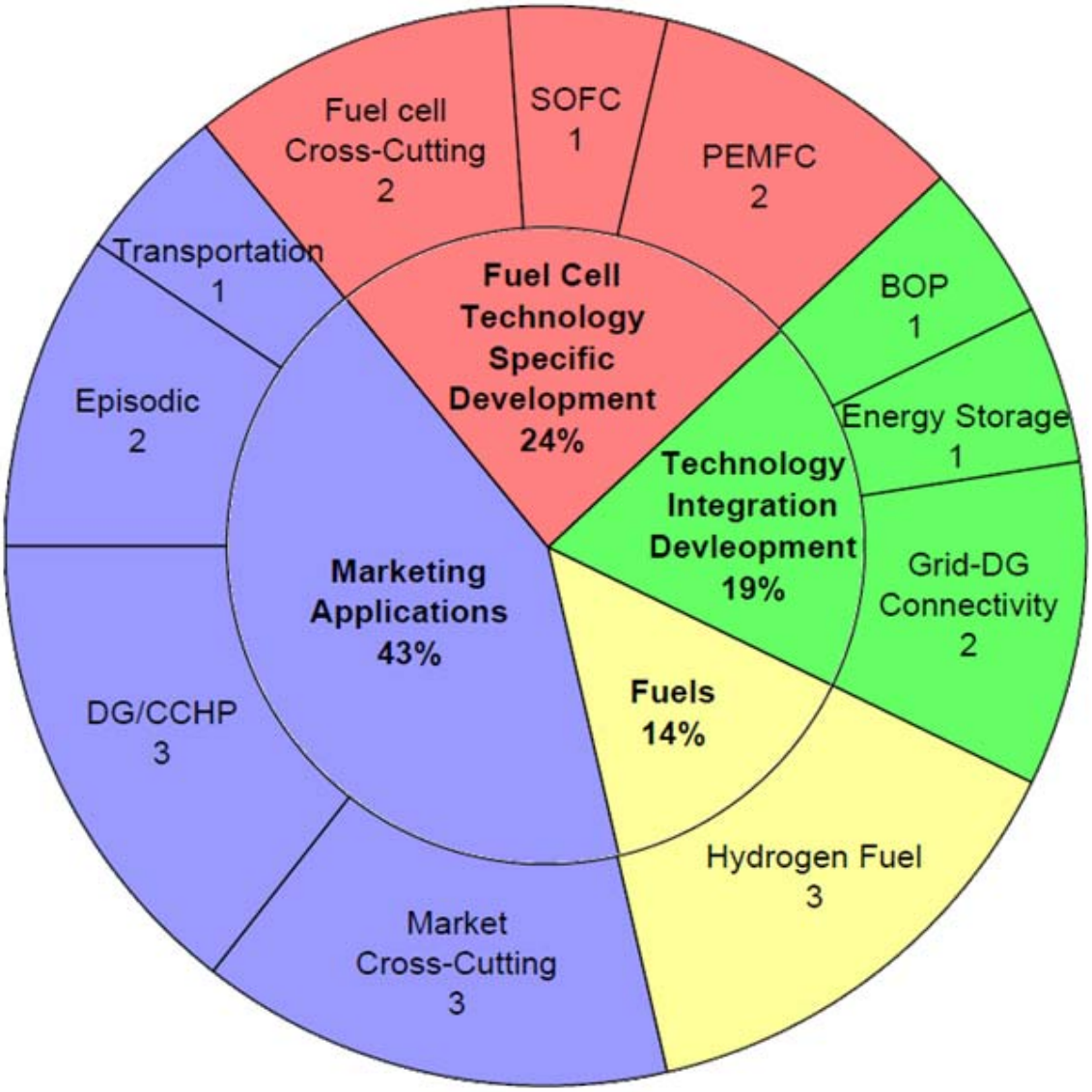

Figure 12: Distribution of Market Transforming Projects

Source: National Fuel Cell Research Center.

Table 34: Market Transforming Projects Table

Category	Project Number	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Grid-DG connectivity	6	86%	Analyze different control strategies and arrangements for optimum grid connections and interactions between customers and the utilities.	1	4	111	75
DG/CCHP	4	85%	Augment deployment activities for fuel cell CCHP systems	1	5	237	180
Grid-DG connectivity	7	84%	Design and develop a smart controller to autonomously connect DG systems to the electricity distribution network and develop corresponding metering technology and controls to interface with DG systems	2	6	128	128
DG/CCHP	2	74%	Grid connectivity of fuel cell CCHP and sale of electricity to the grid	5	22	120	94
DG/CCHP	7	71%	Simplify DG/CCHP system siting processes and requirements	7	33	87	71
SOFC	5	69%	Develop intermediate temperature SOFCs	5	37	230	202
PEMFC	5	69%	Development and optimization of PEMFC electrocatalysts	1	40	190	151
Episodic	5	64%	Augment deployment activities for fuel cell based peak shaving systems	4	53	188	147
Market cross-cutting	4	62%	Establish a study that evaluates the needs and opportunities for implementing subsidies, buy-downs, other incentives and mandates to support fuel cell development and commercialization	1	60	77	52
Energy storage	4	62%	Explore the integration of fuel cells and energy storage systems with intermittent, centralized wind power systems	3	62	119	159
Fuel cell system cross-cutting	3	60%	Further develop manufacturability of fuel cells and fuel cell systems	6	70	135	105
Hydrogen Fuel	20	58%	Improve gas separation and purification technology	5	79	182	198
Episodic	3	56%	Augment deployment activities for fuel cell backup power systems	7	91	181	132
Market cross-cutting	13	55%	Conduct a study to determine how fuel cell technology can be used to enable more significant use of intermittent renewable power generation	4	98	108	100
Market cross-cutting	14	54%	Explore the potential for fuel cell systems to reduce criteria pollutants and greenhouse gas emissions throughout California	5	103	80	53
Hydrogen Fuel	12	53%	Explore the needs and opportunities for governmental mandates and financial incentives for hydrogen production, delivery and storage	10	108	78	55
Transportation	4	51%	Increase deployment activities for heavy duty on-road fuel cell vehicles	5	123	215	226
Fuel cell system cross-cutting	21	49%	Explore and address fuel cell system durability and lifetime for stationary/continuous fuel cell power applications	10	134	86	144
PEMFC	2	44%	Optimize PEMFC membrane materials and operation	7	169	92	128
Balance of plant	3	41%	Optimize major BOP components and instrumentation (e.g., sensors, controls) to improve performance and economics	6	180	111	75
Hydrogen Fuel	29	38%	Exploration of novel hydrogen storage and distribution techniques	23	194	177	199

5.0 Fuel Cell Technology Roadmap

The Fuel Cell Technology Roadmap is one of the major achievements of this work. This roadmap document collects the responses from all of the surveys and feedback from all of the conferences and workshops to succinctly summarize the most promising technology categories and to recommend the categories that should be preferentially pursued.

5.1. Integration with Benchmarks and Milestones

The first step in developing the roadmap is to explore the benchmarks and milestones within the fuel cell sector. Currently, the major fuel cell areas being explored in California can be separated into two groups, research and development, and market development. Within the research and development area, work is primarily being done by the automobile manufactures for transportation and more generally by universities, government organizations, national labs and other companies. The second category is market development. Three primary market focuses are: distributed generation, materials handling and backup power. These activities establish the benchmark for fuel cell research and development in California.

The next step is to outline milestones that must be achieved. In 2005, the California Public Utilities Commission (CPUC) and the Energy Commission published the *Energy Action Plan II: Implementation Roadmap for Energy Policies*. The general purpose for the Energy Action Plan is to establish, not only a vision for the future of the energy sector in California, but also to develop an implementation plan that can be used to achieve the desired goals. Within that document, nine action areas are introduced that the CPUC and the Energy Commission feel are cornerstones in the advancement of California's energy sector. These areas include: energy efficiency; demand response; renewables; electricity adequacy, reliability and infrastructure; electricity market structure; natural gas supply, demand and infrastructure; transportation fuel supply, demand and infrastructure; research, development and deployment; and finally climate change. These areas are used as the general milestones for the fuel cell roadmap. Moving from the current technology status and expanding the scope of the technologies that are developed to address deficiencies in the above mentioned areas will ensure that the energy sector continues to meet ratepayer's needs while expanding environmentally clean practices. Fuel cells provide many unique opportunities within California's energy sector to address the action areas and provide a significant contribution to meeting California's energy goals and milestones.

Though the *Action Areas* from the California Action Plan were developed for the broader energy sector in California, there is a strong overlap between the action areas and the commercialization barriers established for this study. The reason for these two sets of criteria is because the action areas are for the entire energy sector and do not adequately describe all of the required improvements that must be realized to aid in the market acceptance of fuel cell technology. Thus, employing the action areas, as they appear in

the energy action plan, makes the use of the fuel cell commercialization barriers relevant to California markets and to more holistic energy concerns.

Table 35 presents a comparison of the action areas versus the barriers. These similarities serve as the bond between pursing projects to address fuel cell commercialization barriers and addressing barriers to achieve milestones in the energy sector. The bottom and left side of the table contains totals of the identified similarities.

From Table 35 one can see how well the commercialization barriers, developed for the fuel cell roadmap and action plan, address the more broad energy sector issues. For every action area there are several barriers that have the potential to address them. The maximum overlap occurs with the *Electricity* action area with 17 similarities identified. The minimum occurs for the *Climate Change* category with only 3 similarities. This analysis provides verification that the milestones set forth by California for its energy sector can be met by addressing the fuel cell commercialization barriers, which in turn implies that the milestones can be achieved by pursuing the technology projects outlined in this analysis.

Table 35: Comparison Between Commercialization Barriers and California Energy Action Areas

Commercialization Barriers Compared to Action Areas from California's Energy Action Plan	Cost Reduction	Cost / Value to Customer	Durability	Reliability	Efficiency	Transient Operation	Power and Energy Density	Control	Size and Weight	Manufacturing	Maintenance	Installation / Commissioning	Decommissioning / Recycling	Certification	System Integration	Safety	Public Awareness / Acceptance	Customer requirements	Market size	Number of markets	Energy independence	Energy security	Environmental impact	Emissions	
Energy Efficiency																									7
Demand Response																									14
Renewables																									11
Electricity (Adequacy, Reliability, and Infrastructure)																									17
Electricity Market Structure																									14
Natural Gas Supply, Demand and Infrastructure																									11
Transportation Fuel Supply, Demand and Infrastructure																									12
Research, Development, and Deployment																									15
Climate Change																									3
	3	8	2	2	7	8	2	6	2	2	3	4	4	2	5	3	2	4	6	7	4	5	6	7	
	11		29							2	18					3	19				22				

5.2. Roadmap Description

Thus far, benchmarks and milestones have been generally outlined and the commercialization barriers have been identified. Using this information and the results from the technology barrier/gap analysis, the project analysis, and input from the fuel cell community; a fuel cell roadmap is developed. The roadmap outlines the general path that the fuel cell community believes will provide the most beneficial results. Figure 13 presents the fuel cell technology roadmap for California, followed by a description of each category and the reasoning behind their position.

Three main sections comprise the roadmap. First, the benchmark section presents a general synopsis of the activities being pursued in California. This section aids in establishing scope and relevance for the roadmap by presenting the current activities, while providing the desired status for those activities. The second part is the roadmap section of the figure. A general time-scale is introduced and below that is a prioritized list of the technology categories in order of their average importance, as determined from the fuel cell technology surveys. Additionally, the width of each bar represents the average duration for projects within that category and the horizontal position represents the recommended order in which each of the categories should be pursued. The order was established from stakeholder feedback and relative dependencies of one category on another. Additional description and rationale for each category's placement is presented after Figure 13. The last column, the milestone section, presents the commercialization barriers and action areas that the categories are seeking to address. More detail with regard to how the projects within each technology category address the barriers is presented in the action plan.

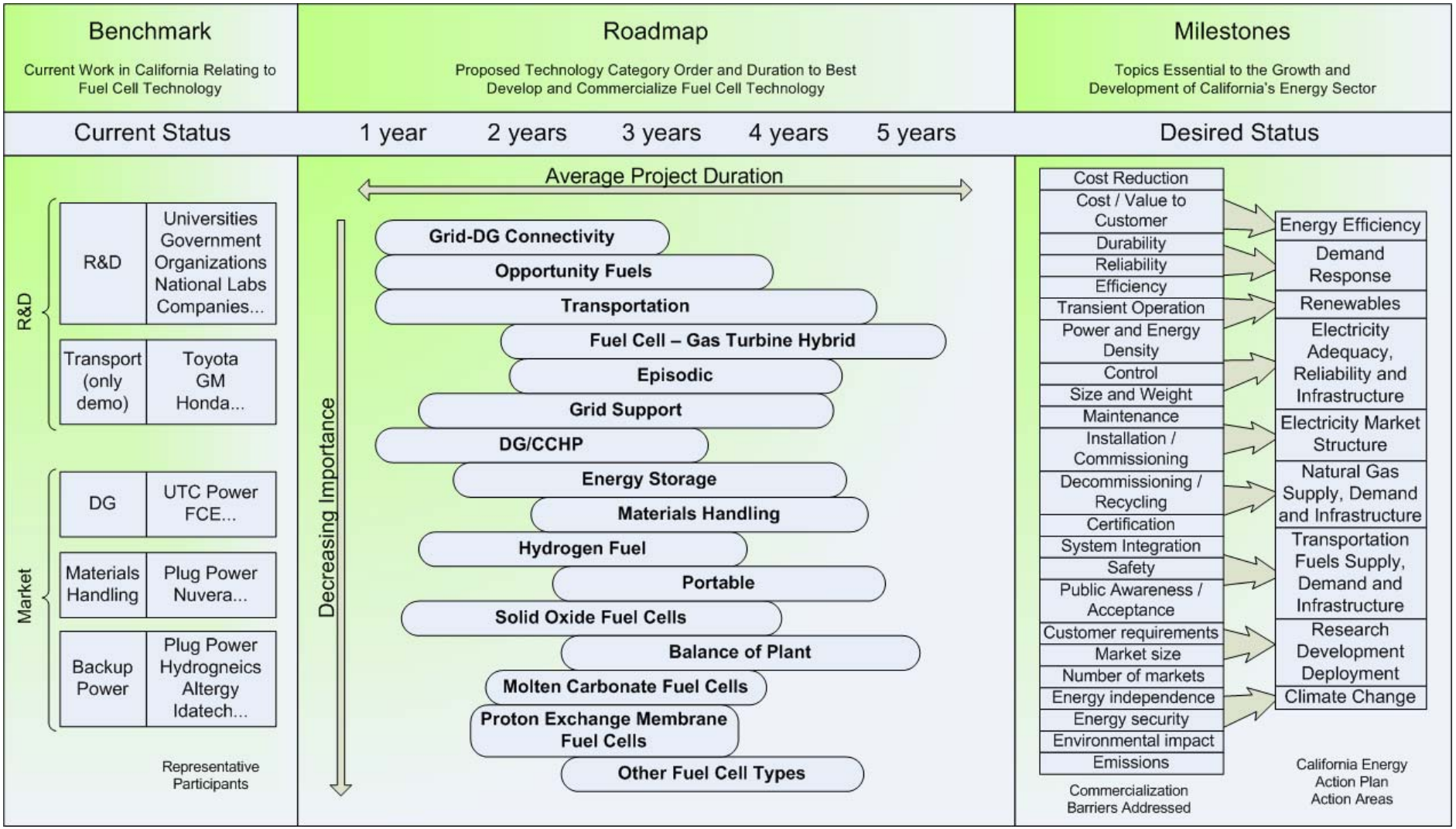

Figure 13: California Fuel Cell Roadmap

Source: National Fuel Cell Research Center.

5.3. Reasoning for Category Placement

Grid-DG Connectivity

As is evident from the projects within the *Grid-DG Connectivity* category, this group primarily concerns the interaction of power generation equipment with the electrical distribution network. Ancillary services as well as practicalities of equipment interconnection and the potential for generation equipment penetration are included. This category has a very high ranking average score while maintaining a low average cost and short average project duration. Thus, this category represents the group of projects that if pursued will have with the most potential benefit to the fuel cell community as well as to the ratepayer, electric utility, and general public. Several of the projects in this category are significant for the further development of other categories, which means that other categories have some degree of dependency upon this category (e.g., grid interconnection procedures and effects, ancillary services).

Opportunity Fuels

The *Opportunity Fuels* category contains many projects with a wide scope. This is reflected by the fact that both the highest ranking and the lowest ranking projects are included within this category. Some of the topics include demonstration and deployment opportunities for opportunity fueled installations, renewable fuels and fuel purification. The use of landfill gas and digester gas as opportunity fuels is seen several times in the highest ranking projects. Thus, the use of these opportunity gases for power and heat generation with fuel cells presents many promising prospects. Additionally, there are many opportunities within this category that can be pursued independent of other research lending to the urgency in pursing projects within this category. The duration of this category is average to long due to the number of demonstration and deployment projects that are included.

Transportation

The top five projects for the *Transportation* category all concern demonstration and deployment activities, two for fueling stations, two for fuel cell vehicles and one for the more general hydrogen vehicles. Due to the infrastructure and manufacturing demands, this category has the longest duration and the second highest projected project cost. Because of this long duration, it is important that actions be taken quickly and decisively guide the development of transportation technologies, thus work should be undertaken now and will continue for many years due to the long duration of transportation related technology activities.

Fuel Cell – Gas Turbine Hybrid

The rank for the average project scores in the *FC-GT Hybrid* category are high; however, the duration is the longest of all categories and the cost is the second most costly for all of the categories. There is a strong desire to further demonstrate and begin deploying this technology. *FC-GT Hybrid* installations should, for the most part, be temporally preceded by *Grid-DG Connectivity*, *DG/CCHP*, and *Grid Support* technology

development. This concept is determined from stakeholder comments on the fuel cell surveys and during the fuel cell workshops.

Episodic

A common theme among all of the categories is the importance of the demonstration and deployment projects, to which the *Episodic* category is no exception. Two of the five highest ranking projects concern demonstrations or deployment while the top project in this category concerns the development of regenerative fuel cells for episodic applications. Replacing alternative forms of backup power and peak shaving can prove beneficial for environmental and potentially cost reasons; however, this category is of average value, cost and duration. Because of this and comments from stakeholders, the start time should be after the previously mentioned categories.

Grid Support

Demonstration and deployment projects represent the majority of the projects included in this category. These types of product development, demonstration and deployment projects require significant funding and time to complete more so than the *Solid Oxide Fuel Cell* category. Competing with the grid, fuel cell power generation can be difficult, but there are many opportunities to provide additional stability, environmental cleanliness, and reduce the infrastructure requirements by installing fuel cell systems with the electrical distribution network. It is on account of these factors that the *Grid Support* category ranked high and the constituent projects should be pursued. The start time for these projects is moved slightly back as many of the projects herein could benefit from the results of the *Grid-DG Connectivity* and *DG/CCHP* categories.

DG/CCHP

The *DG/CCHP* category follows a similar trend as the three previous categories with respect to the focus on demonstration and deployment efforts for distributed generation and combined cooling, heating and power technologies; however, unlike several of the previous categories, *DG/CCHP* have project costs and duration that are average when compared with the other categories. It is likely due to the smaller-scale, distributed nature of the equipment used for this category as compared to the large-scale grid supporting and FC-GT hybrid systems that causes the project costs and duration to be lower. Additionally, this category has eleven projects that were included in the highest ranking projects, which is a large amount when compared to the other categories. This means that the *DG/CCHP* category has many valuable projects that should be considered. Some of the demonstrations can be conducted now while others will require further development in the *Grid-DG Connectivity* category to receive more sufficient warrant. Thus, this category can be pursued now and with a moderate duration and many important projects can be pursued for several years.

Energy Storage

System integration is the primary goal of many of the *Energy Storage* projects including concern for the integration of renewables and hybridization with fuel cells. The scores

for this category and the cost are average while the duration for energy storage projects is comparatively longer than most of the other projects. The development of energy storage technologies must be coincident with the other grid related categories; however, the *Energy Storage* category should be a predecessor of the *Grid-DG Connectivity* and *Grid Support* categories. Energy storage can provide significant benefit for many of the categories, especially those that integrate intermittent energy sources and provide stabilization; however, there are already energy storage technologies that are functional. Thus, significant focus on this category should come after categories like *Grid-DG*, *Opportunity fuels*, *Grid Support* and *DG/CCHP*.

Materials Handling

Medium to high costs and medium to long durations concur with the relatively low score for the *Materials Handling* category. This category includes predominantly demonstration and deployment projects as well as renewable fuel compatibility in the top six ranked projects. Just as with the *Portable* category, advancement of the *Materials Handling* category can influence the overall market acceptance of fuel cells but other markets like grid-DG, DG/CCHP, and grid support arise as more foundational to the further commercialization and market acceptance of fuel cells. There is a growing interest on and availability of fuel cells for materials handling applications, but based on the findings, work in the *Materials Handling* category should commence at a similar time as that of the *Portable* and *Episodic* categories.

Hydrogen Fuel

Thirty projects were included in this category and ten of the thirty projects were selected as the highest ranking projects for further review. There are wide variations in the scope for this category, but the major focus for the hydrogen fuel area is hydrogen production followed by hydrogen storage and distribution. The *Hydrogen Fuel* category has medium project costs and durations compared to the other categories. Development of hydrogen technology is not dependent on any specific category and has the potential to provide synergistic benefit when conducted along with the *Opportunity Fuels* category.

Portable

The *Portable* power category contains demonstration and deployment projects as many other market application categories, but another key concern for this category is with fuel provision, infrastructure and compatibility. Relatively low research costs and average project durations enhance the value of the *Portable* category; however, it is not apparent from literature review or from the project survey and feedback process that the success of this market will dramatically drive the further development of fuel cells so activities in this area should tend to be later on the timeline.

Solid Oxide Fuel Cells

The *Solid Oxide Fuel Cells* category has high project scores, but also has projects that will require substantial funding and time to complete. This category is the highest-ranking fuel cell category. SOFC technology still has many hurdles to overcome when compared

with older, more established fuel cell types like MCFC and PEMFC. This is echoed by the scores for the projects in the SOFC category when compared with the other fuel cell types. Development in this category can occur simultaneously with many of the other categories lending to only a slight offset start time. Additionally, many of the projects were identified as taking a moderately long duration due to the fundamental nature of some of the projects in this group.

Balance of Plant

The *Balance of Plant* projects consistently received low scores and often high costs and long durations. As is corroborated by the diverse projects within this category, balance of plant technology developments in this category have the potential to help many different technologies. Despite this fact, the low average score for this category warrants that the constituent projects be pursued very selectively and generally not before the higher ranking projects.

Molten Carbonate Fuel Cells

Projects within the *Molten Carbonate Fuel Cell* category have low average scores, but they also have low costs and short durations. It is likely that the score for this category is low on account of the previous work done relating to this technology. There are still significant contributions that can be made to this technology category; however, when compared with other technology categories, *Molten Carbonate Fuel Cells* research exhibits a generally lower priority and should be conducted after several of the other technologies.

Proton Exchange Membrane Fuel Cells

Material characterization and optimization, manufacturing and control and system management are the primary issues identified that need to be addressed within PEMFCs. For these topics, the *Proton Exchange Membrane Fuel Cell* category received a low average score, but also low average project cost and the second shortest average duration for projects. As with MCFCs, many of the topics for PEMFCs have been explored or are currently being explored; however, there are still many promising technologies that merit funding. For example, this category contains two market transforming projects that have the potential to revolutionize the applications for which PEMFCs are used. Thus, PEMFC research should follow a similar timeframe as MCFC research and as is consistent with the category rankings. It is also worth noting that research for both PEMFC and MCFC technologies should generally follow after SOFC research.

Other Fuel Cells

This category represents a collection of the remaining fuel cell types (i.e., PAFC, DMFC, etc.). PAFC and DMFC have the lowest average project scores, but conversely have very low predicted costs and duration with PAFC ranking first in the cost and duration parameters. Despite the low cost and short duration for research on other types of fuel cells, it was determined that their potential to impact the fuel cell market was not as

beneficial as the other types of fuel cells or the other fuel cell technology categories. The *Other Fuel Cell Types* category, including PAFC and DMFC was determined to be the least important category to pursue and the start time for related projects conveys this message.

6.0 Fuel Cell Action Plan

Building upon the development of the fuel cell roadmap, the action plan focuses on detailing the specific actions that if pursued will improve the performance and marketability of fuel cells in California. The roadmap presented information about the general direction that the fuel cell community believed that the technology would have to travel to address barriers to fuel cell technology development and commercialization. The action plan presents many more details about each individual project and how each can aid in achieving the milestones.

Information about the priority, the duration, the cost, any interdependencies and the potential for any specific project to address the commercialization barriers is presented for each technology project. The thinking is that having this surfeit of information for each project will empower the reader to think about aspects of each project that are not immediately obvious. Values for all of these fields are a result of surveys given to the fuel cell community, workshops, and additional stakeholder feedback. While the best case scenario is that the fuel cell survey process correctly highlighted the optimum projects, realistically and practically, there will be deviation from the prescribed plan as fuel cell technology, understanding, and scientific discoveries in the fuel cell field continue to mature. Therefore, each action plan presents the optimum research scenario comprised of the highest ranking projects and market transforming projects for each technology category based on the feedback from the fuel cell community obtained in the current study.

6.1. Action Plan Layout

Data from the project tables in Appendix D are used to construct action plans for each technology category. There are several things to note about the structure and format of the action plans. First, only the three highest priority project categories (*Critical*, *High*, and *Medium*) are included in the analysis (not *Low* priority projects). Priority is represented by the shape of the entry for each project. An elongated hexagon represents the *Critical* priority projects, while an elongated circle represents the *High* priority projects and a rectangle represents the *Medium* priority projects, as shown in Figure 14. In each project bar there is the number identification for that project within the category and a short description. The description is provided to reduce the need to consult the appendix when determining the topic of each project. Projects are arranged by decreasing score and equivalently, overall score rank. Additionally, the duration of each project is depicted by the length of the project bar.

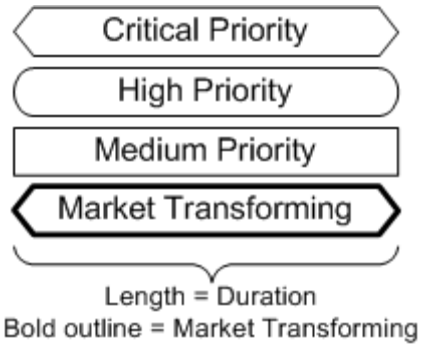

Figure 14: Action Plan Symbols

Cost is presented in the same column as the project dependencies. The length of the green cost bar signifies the projected cost of each project. Given the uncertainty in the exact value of funding required, this section presents the cost value for each project in one of five increments (see Table 36 for details). The cost bar nearest the bottom of the table presents the average for all of the projects included in that technology category of the action plan. If a project has a number on the right side of this column, it means that that particular project exhibits some level of dependence on the project number that is listed. For example, deployment of a particular technology is likely dependent on the successful demonstration of that technology. Thus, the deployment project would be considered dependant on the demonstration projects and the project number for the demonstration project would appear in the deployment project's *Cost and Dependencies* column.

Table 36: Range of Cost Values for Action Plan

Cost Bars	Lower Limit	Upper Limit
	<$1M	$2M
	<$2M	$4M
	<$4M	$6M
	<$6M	$8M
	<$8M	>$10M

The last group of columns contains information about the commercialization barriers that are addressed by each project. Commercialization barrier groups are listed (e.g., cost, performance, and manufacturing). The last group of columns contains information about which commercialization barriers are addressed by each project. Commercialization barrier groups are listed (e.g., cost, performance, manufacturing) and contain a number value representing the number of barriers in that group with the potential of being addressed. Table 37 contains a summary of the commercialization barriers and how they are grouped. Additionally, the last column in Table 37 results from an average of the importance of the values contained in that group and should be used in tandem with the count of barriers for each group to further determine the value of a specific project compared to other projects. Knowledge of how to interpret the

commercialization barrier section of each action plan is important to understanding how well each project can address the barriers. For example, a project with a "1" in the manufacturing box does not imply that it is less important than the performance group with a box containing a "6." There is also the potential for a higher number than there are barriers in that group (e.g., "4" in the cost group box). This is due to the inclusion of "1" and "2" values in the commercialization barrier analysis, where a "2" signifies the most important barrier that can be addressed by that project. The row closest to the bottom of the table in the last columns contains the sum of all of the commercialization barriers for each of the included projects. This information aids in comparisons between technology categories.

To ensure that the methodology and format for the action plans is understood, an example action plan is provided. Figure 15 presents an example action plan with much of the previous description included in comments on the figure.

Table 37: Commercialization Barrier Breakdown

Commercialization Barriers	Barrier Groups	Count of Barriers	Rank of Barriers
Cost Reduction	Cost	2	1st
Cost / Value to Customer			
Durability	Performance	8	**6th**
Reliability			
Efficiency			
Transient Operation			
Power and Energy Density			
Control			
Size and Weight			
Manufacturing	Manufacturing	1	**4th**
Maintenance	Operation	5	**5th**
Installation / Commissioning			
Decommissioning / Recycling			
Certification			
System Integration			
Safety	Safety	1	**7th**
Public Awareness / Acceptance	Markets	4	**2nd**
Customer requirements			
Market size			
Number of markets			
Energy independence	Other	4	**3rd**
Energy security			
Environmental impact			
Emissions			

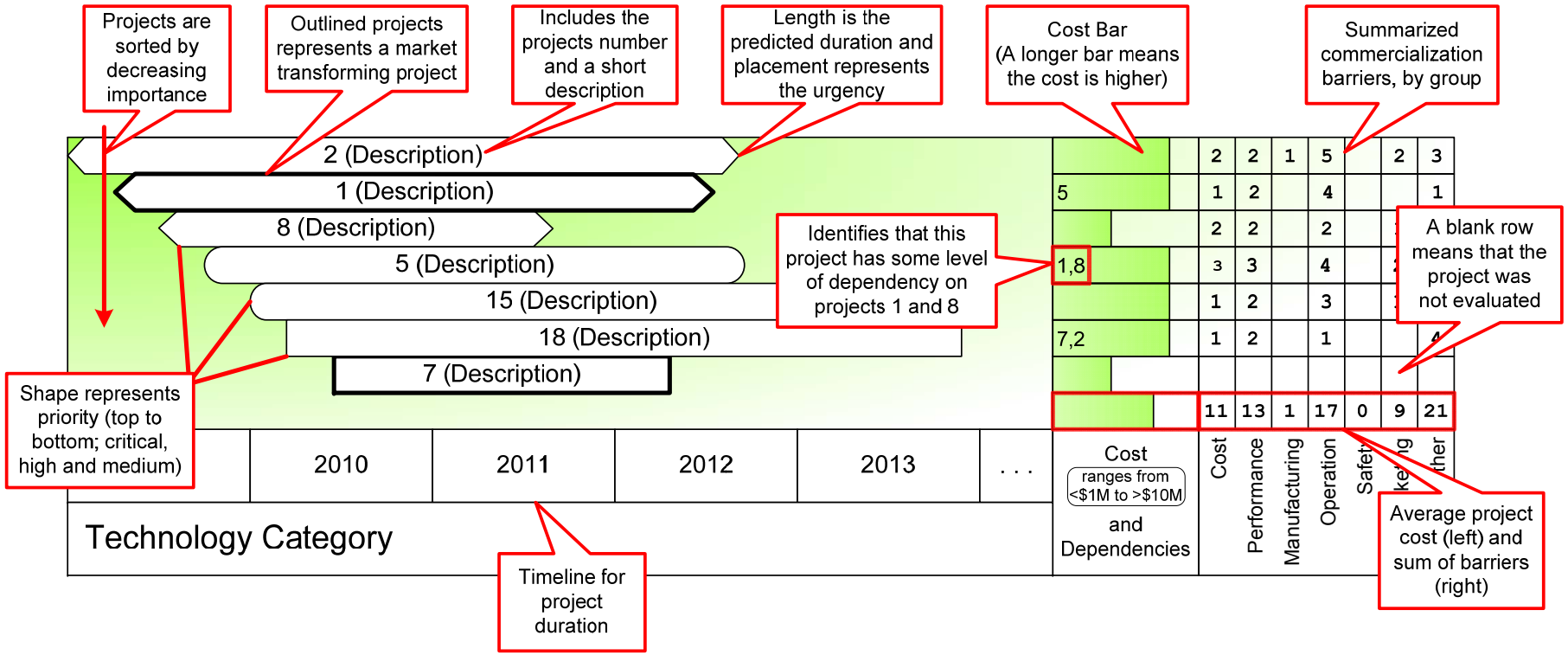

Figure 15: Example Action Plan

Source: National Fuel Cell Research Center.

6.2. Market Applications Action Plan

The following eight figures (Figure 16 through Figure 23) contain the projects that are recommended for the Market Applications areas. A more complete description for each of the projects can be found separated by technology category in Appendix D. Each figure includes a short paragraph describing especially unique findings.

Figure 16 presents the action plan for the Grid Support technology category. The Grid Support area has seven projects included that are considered of importance. This category is strongly focused toward demonstration and deployment projects.

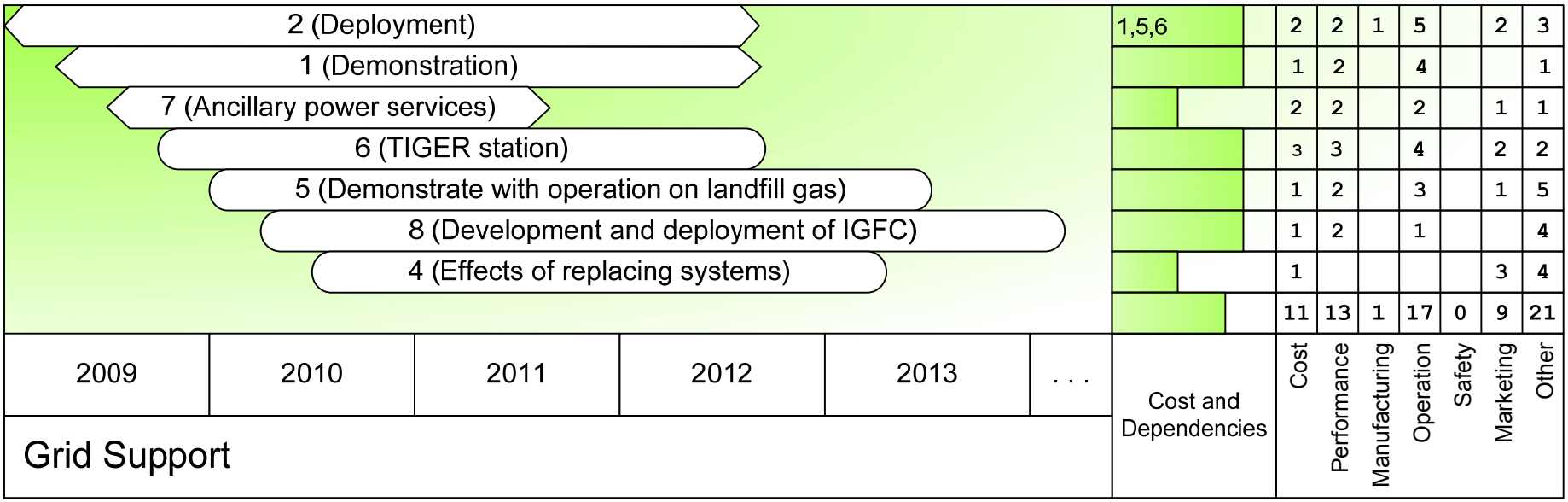

Figure 16: Market Applications Action Plan: Grid Support

Source: National Fuel Cell Research Center.

Figure 17 presents the action plan for the DG/CCHP technology category. The DG/CCHP area has eleven projects included that are considered of importance, three of which are Market Transforming projects. This category has a strong focus toward relatively high cost demonstration and deployment projects as well as several additional lower cost technology analyses.

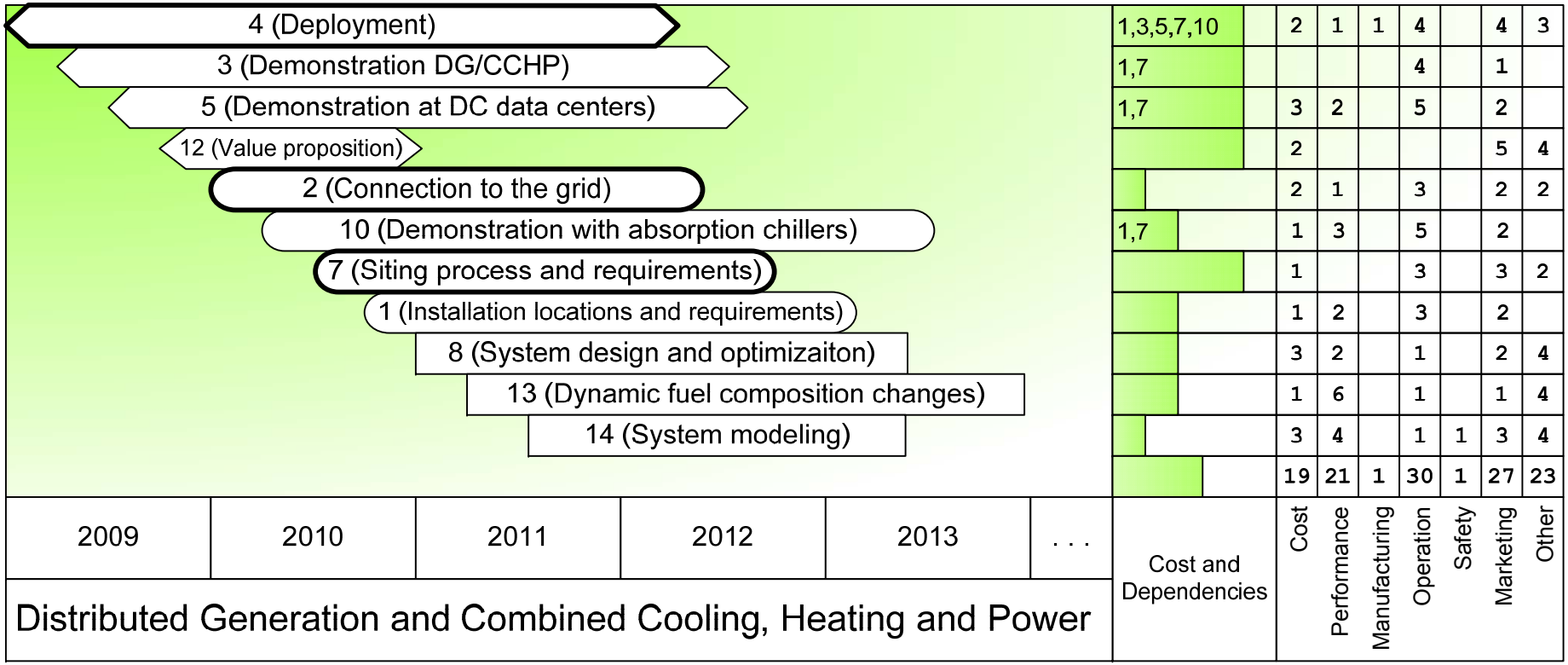

Figure 17: Market Applications Action Plan: DG/CCHP

Source: National Fuel Cell Research Center.

Figure 18 presents the action plan for the Fuel Cell Gas – Turbine Hybrid technology category. The FC-GT Hybrid area includes seven projects that are considered of importance. This category has a strong focus toward demonstration and deployment projects as well as several projects that evaluate and optimize FC-GT Hybrid technology.

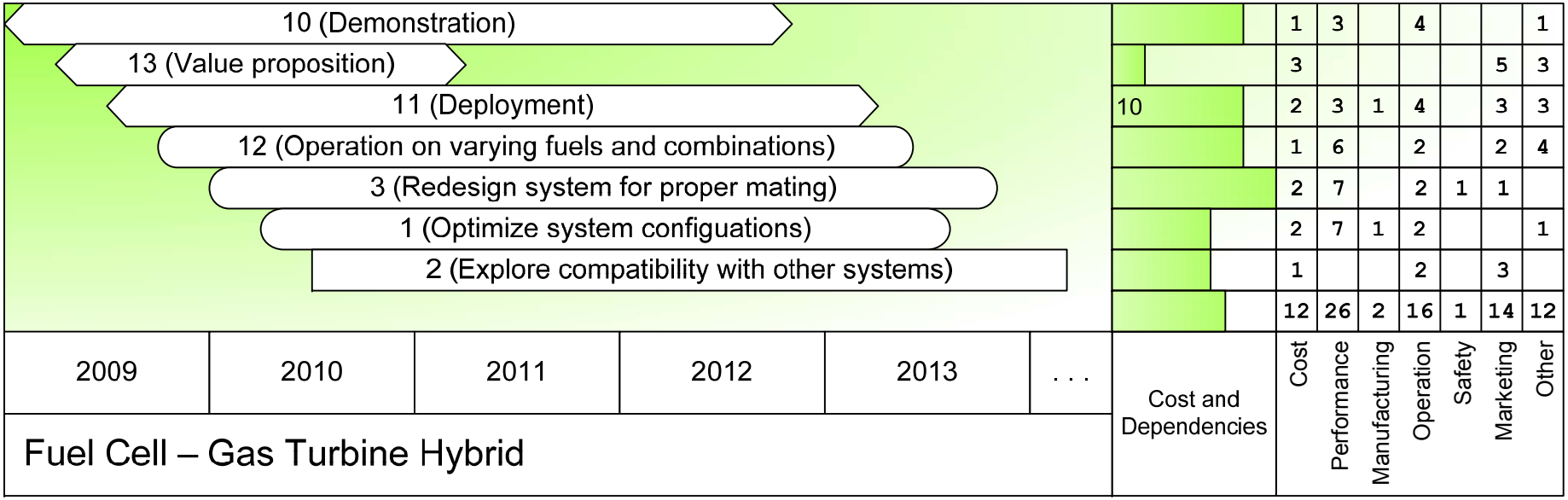

Figure 18: Market Applications Action Plan: FC-GT Hybrid

Source: National Fuel Cell Research Center.

Figure 19 presents the action plan for the Transportation technology category. The Transportation area includes five projects that are considered of importance. Though none are in the Critical priority group, one of the Transportation projects was selected as a Market Transforming project. This category has a very strong focus toward demonstration and deployment projects with all five top ranking projects concerning either demonstration or deployment.

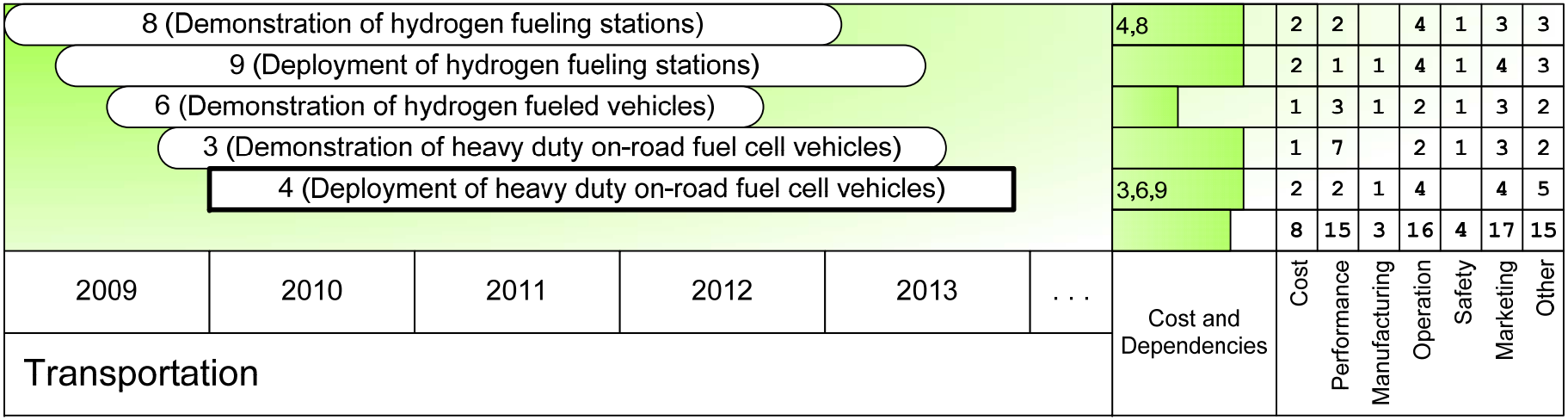

Figure 19: Market Applications Action Plan: Transportation

Source: National Fuel Cell Research Center.

Figure 20 presents the action plan for the Materials Handling technology category. The Materials Handling area includes six projects that are considered of importance, though none are in the Critical priority group. This category has a strong focus toward demonstration and deployment projects with additional focus on fueling concerns for the Materials Handling technology category.

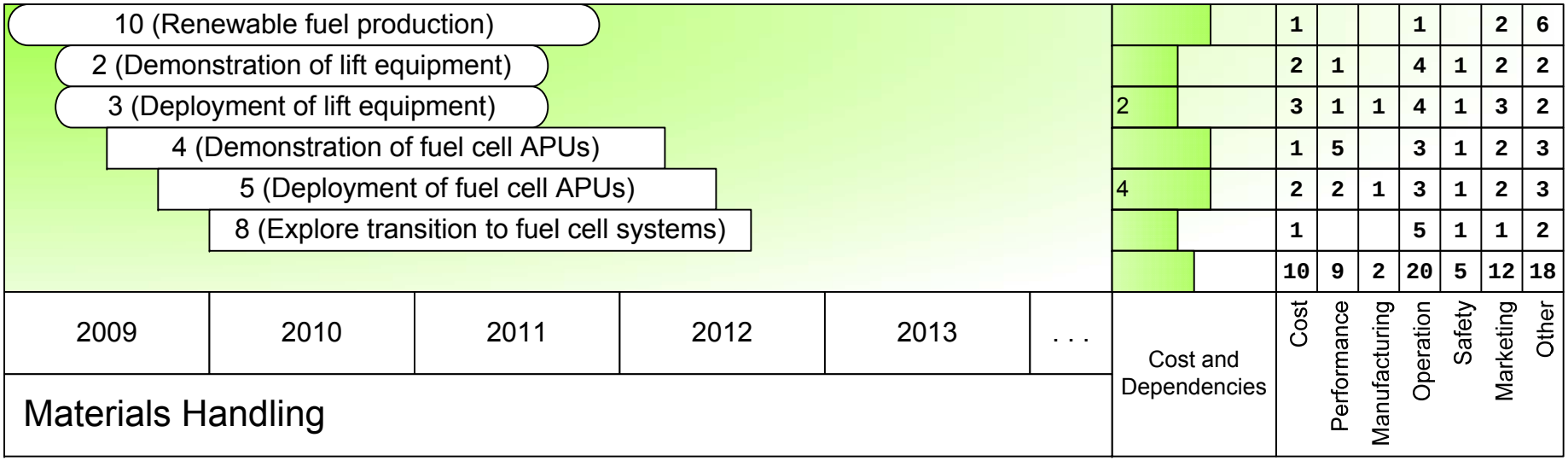

Figure 20: Market Applications Action Plan: Materials Handling

Source: National Fuel Cell Research Center.

Figure 21 presents the action plan for the Episodic Power technology category. The Episodic Power area includes six projects that are considered of importance, two of which are noted as being Market Transforming projects. This category is focused on determining the versatility and value of Episodic Power fuel cell technology.

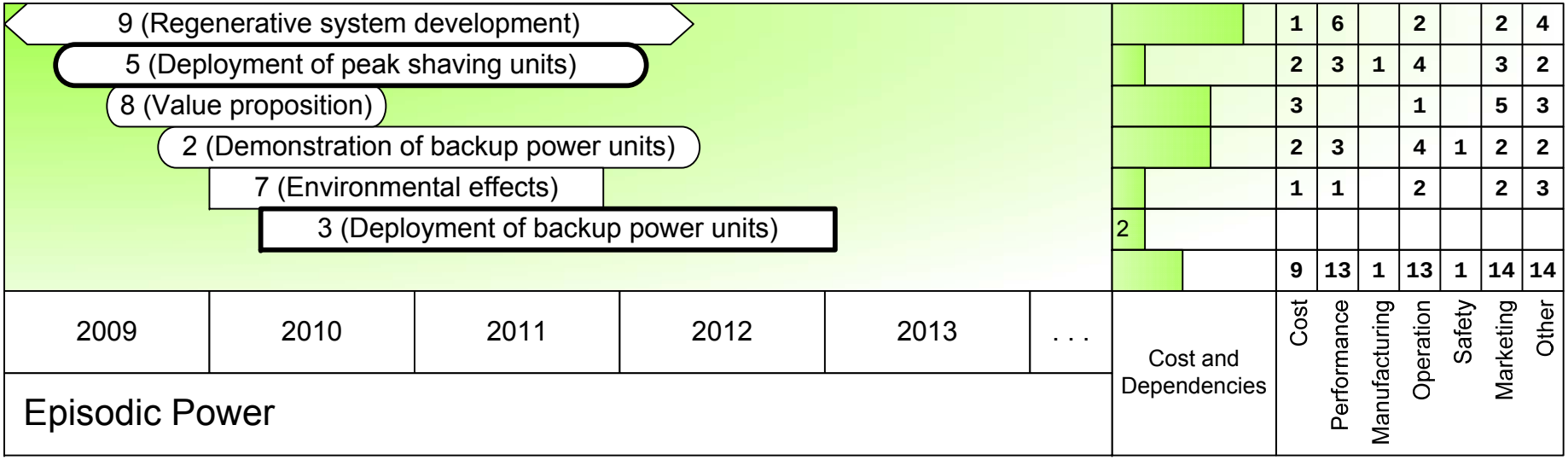

Figure 21: Market Applications Action Plan: Episodic

Source: National Fuel Cell Research Center.

Figure 22 presents the action plan for the Portable Power technology category. The Portable Power area includes six projects that are considered of importance, though none are in the Critical priority group. The projects within this category are focused on determining the versatility and compatibility of Portable Power fuel cell technology with fuel concerns. All six of the projects are relatively inexpensive to pursue even including the demonstration and deployment projects ranking first and second within the Portable Power category.

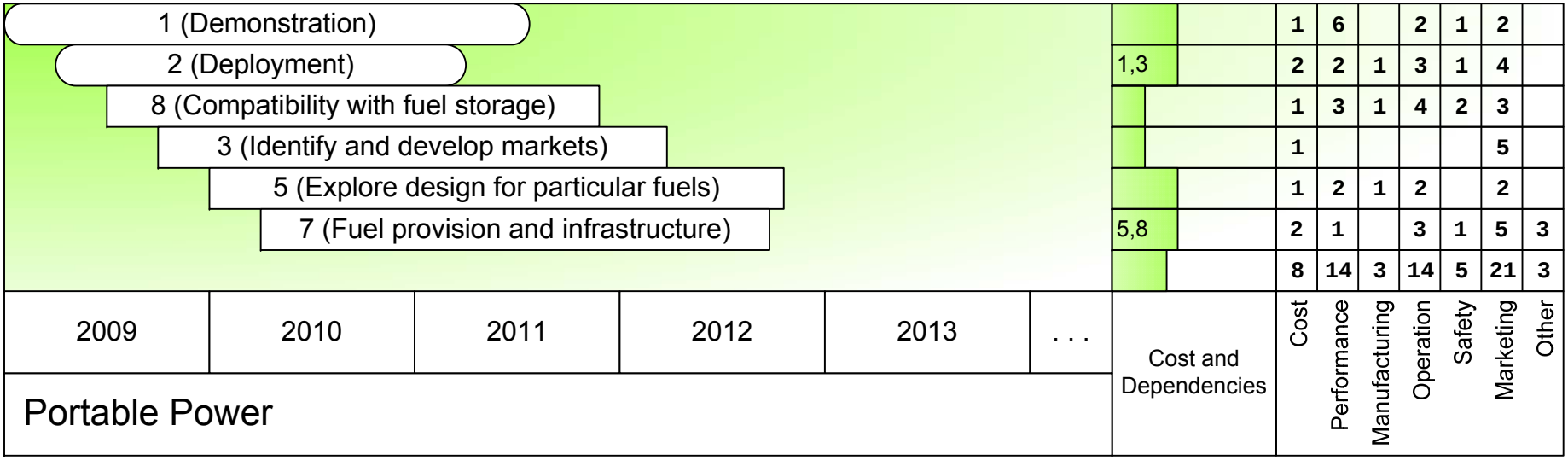

Figure 22: Market Applications Action Plan: Portable

Source: National Fuel Cell Research Center.

Figure 23 presents the action plan for the Market Cross-Cutting technology category. The Market Cross-Cutting area includes six projects that are considered of importance. Though none are in the Critical priority group, three of the projects are noted as Market Transforming projects. The projects within this category, though diverse in nature, are generally focused on exploring the supplementary benefits of pursuing fuel cell technology. All six of the projects are relatively inexpensive to pursue but play a key role in the development and commercialization of fuel cell technology.

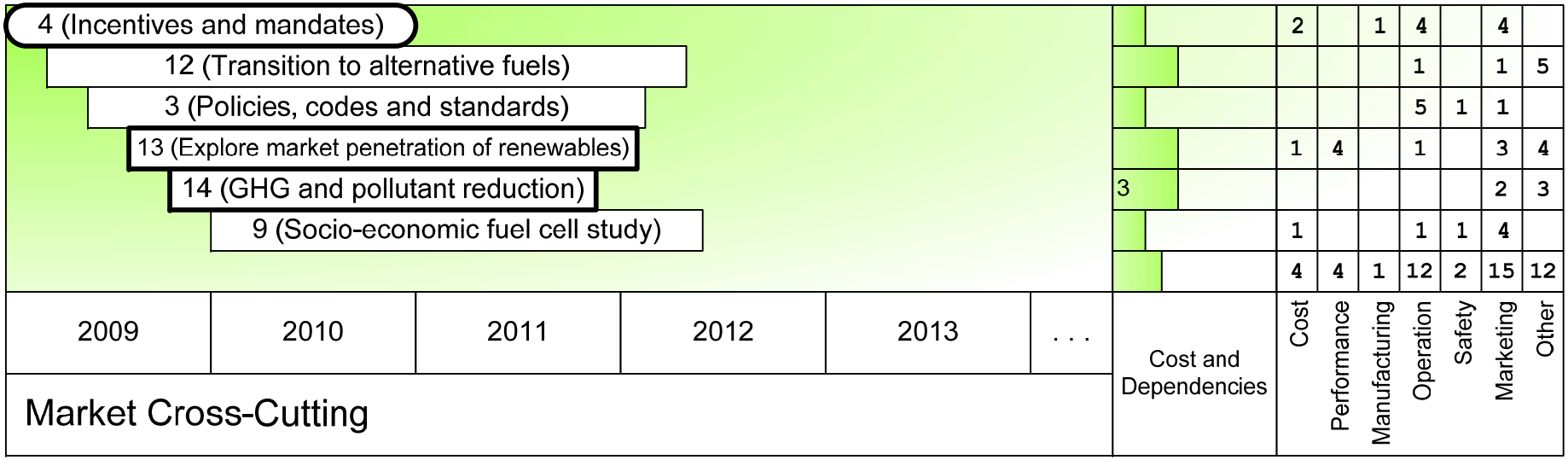

Figure 23: Market Applications Action Plans: Market Cross-Cutting

Source: National Fuel Cell Research Center.

6.3. Fuel Cell Technology Specific Action Plans

The following six figures (Figure 24 through Figure 29) contain the projects that are recommended for the Fuel Cell Technology Specific areas. A more complete description for each of the projects can be found separated by technology category in Appendix D. Each figure includes a short paragraph describing especially unique findings.

Figure 24 presents the action plan for the SOFC technology category. The SOFC area includes six projects that are considered of importance, one of which is a Market Transforming project. The types of projects within this category are diverse and benefits for pursuing these projects are focused predominantly in the cost and performance commercialization barrier groups.

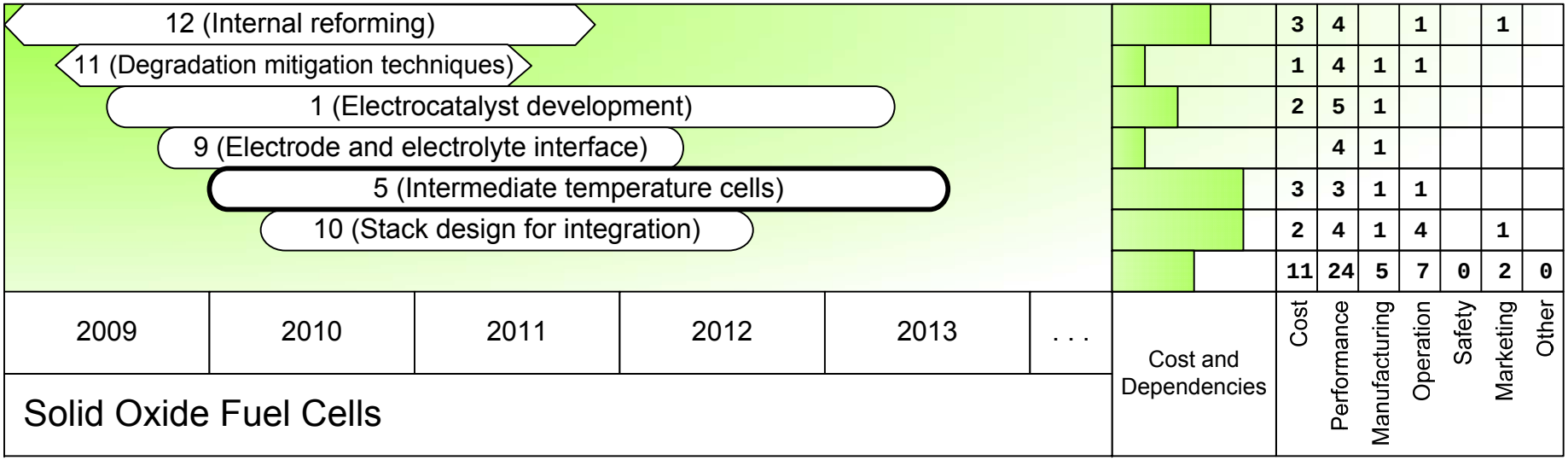

Figure 24: Fuel Cell Technology Specific Action Plans: SOFC

Source: National Fuel Cell Research Center.

Figure 25 presents the action plan for the MCFC technology category. The MCFC area includes five projects that are considered of importance though none are included in the Critical priority project group. As with the SOFC category the types of projects within the MCFC category are diverse and the benefits for pursuing these projects are focused predominantly in the cost and performance commercialization barrier groups.

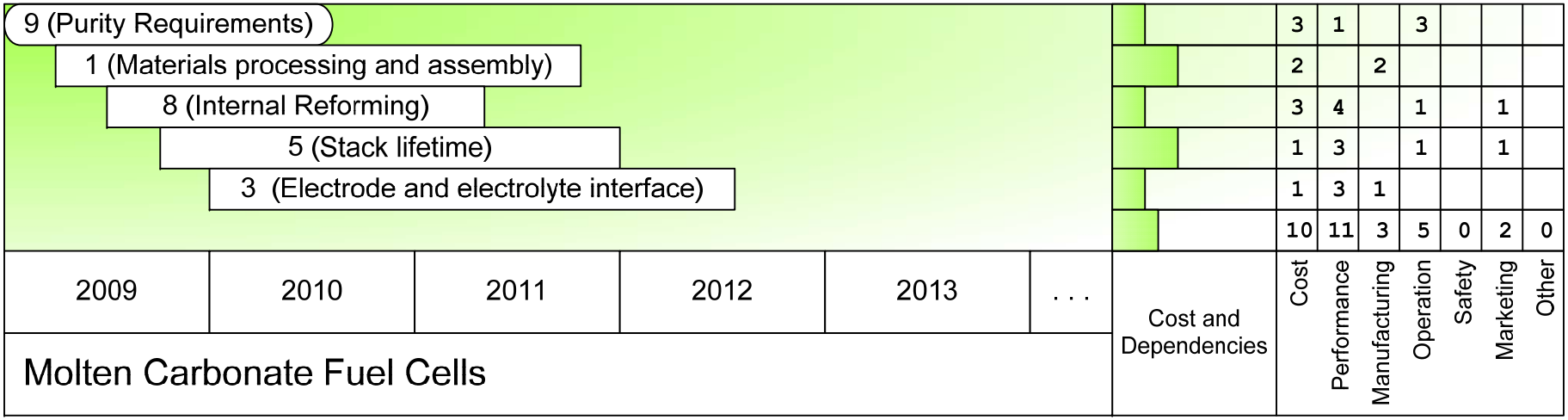

Figure 25: Fuel Cell Technology Specific Action Plans: MCFC

Source: National Fuel Cell Research Center.

Figure 26 presents the action plan for the PEMFC technology category. The PEMFC area includes six projects that are considered of importance. Though none are included in the Critical priority project group, two are considered as having Market Transforming potential. As with the SOFC and MCFC categories the types of projects within the PEMFC category are diverse and the benefits for pursuing these projects are focused predominantly in the cost and performance commercialization barrier groups.

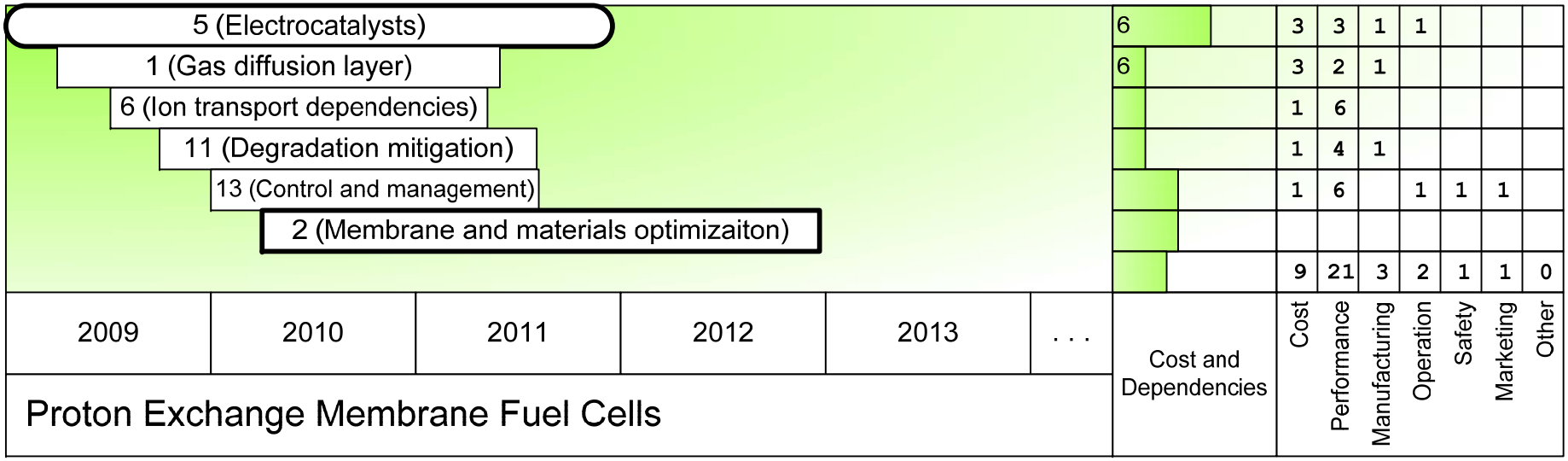

Figure 26: Fuel Cell Technology Specific Action Plans: PEMFC

Source: National Fuel Cell Research Center.

Figure 27 presents the action plan for the PAFC technology category. The PAFC area includes five projects that are considered of importance, though none are included in the Critical priority project group. As with the SOFC and MCFC categories the types of projects within the PAFC category are diverse and the benefits for pursuing these projects are focused predominantly in the cost and performance commercialization barrier groups.

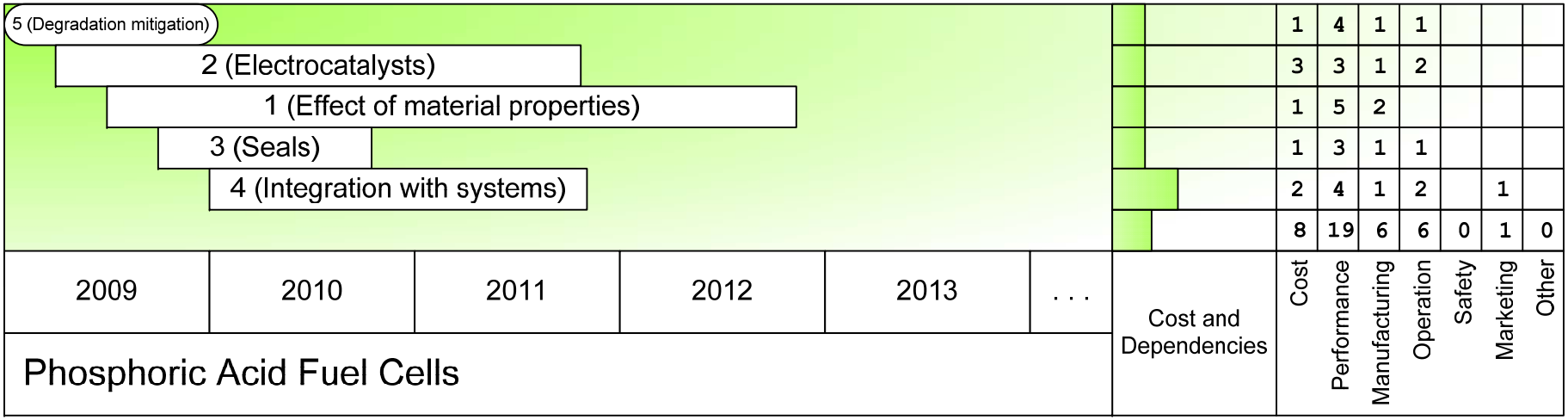

Figure 27: Fuel Cell Technology Specific Action Plans: PAFC

Source: National Fuel Cell Research Center.

Figure 28 presents the action plan for the DMFC technology category. The DMFC area includes five projects that are considered of importance, though none are included in the Critical or High priority project groups. As with the SOFC and MCFC categories the types of projects within the DMFC category are diverse and the benefits for pursuing these projects are focused predominantly in the cost and performance commercialization barrier groups.

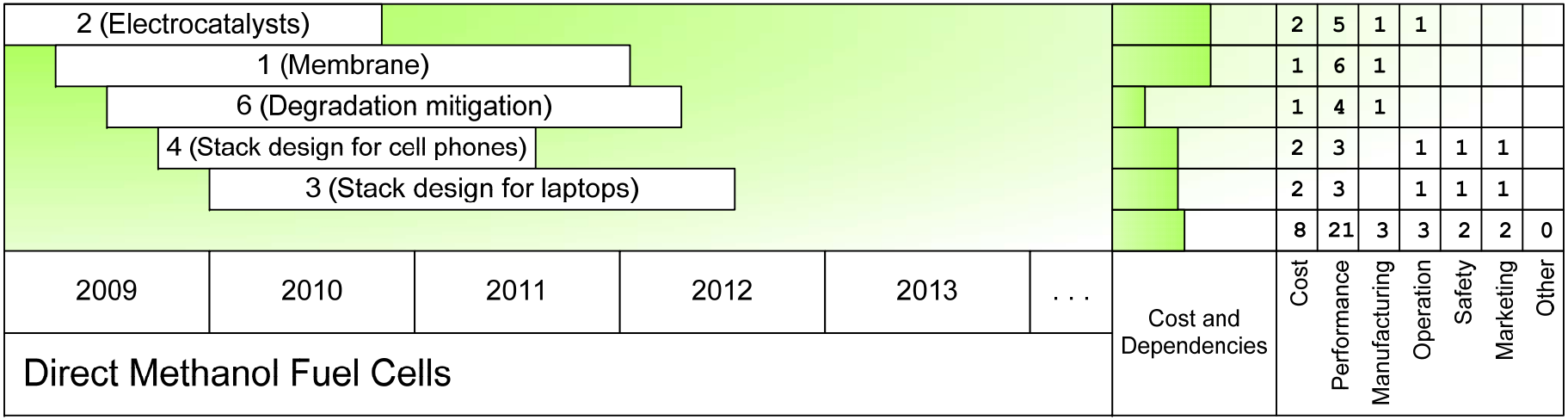

Figure 28: Fuel Cell Technology Specific Action Plans: DMFC

Source: National Fuel Cell Research Center.

Figure 29 presents the action plan for the Fuel Cell Cross-Cutting technology category. The Fuel Cell Cross-Cutting area includes nine projects that are considered of importance, two of which are Market Transforming projects. The projects within this category are diverse in nature and span many different types of projects. The nine projects encompass a wide range of cost and duration properties.

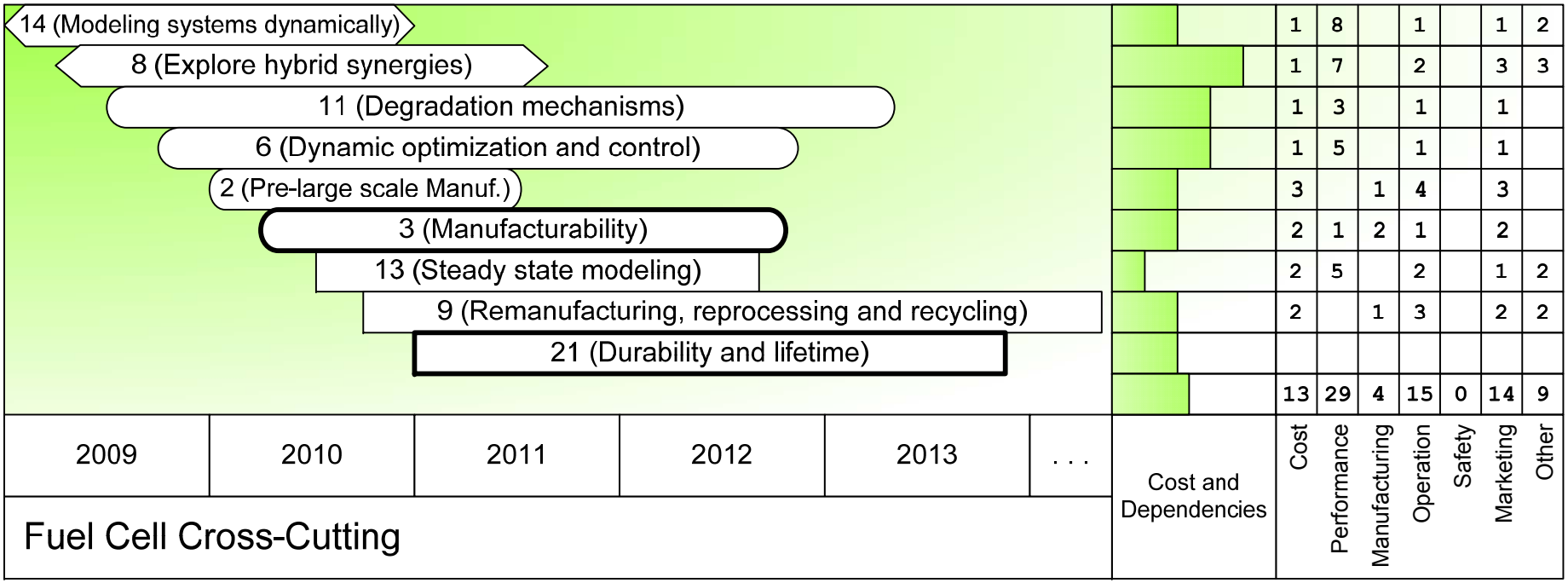

Figure 29: Fuel Cell Technology Specific Action Plans: Fuel Cell Cross-Cutting

Source: National Fuel Cell Research Center.

6.4. Technology Integration Action Plans

The following three figures (Figure 30, Figure 31 and Figure 32) contain the projects that are recommended for the Technology Integration areas. A more complete description for each of the projects can be found separated by technology category in Appendix D. Each figure includes a short paragraph describing especially unique findings.

Figure 30 presents the action plan for the Balance of Plant technology category. The Balance of Plant area includes six projects that are considered of importance, one of which is a Market Transforming project. Within this category there is a strong focus on reforming technology.

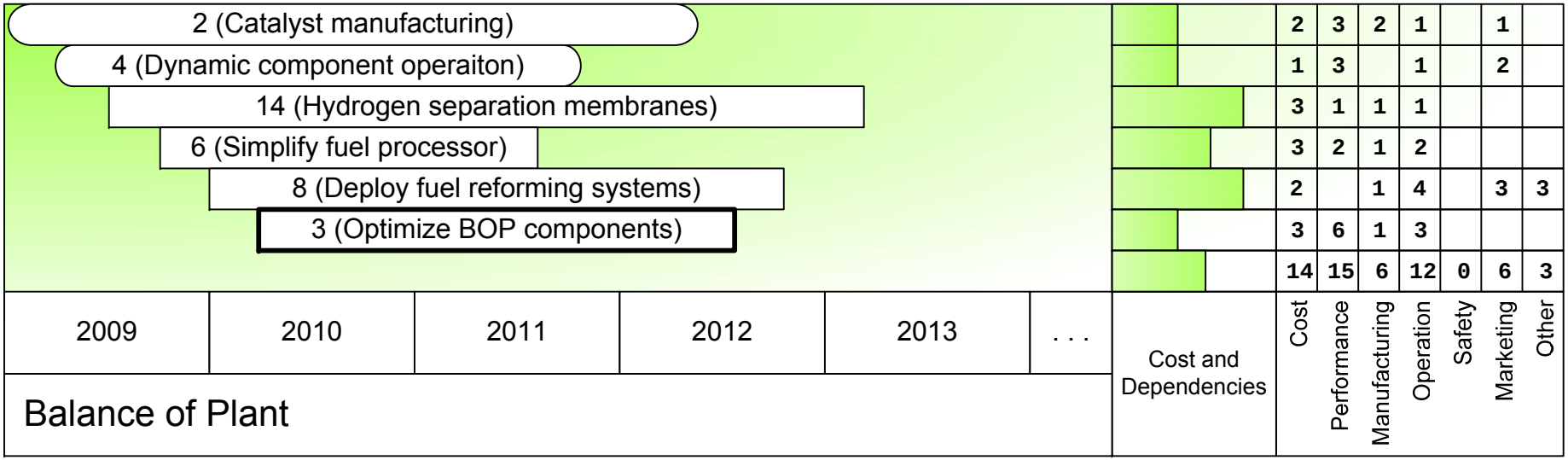

Figure 30: Technology Integration Action Plans: Balance of Plant

Source: National Fuel Cell Research Center.

Figure 31 presents the action plan for the Energy Storage technology category. The Energy Storage area includes five projects that are considered of importance. Though none are included in the Critical priority project group one is included in the Market Transforming project group. Projects within the Energy Storage category are predominantly focused on the integration of fuel cells and energy storage technologies.

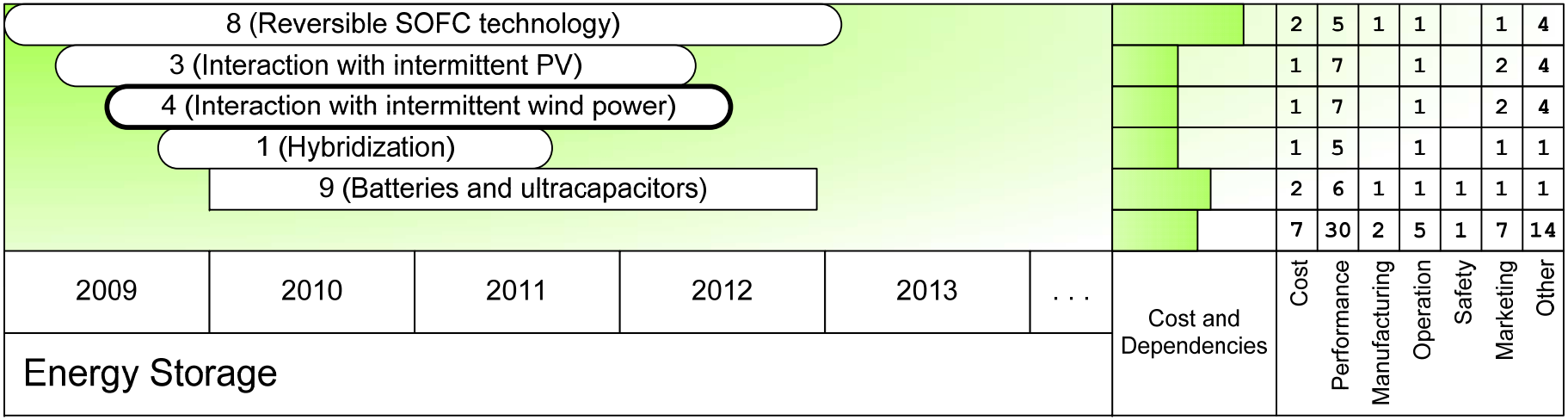

Figure 31: Technology Integration Action Plans: Energy Storage

Source: National Fuel Cell Research Center.

Figure 32 presents the action plan for the Grid-DG Connectivity technology category. The Grid-DG Connectivity area includes seven projects that are considered of importance, two of which are included in the Market Transforming project group. The large number of commercialization barriers that are addressed for the Grid-DG Connectivity projects supports the previous finding that this category is the highest ranking category of all nineteen categories.

Figure 32: Technology Integration Action Plans: Grid–DG Connectivity

Source: National Fuel Cell Research Center.

6.5. Fuel Action Plans

The following two figures (Figure 33 and Figure 34) contain the projects that are recommended for the Fuel areas. A more complete description for each of the projects can be found separated by technology category in Appendix D. Each figure includes a short paragraph describing especially unique findings.

Figure 33 presents the action plan for the Hydrogen Fuel technology category. The Hydrogen Fuel area includes eleven projects out of the total of thirty that are considered of importance. Though none are included in the Critical priority project group three are included in the Market Transforming project group. The types of projects included within the Hydrogen Fuel category well cover the scope of the hydrogen fuel area.

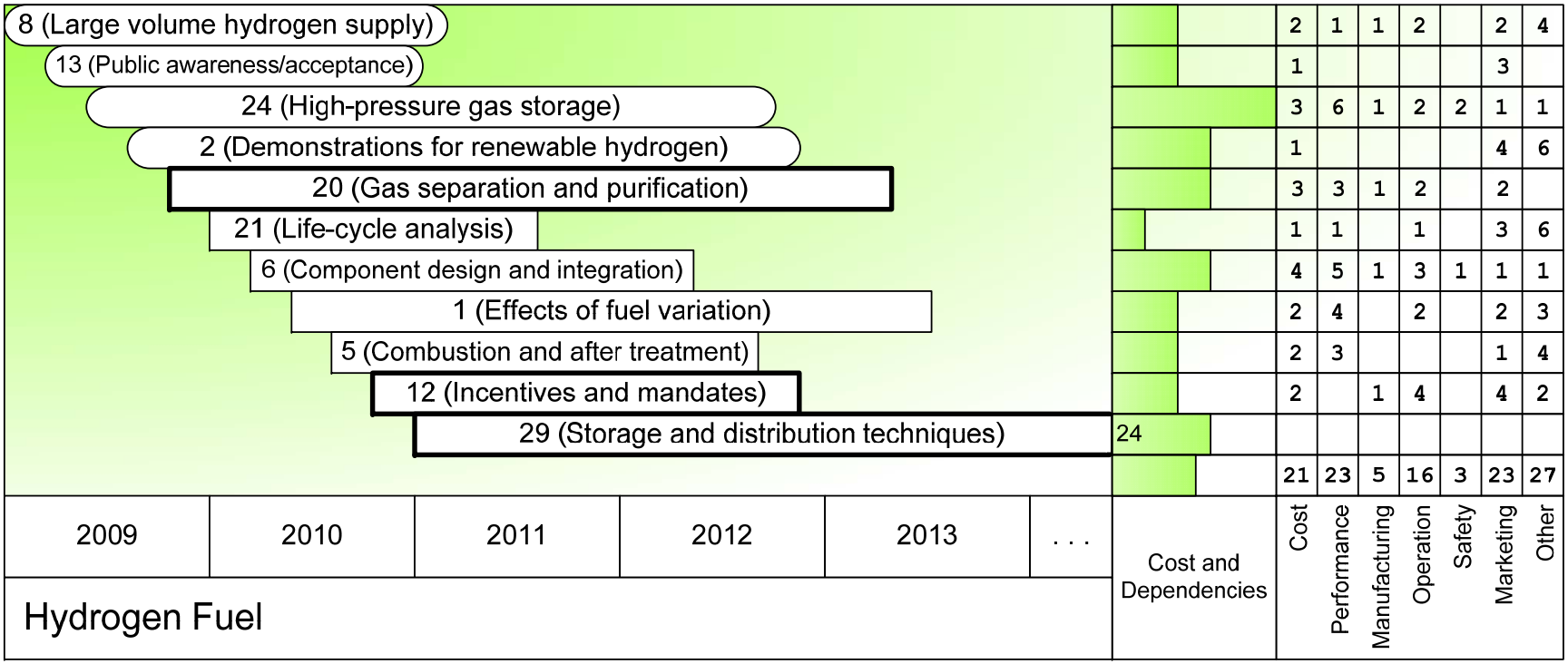

Figure 33: Fuel Action Plans: Hydrogen Fuel

Source: National Fuel Cell Research Center.

Figure 34 presents the action plan for the Opportunity Fuels technology category. The Opportunity Fuels area includes six projects that are considered of importance. The projects within this category have a strong effect on the commercialization barriers in the other group (energy independence and security, environmental impacts and emissions) as noted by the large total value in the other group. Additionally, the Opportunity Fuels category is strongly focused on demonstration and deployment projects.

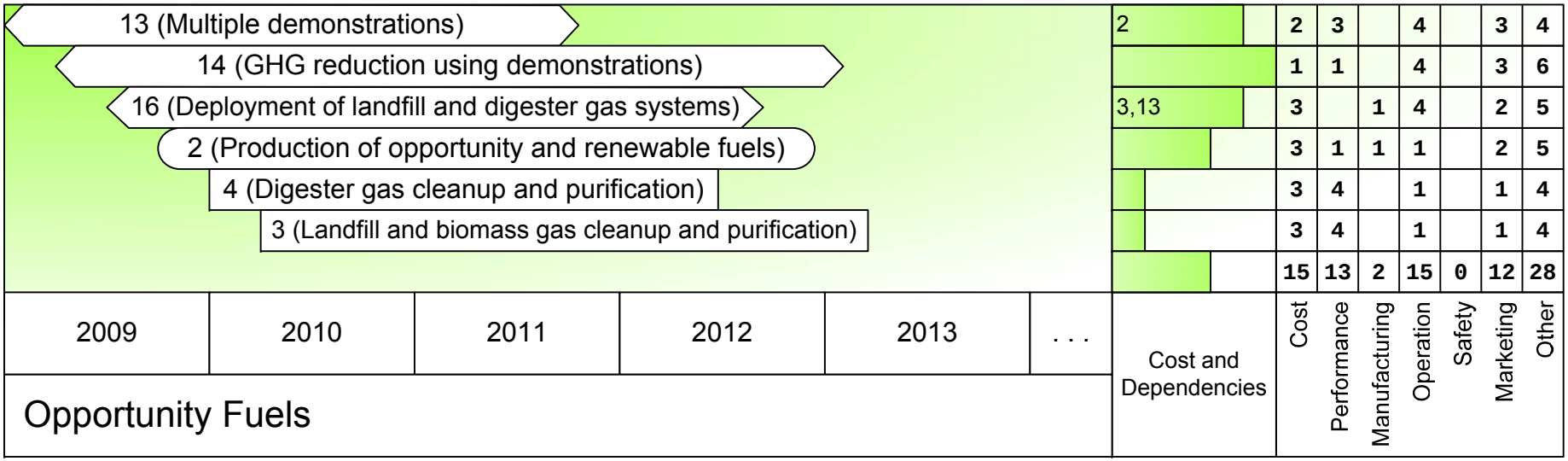

Figure 34: Fuel Action Plans: Opportunity Fuels

Source: National Fuel Cell Research Center.

7.0 Dissemination of Results

Working with the Energy Commission project manager, the resulting California Fuel Cell Roadmap and Action Plan should be put into the appropriate form for dissemination. The goal is to make the results available for stakeholders or other parties that are interested in the future of fuel cells for California and the rest of the world. The roadmap and action plans were developed to contribute to the 5-year plan established by the California Energy Commission and the PIER program. This 5-year plan can help guide the development and market acceptance of fuel cell technology within California and throughout the world.

From the literature review, it is apparent that the required time for addressing technology barriers can be more than five years. Thus, it is important that this material be made available for many years to aid in the refinement of this plan or the development of future plans. Additionally, the multi-faceted nature of this analysis means that information like the benchmarks and milestones (Appendix B) and the list of technology issues (Appendix C) have intrinsic value apart from the current overall analyses. For example, the list of technology issues is far more detailed than the list of projects; so, those interested in learning more about the types of issues that are hindering fuel cell development in a particular area may be interested in reviewing Appendix C independent of the roadmap and action plan. All of this is to say that the continued availability of this document beyond the scope of the current project has the potential to provide additional benefits for the fuel cell community, technology developers, fuel cell users, ratepayers, and the general public.

8.0 Summary and Conclusions

8.1. Summary

Major achievements resulting from this work include identification and classification of fuel cell technology status and the development of a technology roadmap and action plan for use by the California Energy Commission and the Public Interest Energy Research program. Results will be integrated into a 5-year fuel cell technology research, development and deployment plan. The goal of this 5-year plan, like the roadmap and action plan from this work, is to develop a strategy to drive the development and market acceptance of fuel cell technology in the most cost and time effective manner possible.

While the roadmap is meant to be like a compass, pointing technology research, efforts in the direction of where the fuel cell community believes the efforts can produce the greatest benefit, the action plan is like a map used to chart the specific coordinates that the community believes should be taken to further develop and commercialize fuel cell technology. Using these definitions, the roadmap contains information about those general technologies that are of particular interest and includes some insights into the duration and appropriate timing for each technology development and/or demonstration project. Note that the roadmap is based upon analyses of significant survey contributions and feedback from the fuel cell community. The roadmap establishes the areas the fuel cell community believes to be the most critical areas to pursue to address the identified barriers. The action plan completes the fuel cell technology analysis by taking the highest ranking projects along with the expected cost and duration values for each project and organizing them based on their importance. Additionally, the commercialization barriers that each of the highest ranking projects will potentially address is presented in the action plan, thereby establishing a detailed strategy to bridge the gap between fuel cell technology benchmarks and milestones. The overall technique employed for this work provides insights into, not only which fuel cell commercialization barriers pose the most significant challenges to fuel cell development, but also presents a strategy, informed by analyses of significant fuel cell community input, to address those barriers for further development and market acceptance of fuel cells.

Advancing the development and marketability of fuel cells requires that the barriers hindering this development be addressed. Understanding the current technology status (benchmarks), the desired technology status (milestones) and the commercialization barriers hindering further development is required to achieve the desired status for fuel cell technology. Utilizing previous roadmaps and action plans along with extensive feedback from the fuel cell community; a list of benchmarks, milestones and commercialization barriers for fuel cell technology are developed. The barriers or technology gaps represent issues, which if addressed, will enhance the market feasibility and acceptance of fuel cell technologies. It was determined that the best technique to bridge the gap between benchmarks and milestones is to develop a detailed list of projects where each project acts to address a collection of the commercialization barriers.

This technique allows for a high resolution of issues while presenting the material in a form that will be conducive for the California Energy Commission, the PIER program or any other interested group to pursue or solicit proposals for one or more of the prioritized projects.

Prioritization of the collected list of projects was accomplished using the response of the fuel cell community to several surveys, fuel cell workshops and additional stakeholder feedback. Information about the projected cost, duration and overall value for each project (score) resulted from the survey and workshop feedback. These parameters are the main elements used to develop the fuel cell technology roadmap and action plan. Based upon the parameters resulting from the review and survey processes, several analyses have been conducted including an analysis of the most important commercialization barriers; the most important technology categories to pursue (roadmap), which is extended to an analysis of the most important projects (action plan) and lastly the most important types of projects to explore. To develop a clear understanding of the barriers inhibiting the fuel cell technology sector and what can be done to address these barriers, it is critical to concurrently and comprehensively consider the results from all of these analyses efforts. Figure 35 illustrates the most important results from the three main analyses. The figure illustrates the list of benchmarks and milestones used to conduct the commercialization barrier analysis. In addition, the types of projects and technology categories that comprise the complete list of reviewed projects and the market transforming projects were used to determine the types of projects that were most important to pursue. Lastly, Figure 35 shows that all of the analyses rely on the reviewed literature and feedback from fuel cell stakeholders.

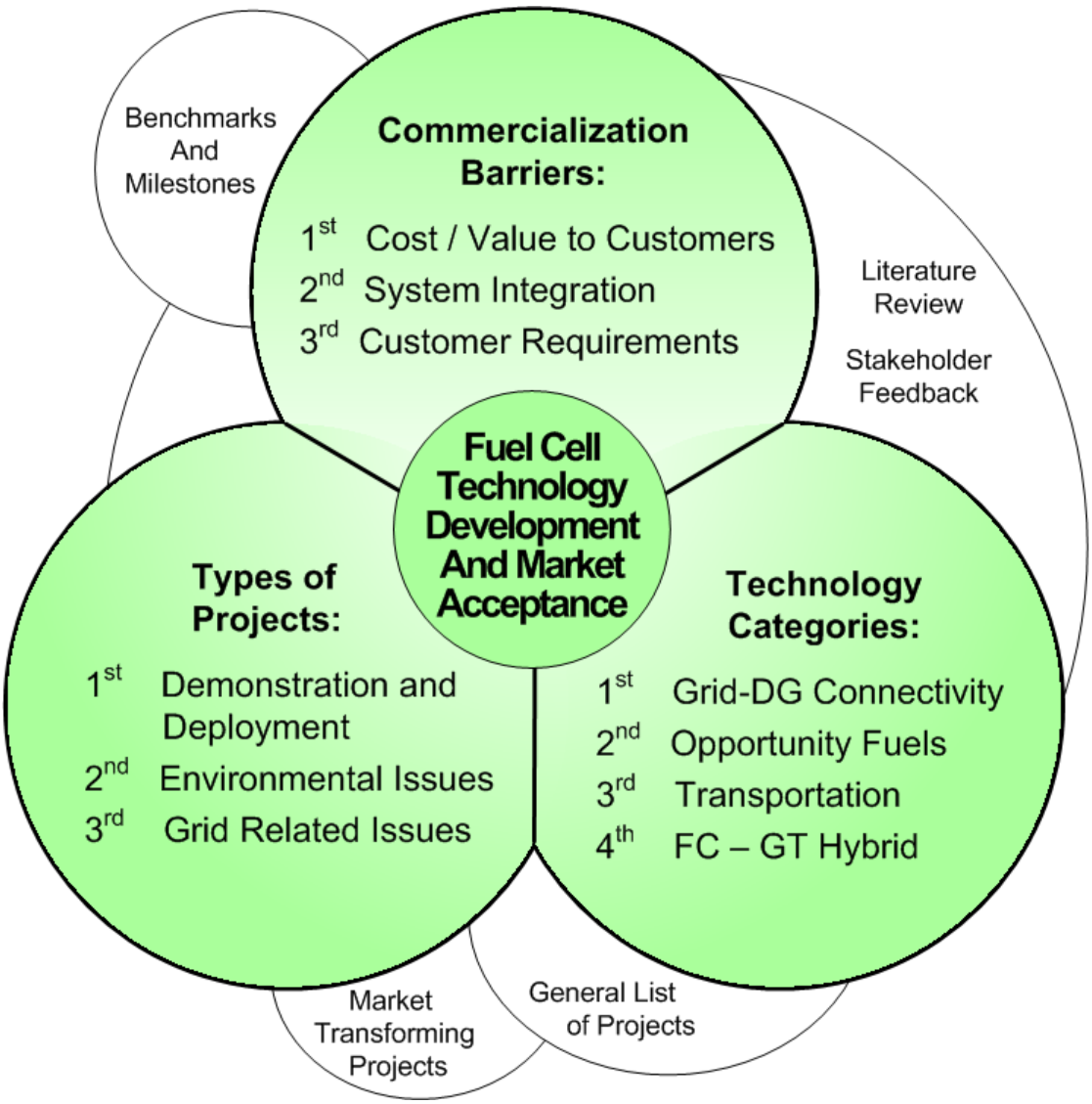

Figure 35: Summary of the Major Findings

The *Cost / Value to Customer* barrier has been identified as the most important parameter when determining the value of a project to bridge the gap between fuel cell technology benchmarks and milestones. The second highest ranking barrier is *System Integration*. These two are followed in order by *Customer Requirements*, *Reliability*, *Control*, *Emissions*, *Efficiency*, and *Cost Reduction*. The least important barriers hindering fuel cell commercialization, as determined by the current surveys and analyses, are *Transient Operation*, *Safety*, *Power and Energy Density*, *Size and Weight*, and *Decommissioning/Recycling*.

The most important technology category to pursue is the *Grid-DG Connectivity* category. This result means if the projects within this category are pursued, they are the most likely to provide the greatest benefit to fuel cell commercialization. The *Grid-DG Connectivity* category encompasses equipment interconnection and interaction with the

electrical distribution network, ancillary services and service agreements between the fuel cell installer and the utility. The second highest ranking category was the *Opportunity Fuels* category. This category includes the production and use of renewable fuels like digester gas and landfill gas and other opportunity fuels. The third highest ranking category is the *Transportation* category followed by, *Fuel Cell – Gas Turbine Hybrid*, *Episodic*, *Grid Support*, *DG/CCHP*, *Energy Storage*, *Fuel Cell Cross-Cutting*, and categories. The ten lowest ranking project categories include *Materials Handling*, *Hydrogen Fuel*, *Portable*, *Solid Oxide Fuel Cell*, *Balance of Plant*, *Market Cross-Cutting*, *MCFC*, *PEMFC*, *PAFC* and *DMFC* categories. A lower ranking does not imply that there are not important topics to address in each of the 19 technology categories, but rather, that the fuel cell community believes there is more benefit in pursuing the higher ranking categories.

The types of projects that were most highly rated are those relating to demonstration or deployment of fuel cell technology. Similarly, environmental and grid related issues are the next most important project types. Thus, the scores for all of the projects relating to improving performance characteristics or the projects that consider demonstration and deployment activities are averaged to determine if any specific groups of projects will provide additional benefits. From this analysis, it was determined that projects relating to demonstration or deployment of fuel cell technology are of higher importance than the typical project. This was corroborated by a 13 percentage point increase in the average score of demonstration and deployment projects over the average of all the projects. Similarly, environmental and grid related issues are 11 percentage points above the average with a significant natural break between them and the next project group. None of the project types were ranked sufficiently below the baseline score to be definitively considered less important than the other project types.

There are several major findings from the fuel cell technology analysis. These major findings are recurring themes from the survey, and analyses results and are oftentimes reiterated by direct stakeholder feedback and comments.

8.2. Conclusions

- There is a great need to pursue grid-connected fuel cell RD&D that addresses fuel cell **electrical distribution network issues** as they relate to fuel cells. This sentiment was echoed by the high average score and rank for the *Grid-DG Connectivity* category and the keyword analysis. For instance, deploying and demonstrating more Grid-connected fuel cell systems that can test connection control strategies and equipment, ancillary service provision and interconnection processes are the types of projects that were considered to be the most important to pursue. Issues associated with providing grid support (for example, at utility substations with very large fuel cell systems) were identified as the third most important type of project to pursue. Addressing fuel cell grid-connected installations and grid related issues also was determined to have a notable impact on fuel cell commercialization barriers facing California and more broadly the world.
- The importance of **demonstration and deployment activities** was a recurring theme throughout the analyses. Survey participants typically ranked these types of projects higher and, as a result, many of the highest rated projects within each category include demonstration or deployment of a specific technology. This is especially true for the *Market Applications* categories. Demonstration and deployment projects have the potential to address many commercialization barriers within the context of a single project. That is to say, a single demonstration project can address multiple barriers like performance, cost, market and other issues while it might take several more fundamental research projects to address the same number of barriers.
- The **development and commercialization** of fuel cell technology is often associated with a timeframe. Fuel cells are currently penetrating distributed generation, materials handling and backup power markets, but, with limited numbers and for limited applications. It is recommended that the concept of *time to commercialization* be replaced with, *remaining barriers to commercialization*. Thus, instead of speculating upon a number of years that are required for widespread market penetration and cost-competitiveness, a set of technology and policy barriers should be used to better express the status of the technology. This will provide a more tangible understanding of the needs for fuel cell technology development and can be used to establish a more detailed and explicit time estimate.
- The **Opportunity Fuels** category was the second most important technology category and contained the highest and third highest ranking projects. Additionally, the importance of this area was explicitly noted in the comments from fuel cell stakeholders and should not go without notice. Opportunity fuels

- The **Fuel Cell – Gas Turbine Hybrid** category should be considered for further research and development. This category was ranked fourth out of all of the nineteen technologies categories and within that category has the second highest ranking project. The fuel cell community feedback highlighted the current challenges facing this area, but also the potential that further development of this technology could have. FC-GT Hybrid system development includes all three of the most important types of projects found in this work (i.e., demonstration and deployment, environmental issues, and grid related issues). This technology has the potential to affect the large-scale stationary power sector as well as the distributed power sector and presents the hybridization of two distinct technologies that can provide unique synergistic benefits.

Glossary

APEP	Advanced Power and Energy Program
APU	Auxiliary power unit
ARB	California Air Resources Board
ASME	American Society of Mechanical Engineers
ASPEN	Advanced Systems for Power Engineering, Inc.
BOP	Balance of Plant
CaFCP	California Fuel Cell Partnership
CAH2Net	California Hydrogen Highway Network
CaSFCC	California Stationary Fuel Cell Collaborative
CCHP	Combined cooling heating power
CCHP	Combined cooling, heating, and power
CCS	Carbon Capture and Sequestration
CERL	Construction Engineering Research Laboratory
CFCC	Colorado Fuel Cell Center
CHBC	California Hydrogen Business Council
CHP	Combined heat and power
CIEE	California Institute for Energy and Environment
CPA	Consumer Power and Conservation Financing Authority
CPUC	California Public Utilities Commission
CSUN	California State University, Northridge
DARPA	Defense Advanced Research Projects Agency
DER	Distributed energy resource
DG	Distributed generation
DGS	Department of General Services
DMFC	Direct methanol fuel cell
DoD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
EERE	Energy Efficiency and Renewable Energy (DOE)
EPA	Environmental Protection Agency
EPAG	Environmentally-Preferred Advanced Energy Generation Program
EPRI	Electric Power Research Institute
ERDC	Engineering Research and Development Center
FC-CC	Fuel Cell Cross-Cutting
FCE	Fuel cell energy
FC-GT	Fuel cell – gas turbine
FT	Fischer Tropsch
GDL	Gas diffusion layer
GHG	Greenhouse gas
GM	General Motors
GTI	Gas Technology Institute
GTL-FT	Gas-to-liquid

HFP	Hydrogen and Fuel Cell Program (European)
HHV	Higher heating value
HVAC	Heating, ventilating and air conditioning
ICE	Internal combustion engine
ICEPAG	International Colloquium on Environmentally Preferred and Advanced Power Generation
IGCC	Integrated gasification combined cycle
IGFC	Integrated gasification fuel cell
IJHE	International Journal of Hydrogen Energy
IPCC	Intergovernmental Panel on Climate Change
ISO	Independent System Operator
JARI	Japan Automobile Research Institute
KAIST	Korean Advanced Institute of Science and Technology
LHV	Lower heating value
MCFC	Molten carbonate fuel cell
MEA	Membrane electrode assembly
MK-CC	Market cross-cutting
NASA	National Aeronautics and Space Administration
NBI	New Building Institute
NEDO	New Energy and Industrial Technology Development Organization
NETL	National Energy Technology Laboratory
NFCRC	National Fuel Cell Research Center
OEM	Original Equipment Manufacturer
PAFC	Phosphoric acid fuel cell
PBI	Polybenzimidazole
PEMFC	Proton exchange membrane fuel cell
PIER	Public Interest Energy Research
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
RD&D	Research, development and demonstration
RDC	Resource Dynamics Corporation
ROI	Return on investment
SAE	Society of Automotive Engineers
SCAQMD	Southern California Air Quality Management District
SCE	Southern California Edison
SCGC	Southern California Gas Company
SDG&E	San Diego Gas & Electric
SECA	Solid State Energy Conversion Alliance
SMR	Steam methane reformation
SOFC	Solid oxide fuel cell
TIGER	Transmission Integrated Grid Energy Resource
UCI	University of California, Irvine
USCHPA	United States Clean Heat and Power Association
USFCC	United States Fuel Cell Council
UTC	United Technologies Corporation

VAR	Volt-amperes reactive
VOC	Volatile organic compounds
W2W	Well-to-wheel

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Appendix A: Fuel Cell Workshop

Fuel Cell Research, Development and Demonstration Roadmap and Action Plan

Workshop Schedule

NFCRC Multi-Functional Room
August 27, 2008

8:30am	Introductions/Agenda Review (Scott Samuelsen)
8:45am	Project Goal and Objectives (Scott Samuelsen)
9:00am	Project Approach (Jack Brouwer)
10:15am	Break
10:30am	Project Findings (Josh Eichman)
12:00pm	Working Lunch (provided)
1:00pm	Breakout Sessions Critique initial findings and project concept generation in each session:
3:00pm	Break
3:15pm	Summary of Breakout Sessions
4:00pm	Open Discussion and Summary Comments
5:00pm	Adjourn

Morning Session Notes

MF Room

ATTENDEES

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FEEDBACK

Outline of Fuel Cell Barriers

Erik Simpkins – Does this list of barriers/issues cut across all FC categories?

Jack Brouwer– Yes, it does

Chuck Sishtla – Where did you include fuel processing topics?

Jack Brouwer – Many of the fuel processing topics are included in the system integration technology category

Erik Simpkins – Was manufacturing and distribution included or intentionally left out?

Jack Brouwer – Manufacturing and distribution topics are embedded in the categories selected.

Erik Simpkins – I would see manufacturing technology as a critical issue (we are 10 years behind where we should be). I would like to see it as one of our review categories from slide 13

Mark Williams – Is there a difference between projects and programs?

Jack Brouwer – For this work we are only dealing with projects.

Grover Coors – Are you only looking at fuel cells and not competing technologies?

Jack Brouwer – Yes, this analysis only explores fuel cells and fuel cell related technologies.

Grover Coors – Do you compare fuel cell barriers to competitive technology issues?

Jack Brouwer – Yes

Mark Williams – Alkaline fuel cells were not included (be it correct or not).

Art Soinski – From the outline of barriers anode and cathode electrodes (I. Materials, 8b and c) are not as parallel as I would expect

Chuck Sishtla – Have you included cleanup technology issues for impurities?

Jack Brouwer – (Led the group through the outline of barriers/issues to find impurity related topics)

Art Soinski – Found IGFC, coal cleanup issues on page 12 of the outline of fuel cell barriers/issues, topic number 4.

Mark Williams – Direct carbon and direct methane fuel cells are not specifically considered.

Art Soinski – How did you condense the list of issues/barriers?

Art Soinski – I see this list as a tool for looking at issues not already being addressed.

UCI Response – Apart from combining issues that were determined to be similar from the reviewed literature, no further reduction of the outline of issues/barriers has been done. This ensures that no information is lost before it can be reviewed for its uniqueness and completeness.

Art Soinski – What is the next step for using this outline to explore the technology direction? (Recognized that so many issues are difficult to sort through) (I am unsure of who will fund but thought that further research and/or dissemination of the outline of barriers/issues would be very unique and useful)

Grover – Are the sources available?

Jack Brouwer – Yes, all of the roadmaps are available online, and expert communications are documented but are not available in any particular resource.

Targets and Stretch Goals

Mark Williams – Costs were referenced for a particular year (e.g., ~400 (2002) $/kW by 2012)

Mark Williams – Must be careful to include source constraints (e.g., eff. based on HHV, LHV)

Art Soinski – What is the difference between a target and stretch goals? – I would not call the first group targets.

Art Soinski – I would like you to explain what is meant by a target when we say is achievable or can be achieved currently (without significant breakthroughs)

UCI Response – We use the term "targets" to represent technology benchmarks that have been or can be achieved with no further technological developments. The term "stretch goals" is used to represent future technology milestones established to stimulate fuel cell technology development and market penetration.

Mark Williams – Targets must be very qualified (e.g., 50 footnotes are used to reference particular targets in U.S. DOE reports)

Art Soinski – Looks at examples where lifetime is 60,000 hours for ICE DG and stretch goals are 60,000 for DG – Why are they not different?

Mark Williams – For small SOFCs, U.S. DOE (EERE) has come out with list of targets (He will call Nancy to check on the availability of those documents)

Erik Simpkins – (Pointed out that two FC companies are present (representation is "thin"))

Jack Brouwer – (Reviewed list of other industry stakeholders from which we have received feedback (mainly survey related)) (e.g., Plug Power, UTC, Siemens, Hydrogenics)

Stakeholder Survey

Grover Coors – How many people submitted the online survey?

Jack Brouwer – Described later during the presentation of findings

Robert Wichert – ("It was publicized to the 27 people that you wanted to take it")

Jack Brouwer – We will send out another bigger request for survey feedback soon

Findings

Robert Wichert – Did we agonize over the analysis techniques of your data? – Especially the normalization technique?

UCI Response – Yes! We tried several techniques and found the normalization technique used to be the most effective at establishing priority among the selected projects. The selected normalization technique is effective at ensuring that each respondent's scores are distributed over the entire scale.

Robert Wichert – What if the respondents didn't like the projects at all?

Jack Brouwer – Currently, this is captured in the comments section.

UCI Response – Additionally, if the respondents completed the evaluation of projects that they did not think were important their score reflected their disinterest in that project.

Art Soinski – I am concerned with the small number of respondents – Is the list of respondents really representative of the community? – Do the people really represent or even understand what they are scoring? – Do you want to submit eventually to a much broader audience?

Jack Brouwer – We are sure our audience is competent, but it is too small to be representative of the entire community – BUT, this is just used for screening and honing of the survey – the rest of the survey will be sent to a broader audience (e.g., FC seminar participants, USFCC members)

Eric Simpkins – What survey should future respondents take?

Jack Brouwer – The refined, smaller survey – less labor intensive, more focused – might miss projects, but, hope that responding community will identify those that we might have missed.

Jonathan Foster – What does "T" indicate in the table?

Josh Eichman – The "T" is used for projects that are tied – two or more projects that have the same score

Robert Wichert – Did everyone that reviewed a single category review other categories?

Josh Eichman – No, we asked the initial survey participants to complete as many surveys as they could but only required a subset of the seven surveys to be

completed. While I feel confident that the initial survey results are comparable within each category, it is difficult to compare projects between different categories.

Adewale Oshinuga – Where can we see all of the project scores?

Josh Eichman – They are all shown in the survey results charts (slides 44 and 69), but, only those projects that have highest rank (top seven) are described and included in the lists on the slides following the results charts.

Grover Coors – Why are there 21 projects in the list for DG/CCHP when only 15 were reviewed?

Josh Eichman – The additional projects resulted from suggestions by the survey respondents and additional literature review information.

Eric Simpkins – What is the interpretation of current fuels and alternative fuels?

UCI Response – Current fuels include the dominant fuels that are currently used (e.g., natural gas, oil, coal) while alternative fuels include less commonly used fuels and renewable fuels (e.g., synthesis gas, landfill gas, digester gas, hydrogen)

Richard Kriete – Not only the transition in the marketplace from current fuels to alternative fuels, but also the "real-time" transition of systems from operation on current to alternative fuels (and back) is an important technology development issue (PROJECT CONCEPT)

Richard Kriete – For FC-GT hybrid projects are you considering fired or non-fired gas turbines?

Josh Eichman – Either/both are included based on the project description.

Grover Coors – If you weight the overall ranking by the number of responses, this could help with overall ranking!

Robert Wichert – Are the online survey scores weighted AND normalized?

Josh Eichman – No, they are only weighted because the simplified scoring criteria and larger number of respondents meant that there was no need to normalize.

Art Soinski – We cannot now sell electricity to the grid (under Rule 21) (In response to seeing the regenerative fuel cell system project ranked highest in the episodic power category)

Jack Brouwer – Yes, but, you can co-meter

Joe Heinzman – You can sell power back to the utility through a utility procurement – especially helpful if the technology producing the power is renewable – there is now a standard tariff for selling waste-water digester gas power back into the grid

Art Soinski – I am surprised with the high ranking of FC-GT projects. They do have high efficiency, but, they are probably not a near term solution for CA ratepayers.

Scott Samuelsen – NFCRC demo in 2003; FCE has a hybrid, commercial launch soon, demonstrated in Montana; Rolls Royce coming out with a unit; U.S. DOE encouraging hybrids

Mark Williams – U.S. DoD and DARPA need hybrid systems to meet their demands, especially on the battlefield.

Art Soinski – What does "grid support" mean?

UCI Response – The "grid support" category encompasses fuel cell technology that is used to improve or enhance the performance of the electrical distribution network (e.g., ancillary electrical services, reactive power management and generation, phase angle correction, power generation)

Art Soinski – Grid support to me means dealing with the ISO at large power levels.

UCI Response – The intention of the "grid support" is for identifying projects in areas like micro-grid and distribution level ancillary services as opposed to large-scale power generation.

Scott Samuelsen – Yes, the topics for grid supporting fuel cells are at the smaller distributed scale rather than central power scale.

James Corlett – What does TIGER mean?

Josh Eichman – TIGER stations seek to reduce the need for additional utility infrastructure by strategically locating generation equipment on the electrical distribution network.

Scott Samuelsen – TIGER stations are a grid/utility resource to defer need for additional transmission wires.

Grover Coors – What does renewable fuel use in materials handling mean? What renewable fuel?

Josh Eichman – Fuels like hydrogen, methanol or synthesis gas that can be generated renewably from various primary energy sources.

Art Soinski – Why do we need incentives or a mandate (not in favor of command and control approaches) for portable power applications? Portable photovoltaic power market has developed without any incentives. Is there a California ratepayer or citizen benefit?

Joe Heinzman – It could be that there is a significant incentive already in the marketplace (e.g., due to high cost of battery (AA as example up to $50/kWh), emissions) – What about use of portable fuel cells instead of diesel generators at construction sites?

Jack Brouwer – It could be that the study recommended is what would investigate all of these possibilities.

Robert Wichert – Charger efficiencies are also of concern. Replacing chargers with fuel cells has the potential to reduce emissions.

Tim Brown – What is meant by "vehicle-to-grid" impacts?

Josh Eichman – The "vehicle-to-grid" concept typically entails two-way flow of power – from vehicles to the electrical distribution network and vice versa, both of which are considered.

Art Soinski – Agrees that funding categories should be increased with > $1M being the smallest category. I could not fund millions of dollars worth of projects in $100,000 increments.

Art Soinski – What does exploring the necessary return on investment (ROI) for DG/CCHP projects mean in the survey comments?

Joe Heinzman – It could be that there is a need for showing a certain ROI before it would be considered for a demonstration project.

Art Soinski – I certainly agree with the need for more FC fundamental research projects comment!

UCI Response – The additional technology review categories that are represented in the full fuel cell technology project list (last section of workshop handout) contain projects that encompass fundamental fuel cell issues.

Robert Wichert – Consider standardizing the use of the terms "demonstrate" (1-yr., more R&D, DG/CCHP) vs. "deploy" (suggests full life and more)

Mike Tollstrup – Demonstration implies R&D, not proven

Joe Heinzman – Deployment implies several (more than just one) that may include some scale of product that can help stimulate the market

Joe Heinzman – Two hours to complete a survey is still too much time

Mike Tollstrup – It is difficult, especially to rate those projects that were not good – consider a question up front like: "Is this project worthy of consideration?" If the answer is NO then the respondent skips to the next project.

Eric Simpkins – It is important that you know who (at least organization) has responded. Making the organization/affiliation questions a "required field" in the survey will ensure that you receive the necessary respondent information.

Mark Williams – If we get responses from all of the FC Seminar attendees it will be a real "mixed bag" – How would you weight these inputs?

Green Breakout Session

ELF 116

ATTENDEES

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FEEDBACK ON APPROACH

- How were different projects determined?
    - Were these a response to the obstacles standing between current status and future stretch goals (or "vision")? Yes, they came from perceived obstacles.
    - However, the projects used in this study do not necessarily enable the final vision
    - What are the show-stopping barriers? What projects best address these obstacles? What barriers are not being addressed by other research?
    - We need a roadmap that distinguishes the individual barriers along the way and we need to address each of these. This roadmap can be put together after survey responses are collected
- Is there enough time to complete the surveys and gather responses?
- We need a roadmap that distinguishes a path to reach our milestones.
- Within each technology, what is missing to reach commercialization?

- For fuel cells, we need to advance technology to the point where subsidies may push commercialization
- For literature survey DOE peer reviews should be included.
- Make survey results a percentage instead of adjusted raw scores.
    - Adding new categories will mess things up in the future
- What will be publicly funded?

FEEDBACK ON FINDINGS

- Should APU's/locomotives be categorized with material handling?
- Bio-diesel and GTL-FT were omitted in list of fuels
    - Other sources of bio-fuel (algae)
- Several examples of projects that "aren't projects", e.g., Establish high volume demand for GT hybrid systems – not really a project – everyone is already trying to do this; what's the end result, how is this different than what's been done before
    - Could re-word it to be like CT 100
        - This is successful due to CT manufacturers (though CT manufacturers are not required), might have helped to sell project politically.
        - Would this be applicable to CA?
- SECA program – R&D well funded now
    - Smaller spin-off applications not covered by DOE
        - E.g., APUs, smaller sized generator systems, unmanned underwater application
        - Smaller bio-gas applications
        - Residential applications
        - DG applications (e.g., Nippon Oil)
        - These things can add volume and help overall SECA effort
- FC turbine hybrid efficiency is attractive if you don't have heat requirement, plus you can more easily track load

- Better fuel cell load following, issue is not technical. It is an issue of stack life.

FEEDBACK ON ADDITIONAL PROJECT CONCEPTS

- Need to purposely design GT for FC hybrids.
- Include distinction between fired and non-fired GT hybrid systems.
    - How to operate hybrid system, may want to fire turbine at particular times of day
- Municipal applications: waste heat cannot be used many times at the same location where bio-fuels are located. Without added CHP, cost does not work out.
- Carbon emissions are also priority for some municipalities. This reduces the cost issue
- Need to demonstrate that FCs are reliable, that they've been done before – need to convince "risk-adverse" utilities that they work
- What availability data is available to demonstrate the success of fuel cells?
- What other problems do municipalities see?
    - Can we use ag-waste or vineyard waste? (year round availability issue)
    - Dairies
    - Landfill gas
    - Water treatment
- Want to start hydrogen fueling of vehicles via bio-fuel/waste.
    - No vehicles readily available, yet
    - Retrofit cars for H_2 ICE?
- Counties passing bills to allow homeowners to invest in solar etc. and pay for them via property tax. Assets stay with property. Don't need to worry about long term investment (AB 811)
- District and/or neighborhood CHP applications
    - Being done in Hawaii, Seattle
    - Environmental justice may be a concern for re-powering existing applications

- Integrated residential electricity, heat, and transportation
    - Too much waste in current system
    - Power park, district heating, combine systems can eliminate waste
        - need to change the way we design infrastructure
- Need more renewables.
    - Intermittency issues, can be aided by PHEV
    - Can FCs be used to enable more renewable
        - Generate H2, grid support so transmission can be used for far-located renewables
- PEM & Pt – must find catalyst alternative
- Fuel cells for back-up generation and peak shaving
- MCFC load following capability/materials development/sufficient stack life
- MCFC stack life improvements
    - FCE has taken their MCFC lifetime from 25,000 to 40,000 hrs
- Stack degradation across all FC types
    - Stationary PEMs need 40,000, vehicles need 5,000 (in vehicle)
    - More pressing issue for peak shaving applications

Red Breakout Session

MF Room

ATTENDEES

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FEEDBACK ON APPROACH

- Concern for project review equality (i.e., stationary FC groups not reviewing transportation)
    - Transportation projects have long time to benefit/commercialization
    - Portable tech. survey candidates
- Meaning of portable?
- Increase participation and knowledge of participant affiliation
- Size and scope of survey
    - Adjust size to increase response
    - Sufficient distribution of industry/market/governmental cross-section
- Bias resulting from criteria selection

- Criteria modification: how essential is state funding, is there a need for match funding
    - Clarify or remove funding categories
- Focus Group: 12-15 people in a room take survey
    - Used to refine survey

FEEDBACK ON FINDINGS

- Caution including all projects submitted (use discretion)
    - Ex. DOE doesn't think on-board reforming for transportation is important
- Suggest "portable generator, and micro" category
- Avoid normalization (if possible) and encourage use of entire range
- Suggested not combining initial and online
- Deploy versus demonstrate (use judgment)
    - Deploy in use of lifetime or product, replacement at discretion of user
    - Deployment for market (e.g., backup power)
    - Demonstrate shorter term (alpha, beta projects)
- Missouri University of Science and technology (Stationary finding)

FEEDBACK ON ADDITIONAL PROJECT CONCEPTS

- High value placed on materials handling from fuel provider
- Fill in place storage devices (stationary)
    - Fuel distribution scenarios
- High pressure tubes (transportation)
- Use of DG may require different fuel distribution (on-site versus fueling station)
- Comparison between centralized and distributed hydrogen generation
- Paradigm/product shifts (ex. bottled gases to reforming)
- Inclusion of renewable power in Stationary market application

    - Provide benefit to market through renewable power
- Comparison of trade-offs in related technologies

Summary of Breakout Session Notes

MF room

FEEDBACK ON APPROACH

- With regard to ensuring all suggestions (e.g., projects, issues, criteria) are considered, who applies the discretion?
- Have the reviewer pick the top 7-15 projects that he or she thinks are the most important and have them review those
    - Include additional question – "No because it's a bad project" or "No I don't want to answer"
- Lower time to payoff evaluation criteria weight (Art Soinski)
    - To business time to payoff is very important
    - To ratepayers time to payoff may not be so important
- How will you/anyone anticipate match funding?
- Clarify status criteria (online survey)
    - Separate into two categories or reword
    - One addresses duplicity
    - Other looks for leverage
        - Leverage leads to deployment
        - Leverage is difficult to use as evaluation criteria

FEEDBACK ON FINDINGS

- DMFC crossover identified as a critical DMFC issue
- Nickel creep identified as a critical materials issue
- Co-processing of agriculture and dairy waste makes for year round availability but entities that sell the waste must have the appropriate certification

FEEDBACK ON ADDITIONAL PROJECT CONCEPTS

- Landfill and digester gas projects suggested
- DC Data center related projects

Appendix B: Benchmarks and Milestones

I. Benchmarks

1. Stationary Central Power

2. Stationary Distributed Heating, Cooling and Power

Availability

a. 95% for PAFC systems [2d; μ]

Capacity factor

a. 50% for typical DG applications (ICE engine based) [1a2; μ]

Cost

a. $700/kW installed for typical DG technology (ICE engine based) [1a2; μ]

b. $0.015-0.03/kWh for operation and maintenance of DG applications [1a2; μ]

   i. Includes periodic overhauls

   ii. Does not include fuel costs

c. $3,000-10,000/kW for 80-1,000kW PEMFC systems [1a2; μ]

d. >$1,000/kW for SOFC systems [2a; μ]

e. >$3,500/kW for PAFC systems [2d; μ]

Degradation

a. ~3.5mV reduction per 1,000 hours of operation for typical tubular SOFC [2a; ν]

b. 1-1.5mV reduction per 1,000 hours of operation for state-of-the-art tubular SOFC [2a; ν]

c. 25mV reduction per 1,000 hours of operation for planar SOFC (not much data available) [2a; ν]

d. ~20mV reduction per 1,000 hours of operation for current typical MCFC [2b; ν]

e. ~5mV reduction per 1,000 hours of operation for state-of-the-art MCFC [2b; ν]

f. 2mV reduction per 1,000 hours of operation for MCFC [2b; ν]

g. 20-25mV reduction per 1,000 hours of operation for state-of-the-art AFC (2007) [2f; ν]

h. 2-3mV reduction per 1,000 hours of operation for PAFC [2d; ν]

Efficiency

a. 35-50% for DG typical applications (ICE engine based) [1a2; μ]
b. <30% for PEMFC on reformate fuel [1a2; μ]
c. ~55% for PEMFC on hydrogen fuel [1a2; μ]
d. ~35%, 3-10kW SOFC [2a; μ]
e. ~50%, >100kW SOFC [2a; μ]
f. 35-38% for PAFC systems [2d; μ]

Emissions

a. ~Zero emissions for PEMFC [1a2; μ]

Life

a. 60,000 hours for typical DG applications (ICE engine based) [1a2; μ]
    i. 13-14 years given on/off operation
b. 5,000-10,000 hours (single cell and mini-stacks) [1a2; μ]
c. 50,000 – 100,000 hour lifetimes possible for tubular SOFC [2a; ν]
d. 4,000 – 8,000 hour lifetime for planar SOFC [2a; ν]
e. ~80,000 hours on single tubular SOFC cell [2a; μ]
f. ~20,000 hours on tubular SOFC stack [2a; μ]
g. ~3,000 hours on planar mini SOFC stacks [2a; μ]
h. 15,000 – 25,000 hour lifetime for typical MCFC [2b; ν]
i. 4,000 – 8,000 hour lifetime for PEMFC [2c; ν]
j. 40,000 – 50,000 hour lifetime for PAFC [2d; ν]
k. 40,000 hours with minimal degradation for PAFC systems [2d; μ]
l. 4,000 – 8,000 hour lifetime for typical AFC [2f; ν]

3. Transportation

Cost

a. $5/gge for hydrogen at filling station (2003) [4a; ς]

Degradation

a. ~20mV reduction per 1,000 hours of operation for state-of-the-art PEMFC [2c; ν]

Other

a. Hydrogen fuel quality (μmol/mol = ppm) [4a; ς]

   i. 5 ppm water

   ii. 2 ppm total hydrocarbons

   iii. 5 ppm oxygen

   iv. 100 ppm helium, nitrogen or argon

   v. 1 ppm carbon dioxide

   vi. 0.2 ppm carbon monoxide

   vii. 0.004 ppm sulfur

      1. Hydrogen sulfide (H_2S)

      2. Carbonyl sulfide (COS)

      3. Carbon disulfide (CS_2)

      4. Mercaptans

   viii. 0.01 ppm formaldehyde

   ix. 0.2 ppm formic acid

   x. 0.1 ppm ammonia

   xi. 0.05 ppm total halogenates

   xii. <10 μm particulate size

   xiii. 1 μg/L H_2 particulate concentration

4. Materials Handling Equipment

5. Portable Power

II. Milestones

1. Stationary Central Power

Cost

a. < $400/kW [2; DOE SECA goal by 2010]

b. $400/kW for phase 3 SOFC systems (2010) [2a; ϱ]

c. $400/kW for phase 2 and 3 coal based fuel cell systems (2010 and 2015) [2a; SECA 2007]

Efficiency

a. 35-55% for phase 1, 3-10kW SOFC systems (2005) [2a; ϱ]

d. 40-60% for phase 2 and 3, 3-10kW SOFC systems (2008 and 2010) [2a; ϱ]

e. 45% for phase 1, 500kW coal based fuel cell systems (2008) [2a; ϱ]

f. 50% for phase 2, 2MW coal based fuel cell systems (2010) [2a; ϱ]

g. 50% for phase 3, 50MW coal based fuel cell systems (2015) [2a; ϱ]

2. Stationary Distributed Heating, Cooling and Power

Availability

a. 92-98% for DG applications [1a2; μ]

Cost

a. $400-600/kW for DG applications without installation [1a2; μ]

   i. Installation around 50-100% of capital cost ($600 for low to $1200/kW for high efficiency systems)

b. $0.01-0.015/kWh for operation and maintenance of DG applications [1a2; μ]

   i. Includes routine maintenance and overhauls (fuel cell stack replacement, etc.)

c. < $1,000/kW [2; Wu 2006]

d. < $1,500/kW PAFC [2; Binder 2006]

e. <~10 cents/kWhr [2; Wu 2006]

f. Cost of $2,000-$2,500/kW between 2007-2009 [2; Binder 2006]

g. $300-1,000/kW for stationary fuel cell systems [2, 1a; α]

h. ~$800/kW by 2007 for SOFC systems [2a; μ]

i. ~$400/kW by 2012 for SOFC systems [2a; μ]

j. $35-40/kW with 5,000 hour service life for PEMFC systems [2c; π]

k. $300/kW for 80kW reformate based PEMFC system [2c; μ]

l. $125/kW for 80kW hydrogen based PEMFC system [2c; μ]

m. <$300/kW for PEMFC operating on fossil fuels (100kW at automotive production volumes) [2c; μ]

n. <$150/kW for PEMFC operating on hydrogen fuel (100kW at automotive production volumes) [2c; μ]

o. $2,000-4,000/kW for small (~5kW) backup PEMFC [2c; EPRI DG 2006]

p. $750/kW$_e$ for a stationary PEMFC system operating on reformate (5-250kW) by 2011 [2c; ς]

q. $530/kWe for a stationary PEMFC stack operating on reformate (5-250kW) by 2011 [2c; ς]

r. $10/kW for the MEA by 2010 [2c; ς]

s. $5/kW for the MEA by 2015 [2c; ς]

t. $5/kW for bipolar plates by 2010 [2c; ς]

u. $3/kW for bipolar plates by 2015 [2c; ς]

Degradation

a. 500ppm steady state CO tolerance with maximum 2% air bleed for a stationary PEMFC stack operating on reformate (5-250kW) by 2011 [2c; ς]

b. 1,000ppm transient CO tolerance for a stationary PEMFC stack operating on reformate (5-250kW) by 2011 [2c; ς]

c. 10% of MEA power density over lifetime by 2010 [2c; ς]

d. 5% of MEA power density over lifetime by 2015 [2c; ς]

e. <1 μA/cm^2 of bipolar plate corrosion by 2010 and 2015 [2c; ς]

f. 1ppm CO in steady state product stream for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

g. 25ppm CO in transient product stream for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

h. <4ppm H_2S in product stream for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

i. <0.1ppm NH_3 in product stream for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

Efficiency

a. 35-50% for DG applications [1a2; μ]

b. <35% for PEMFC on reformate fuel [1a2; μ]

c. ~60% for PEMFC on hydrogen fuel [1a2; μ]

d. 35-45% for 3-10kW SOFC systems [2a; μ]

e. ~55% for >100kW SOFC systems [2a; μ]

f. ~65% for >3,000kW SOFC systems [2a; μ]

g. 40% (electrical) at rated power for a stationary PEMFC system operating on reformate (5-250kW) by 2011 [2c; ς]

h. 80% (with CHP) at rated power for a stationary PEMFC system operating on reformate (5-250kW) by 2011 [2c; ς]

Emissions

a. 0.07 lb NO_x/MWh for DG applications (non-attainment, Ca ARB 2007) [1a2; μ]

b. 0.3 lb NO_x/MWh for DG applications (attainment, RAP model phase 2, 2008) [1a2; μ]

c. ~Zero for PEMFC [1a2; μ]

d. <1.5 g/1000kWh of combined NO_x, CO, SO_x, hydrocarbons and PM for a stationary PEMFC system operating on reformate (5-250kW) by 2011 [2c; ς]

Incentives

a. Credit of one-third the cost up to $1,000/kW for business and residential property [1; ξ]

b. Additional 10% tax credit for utilizing CCHP (residential, business, commercial properties) [1; ξ]

c. $1,000/kW buy-down to the installer of fuel cells [1; ξ]

d. $18 million Buy-down program in 2004 with a peak at $35 million in 2006 [1; ξ]

Life

a. 40,000-60,000 hour lifetime for DG applications [1a2; μ]

b. 50,000 hours for stationary fuel cell systems [2, 1a; α]

c. 40,000 hours for DG SOFC systems [2a; μ]

d. 40,000 hours at <10% rated power degradation for a stationary PEMFC system operating on reformate (5-250kW) by 2011 [2c; ς]

e. 40,000 hours for a stationary PEMFC stack operating on reformate (5-250kW) by 2011 [2c; ς]

f. 80,000 hour stack life for PAFC in 2007 [2d; Binder 2006]

g. 40,000 hours for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

Noise

a. <55dBa at 10m for a stationary PEMFC system operating on reformate (5-250kW) by 2011 [2c; ς]

Other

a. <120°C operating temperature for MEAs by 2010 and 2015 [2c; ς]

b. 300 mA/cm^2 at 25% of rated power (0.8V) for MEAs by 2010 and 2015 [2c; ς]

c. 250 mA/cm^2 at 25% of rated power for MEAs by 2010 and 2015 [2c; ς]

d. 1,000 mW/cm^2 at rated power for MEAs by 2010 and 2015 [2c; ς]

e. <2E-6 cm^3 sec^{-1} cm^{-2} at 80°C and 3 atmosphere of hydrogen permeation flux for bipolar plates by 2010 and 2015 [2c; ς]

f. 0.01 ohm-cm of resistivity (includes contact resistance) for bipolar plates by 2010 and 2015 [2c; ς]

g. <25 MPa flexural strength for bipolar plates by 2010 and 2015 [2c; ς]

h. 3-5% deflection at mid span for bipolar plates by 2010 and 2015 [2c; ς]

Power

a. 2-200 kW for stationary fuel cell systems [2, 1a; α]

b. <0.4 kg/kW for bipolar plates by 2010 and 2015 [2c; ς]

Sensors

a. Sulfur compound sensor (H_2S, SO_2, organic sulfur) [3; ς]

    i. Operating temperature: -40°C to 300°C

    ii. Measurement range b: 0.001 to 0.5 ppm

iii. Response time: <1 min at 0.05 ppm

iv. Gas environment: H_2, CO, CO_2, hydrocarbons, water vapor

b. Flow rate sensor for fuel processor output [3; ς]

i. Flow rate range: depending on fuel cell size, maximum flow rate ranges from 30 - 7,500 SLPM

ii. Temperature: 0-100°C

iii. Gas environment: high-humidity reformer / partial oxidation gas: H2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure

c. Differential pressure sensor in fuel cell stack [3; ς]

i. Range: 0–1 psi or (0–10 or 1–3 psi, depending on the design of the fuel cell system)

ii. Temperature range: 30–120°C

iii. Survivability: –40°C

iv. Response time: <1 sec

v. Accuracy: 1% full scale (including drift)

vi. Lifetime: 10 years

vii. Other: Measure pressure in the presence of liquid and gas phases

d. Ammonia sensor [3; ς]

i. Operating temperature: 70–150°C

ii. Measurement range: 0.15 ppm

iii. Selectivity: <0.1 ppm from gas mixtures

iv. Lifetime: 5–10 years

v. Response time: <1 min at 0.1 ppm

vi. Gas environment: high-humidity reformer / partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure

e. Carbon monoxide sensor for reformate from stationary fuel processor to PEM stack

i. Measurement range: 100–1000 ppm

ii. Operational temperature: 250°C

iii. Response time: 0.1–1 sec

iv. Gas environment: high-humidity reformer / partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure

v. Accuracy: <2% full scale

Transient Response

a. 1/1000 of seconds for dynamic response of stationary fuel cell systems [2, 1a; α]

b. <3 second dynamic response for 10-90% of rated power for a stationary PEMFC system operating on reformate (5-250kW) by 2011 [2c; ς]

c. 1 second dynamic response for a 10-90% of rated power for a stationary PEMFC stack operating on reformate (5-250kW) by 2011 [2c; ς]

d. 1 minute dynamic response for a 10-90% of rated power for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

e. <30 minutes to start from -20°C to rated power for a stationary PEMFC system operating on reformate (5-250kW) by 2011 [2c; ς]

f. Survivable operation from -35°C to 40°C for a stationary PEMFC stack and system operating on reformate (5-250kW) by 2011 [2c; ς]

g. <0.5 seconds to start from -20°C for a stationary PEMFC stack operating on reformate (5-250kW) by 2011 [2c; ς]

h. <30 minutes to start from -20°C to rated power for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

i. Survivable operation from -35°C to 40°C for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

3. Transportation

Cost

a. $3.00 per gallon gasoline equivalent [1b; Garland1 2006]

b. $2-3 per gallon of gasoline equivalent for hydrogen [1b; π]

c. Cost 10 times that of a comparable 40 foot bus (Gen I 2003-2007) [1b2; Koyama 2006]

d. Cost less than 4 times a comparable bus (Gen II 2007-2010) [1b2; Koyama 2006]

e. Cost less than 2 times a comparable bus (Gen III 2010-2015+) [1b2; Koyama 2006]

f. \$45/kW$_e$ for an 80kW$_e$ integrated transportation fuel cell system by 2010 [1b-c; ς]

g. \$30/kW$_e$ for an 80kW$_e$ integrated transportation fuel cell system by 2015 [1b-c; ς]

h. \$25/kW$_e$ for an 80kW$_e$ transportation fuel cell stack by 2010 [1b-c; ς]

i. \$15/kW$_e$ for an 80kW$_e$ transportation fuel cell stack by 2015 [1b-c; ς]

j. \$400 for a compressor/expander with a 80kW$_e$ transportation fuel cell system by 2010 [1b; ς]

k. \$200 for a compressor/expander with a 80kW$_e$ transportation fuel cell system by 2015 [1b; ς]

l. \$20 for a fuel cell membrane for use in transportation applications by 2010 and 2015 [1b-c; ς]

m. \$5/kW for the electrocatalyst for use in transportation applications by 2010 [1b-c; ς]

n. \$3/kW for the electrocatalyst for use in transportation applications by 2010 [1b-c; ς]

o. \$50-100/kW for transportation fuel cell systems [2, 1b; α]

p. \$220/kW$_e$ for a hydrogen fuel processor (5-250kW) by 2011 [3f; ς]

q. \$2/gge for hydrogen at filling station (2015) [4a; ς]

Efficiency

a. 85% motor and motor controller (DC input) for a compressor/expander with a 80kW$_e$ transportation fuel cell system by 2010 and 2015 [1b; ς]

b. 80/80% compressor/expander at full flow for an 80kW$_e$ transportation fuel cell system by 2010 and 2015 [1b; ς]

c. 60/50% compressor/expander at 20-25% flow for an 80kW$_e$ transportation fuel cell system by 2010 and 2015 [1b; ς]

d. Exceed fuel efficiency of comparable bus by 25% (Gen I 2003-2007) [1b2; Koyama 2006]

e. 7 miles per gallon equivalent (Gen II 2007-2010) [1b2; Koyama 2006]

f. 10 miles per gallon equivalent (Gen III 2010-2015+) [1b2; Koyama 2006]

g. 60% at 25% rated power for an 80kW$_e$ integrated transportation fuel cell system by 2010 [1b-c; ς]

h. 60% at 25% rated power for an 80kW$_e$ integrated transportation fuel cell system by 2015 [1b-c; ς]

i. 50% at rated power for an 80kW$_e$ integrated transportation fuel cell system by 2010 [1b-c; ς]

j. 50% at rated power for an 80kW$_e$ integrated transportation fuel cell system by 2015 [1b-c; ς]

k. 65% at 25% rated power for an 80kW$_e$ transportation fuel cell stack by 2010 and 2015 [1b-c; ς]

l. 55% at 25% rated power for an 80kW$_e$ transportation fuel cell stack by 2010 and 2015 [1b-c; ς]

Emissions

a. Exceed 2004 EPA and CARB emissions standards (Gen I 2003-2007) [1b1; Koyama 2006]

b. Exceed EPA 2007 bus emissions standards (Gen II 2007-2010) [1b2; Koyama 2006]

c. Exceed all bus emissions (Gen III 2010-2015+) [1b2; Koyama 2006]

Incentives

a. 50% of incremental cost for passenger trucks [1b; ξ]

b. Additional 50% based on emissions, efficiency and fuel choice for passenger trucks (overall per-vehicle cap) [1b; ξ]

c. $4,000 credit new cars and light trucks [1b; ξ]

d. Additional credit up to $4,000 depending on vehicle efficiency for passenger vehicles [1b; ξ]

e. Capital grant program for heavy trucks and buses [1b; ξ]

Life

a. 2,000 hour transportation fuel cell durability [1b; Garland1 2006]

b. 2 year useful life for fuel cell bus (Gen I 2003-2007) [1b2; Koyama 2006]

c. 4-6 year useful life for fuel cell bus (Gen II 2007-2010) [1b2; Koyama 2006]

d. 6 year useful life for fuel cell bus (Gen III 2010-2015+) [1b2; Koyama 2006]

e. 5,000 hours with cycling for an 80kW$_e$ integrated transportation fuel cell system by 2010 [1b-c; ς]

f. 5,000 hours with cycling for an 80kW$_e$ integrated transportation fuel cell system by 2015 [1b-c; ς]

g. 5,000 hours with cycling for an 80kW$_e$ transportation fuel cell stack by 2010 [1b-c; ς]

h. 5,000 hours with cycling for an 80kW$_e$ transportation fuel cell stack by 2015 [1b-c; ς]

i. 5,000 hours for transportation fuel cell systems [2, 1b; α]

Noise

a. 65dBa at 1m for a compressor/expander with a 80kW$_e$ transportation fuel cell system by 2010 and 2015 [1b; ς]

Other

a. 2 mA/cm^2 crossover of oxygen crossover for a fuel cell membrane for use in transportation applications by 2010 and 2015 [1b-c; ς]

b. 2 mA/cm^2 crossover of hydrogen crossover for a fuel cell membrane for use in transportation applications by 2010 and 2015 [1b-c; ς]

c. 0.1 S/cm conductivity for membrane at operating temperature for use in transportation applications by 2010 and 2015 [1b-c; ς]

d. 0.07 S/cm conductivity for membrane at 20°C for use in transportation applications by 2010 and 2015 [1b-c; ς]

e. 0.01 S/cm conductivity for membrane at -20°C for use in transportation applications by 2010 and 2015 [1b-c; ς]

f. >100 S/cm conductivity for bipolar plates by 2010 and 2015 [2c; ς]

g. 0.02 ohm-cm^2 area specific resistance for use in transportation applications by 2010 and 2015 [1b-c; ς]

h. 0.3 g/kW electrocatalyst at rated power for the total platinum group metal content for use in transportation applications by 2010 [1b-c; ς]

i. 0.2 g/kW electrocatalyst at rated power for the total platinum group metal content for use in transportation applications by 2015 [1b-c; ς]

j. 0.3 mg PGM/cm^2 electrocatalyst of the electrode area for the platinum loading for use in transportation applications by 2010 [1b-c; ς]

k. 0.2 mg PGM/cm^2 electrocatalyst of the electrode area for the platinum loading for use in transportation applications by 2015 [1b-c; ς]

l. <40% electrocatalyst electrochemical area lost for transportation applications by 2010 and 2015 [1b-c; ς]

m. <30% electrocatalyst support loss for transportation applications by 2010 and 2015 [1b-c; ς]

n. 0.44 A/mg Pt electrocatalyst at 900 mV for the mass activity for transportation applications by 2010 and 2015 [1b-c; ς]

o. 720 $\mu A/cm^2$ at 900 mV for the specific activity for membranes used in transportation applications by 2010 and 2015 [1b-c; ς]

p. >130 A/cm^3 at 900 mV of non-Pt catalyst activity per volume of supported catalyst used in transportation applications by 2010 [1b-c; ς]

q. 300 A/cm^3 at 900 mV of non-Pt catalyst activity per volume of supported catalyst used in transportation applications by 2015 [1b-c; ς]

Power

a. 650 W/L power density for an 80kW_e integrated transportation fuel cell system by 2010 [1b-c; ς]

b. 650 W/L power density for an 80kW_e integrated transportation fuel cell system by 2015 [1b-c; ς]

c. 2,000 W/L net power density for an 80kW_e transportation fuel cell stack by 2010 [1b-c; ς]

d. 2,000 W/L net power density for an 80kW_e transportation fuel cell stack by 2015 [1b-c; ς]

e. 5.4kW_e input power required with an expander at full load, 40°C for a compressor for an 80kW_e transportation fuel cell system by 2010 and 2015 [1b; ς]

f. 12.8kW_e input power required without an expander at full load, 40°C for a compressor for an 80kW_e transportation fuel cell system by 2010 and 2015 [1b; ς]

g. 4.4kW_e input power required with an expander at full load, 20°C for a compressor for an 80kW_e transportation fuel cell system by 2010 and 2015 [1b; ς]

h. 11.6kW_e input power required without an expander at full load, 20°C for a compressor for an 80kW_e transportation fuel cell system by 2010 and 2015 [1b; ς]

i. 250 mile vehicle range [1b; Garland1 2006]

j. ≥300 mile range (most light duty vehicles) [1b; π]

k. 50-100 kW for transportation fuel cell systems [2, 1b;α]

l. 650 W/kg specific power for an 80kW$_e$ integrated transportation fuel cell system by 2010 [1b-c; ς]

m. 650 W/kg specific power for an 80kW$_e$ integrated transportation fuel cell system by 2015 [1b-c; ς]

n. 2,000 W/kg net specific power for 80kW$_e$ transportation fuel cell stack by 2010 [1b-c; ς]

o. 2,000 W/kg net specific power for 80kW$_e$ transportation fuel cell stack by 2015 [1b-c; ς]

Sales Volume

a. 500,000 units/year of PEM fuel cells [1a2; μ]

b. 5,000 passenger vehicles annually or 50% of fleet [1b; ξ]

c. 1,000 transit buses or 50% of federally subsidized purchases annually [1b; ξ]

d. 50% federal subsidy on fleet vehicle purchases annually [1b; ξ]

e. Mobile equipment and specialty vehicles, sales volume target set by Cabinet secretaries [1c; ξ]

f. Additional fueling stations to meet fleet vehicle program requirements [4, 1b-c; ξ]

Sensors

a. Carbon monoxide sensor for stored 99.99% pure H_2 at transportation fueling station

    i. Measurement range: 0.1 – 0.5 ppm

    ii. Operational temperature: <150°C

    iii. Response time: 0.1–1 sec

    iv. Gas environment: dry hydrogen at 1-700 atm total pressure

    v. Accuracy: <2% full scale

b. Hydrogen sensor in fuel processor output [3; ς]

    i. Measurement range: 25%–100%

    ii. Operating temperature: 70°–150°C

    iii. Response time: 0.1–1 sec for 90% response to step change

iv. Gas environment: 1–3 atm total pressure, 10–30 mol% water, 30%–75% total H_2, CO_2, N_2

v. Accuracy: <2% full scale

c. Hydrogen sensor in ambient air [3; ς]

i. Measurement range: full confidence of the ability to detect half of the lower explosion limit

ii. Temperature range: -30°C to 80°C

iii. Response time: under 1 sec

iv. Gas environment: ambient air, 10–98% relative humidity range

v. Lifetime: 10 years

vi. Interference resistant

d. Temperature sensor [3; ς]

i. Operating range: -40°C to 150°C

ii. Response time: in the -40°C to 100°C range <0.5 sec with 1.5% full.-scale accuracy (including drift); in the 100–150°C range, a response time <1 sec

iii. Lifetime: 10 years

iv. Gas environment: high-humidity air or H_2 at 1-3 atm (see Appendix C for concentration)

v. Insensitive to flow velocity

e. Relative humidity for cathode and anode gas streams [3; ς]

i. Operating temperature: 0-120°C

ii. Response time: <0.5 sec

iii. Relative humidity: 20–100%

iv. Accuracy: 1% full scale (including drift)

v. Lifetime: 10 years

vi. Gas environment: high-humidity air, reformate or H_2 at 1-3 atm (see Appendix C for concentration)

f. Oxygen sensor at cathode exit [3; ς]

i. Measurement range: 0–50% O_2

ii. Operating temperature: 30–120°C

iii. Response time: <0.5 sec

iv. Accuracy: 1% full scale (including drift)

v. Lifetime: 10 years

vi. Gas environment: CO_2, N_2, H_2O at 1–3 atm

g. Flow rate sensor for direct H_2 system [3; ς]

i. Flow rate maximum: 2,500 SLPM for wet H_2

ii. Flow rate maximum: 1,000 SLPM for dry H_2

iii. Gas environment: H_2 dry (see Appendix C for concentration), 25-100% relative humidity plus N_2

iv. Lifetime: 10 years

v. Accuracy: ±5% full scale (including drift)

Size and weight

a. 15 liter volume for a compressor/expander with a 80kW$_e$ transportation fuel cell system by 2010 and 2015 [1b; ς]

b. 15 kg weight for a compressor/expander with a 80kW$_e$ transportation fuel cell system by 2010 and 2015 [1b; ς]

Transient Response

a. 1 second dynamic response for a 10-90% of maximum airflow for a compressor/expander with a 80kW$_e$ transportation fuel cell system by 2010 and 2015 [1b; ς]

b. Turndown ratio of 10:1 for a compressor/expander with a 80kW$_e$ transportation fuel cell system by 2010 and 2015 [1b; ς]

c. 1 second dynamic response for 10-90% of rated power for an 80kW$_e$ integrated transportation fuel cell system by 2010 and 2015 [1b-c; ς]

d. 1 second dynamic response for 10-90% of rated power for an 80kW$_e$ transportation fuel cell stack by 2010 and 2015 [1b-c; ς]

e. 1/10 of seconds for dynamic response of transportation fuel cell systems [2, 1b; α]

f. 5 MJ of energy for startup and shutdown from -20°C for an 80kW$_e$ integrated transportation fuel cell system by 2010 and 2015 [1b-c; ς]

g. 1 MJ of energy for startup and shutdown from +20°C for an 80kW$_e$ integrated transportation fuel cell system by 2010 and 2015 [1b-c; ς]

h. 5 MJ of energy for startup and shutdown from -20°C for an 80kW$_e$ transportation fuel cell stack by 2010 and 2015 [1b-c; ς]

i. 1 MJ of energy for startup and shutdown from +20°C for an 80kW$_e$ transportation fuel cell stack by 2010 and 2015 [1b-c; ς]

j. -40°C startup for an 80kW$_e$ integrated transportation fuel cell system by 2010 and 2015 [1b-c; ς]

k. -40°C startup for an 80kW$_e$ transportation fuel cell stack by 2010 and 2015 [1b-c; ς]

l. 30 seconds to start from -20°C to 50% of rated power for an 80kW$_e$ transportation fuel cell stack by 2010 and 2015 [1b-c; ς]

m. 5 seconds to start from +20°C to 50% of rated power for an 80kW$_e$ transportation fuel cell stack by 2010 and 2015 [1b-c; ς]

4. Materials Handling Equipment

Cost

a. $400/kW$_e$ for APUs and truck refrigeration units by 2010 and 2015 (based on 100,000 units/year) [1c; ς]

Efficiency

a. 35% at rated power for APUs and truck refrigeration units by 2010 [1c; ς]

b. 40% at rated power for APUs and truck refrigeration units by 2015 [1c; ς]

Incentives

a. 50% credit for the cost of a hydrogen fueling station up to $150,000 [4; ξ]

b. 50% of fuel infrastructure may be expensed in the year installed [4; ξ]

c. Fuel tax credit from 2003 to 2012 [4; ξ]

Life

a. 150 cold-start cycles over lifetime for APUs and truck refrigeration units by 2010 [1c; ς]

b. 250 cold-start cycles over lifetime for APUs and truck refrigeration units by 2015 [1c; ς]

c. 20,000 hours for APUs and truck refrigeration units by 2010 [1c; ς]

d. 35,000 hours for APUs and truck refrigeration units by 2015 [1c; ς]

e. 5,000 hours for APU SOFC systems [2a; μ]

Power

a. 100 W/L power density for APUs and truck refrigeration units by 2010 and 2015 [1c; ς]

b. 100 W/kg specific power for APUs and truck refrigeration units by 2010 and 2015 [1c; ς]

Transient Response

a. 15-30 minutes to startup for APUs and truck refrigeration units by 2010 and 2015 [1c; ς]

5. Portable Power

Cost

a. $3/W for consumer electronics (≤50W) by 2010 [1e; ς]

Energy Density

a. 1,000 Wh/L for consumer electronics (≤50W) by 2010 [1e; ς]

Incentives

a. Credit of one-third the cost up $1,000/kW for portable power systems from 2003 to 2007 [1e; ξ]

b. 50% of portable power infrastructure cost expensed in year installed for businesses [1e; ξ]

Life

a. 5,000 hours for consumer electronics (≤50W) by 2010 [1e; ς]

Power

a. 100 W/L power density for consumer electronics (≤50W) by 2010 [1e; ς]

b. 100 W/kg specific power for consumer electronics (≤50W) by 2010 [1e; ς]

Appendix C: List of Technology Issues

Below is the complete list of development issues identified from fuel cell literature, workshops and additional stakeholder feedback. All of the issues use the referencing schema developed earlier in this document. Topics are separated into seven groups:

I. Materials Science

II. Cell and stack developments

III. Lifetime and operation challenges

IV. Systems integration and technology

V. Integration into the application environment

VI. Cross-cutting technology development and analyses

VII. Technically related market, policy and education barriers

The seven groups are separated into subsets by five technology categories

1. Market applications

2. Fuel cell technology specific developments

3. Technology integration development

4. Fuels

5. Other

I. Materials Science

1. Market Applications

2. Fuel Cell Technology Specific Developments

1. Understanding of material impurity effects on electrolyte fabrication and performance [2; γ]
2. Ion transport dependence on temperature, humidity, acidity, etc. [2; π]
3. Availability of hydrogen conversion equipment, material durability and reliability tests [2; α]
4. DMFC membrane concerns [2e; Θ]
    a. Reduce water and methanol diffusion
    b. Develop composite membranes

5. Selection of sealing material [2; Γ, Θ]
    a. Decrease seal leak rate
    b. Seals must tolerate entire operating temperature and humidity range
    c. Explore seal degradation mechanisms
6. Manufacturing parameter effects on catalyst layer [2c; ϕ]
    a. Accelerated surface treatment methods
7. Fuel cell thin film manufacturing [2; θ]
    a. Cost
    b. Delamination
    c. Layer integrity
    d. Technique development
8. Electrodes [2; θ, Γ, Stevenson 2005, Σ]
    a. Corrosion of electrode supports [2; Γ]
    b. Material selection
        i. Nano-materials
        ii. Study of effects of different alloy compositions [2; Σ]
    c. Material cost
    d. Anode
        i. Catalyst surface modification
        ii. Characterize thermodynamics/kinetics
        iii. Multi-component catalysts
    e. Cathode [2; Stevenson 2005]
        i. Electrocatalysts
        ii. Interface modification
        iii. Microstructure optimization
        iv. Mixed conduction
9. SOFC electrocatalyst [2a; Γ, μ, θ, JM Bae ICEPAG 2008]
    a. Nickel coarsening/agglomeration and creep
    b. Alternative catalyst materials

        i. Ceria catalyst better than alumina based catalyst (reduce coking) [2a; JM Bae ICEPAG 2008]

    c. Improve oxygen reduction reaction (ORR) kinetics

    d. Electrocatalyst tolerance to air, fuel and system-derived impurities [2a; Γ, μ]

        i. Reaction with other cell components/reactants [2a; θ]

        ii. Sulfur tolerant anodes [2a; μ]

10. Tubular solid oxide fuel cell material concerns [2a; γ, μ, ω, Θ, θ]

    a. Low power density [2a; μ, ω]

    b. Lower cost materials

        i. Expensive raw materials satisfying high purity requirements might not be necessary

    c. Lower cost electrolyte

        i. Current technique (electro-chemical-vapor deposition) requires high vacuum environment

            1. Avoid vacuum processing (ferritic; rare earth treatment) [2a; Wayne Surdoval ICEPAG 2008]

        ii. Explore batch processing

    d. Techniques for reducing ohmic polarization [2a; θ, μ]

        i. Electron path length

        ii. Ion path length

    e. Sulfur tolerant materials [2a; γ, Θ]

        i. Nickel sensitive to sulfur compounds

        ii. Explore alternative anode materials (e.g., Monel alloys)

    f. Degradation from repeated oxidation and reduction cycles [2a; AVD MS thesis]

    g. Delamination due to thermal stress [2a; AVD MS thesis]

11. Planar/monolithic solid oxide fuel cell material concerns [2a; γ, χ, Θ, θ, μ]

    a. Lower operating temperature materials [2a; χ, Θ, θ]

    b. High contact resistance between interconnects and electrodes [2a; μ]

        i. Varies due to thermal cycling (complicates cycle resistant seals) [2a; μ]

c. Hydrogen diffusion resistance (anode supported at high utilizations) [2a; μ]

d. Interconnect materials

i. Interconnect materials do not densify fully when fired

ii. Explore new materials, dopants and fillers

e. Short life of peripheral seals [2a; Simon 2006, μ, Θ]

i. Need for perfectly flat plates

1. Because of amount of pressure required to achieve seal

ii. Use of brittle seals

1. Ceramics

2. Glass

f. Degradation from repeated oxidation and reduction cycles [2a; AVD MS thesis]

g. Delamination due to thermal stress [2a; AVD MS thesis]

12. High-temperature fuel cell material assembly [2a; Simon 2006]

a. Non-uniform coatings

b. Firing problems

c. Coefficient of expansion mismatch for three layers

i. Warping

ii. Cracking

13. Low-temperature oxide-ion conductors for broadening material choices [2a, 2b; α, γ]

a. Less expensive interconnects [2a, 2b; γ]

b. Low-temperature operation allows for the use of more metals [2a, 2b; γ]

14. High-temperature ceramic fuel cell interconnects [2a, 2b; Stevenson 2005]

a. Conductivity improvement

b. Compatibility with other cell materials

c. Manufacturability improvement

15. High-temperature metallic fuel cell interconnects [2a, 2b; Stevenson 2005, μ]

a. Coatings

        i. Prevent/remove oxidation
        ii. Prevent chromium poisoning
    b. Cost
    c. Modifying composition of alloys
    d. Electrode to interconnect interface material
16. High-temperature fuel cell material processing concerns [2a, 2b; Xinyu Lu ICEPAG 2008, Stevenson 2005]
    a. As many as three sintering steps
    b. High cost
    c. Lower cost precursor processing [2; Stevenson 2005]
    d. Sulfur hydride formation
17. High-temperature fuel cell seals [2a, 2b; Stevenson 2005, Θ]
    a. Brazes
    b. Compliant seals
    c. Glass and compressive seals
    d. High temperature ceramic or composite seals
    e. Self-healing materials
18. Inadequate material mixing methods (e.g., mechanical mixing of SSR) [2a, 2b; AVD MS thesis]
19. MCFC electrode issues [2b; γ, Θ]
    a. Electrode corrosion [2b; Θ]
    b. Anode
        i. Nickel stability issues
        ii. Nickel/Chrome alloys are costly and have low strength
    c. Cathode
        i. Chemical reaction and dissolution (nickel)
        ii. Need material that at high temperatures has:
            1. High (adequate) electrical conductivity
            2. Structural strength
            3. Low solubility in molten alkali carbonates

20. Fuel cell carbon component purity levels [2c; α]
    a. Bipolar plates
    b. Catalyst layer
    c. Gas diffusion layer
21. PEMFC gas diffusion layer optimization [2c; Γ]
    a. Optimized pore structure, conductivity, hydrophobicity and coating materials and techniques to improve performance
    b. Understanding of GDL degradation mechanisms
22. PEMFC membrane optimization [2c; γ, Γ, υ, θ, ω, π, Θ, χ, Π, Σ]
    a. Develop sustainable MEA designs
        i. Recycling or reclamation of catalyst and membrane materials [2c; Γ]
        ii. Re-use of cell components [2c; Γ]
    b. High membrane cost
        i. Develop ionomers with lower costs
            1. Increase stability (x-y)
            2. Introduce hydrocarbon ionomers
        ii. Low cost membranes that can operate on life reducing fuel streams [2c; μ]
    c. Membrane durability and lifetime [2c; υ, θ, ω]
    d. Limited membrane thickness
    e. Ion transport
        i. Limited ionic conductivity ranges
        ii. Dependence on temperature and humidity
    f. Membrane hydration
        i. Explore passive humidification (e.g., self humidification) [2c; Θ, Σ]
        ii. PEMFC operation at low relative humidity [2c; π, Θ]
        iii. Low-humidity membrane operation [2c; μ, υ]
    g. Development of high temperature membranes [2c; μ, ω, χ]
        i. Operating temperature range between 150°C and 300°C [2c; υ]

ii. Improved durability especially to impurities in the reformate

iii. Higher cell power density [2c; μ]

h. Fuel cell separators [2c, 2d; υ, ω]

i. Highly conductive, low-cost metal separators [2c, 2d; ω]

ii. Low-cost carbon separators [2c, 2d; ω]

iii. e.g., molded carbon, metallic glass

i. Purification [2c; π]

j. Integrated nano-scale architectures [2c; π]

k. Alternative materials [2c; γ, υ, FC RD&D Workshop]

i. Hydrocarbon

1. Allows higher and lower temperature operation [2c; Honda]

2. Enables quicker startup [2c; Honda]

ii. PBI

iii. Teflon polymer electrolyte (cross-linked) [2c; υ]

23. Novel materials for fuel cell water management [2c; Stone 2006]

24. High-temperature PEMFC materials science [2c; α]

25. Better low-temperature fuel cell electrocatalysts [2c, 2d, 2e; α, π, υ, Γ, Θ, σ, θ]

a. PEMFC electrocatalyst [2c; π, υ, θ]

i. Understanding catalytic behavior versus catalyst composition, crystal structure, and morphology

ii. Platinum agglomeration [2c; θ]

iii. Reaction/dissolution [2c; θ]

iv. Reduce PEMFC and PAFC catalyst loading [2c; σ, π, υ, θ]

1. $0.4 mg/cm^2$ to $0.04 mg/cm^2$ [2c; θ]

v. Inorganic electrocatalyst supports (titanium dioxide) [2c; υ]

b. Find alternative catalyst materials [2c, 2d, 2e; α, ω]

i. Non-precious metal catalysts for low temperature applications [2c, 2d, 2e; α]

ii. Need low-cost alternatives [2c, 2d, 2e; ω]

c. Tolerance to air, fuel and system derived impurities [2; Γ]

i. Anode tolerance to carbon monoxide [2c, 2d, 2e; υ, α]

ii. Tolerance to sulfur in fuel [2; Θ]

d. Reduce cathode over-potential

e. Engineered electrocatalysts layers [2c; Simon 2006]

f. Catalyst with improved methanol oxidation [2; Θ]

g. Catalyst loading reduction (with enhanced voltage efficiencies) [2c; υ, Simon 2006, ω, Γ, Θ]

26. PAFC separator plate materials [2d; μ]

27. Development of PAFCs with lower operation temperatures [2d; μ]

a. Material life

b. Control of liquid electrolyte loss

28. Brittle material set for phosphoric acid fuel cells [2d; γ]

3. Technology Integration Development

29. Advanced heat-treatment [3; ϕ]

a. Thick-walled pressure vessels

b. Shift reactors and reformers

30. Oxygen separation by ion transport membrane (ITM) [3a; θ]

31. Surface treatment [3; ϕ]

a. Develop pipe coating techniques

b. Unique brazing alloys

c. Low-cost cladding techniques (e.g., nickel)

i. Reaction vessel coatings

d. Accelerated surface treatment methods

i. Non-conformal surface coating (e.g., heat exchanger catalyst)

32. Control and speed of catalyst layer manufacture [3a; ϕ]

a. Provide precise control of catalyst and membrane distribution and porosity

b. High-speed manufacturing of complex three-dimensional geometries

33. Corrosion resistant and high-temperature turbo machinery materials [3a; α, Θ, Σ]
    a. Compressors
    b. Blowers [3a; α, Σ]
    c. Turbines
34. Novel materials for reformer systems [3a; ξ, ω]
    a. Improve hydrogen permeable membrane [3a; ω]
35. Reduction of BOP catalyst loading (e.g., platinum) [3a; ω]
36. Develop multiple function catalysts (e.g., for fuel cell and reformer) [3a; ϕ]

4. Fuels

37. Hydrogen generation from solar photolysis [4a3; α]
    a. Need more efficient water splitting semiconductor materials
    b. Need higher material corrosion resistance to water
38. Hydrogen embrittlement of materials [4a1, 4a4; α, Γ]
39. Hydrogen storage media development [4a4; β, ϕ]
    a. Hydrogen containment tank material [4a4; δ, ϕ, π]
        i. Metal
            1. Annealing techniques [4a4; ϕ]
        ii. Composite
    b. Novel hydrogen storage materials [4a4; π]
    c. Efficiency
    d. Fill speed
    e. Cost
    f. Safety
40. Nano-scale catalysts [4a4; π]
    a. Design
    b. Synthesis and screening techniques
    c. Characterization techniques
    d. Theory, modeling and simulation
41. Understanding of interaction of hydrogen with other materials [4a4; π]

a. Surface

b. Interface

c. Grain boundaries

d. Bulk defects

5. Other

42. Material recycling [5; ξ]

43. "Bio-inspired" materials and processing techniques [5; π]

II. Cell and stack developments

1. Market Applications

2. Fuel Cell Technology Specific Developments

1. Fuel cell manufacturing barriers [2; ϕ, α, γ, θ, Γ, ξ, τ, Θ, Σ]

    a. High product volume manufacturing [2; Θ]

    b. Design for manufacturing techniques [1; ϕ, ξ, Γ]

    c. Consistency and quality control [2; α, ϕ, Γ]

        i. Maintain mechanical, chemical and thermal stability over entire temperature and humidity range during manufacturing of components (e.g., membranes) [2; Γ]

        ii. Defect definition and detection (e.g., membrane) [2; ϕ]

        iii. Uniformity in manufacturing (e.g., size, thickness) [2; γ]

    d. Innovative designs and safety technologies [2; α, ϕ]

    e. In-situ and ex-situ testing method development (e.g., MEAs) [2; ϕ, θ, Γ, Θ, Σ]

    f. Continuous line manufacturing [2; ϕ]

        i. In-line testing

        ii. In-process leak testing

        iii. In-line surface treatment processes

    g. High-speed fuel cell component manufacturing methods [2; ϕ, Γ]

        i. Forming, stamping and molding of bipolar plates [2c; ϕ]

        ii. High tolerance

iii. Rapid prototyping

iv. Flexible tooling

h. High-speed and continuous welding, joining and sealing processes [2; ϕ, Γ]

i. Low-temperature metal joining techniques [2; ϕ]

1. Prevent catalyst damage

ii. MEA and bipolar plate sealing [2c; ϕ]

iii. High-temperature curing seals

iv. Laser welding methods are too slow or too expensive for metallic bipolar plates [2c; ϕ]

v. Fiber laser welders need speeds greater than 50 meters per minute

vi. Fast bonding methods for bipolar plates [2c; ϕ]

i. Cell and stack assembly [2; ϕ, Γ]

i. Automated assembly process

1. Maintain alignment during assembly

2. Eliminate testing during stack assembly

3. Maintain proper load during assembly [2; Γ]

ii. Design of component packaging to simplify stack assembly (e.g., MEA)

iii. Low-stress clamping methods

j. Integration of CAD modeling tools with manufacture (e.g., MEA) [2; ϕ]

k. Investment in technology development and manufacturing methodologies [2; α, τ]

l. Cell and stack cost reductions from large-scale manufacturing [2; τ, ϕ, Γ]

m. Accelerated stack "break-in" methods [2; ϕ]

2. Develop stack lifetime prediction methods [2; Θ]

3. Develop reversible fuel cells [2, 1; χ, Θ, Ξ, θ]

a. Oxidation of nickel during reverse SOFC operation [2a; θ]

b. Address intermittent availability of renewables [4b, 1; χ]

4. Fuel crossover and leakage [2; Γ, Π, θ]

    a. Reduce crossover of methanol during DMFC operation [2e, 1e; Γ]

5. Fuel and oxidant flow-field design and flow manifolding [2; θ, Θ]
    a. Channel shape and pathway
    b. Design for sealing of manifold
6. Cell and stack geometry constraints [2; θ, ϕ]
    a. SOFC cell production size
    b. Standardized MEA dimensions [2c; ϕ]
7. Stack orientation constraints [2; θ]
    a. Vertical stack design [2c; Honda]
    b. Horizontal stack design
8. Flow and electrical connection design [2; θ]
    a. E.g., Cascade-in-series, parallel
    b. Match electrical connection scheme to electrical output requirements
9. Efficiency losses from cell to stack configuration [2; θ, α]
    a. Multiple fuel cell sealing and joining to create stack [2; α]
    b. Cell variations
    c. Interconnect losses
10. Fuel cell anode oxidation recovery [2; ν]
11. Stack performance degradation over lifetime [2; Γ, μ, Π, Σ]
    a. Stack performance does not follow from cell performance projections [2; μ]
    b. Degradation measurement standard [2; Σ]
12. Stack performance analysis equipment [2, θ]
    a. Impedance analysis
    b. Cyclic voltammetery
    c. Potentiostat
13. Fuel cell degradation mechanisms [2; ν, Θ, Xinyu Lu ICEPAG 2008]
    a. Corrosion
        i. Chemical
        ii. Electrochemical

b. Erosion

    i. Abrasive action

c. Oxidation and reduction

    i. Especially concerning in the presence of;

        1. High temperature

        2. Highly reducing environment

        3. Highly oxidizing environment

        4. Electric fields

    ii. SOFC electrolytes and interconnects stability in oxidizing and reducing environments

        1. Chemical stability

            a. Limit chemical interaction with other cell components

            b. SOFC chrome poisoning

        2. Morphological stability

        3. Dimensional stability

d. Mechanical failures [2a; Xinyu Lu ICEPAG 2008]

    i. Cracking

    ii. Mechanical delamination

    iii. Reactivity amongst cell components

e. Thermal stresses [2; ν, Θ]

    i. Coefficients of thermal expansion mismatch causes stresses

    ii. Cracking

    iii. Delamination

    iv. Loss of porous microstructure

f. Chemical reaction and stresses

g. Chemical reaction

    i. With other FC components

    ii. With reactant and/or product gases

h. Sorption

        i. Adsorption
        ii. Absorption
    i. Chemical species poisoning
        i. Carbon monoxide
        ii. Sulfur
    j. Dynamics – cyclic operation
        i. Non-uniformity or defect propagation
    k. Dehydration (e.g., PEMFC)
        i. Operating conditions
        ii. Membrane electrode assembly structure
        iii. System design
    l. Freezing (e.g., PEMFC, PAFC, AFC)
    m. Mass transport limitations due to:
        i. Pore size reduction
        ii. Coarsening of porous materials
        iii. Contaminant plugging
    n. Carbon deposition (e.g., DMFC, SOFC, MCFC with HC in fuel)
    o. Morphology/structural changes
    p. Sintering (e.g., SOFC)
    q. Grain boundary growth
    r. Constituent element concentration within FC component
14. Catalyst recycling [2; θ, ϕ, Θ]
    a. Separate from other components
    b. Collection [2; ϕ]
    c. Reprocessing
15. Increase limiting current density [2; θ]
    a. Optimize diffusion, porosity, tortuosity, fuel flow and composition
16. Accelerate fuel cell design selection [2; Stone 2006, Θ, θ]
    a. Accelerated testing method development [2; Θ, θ]

b. Define fuel cell characteristics via accelerated testing procedures

i. Durability

ii. Reliability

iii. Impurity tolerance

17. Complex fabrication process for tubular SOFC [2a; μ]

18. High-temperature flow manifolding [2a; γ]

a. Flow cross-leakage when manifolding

b. Explore flexible seals

19. Intermediate temperature SOFC operation [2a; Θ, χ, θ]

20. Focus of hydrogen fueled PEMFC technology should be on lifetime, reliability and capital cost [2c; ψ]

21. MCFC stack degradation and life [2b; μ, Θ, Π]

a. Carbonate depletion [2b; Θ]

22. High-temperature PEMFC cell and stack assembly [2c; α, ξ, π]

a. Operation at high temperatures and high pressures [2c; π]

23. PEMFC bipolar plates [2c; α, Γ, π, Σ]

a. Weight and volume reduction [2c; Γ]

b. Scalable fabrication process [2c; Γ]

c. Metal

i. Stainless steel flow plates [2c; Honda]

1. Provide needed compression so no tension rods are required

2. Quick heat up

d. Plastic

e. Composite

f. Coatings [2c; π, Σ]

i. Prevent corrosion

ii. Oxide removal prior to coating [2; Σ]

24. PEMFC gas diffusion layers [2c; α]

a. Cost reduction [2c; Stone 2006]

b. Increase throughput [2c; Stone 2006]

c. Improve performance (e.g., flooding) [2c; TMB dissertation]

25. Improved PEMFC tear resistance [2c; γ]

a. Cells can tear when subjected to high differential pressures

b. Explore cross-linking of polysulfones (at expense of proton conduction rates)

26. Improved PEMFC cathode performance [2c; γ]

a. Limiting gas permeability (nitrogen blanket on air side)

b. Explore increasing ionic conductivity to offset the effect of gas permeability

27. Improved cell cooling [2c; γ]

a. Hot spots limit low current density stack operation

b. Explore cooling options to improve performance (power density and costs)

28. Stack cost, durability and performance levels [2; χ, Γ]

3. Technology Integration Development

4. Fuels

5. Other

III. Lifetime and operation challenges

1. Market Applications

1. Variable FC-GT system operating parameters [1a3; ε, η]

a. Pressure ratios

b. Mass flows [1a3; η]

c. Output powers [1a3; η]

d. Firing temperatures

e. Operating conditions

2. FC-GT system operation and control [1a3; Π]

a. Fired versus non-fired gas turbine operation (e.g., fire at certain time of day or for particular load demand)

3. FC-GT load matching (following) [1a3; ε, ζ]

a. Durability from cycling [1a3; ζ]

b. Efficiency at different power output [1a3; ζ]

i. Long-term slow power changes can be handled with a fuel control

ii. Long-term high power changes will require more complex solution

1. Air flow adjustment

2. Fuel flow adjustment

3. Recuperator bypass

c. Load balancing between FC and GT

i. Short-term power changes can be handled by FC

d. Transients over entire duty cycle

4. FC-GT Startup [1a3; ε, ζ, η]

a. Combustor still required [1a3; η]

b. Control scheme [1a3; ζ]

c. Surge possibility [1a3; ζ]

d. Oxidation of anode [1a3; ζ]

5. FC-GT System upset (load loss) [1a3; ε, ζ, θ]

a. Fuel and air are still pumped through system for a very short time but can create serious safety concerns

b. Hot standby [1a3; ζ]

c. Turbine over-speed [1a3; θ]

d. Bleed and bypass valves [1a3; θ]

6. PEMFC fuel processing development for backup power to operate on a variety of fuels [1d, 2c; γ]

a. Propane

b. Liquefied petroleum gas

c. Methanol

d. Natural gas

e. Diesel

2. Fuel Cell Technology Specific Developments

7. Fuel cell contamination effects [2; α, ω]
    a. Oxidant impurities [2; θ]
    b. Long- and short-term
8. Performance under diverse climactic conditions and locations [2; α, Θ, Π, θ]
    a. Focus on low-temperature fuel cells [2; θ]
    b. Freezing conditions
    c. Cold-start
    d. Operation with salt in air [2; Θ]
    e. Operation while submerged (e.g., underwater) [2; Π]
9. Capture and cleanup of exhaust [2; θ]
    a. Carbon emissions from fuel reforming [4; θ]
    b. Constituents
        i. Carbon dioxide
        ii. Oxides of nitrogen
        iii. Oxides of sulfur
        iv. Hydrides
        v. Hydrocarbons
        vi. Steam
10. Fuel cell operation at high fuel utilizations [2; Θ, θ]
11. Operation and control after partial stack failure [2; θ]
12. Gas purging [2; ε, θ]
    a. Interaction with or use of hydrogen storage for purging [4a4; θ]
    b. Fuel cell stack [2; ε]
        i. Flood the system with inert gas
            1. Not economically feasible or practical for large systems
        ii. Use a blow-off valve to stop turbine and release air before it reaches the FC and divert gas flow to gas generator
            1. Need to ensure that no flammable mixtures result
        iii. Methane as a purging fuel at startup as opposed to N_2 and H_2
13. FC system load matching (i.e., load following) [2; θ, Π]

a. Durability from cycling

b. Efficiency at different power output

i. Long-term slow power changes can be handled with a fuel control

ii. Long-term high power changes will require more complex solution

1. Air flow adjustment

2. Fuel flow adjustment

c. Energy storage

i. Batteries

ii. Capacitors

iii. Pump storage

d. Transients over entire duty cycle

14. Exhaust gas recirculation [2; Σ, γ]

15. Fuel cell shutdown [2; θ]

a. Safety

i. Cooling rate

ii. Residual electrical charge

iii. Residual fuel

b. Low-temperature fuel cell longevity

i. Water management

ii. High OCV corrosion

c. High-temperature fuel cell thermal cycling

i. Thermal stress

ii. Uneven temperature distribution

iii. Effect on stack life and performance

iv. Vitrification of MCFC electrolyte

16. Prove fuel cell performance reliability and durability over long-term tests [2; α, Π, θ]

a. PAFCs only units with substantial commercial experience (2002)

b. MCFC units gaining much commercial experience (2008) [2b; θ]

17. SOFC and MCFC system upset (load loss) [2a, 2b; θ]
    a. Cooling control
        i. Thermal stress
    b. Oxidation of anode
    c. Hot standby
    d. Safety
        i. Residual fuel
18. SOFC mechanical stress due to thermal cycling [2a; Simon 2006]
    a. Planar can tolerate less thermal cycles than tubular because tubular can expand downward
    b. Leads to long starting and stopping cycles
        i. Temperature is ramped slowly
        ii. Some caused by differences in reforming zone and reaction zone
19. High-temperature fuel cell startup [2a, 2b; θ, ω]
    a. Cold startup
    b. Warm standby
    c. Intermittent operation
    d. In-situ anode reduction
    e. Thermal cycling
    f. Thermal stress
    g. Turn-key operation
    h. Oxidation of anode
20. PEMFC membrane durability [2c; α, ξ]
21. Low-temperature fuel cell catalyst poisoning from carbon monoxide [2c, 2d; β, γ]
    a. Requires extensive gas clean-up
    b. Higher operating temperature alleviates problem
    c. Adjust temperature and pressure to increase catalyst resistance [2c; γ]

22. Heat shed for low-temperature fuel cells (during elevated temperature operation) [2c, 2d; Honda]
23. Low-temperature fuel cell startup [2c, 2d, 2e; θ]
    a. Freezing conditions startup
    b. Energy storage management
        i. Batteries
        ii. Capacitors
    c. Reformer heat-up and intermittent operation
    d. Turn-key operation

3. Technology Integration Development

24. Prevent fuel starvation [3a; θ]

4. Fuels

25. Fuel purity requirements for fuel cells [4, 2; α, ξ]
    a. Hydrogen purity requirements [4; ξ, Θ, θ]
        i. Purity of reformed fuel stream
26. Fuel processing impurities [4; Θ, β, γ, θ]
    a. Desulphurization technology (removal and disposal) [4; γ, Θ, β, Σ]
        i. Mercaptan in natural gas [4; θ]
        ii. Sulfur poisoning even at high temperatures [4; β]
        iii. Effect of water content on desulphurization [4; Σ]
        iv. Amounts and types of sulfur [4; Σ]
    b. Coal (e.g., chlorine, lead, mercury) [4; Θ, Σ]
    c. Biomass (e.g., sulfur, chlorine, silica)
27. Carbon formation (coking) prevention for fuel reforming [4; θ, Simon 2006]
    a. Steam to carbon ratio
    b. Coking if fuel-air ratio not correct [2; Simon 2006]
28. Hydrogen-natural gas fuel blend performance [4a; α, Θ, δ]
    a. Explore efficiency effect [4a; δ]
    b. Explore emission reduction capabilities [4a; δ]
29. Accommodate fuel variations (i.e., fuel flexibility) [4; γ, χ, Θ, π, Π]

a. Real-time or dynamic fuel type changes [4; Π]

b. Impact on fuel cell performance and durability [4; π]

c. Impurity tolerance [4; π, Θ]

30. High cost of hydrogen production [4a3; β, α, Γ]

    a. Hydrogen production and delivery costs are high relative to conventional fuels [4a3; α, Γ]

    b. Inefficiencies with fuel reforming in comparison to competing technology [4a3; β]

31. Improve and optimize reforming of opportunity and renewable fuels [4b; chp_opportunityfuels, Θ, Γ, Π, θ]

    a. Temporal availability of fuel feedstocks [4b; Π]

        i. Year-round waste availability (e.g., agriculture waste)

        ii. Blending waste streams to increase availability (e.g., agricultural waste with dairy waste)

    b. Opportunity fuel clean-up, pressurization and preparation for transport [4b; θ]

    c. Process control, system and safety monitoring [4; Θ]

    d. Biomass fuels

        i. Anaerobic digester gas (promising)

            1. Agricultural and food-processing sources [4b; Remick 2006]

            2. Waste water treatment plants [4b; Binder 2006]

            3. Must remove siloxane

        ii. Biomass gas (promising)

        iii. Black liquor

        iv. Crop residues

        v. Ethanol

        vi. Food processing waste

        vii. Landfill gas (promising)

        viii. Municipal solid waste (and refuse derived fuel)

        ix. Sludge waste

        x. Wood and wood waste

e. Fossil fuel derivatives

i. Coalbed methane (promising)

ii. Wellhead gas

f. Industrial process waste and byproducts

i. Blast furnace gas

ii. Coke (coal and petroleum)

iii. Coke oven gas

iv. Industrial VOC's

v. Textile waste

g. Develop processing methods for maximizing the methane production from waste steams [4a3, 4b; Remick 2006]

5. Other

IV. Systems integration and technology

1. Market Applications

1. Develop more robust or "ruggidized" products [1; ω, σ]

   a. E.g., environmental resistance

2. IGFC plant development [1a1a; ϱ]

   a. Coal contaminants

   b. Pressurization

   c. Failure analysis

   d. Systems integration

   e. Balance of plant

   f. Materials

   g. Manufacturing

   h. Controls

   i. Instrumentation

3. Carbon dioxide separation for IGFC and IGCC plants [1a1a; θ]

   a. Configuration

      i. Pre-SOFC

        ii. Post-SOFC

4. IGCC gas clean-up [1a1a; θ]
    a. Techniques
        i. Acid gas removal (AGR) (with Selexol)
    b. Contaminants
        i. Mercury
        ii. Sulfur
5. Develop large-scale carbon dioxide capture and sequestration technology (CCS) [1a1b; α, π, θ]
    a. Allows for low-carbon emission hydrogen production
    b. For use in IGCC plants [1a1a; θ]
    c. Integrate CCS technologies into hydrogen production plants
    d. Cost reductions
        i. Advanced water-gas shift
        ii. Separation
        iii. Cleanup
        iv. Process intensification
    e. Co-production of hydrogen and electric power (multi-fueled, oxygen-blow gasification) [1a1b; π]
    f. Environmental concerns [1a1b; π]
    g. Reformation of coal-derived carriers with high hydrogen content [1a1b; π]
        i. Computational methods
        ii. Advanced technologies
6. Optimum distribution of heat, cooling, electricity, hydrogen, etc. from multi-generation systems [1a2; Binder 2006]
7. Optimized FC-GT system design parameters [1a3; ε, η, ζ]
    a. Pressure ratios
        i. Low turbine inlet pressure from large pressure drop between fuel cell and turbine [1a3; ζ]
    b. Mass flows [1a3; η]

c. Output powers [1a3; η]

d. Firing temperatures

i. Turbine firing temperature must be low to match fuel cell [1a3; η]

e. Operating conditions

8. FC-GT system design opportunities [1a3; η]

a. Compatibility with gasification [1a3, 1a1a; η]

b. Operation with mini- or micro-turbines

c. Compatibility with clean-coal technologies

d. Compatibility with carbon sequestration [1a3, 1a1b; η]

e. Compatibility with hydrogen economy

9. FC-GT hybrid data [1a3; ε, η, ζ]

a. Intelligent sensor development [1a3; η]

b. Determining system operational features and corresponding values [1a3; ζ]

i. Compressor performance maps

ii. Turbine performance maps

iii. Turbo machinery moment of inertia

10. Concurrent dynamic and materials/stress analyses for FC-GT hybrid systems [1a3; ε]

11. Optimized FC-GT mating configuration [1a3; ε, ζ, Θ, Π]

a. Direct or indirect

b. Regular or inverted Brayton [1a3; Geo Richards ICEPAG 2008]

c. Turbine selection (mini, micro, regular) [1a3; ζ]

i. Turbo machinery primary goal is to accommodate fuel cell

ii. Size turbine for pressure requirement

d. Multiple stage compressors or turbines [1a3; ζ]

e. Reconfiguration of major components

f. FC-GT systems typically use a SOFC or MCFC [1a3, 2a; ζ]

g. Fuel cell optimization with other high-pressure equipment [1a; Θ]

12. Fuel cell and turbine dynamics, management and control [1a3; ε, ζ]
    a. System operational features
        i. System balance
        ii. Flow matching
        iii. Recycle ratios (fuel and air) [1a3; ζ]
        iv. Shaft speed [1a3; ζ]
    b. Thermal management
        i. Temperature stability
    c. Safety
13. Additional FC-GT hybrid equipment requirement [1a3; η, ζ]
    a. Valves
        i. High temperature bypass valves [1a3; ζ]
    b. Ducting
        i. Smaller diameter piping for pressurized system [1a3; FC-GT hybrid short course 2006]
    c. Control equipment
    d. Machine tool development to match specifications
14. Blower development [1a3; James Maclay ICEPAG 2008, ϱ, ζ, ε]
    a. High-temperature operation [1a3; ε]
        i. High efficiency
        ii. Low cost
        iii. Simplicity
    b. Commercial availability of high-temperature blowers [1a3; ζ]
    c. Blower versus ejector [1a3; ζ]
15. Ejector development [1a3; ζ]
    a. parasitic losses
16. Turbine and compressor development [1a3, 3a; ε, ζ, η, μ]
    a. Interfacing requirements
        i. Axial versus radial components [1a3; ζ]
        ii. Increased turbine thrust load requirement [1a3; η]

iii. Optimize control strategy

iv. Separate turbine and compressor [1a3; ζ]

1. Aid in mating hybrid system components

2. Control systems independently

3. Affects system efficiency

b. Intercooling developments

c. Recuperation developments

d. Surge margin avoidance

i. Especially for large; direct; pressurized hybrids [1a3; η]

1. Large plenum volume

ii. Understand off-shelf component surge conditions [1a3; ζ]

e. Turbine hot section life

i. Turbine and compressor life depends on; [1a3; ζ]

1. Shaft speed

2. Temperature

3. Materials (e.g., corrosion resistance)

4. Fuel composition

f. Structural integrity

g. Speed control [1a3; ζ]

i. Asynchronous generator

ii. Synchronous generator

h. Bearings seizing

i. Magnetic bearings [3a; μ]

17. Combustor [1a3; ε, γ, ζ, η, Θ]

a. Anode exhaust gas oxidizer [1a3; γ]

i. Catalytic (electrochemical) oxidizer [1a3; ζ]

ii. Typical oxidizer

b. Still required during startup and off-design operation [1a3; η]

c. Combustor fuel flexibility (e.g., blended fuels) [4; Θ]

d. Turn-down capacity (0-100%)

e. Stability

f. Use of vitiated air

g. Withstand higher inlet air temperatures

h. Pressure drop

i. Emissions

j. Efficiency

18. FC-GT fuel processor concerns [1a3, 4a3; ε, ζ, Θ]

    a. Thermal management

    b. High pressure operation

    c. Fuel variability and flexibility

        i. Understand impact of fuel variation [4; ζ]

            1. Blending with hydrogen [4a; Θ]

            2. Local, seasonal variation

            3. International variation

    d. Contaminant/odorant tolerance and removal

        i. Sulfur tolerance

    e. Eliminate need for steam

19. New engine and turbine designs to lower emissions on hydrogen and renewable fuels [1a3, 4; α]

    a. Catalytic combustion

    b. Optimize combustion and after-treatment strategies to maximize power density and efficiency while minimizing emissions

        i. Control strategy development for hydrogen and hydrogen-enriched fuels

        ii. Flow handling and engine management systems

        iii. Lean, premixed combustion is preferred technology for stationary turbines to control emissions (acoustic instabilities)

        iv. More information about hydrogen combustion flame characteristics

20. High FC-GT system pressure versus atmospheric operation [1a3; FC-GT hybrid short course 2006]

a. Atmospheric

i. May require additional heat exchangers

ii. May create more severe temperature conditions

iii. Decouples pressure ratio from fuel cell conditions

b. Pressurized

i. Depressurization of fuel cell

ii. Requires more parameter matching (e.g., pressure ratio, temperatures)

iii. Higher thermal efficiency

iv. Higher Nernst potential

v. Lower fuel cell losses (activation and concentration polarizations)

21. Fuel cell cost reduction and reliability improvements are the highest priority [1b; ξ]

    a. Increase durability for automotive applications [1b; ϕ]

    b. Cost reduction for automotive applications [1b; ϕ]

2. Fuel Cell Technology Specific Developments

22. Miniaturized component design and optimization [2; β, ξ, Θ]

23. Thermal management [2; γ, μ]

    a. Minimize heat loss through system integration

24. Water management [2; θ]

25. Standardization of fuel cell components [2; β, σ, Θ]

26. Fuel cell integration with other energy conversion devices [2; θ]

    a. Thermoelectric

    b. Photovoltaic

    c. Wind

27. Power plant packaging [2; β]

    a. Especially for transportation systems

28. Look at techniques to reduce FC power required by equipment [2; Harris 2006]

    a. Battery dominant hybrids

29. Fuel cell system manufacturing barriers [2; ϕ, ξ, χ]
    a. Flexible manufacturing [2; ϕ]
    b. Design for manufacturing techniques [2; ϕ, ξ]
        i. "Frameless" fuel cell systems [2; ϕ]
    c. Low volume, low cost manufacturing techniques [2; ξ]
    d. High volume, low cost manufacturing techniques [2; ϕ, ξ]
    e. Non-destructive testing methods [2; ϕ]
    f. In-line testing methods [2; ϕ]
        i. Eliminate off-line subsystem testing
        ii. Eliminate off-line power system testing
    g. Enhance manufacturability of all fuel cell system types [2; χ]
        i. Manufacturing improvements in one discipline present value in other disciplines [2; ϕ]
    h. Create a national facility for flexible automated manufacturing [2; ϕ]

3. Technology Integration Development

30. BOP component cost and integration [3a; α, ω, β, σ, Θ]
    a. Fuel processing equipment
    b. Power conditioning
    c. Thermal integration [3a; Θ]
    d. Thermal storage and management
    e. Water management [3a; α, ω]
    f. Standardization of components [3a; β, σ, Θ]
        i. E.g., hydrogen gas connectors [3a; Θ]
31. Oxy combustion [3; Ashok Rao ICEPAG 2008]
    a. Constitutes major component cost
    b. Higher plant cost
    c. Large amount of O_2
    d. Membrane transport
    e. Retrofitting possible but challenging
32. In-line leak detection hardware for BOP [3a; ϕ]

33. Fast and simple sealing of BOP components [3a; ϕ, Γ]

34. Optimize system components [3a; ξ, μ, σ, χ, Γ]

    a. Establish inexpensive and compact hydrogen sensor production process [3a, 4a; ϕ]

    b. Reduce BOP parasitic losses [3a; μ, ω]

    c. Maximize balance of plant component utilization [3a; ξ]

    d. Compact and modular structure [3a; ω]

    e. Integrate the production processes of high-cost components [3a; σ]

    f. Mass and volume reductions (where applicable) [3a; χ]

35. System or power Electronics [3c, 1a3; ε, ξ, Θ]

    a. Need fully integrated power conditioning devices [1a3; η]

        i. Converters

        ii. Generators

        iii. Inverters

        iv. Rectifiers

    b. Cost

        i. Optimization for DC to AC conversion [3c, ϱ]

    c. Efficiency

        i. Optimization for DC to AC conversion [3c, ϱ]

    d. Robustness

    e. Cooling for various conditions [3, 1a3; ε, μ]

    f. Paralleling and islanding

    g. Modularity and standardization

    h. Control

36. Ancillary grid services (e.g., power factor, phase angle) [3c; λ]

    a. Costs more for customer to generate "cleaner power"

        i. Lack of customer incentives

        ii. Increases inverter costs

        iii. Power filter increases system costs

        iv. Currently no payment to customers for ancillary services

37. Power generation with reactive power (VAR) support [3c; Hessenius 2006, Russ Neal ICEPAG 2008]
    a. VAR support not often required by utility
    b. VAR support has potential benefits
        i. Reduce circuit current flows
        ii. Reduce distribution line losses
        iii. Maintain circuit voltage more effectively
        iv. Reactive power sent over long distances can collapse the network [3c; Russ Neal ICEPAG 2008]
    c. Many fuel cells installations have VAR support but do not utilize it because there is no apparent gain to the consumer
38. Grid load demand profile not perfect sinusoid [3c; λ]
    a. Line switching required
    b. Filtering required
        i. Equipment has increasingly stringent power requirements
        ii. Power filter location
            1. Can be anywhere between the grid transformers and the end of that line
39. Active versus passive distribution network control and communications strategy [3c; λ, Θ, Lopes 2007]
    a. Active management can allow for better system control
        i. Development of intelligent communication equipment [3c; Θ]
    b. Passive management
        i. Voltage rise due to abrupt load adjustment
        ii. Voltage rise accompanied by low probability of occurrence (for given example) [3c; Lopes 2007]
        iii. Voltage rise can be corrected with proper ancillary service contribution [3c; Lopes 2007]
    c. Master controller / "black box" dilemma
        i. Make smart distributed generation controllers
        ii. Utility makes control decisions
    d. Cost/return optimization strategy

        i. Follow customer optimization protocol
        ii. Follow utility protocol (peaking)
        iii. Combination of customer and utility interests

40. Inverter technologies [3c; γ, Θ]
    a. Reduce cost of inverter and other grid connectors [3c; Θ]
    b. Solid state switching
        i. Silicon based systems have speed and power limitations
    c. Combined voltage regulator and inverter
        i. To accommodate fuel cell voltage and current changes
    d. Multiple input inverter system
    e. Improved capacitors
        i. Improve voltage and current ratings with minimal affect on performance
    f. Utility interface
        i. Standardized connection interface that allows;
            1. Synchronization
            2. Load sharing
            3. Power factor correction

41. Heat exchanger optimization and integration [3a; Zabalza 2006, ϕ, ϱ, ε, Θ, μ, η, ζ, Σ]
    a. High temperature operation [3a; ε]
        i. High efficiency [3e; ϱ]
        ii. Low cost [3a; ϱ]
        iii. Simplicity [3a; ϱ]
    b. High efficiency operation
    c. Manufacture of low-cost, high-volume heat exchangers [3a; ϕ]
    d. Material selection
        i. E.g., catalyst coated heat exchanger components [3a; Σ]
    e. FC-GT hybrid system heat exchanger concerns [1a3; η]
        i. Eliminate use of recuperator (e.g., mixing, recycling)

ii. Higher exergy from lower temperature heat transfer [1a3; ζ]

f. Needed to maintain stream separation [3a; ζ]

g. Thermal cycling [3a; μ]

h. Durability [3a; μ]

i. Corrosion [3a; μ]

42. Small reformer development and demonstration [3a; α, ξ, Θ]

    a. Small fossil-fuel reformers can provide hydrogen to initial vehicle fleets; "retail sales points"

    b. Can bring down costs

    c. Need increased reliability

    d. Need longer catalyst life

    e. Need better integration with fuel cells and fuel storage

    f. Inefficient and bulky [3a; ξ]

    g. Need development and optimization to better match application requirements [3a; ξ]

    h. "Microreformers" for small fuel cell systems [3a; Θ]

43. Improvements in reformer response times and efficiency [3a; Σ, θ]

    a. Long startup time for steam methane reformers

    b. External water requirement for steam methane reformers

    c. Steam methane reformers are larger than alternative technologies

    d. Reformer heat-up and intermittent operation [3a; θ]

44. Simplify fuel processor complexity [3a; μ, ω]

    a. Combine three stage reformer into one reactor [3a; ω]

    b. Reduce losses due to heat removal [3a; μ]

45. BOP manufacturing barriers [3; ϕ, ξ, χ]

    a. Flexible manufacturing [3; ϕ]

    b. Low volume, low cost manufacturing techniques [3; ξ]

    c. High volume, low cost manufacturing techniques [3; ϕ, ξ]

    d. Non-destructive testing methods [3; ϕ]

    e. In-line testing methods [3; ϕ]

i. Eliminate off-line subsystem testing

ii. Eliminate off-line power system testing

f. Create a national facility for flexible automated manufacturing [3; ϕ]

4. Fuels

46. Development of fuel producing, processing and reforming methods [4; α, θ, δ, π, Γ, γ, Δ, Θ, Π]

a. Biological [4a3; Γ, π, δ, α, θ]

i. Biomass gasification [4, 1a1a; Δ, Θ, θ]

1. Gas cleanup (e.g., hot gas, synthesis gas)

2. Ash removal [4, 1a1a; Θ]

3. Land use properties

4. Competition between use for hydrogen or other synthetic fuels

ii. Bio-fuel combination with a high temperature fuel cell [2a; δ]

iii. Digestion processes [4a3; π]

iv. Potential for "low-tech" hydrogen production [4a3; α]

v. Understanding of hydrogen production in living organisms [4a3; π]

vi. Increase light utilization efficiency

vii. Increased rate of hydrogen production

viii. Improved continuity of photoproduction

ix. Increased hydrogen molar yield

x. Biological and biochemical organisms [4a3; Γ, π]

1. Algae (e.g., green) [4a3; Γ, θ]

2. Fermentative micro-organism system [4a3; π]

a. Hydrogen production during photosynthesis

3. Cyanobactreia

4. Photosynthetic bacteria

5. Dark fermentative microorganisms

b. Electrolysis [4a3; α, Γ, Δ, Θ]

i. Electrical conversion [4a3; Θ]

1. Avoidance of DC/AC inversion to prevent electrolyzer damage

2. Use of decentralized short DC connections

ii. Competition with direct use of renewable electricity [4a3; Δ]

iii. Optimize for high-pressure and high-temperature electrolysis [4a3; α, Θ]

iv. Could provide early market opportunities with cost reductions

v. Cost reductions could encourage distributed generation

vi. Explore available synergies (e.g., photovoltaic, solar-thermal, geothermal) [4a3; Θ, π]

1. Reversible fuel cells

2. Intermittent and variable power quality Electrolyzer operation (wind/solar)

vii. Develop new materials and systems to increase efficiency and reduce system cost [4a3; Γ]

viii. Redesign electrolysis systems to reduce necessary capital costs [4a3; Γ]

1. System packaging and optimization [4a3; Θ]

2. Develop utility-scale electrolyzers [4a3; Γ]

c. Thermochemical reactions (thermolysis)

i. Develop high temperatures cycles [4; Γ, δ]

ii. Oriented to large-scale production [4; δ]

iii. Develop durable materials and systems [4; Γ]

iv. Hydrogen capture after separation [4; Θ]

d. Plasma reforming [4; Θ]

e. Solar photolysis [4; α, Γ]

i. Potential for lower cost and higher efficiencies for solar energy collection

ii. Establish operating requirements [4; Γ]

iii. Develop system components, materials and systems [4; Γ]

iv. Integration with solar concentration [4; Γ]

f. Alcohol reforming [4; γ]

g. Gas to liquid conversion [4, 1b-c; FC RD&D Workshop]

i. Fischer-Tropsch process

ii. Bio-diesel

h. Heavy liquid petroleum reforming [4; γ, Δ]

i. Steam methane reformation limited to low carbon hydrocarbons [4a3; JM Bae ICEPAG 2008]

ii. SOFCs reform only light hydrocarbons [2a, 4a3; Simon 2006]

i. Unmixed fuel reforming [4; γ]

j. Coal gasification and reformation [4, 1a1a; γ]

i. Emissions limit plant locations

ii. Must transport hydrogen to point of use

k. Product heat support from nuclear energy generation plants [4a3; α, π, Δ, Γ]

i. Develop new or optimize processes for producing hydrogen with nuclear energy [4a3; α, Γ]

1. high temperature electrolysis

2. Thermochemical cycles (sulfur-based)

ii. Include thermochemical water splitting into future nuclear plant designs

iii. Gen IV nuclear reactor technologies

47. Gas separation and purification process improvements [4; α, Γ, Θ, ω]

a. Difficult to scale-down purification systems (large central – small distributed)

b. Oxygen separation is very expensive part of gasification plant

c. Hydrogen separation/purification [4; ω, θ]

d. CO_2 separation/purification [4; ω, θ]

48. Safety during accidental or intentional fuel release [4; θ]

49. Hydrogen delivery component improvements [4a1; α, δ, ϕ]

a. Breakaway hoses (e.g., high-pressure)

b. Compressors

i. Fuel for operation in remote areas

ii. Long-term operation

c. Hydrogen sensors

d. Odorization

e. Pipelines and tubing

i. Minimize leakage (methane; hydrogen) [4a1; δ]

ii. Low-cost tube forming process [4a1; ϕ]

f. Robotic fuelers

g. Seals

i. Minimize leakage (methane; hydrogen) [4a1; δ]

h. Transportation containers

i. Valves

50. Hydrogen delivery component integration into the system [4a1; α]

51. Novel desulphurization technology [4; ξ, Θ]

52. Maximize use of current fuel delivery infrastructure [4; ξ]

5. Other

V. Integration into the application environment

1. Market Applications

1. Increase system demonstration efforts [1; ξ, τ, σ, χ, Γ, Λ, Θ, Π, Harris 2006]

a. Continue demonstrations of products nearing commercialization [1; Harris 2006]

b. Coordinate development of codes and standards to demonstration projects [1; σ]

c. Validate system operation and product reliability [1; ξ, σ, χ, Γ]

i. Support the cost and value propositions of fuel cell technology [1; σ]

ii. Verify product performance [1; χ]

d. Demonstration examples [1; ξ, Θ]

i. District and/or neighborhood CHP applications [1; FC RD&D Workshop]

            1. Integrate heating, electricity and transportation services

        ii. Multiple pathway approach

        iii. Regional fuel cell vehicle refueling corridors

            1. Use fueling infrastructure to demonstrate fueling solutions [1; σ]

        iv. Power Parks [1; τ, ξ]

        v. Demonstration communities for fuel infrastructure (energy clusters) [1; τ, ξ]

            1. Hydrogen pipeline cluster [4; Θ]

        vi. Utilize existing or extended pipeline corridors

        vii. "Multiple Use" installations including power generation and vehicle fueling

        viii. Hydrogen and hydrogen carrier fuels remain in the mix

        ix. Carbon capture and sequestration plants [1a; Θ]

    e. Focus on high efficiency demonstrations with opportunities for waste heat conversion (e.g., CHP) [1; Λ]

    f. Focus on DG systems that can provide backup power [1d; Λ]

        i. Must be secure against natural disasters

        ii. E.g., emergency services, telecommunications, medical facilities, remote areas [1d; Λ, θ]

2. Expanded data collection efforts at demonstration sites [1; α, σ]

3. Portable fuel cell compatibility with current devices [1e; Θ]

4. Fuel cartridge development for portable applications (e.g., hydrogen, methanol) [1e, 4a, 2e; Θ]

5. Central plant competition [1a1; Simon panel 2006 (pg229)]

    a. Difficult to compete with 30-35% efficient large scale plants as opposed to smaller less efficient power plants.

6. IGCC retrofit to current coal plants [1a1a; Wayne Surdoval ICEPAG 2008]

7. Understanding thermal and electric load profiles for CHP [1a2; θ]

8. CHP system sizing and integration [1a2; θ]

9. Equipment siting process and requirements [1; γ, χ, CSUN ICEPAG 2008]

    a. Simplify installation process of fuel cell technology [1; χ]

b. Finding appropriate locations

c. Obtaining and supporting site insurance

d. Operation protocol

i. Manned

ii. Un-manned

e. Site preparation [2; CSUN ICEPAG 2008]

i. Foundation for heavy systems

ii. Fuel line (natural gas) to location

10. Optimization of waste heat for CHP applications [1a2; κ]

a. Industrial processes

b. Heating (e.g., pool, laundry)

11. Building load fluctuation effects on CHP equipment [1a2; θ]

12. Inconsistent maintenance on DG equipment [1a2, 3a; DG DOE 1999]

a. Equipment warranty from company

b. Maintenance personnel

c. Maintenance costs

d. Third party equipment maintenance agreements

1. Purchase of electricity from utility customers

13. Absorption chilling for improved CHP performance [1a2a; θ, Liao 2004, κ, NBI SCE 1998, Kohlenback_2007]

a. Building load fluctuation effects on absorption chillers [1a2a; Liao 2004]

i. Transient operation

1. Require robust control strategy

2. When inlet temperature changes there is a delay in output [1a2a; Kohlenback_2007]

ii. Diurnal operation adjustments

iii. Seasonal operation adjustments

b. Capital cost for absorption chillers is higher than conventional electrical systems [1a2a; κ]

i. Can be sensible for areas with expensive electricity [1a2a; NBI SCE 1998]

        1. Peak shaving

    ii. District loops provide good integration

c. Absorption chiller deployment strategy [1a2a; κ]

    i. Lack of demonstrations with fuel cells

    ii. No commitment between fuel cell and absorption chiller manufacturers

d. Control strategy for absorption chiller [1a2a; κ]

    i. Robust

    ii. Reliable

e. Crystallization of absorption chiller working fluid [1a2a; Liao 2004, κ]

    i. Mass fraction of salt must stay below solubility limit (super saturation)

    ii. Fluid temperature control strategies

    iii. Fluid pressure control strategies (less important than temperature and mass fraction)

    iv. Limit nucleation sites for crystal growth

    v. Mechanical redesigns

    vi. Chemical additives

f. Absorption chiller system selection [1a2a; κ]

    i. Air or water cooled

        1. Air cooled yields lower cooling capacity

        2. Water requires more complex balance of plant (a cooling tower)

        3. Air cooled best in location where water is scarce

    ii. Direct or indirect fueled

        1. Direct fueled uses exhaust gases to input heat

        2. Indirect fueled uses steam or another transfer fluid to input heat

    iii. Refrigerant/absorbent selection

        1. Water and lithium bromide

        2. Ammonia and water

iv. Single; double or triple effect

1. Triple effect chillers can achieve similar efficiencies as that of electrical chillers [1a2a; NBI SCE 1998]

v. Use of cooling storage tank

vi. Typical applications [1a2a; Liao 2004]

1. District heating system
2. Exhaust heat
3. Engine jacket
4. Industrial process (especially steam)

g. Combination absorption chiller conventional HVAC system [1a2a; Liao 2004]

i. Use absorption chillers for base load along with conventional HVAC

ii. Hastens payback

iii. Optimizes cooling systems for CHP applications

iv. Can be used when power is most expensive to decrease electricity consumption

h. Maintaining cooling tower chemistry [1a2a; κ]

i. Poor cooling tower management results in scale and sludge buildup in the system

ii. leaning can require system down time

i. Absorption chiller system leakage [1a2a; κ]

j. Absorption chilling systems require regular non-condensable gas purging (weekly, monthly) [1a2a; κ]

14. Matching absorption chiller to fuel cells [1a2a; κ]

a. Exhaust composition incompatibility

i. Currently designed for internal combustion engines and micro turbine generators

b. System temperature set points

c. Acid dew point (sulfuric, carbonic, nitric, hydrochloric, hydrobromic) for gas driven systems

d. Back pressure limitations

e. Fuel cells provide a high ratio of electricity to heat

i. Conventional air conditioning units will be needed if electricity cannot be used elsewhere

ii. Excess electricity could be sold to grid, stored, etc.

15. Interaction of FC and FC-GT systems with one another and grid [1a3; ε]

16. Determining performance and cost implications for FC hybridization [1a3; ε]

17. Meeting customer expectations (e.g., range, reliability) [1b; α, χ, ϕ, Γ]

a. Vehicles need a redesign to achieve the necessary range [1b; α]

i. Vehicle range (200-250 miles FC vehicle, 380-400 miles ICE)

b. Public needs to be convinced of the value of hydrogen-fueled vehicles [4a, 1b; α]

c. Hydrogen storage technology should meet acceptable range and duration [4a4, 1b, 1e; α, χ, ϕ, Γ]

i. Hydrogen storage should match gasoline equivalent driving range [4a4, 1b; α]

ii. Establish mobile application requirements for hydrogen storage technologies [4a4, 1b; α]

iii. Vehicles need range of 300 miles [4a4, 1b; Γ]

d. Air-filtration for off-road vehicle applications [1b4; Γ]

18. Fuel infrastructure for transportation applications [1b, 1c, 4a1; Wu 2006, θ]

a. Must be more well distributed than stationary hydrogen fuel infrastructure [4a1; θ]

19. Experience, cost and convenience for dispensing system designs [1b, 1c, 4a; Θ, α, δ]

a. Self-service refueling facilities [1b, 1c, 4a; α, δ]

b. More permanent demonstration stations [4a; δ]

c. Need convenient and constant availability [4a; δ]

d. Refueling station component development and standardization [4a; Θ, δ]

i. E.g., dispenser, nozzles, gas sensors, flow sensors

20. Economics of long distance gas transport and storage [1b, 1c, 4a1; α, δ]

a. Stranded assets [4a1; δ]

21. Develop goods movement markets using fuel cell power [1b, 1c, 2; Θ, θ]

a. Lifts (e.g., forklift, scissors lift) [1b, 1c, 2; θ]

b. Auxiliary power units (e.g., ship, tractor trailer, locomotive, aircraft)

22. Low cost, non-invasive product testing and evaluation [1; ξ]

23. Industry standard testing procedure [1; ϕ]

24. Produce a common fuel cell module that can accommodate vast markets [1; ϱ]

    a. Increases prospects of achieving high-volume demand and production

    b. Reduces costs

25. Develop supply chain [1; σ, Θ, Harris 2006]

    a. Develop system suppliers (OEM), material suppliers and component suppliers (SME) [σ, Θ, Harris 2006]

    b. Establish a method to share technical information between fuel cell developers, suppliers and researchers

    c. Stimulate investment toward component design

    d. Identify supply chain gaps

    e. Establish appropriate benchmarks and performance standards [1; σ, Θ]

26. Control of system thermal, acoustic and magnetic signature [1; Θ]

2. Fuel Cell Technology Specific Developments

27. Remanufacturing, reprocessing and requalifying process for fuel cell equipment [2; ϕ]

28. Fuel cell system maintenance concerns [2; θ, Zabalza 2006]

    a. Equipment location and position (e.g., beneath power lines, stack orientation)

    b. Experience and proficiency of maintenance personnel

        i. Trained

        ii. Untrained

    c. Remote monitoring capabilities

    d. Scheduled maintenance [2; Zabalza 2006]

        i. e.g., filters, fluid, stacks

    e. Unscheduled maintenance [2; Zabalza 2006]

        i. e.g., fans, pumps, blowers, batteries

29. Fuel cell technology requires proven reliability [2; Wu 2006]

30. Limited end user fuel cell experience [2; Harris 2006]
    a. Be a user of the technology
    b. Be a reference account
31. Profitable fuel cell operations during pre-large-scale manufacturing [2; α, ϕ]
    a. Processes for interim manufacturing and assembly volumes (i.e., 5,000-50,000 units) [2; ϕ]
32. Scale-up fuel cell manufacturing volume to address cost [2; α, σ, τ, Θ]
33. Limited long-term planar SOFC durability tests have been conducted [2a; μ]
34. Sodium borohydride fuel cell capabilities (e.g., reversible) [2; Σ, θ, Millennium Cell, Π]
    a. Corrosion issues

3. Technology Integration Development

35. Remanufacturing, reprocessing and requalifying process for BOP equipment [3a; ϕ]
36. Humidification/dehumidification technology [3a; θ]
    a. Desiccant dehumidifiers
37. Improved sensors, controls and instrumentation [3; α, Θ, θ]
    a. Low-cost
    b. Durable
    c. Fast-response
    d. Low power consumption
    e. Flexible operation conditions [3a; θ]
38. Development of phase change and other thermal energy storage materials (e.g., molten salts) [3b; θ]
39. Electrical storage systems for fuel cell hybrid system applications [3b; Θ, ω]
    a. Dynamic response
    b. Ultracapacitor development
    c. High-performance battery system development for next-generation vehicles [3a; ω]
        i. Innovative battery construction methods based on new concepts and materials

        ii. Technology to control battery reaction
        iii. Clarification of battery degradation mechanisms
        iv. Battery safety standards
        v. Standardized battery test methods

40. Solar cells and photocatalyst performance [3, 1; π]
    a. Understanding of light-induced dynamic processes
        i. Molecules
        ii. Polymers
        iii. Semiconductor nanoparticles
    b. Efficient light harvesting
    c. Charge separation
    d. Fuel formation
41. Understand the interaction of energy storage systems with intermittent renewables [3b; θ]
42. Grid harmonics and interference [3c; Russ Neal ICEPAG 2008]
43. Electricity transmission system integration [3c; λ]
    a. Finding appropriate real estate
        i. Health and safety of humans and wildlife
        ii. Most cost effective path from source to sink
    b. Implications of above and below ground lines
    c. Design and maintenance
    d. Sizing of sources and sinks
44. Electricity restoration duration for customers with and without DG [3c; DG DOE 1999]
45. Islanding safety and reliability [3c; DG DOE 1999]
46. Power reliability and security as distributed generation penetration increases [3c; Hamilton 2006, DG DOE 1999, Lopes 2007]
    a. Short term stability (first swing) [3c; Lopes 2007]
    b. Long term dynamic stability [3c; Lopes 2007]
    c. Voltage collapse [3c; Lopes 2007]

47. Diurnal electricity supply profile not constant [3c; λ]
    a. Increases load on grid (peak time)
    b. Not sufficient energy storage to smooth load profile
        i. Battery storage
        ii. Hydrogen storage
        iii. Water potential energy storage (pump storage)
48. Metering technology [3c; λ]
    a. Net
    b. Variable price
49. DG processes and techniques for interconnection into the electrical distribution network [3c; DG DOE 1999, ξ, χ, Lopes 2007, Σ]
    a. Plug-and-play interconnection solution [3c; ξ]
    b. Fit and forget policy as opposed to integration through planning of distribution networks [3c; Lopes 2007]
    c. Typical DG grid connection process
        i. Initial Contact with utility
        ii. Project information is transmitted to utility
        iii. Utility performs engineering analysis
        iv. Customer accepts and authorizes project
        v. Engineering/Project review meetings held
        vi. Project is engineered and constructed
        vii. Inspection of interconnection and protective equipment
    d. Process is dependant on location and affiliated utility
    e. Utility procurement opportunities [3c; Σ]

4. Fuels

50. Meet or exceed fuel processing application requirements [4; ϱ, Γ, θ]
    a. Water
    b. Minimize space needed (minimize volume) [4; Γ, ϱ]
    c. Transient capability
    d. Lifetime [4; θ]

e. Availability [4; θ]

f. Fuel flexibility [4; θ]

51. Lack of commercially available, low-cost hydrogen and alternative fuel technologies when compared to current technologies [4a, 4b; α, τ]

52. Increase hydrogen technology demonstrations [4a; α, ξ]

    a. Hydrogen technology proving ground [4a; ξ]

    b. Validate high-pressure tanks

    c. Validate cryogenic tanks

    d. Hydrogen production technologies

53. Focus on near-term end use of hydrogen before nationwide delivery infrastructure is installed [4a; α]

54. Locate fuel processing or reformation equipment near fuel source [4; Π, θ]

    a. Heat load often not at location of fuel generation (e.g., bio-gas for municipalities)

55. Experience and knowledge for maintenance and operation of hydrogen technologies [4a; α]

56. Hydrogen testing, validation and certification [4a; α, ϕ]

    a. Explore need for a governing organization

    b. Identify components requiring validation and testing protocols [4a; α, ϕ]

    c. Include representatives from insurance companies; government agencies; national laboratories; and industry

57. Hydrogen conversion performance data availability (especially for hydrogen engines and turbines) [4a; α, Garland1 2006]

    a. Efficiency

    b. Emissions

    c. Lack of real-world transportation component data [1b; Garland1 2006]

    d. Safety

58. Hydrogen pipeline design and performance [4a1; α, π, Γ, Θ, δ]

    a. Gas selection (e.g., multi-gas, hydrogen)

        i. Use current natural gas lines for hydrogen [4a1; Θ]

    b. Reduce capital costs [4a1; Γ]

    c. Ensure safety, reliability and durability [4a1; Γ]

d. Data for hydrogen pipeline design [4a1; α]

i. Cost

ii. Materials

iii. Leakage [4a1; δ]

59. Infrastructure requirements for different storage technologies [4a, 4b, 1b, 1c; α, Θ]

a. Flexibility of industrial filling plants to supply different fuels and larger volumes [4; Θ]

b. Chemical hydrides require unique infrastructure development [4a4; α]

i. Production technology

ii. Delivery technology

iii. Recycling technology

c. Hydrogen storage technology should be compatible with fueling infrastructure [4a4; α]

60. Improve efficiency and reduce emissions of fossil fuel hydrogen production [4a3; α]

61. Performance optimization with hydrogen storage devices [4a4; π, Θ]

a. Reversible storage materials (e.g., portable applications) [4a4; π, Θ]

b. Regenerative storage materials

62. Filling and discharging of storage device [4; α, Π]

a. Fill in-place storage devices [4; FC RD&D Workshop]

63. Develop large-scale hydrogen storage media production process [4a4; α]

a. Design and scale-up for volume and cost

i. Fuel cell vehicle introduction rate

ii. Low demand

b. Explore efficient mass production processes

64. High-pressure hydrogen storage technology (i.e., 5,000-10,000 psi) [4a4; α, ϕ, π, Γ, Δ]

a. Capable service pressure

b. Conformable or quasi-conformable shapes [4a4; ϕ, α, Γ]

c. Impact resistance

d. Integrated or embedded sensors

e. System costs

i. Reduce necessary carbon fiber and processing cost [4a4, 3a; ϕ, Γ]

ii. Establish high-speed filament winding process [4a4; Γ]

f. System integration

g. System packing (e.g., tubes)

h. Safety

i. Low energy density

j. Capacity or weight efficiency [4a4; α, ϕ]

65. Liquid fuel storage development [4a4; α, ϕ, Γ, Θ, Δ]

a. Reduce losses due to boil-off [4a4; Θ]

b. Integration with hydrogen production facilities [4a; Θ]

c. Improved insulation during transport and use [4a4; Δ]

d. Reduce cost of liquefaction [4a4; Γ, Θ]

e. Explore new approaches to liquefy hydrogen [4a4; Γ]

f. Cryogas tank development

i. Substitute for nickel alloy to reduce costs [4a4; ϕ]

g. Energy intensive

i. About one-third of energy is lost during conversion

ii. Handling requirements

iii. Requires cryogenic containers

66. Solid state storage development (e.g., metal and carbon structure) [4; α, ϕ, Γ, Θ]

a. Advanced solid storage material processing methods [4; ϕ]

b. Adsorption/desorption [4a4; α, Γ, Θ]

i. Alanates (better weight performance than metal hydrides)

ii. Carbon nanotubes are currently most promising carbon material

iii. Fundamental understanding of adsorption/desorption processes

iv. High-volume manufacturing for adsorption/desorption processes

v. Adjustable porosity [4a4; Γ]

c. Metal hydrides [4a4; α, Γ]

i. Find novel hydride materials [4a4; Γ]

1. Combinatorial testing

2. Molecular modeling screening methods

ii. Conformable shape

iii. Heavy storage media

iv. Capitalize on lower pressure operation for safer and lower cost operation

v. Requires thermal management

vi. Volumetric storage efficiency

67. Chemical hydride storage development [4a4; α, π, Γ, Δ]

a. Process cost

b. Process efficiency

c. Provide good volumetric storage efficiency

d. Provide increased safety since hydrogen is bound in solution

i. E.g., stored in liquid alkaline solution

e. Regeneration processes [4a4; Γ, Δ]

i. Product/spent material removal

ii. Waste product handling [4a4; Δ]

68. Understanding and optimization of fundamental hydrogen storage processes [4a4; α, π]

a. Alanates

b. Carbon adsorption (nanostructure)

c. Hydrides

69. Fuel distribution strategies [4, 1a2; Π]

a. On-site versus fueling stations

b. Changes resulting from market penetration of DG systems

c. Fuel transportation routing (e.g., multiple stops for fuel transportation vehicles)

70. Other new hydrogen storage technology development [4a4; α, Θ, π]

a. Storage technology improvements are likely; however, a breakthrough may be necessary

b. Technology selection for hydrogen storage using carbon nanotubes [4a4; π]

i. Purity (undoped)

ii. Single-walled

iii. Six weight percent of hydrogen material capacity

71. Concerns for bulk hydrogen storage [4a4; Γ, Θ]

a. Reduce footprint and increase capacity

b. Reduce cost

c. Maintain safe storage and operation

d. Explore possible bulk hydrogen storage options

i. Large-scale underground storage [4a4; Θ]

72. Address substantial cost of building a hydrogen infrastructure [4a; τ, ϕ, Γ, α]

a. Reduce hydrogen production and delivery costs [4a; ϕ, Γ]

b. Infrastructure investment is hindered without advanced hydrogen storage solutions [4a1, 1b, 1c; α]

c. High risk of hydrogen infrastructure investment due to technology status [4a; Γ]

d. Reduce hydrogen storage costs [4a4; α, ϕ]

e. Reduce raw materials cost [4a; α]

73. Establish a supplier base for hydrogen system manufacturing and components [4a; ϕ, Γ]

5. Other

74. Avoid "lock-in" technologies [5; Θ]

VI. Cross-cutting technology development and analyses

1. Market Applications

1. DOD Installation applications [1; θ, Binder 2006]

a. Stationary power applications similar to typical CHP

i. 11 central heat plants [2; Binder 2006]

ii. 7 hospital utility sites [2; Binder 2006]

iii. 3 pool/gymnasiums [2; Binder 2006]

iv. Others [2; Binder 2006]

1. Barracks
2. Dining facility
3. Laundry
4. National Guard armory
5. Launch control building
6. Office
7. Evaporator process

b. Logistics fuel requirements for mobile and transportation applications [4, 1; θ]

c. Soldier requirements

i. Weight

ii. Energy density

iii. Disposal

d. Battlefield requirements

i. Shock and vibration

ii. Thermal signature

iii. Acoustic signature

2. Development and application of computational tools to conduct safety studies [1; Θ]

3. Modeling fuel cell and absorption chiller systems [1a2a; κ]

4. Market feasibility assessment [1; θ, π]

a. Stationary power applications

b. Transportation power applications

c. Materials handling power applications

d. Episodic power applications

e. Portable power applications [1; π]

5. Modeling of gas turbine and fuel cell operation [1a3; γ, ζ, η]

a. Static and dynamic

b. Accurate models of equipment and integration

i. Model accuracy versus model stability and computational intensity

c. Accurate determination of time constants

d. Fuel cell reformation information, constants, data [1a3; ζ]

e. Control logic for feed forward and soft shutdown [1a3; η]

6. Identify potential funding sources [1; σ]

7. Conduct socio-economic study to aid in market and policy development [1; Θ]

a. E.g., employment, economic growth, competitiveness

b. Include intrinsic and extrinsic characteristic analyses

i. Intrinsic: hydrogen's physical properties

ii. Extrinsic: a given commodities effect on fuel cell marketability (e.g., oil, natural gas)

8. Energy and greenhouse gas intensity of new technologies [1; θ]

a. New fuels

i. Hydrogen

ii. Renewable fuels

iii. Other alternative fuels

b. Energy conversion devices

i. Fuel cells

ii. Turbomachinery

iii. Engines

iv. Renewable power

c. Energy storage devices

2. Fuel Cell Technology Specific Developments

9. Explore economic and environmental dispatch for fuel cell systems [2; θ, Θ]

a. Analysis of fuel cell value proposition

b. Potential impacts of hydrogen and fuel cell technology [4; Θ]

c. Long-term and short-term

10. Establish relationship between fuel cell performance and manufacturing parameters (e.g., variability) [2; ϕ, Σ]
    a. Using modeling tools can enhance product manufacturability
    b. Relationship between physical and performance properties of manufacturing MEAs [2c; ϕ]
    c. Influence of stamping components on fuel cell performance [2; Σ]
11. Understanding and optimization of fuel cell internal reformation [2a, 2b; Θ]
12. Understanding and development of material characterization methods [2; α, Θ]
    a. E.g., membrane degradation mechanisms
    b. E.g., understanding of advanced ceramic materials
13. Conduct a life-cycle cost assessment for stack, BOP and fuel storage areas [2; σ]
14. Electrochemistry modeling techniques [2; θ]
15. Thermodynamic fuel cell systems analyses [2; θ]
16. Thermodynamic fuel production and processing analyses [2; θ]
17. Dynamic fuel cell systems analyses and controls development [2; θ]
18. Advanced fuel cell sensors and instrumentation [2; Garland1 2006]
19. Need for technology development iterations [2; Harris 2006]
20. Fuel cell competition with other technologies [2; Wu 2006, Π, θ]
    a. Batteries [2; θ]
    b. Gas turbines
    c. Hybrid systems (e.g., plug-in vehicles)
    d. Biofuels (e.g., ethanol, biodiesel)
21. Design models for fuel cell systems [2; ϱ, Σ]
    a. Establish reliable operating space
    b. Guide manufacturing
    c. Integrate with modeling software (e.g., ASPEN) [2; Σ]
22. Identification and evaluation of fuel cell degradation mechanisms [2; υ, ω, Θ, Stone 2006]
    a. Quantify and qualify degradation mechanisms
    b. Understanding PEMFC membrane degradation [2c; Stone 2006]

c. E.g., PEMFC system degradation due to water transport [2c; υ]

3. Technology Integration Development

23. Develop an understanding for the interconnections between components, system costs, environmental impacts, social impacts and system trade-offs. [3; Γ]
24. Reliable measurements and standards to enhance quality control [3a; ϕ]
25. Modeling of integrated fuel cell and energy storage systems [3b; θ]
26. Electric utility grid network modeling [3c; λ, ξ]
    a. Lack of demonstration data
    b. Simplifications required to represent large grid models
        i. Inclusion of ancillary services
        ii. Inverted sources do not behave like inductive sources
    c. Without simplifications very computationally intensive

4. Fuels

27. Conduct a study on electrolysis to establish a focus on near-term development effort and goals [4a3, α]
    a. Efficiency
    b. Capital cost
    c. Product price
28. Modeling and simulation of hydrogen separation and purification processes and mechanisms [4a; π]
29. Customer demands for hydrogen and alternative fueling [4a, 4b; α, τ]
    a. Affordability
    b. Convenience
    c. Environmental friendliness
    d. Safety concerns
30. Modeling of containment vessel cost and vessel manufacturing [4a4, 3a; ϕ]
31. Assessment of the impact of hydrogen on the climate and atmosphere [4; Θ]
32. Life-cycle assessment of hydrogen storage systems [4a4; Γ]
    a. On- and off-board storage
    b. Hybrid system concepts

33. Life-cycle analysis for fuel delivery alternatives [4a1; α, Γ, Θ]
    a. Investigation of hydrogen management components needed at filling and fueling stations [4a; Θ]
    b. Cost of hydrogen delivery technologies versus conventional fuels
        i. Tube trailer weight and capacity
        ii. Low energy density of compressed hydrogen
        iii. Liquefaction energy requirements
        iv. Small-scale hydrogen production is not cost effective
    c. Determine the overall cost of delivery alternatives
        i. Address all fuel delivery points
        ii. Maintaining current fuel infrastructure
        iii. Existing infrastructure conversion for hydrogen use
34. Life-cycle assessment of hydrogen and alternative fuel production technologies [4a3, 4b; δ, Θ]
    a. Understanding of degradation mechanisms for fuel production systems [4a3, 4b; Θ]
    b. Explore environmental effects
    c. Will require data from production plants
    d. Will require more extensive biomass studies (different sources)

5. Other

VII. Technically related market, policy and education barriers

1. Market Applications

1. Access to affordable capital for new technology investment [1; θ, α]
    a. Hydrogen economy [4a; α]
    b. Fuel cells
    c. Carbon sequestration
2. Incentive contracts among multiple teams linked to achievement of milestones needed for commercialization as opposed to picking winning technologies [1; Simon 2006]
3. Institute regulations, codes and standards [1; α, σ, χ, Γ, ξ, Θ, π, ω]

a. Ensure distributed generation systems are valued appropriately [1; α, ξ]

i. Right to system information [1; ξ]

ii. Right to backup power [1; ξ]

b. Harmonization of national and international codes [1; α, π, ξ, σ, Γ, Θ]

c. Create standards agreements for fire insurance and building code officials

d. Material and process qualifying protocol [1; ϕ]

e. Nationwide interconnection agreements to allow connection to grid without punitive costs, policies or actions

f. Utilize local restrictions [1; Θ]

g. Enact emissions restrictions [1; Θ]

h. Deregulation to aid in the commercialization of fuel cell applications [1; ω]

i. e.g., carrying portable hydrogen fuel cells onboard aircrafts

4. Explore emissions trading effect on the energy market [1, 4; α]

5. Externality evaluation and valuation (e.g., carbon tax) [1, 4; α]

6. Market support [1; ξ, α, σ, Θ, χ, ψ, Ballard, δ]

a. Incentives and government mandates [1, 4a; α, σ, ξ, Θ]

i. Consider government incentives for new technologies

ii. Consider financial incentives for hydrogen delivery

iii. Explore need for fuel cell subsidies [1; Θ]

iv. Subsidy for "green" vehicles while commercial volume is achieved [1b, 1c; Ballard]

1. Clean fuel tax subsidy for users of hydrogen [1; σ]

2. Production incentives for hydrogen [1; σ]

v. Stimulate growth and investment incentives for key component developers/suppliers [2; Ballard]

vi. Short-term incentives will promote early fuel cell technology adoption [1; ξ]

1. Reduce capital costs [1; ψ]

vii. Use incentives to reduce risk for fuel cell investments [1; σ, χ]

1. Manufacturing [1; σ]

2. Large-scale fuel cell projects [1; χ]

b. Buy-down programs

c. Non-financial incentives

d. Consider general technology promotion (technology neutrality) [4a; δ]

7. Distributed generation market establishment [1a2; DG DOE 1999]

a. Baseload

b. Micro-grids

c. Peak shaving

d. Power quality

i. Premium power

ii. "Green" power

e. Standby/backup

8. Focus government involvement on low-carbon-emission and carbon dioxide capture and sequestration technologies [1a1b; α]

9. Creation and enforcement of permitting code, standards and regulations for DG [1a2; γ, β]

a. Output based standards

b. Must occur years before large-scale commercialization [1a2; β]

i. Interactive

ii. Time consuming

c. Emissions regulations

10. Standby, termination and other distribution charges [1a2, 3c; γ]

11. Optimize DG equipment depreciation schedule to maximize product value [1a2; γ]

12. Market awareness and acceptance [1; σ, α, θ, ψ, Θ, CHP Roadmap 2000]

a. Industry conservative stance on new technology [1; Wu 2006]

b. Establish high-volume demand to help address cost [1; α]

c. Industry needs to create consumer demand for hydrogen and hydrogen products [1, 4a; α]

d. Determine current public perception of fuel cell industry [1; Θ]

e. Identification and characterization of CHP markets [1a2; CHP Roadmap 2000]

    i. Industrial plants

    ii. Buildings

        1. Office and retail buildings; water and waste management facilities; and individual schools and hospitals.

    iii. District energy systems

        1. College campuses; hospital complexes; military bases; industrial plants

    iv. Federal facilities

f. Identification and characterization of transportation applications [1b, 1c; θ]

    i. Airplane

    ii. Busses

    iii. Cars

        1. Recreational vehicles (Cummins)

    iv. Lift devices (e.g., forklift)

    v. Auxiliary power systems

        1. Ships (primary power while in ports)

        2. Tractor trailers (i.e., overnight trucks)

    vi. Scooters

    vii. Locomotive

13. Include backup power applications in self-generation program [1d; Harris 2006]

14. Portable fuel cell vertical market integration [1e; Wu 2006]

15. State owned/run organizations as early adopters (e.g., government) [1; ξ, σ, Ballard]

    a. Gives fuel cells applications credibility

    b. Government research priority while in pre-competitive condition

    c. Provides research and funding

16. Adjustments to intellectual property provisions [1; ξ]

    a. Stimulate cooperative research programs

17. Coordinated management [1; ξ]
    a. Continuing consultation amongst government, industry and universities
    b. Government should choose lead national laboratories
    c. Coordinating role for White House
    d. Pursue development partners [1; σ]
        i. Strengthen geographic clusters
18. Long-term resource and education commitment for all levels [1; α, τ, σ, ξ, δ, Γ]
    a. Need to personalize the environmental situation and solution strategies [1; α]
        i. Consumers might think that there is no apparent need for change
    b. Education target audiences (education for most influential audiences is a higher priority) [1; δ, ξ, σ, χ, Γ]
        i. Consumers (residential, commercial, industrial)
        ii. Industry
        iii. Media
        iv. Multilateral institutions (World bank, development banks)
        v. Non-governmental organizations
        vi. Professional and trade associations
        vii. Public policy makers (federal, state, local)
        viii. Research and development community
        ix. Students and educators
            1. Kindergarten to grade 12
            2. Vocational
            3. Four-year engineering
            4. Advanced-degree students
    c. Participating organization
        i. Education agencies and boards
        ii. National Science Teachers Association
        iii. Textbook publishing companies

iv. U.S. Department of Education

d. Product recognition tag would be beneficial (e.g., energy star)

e. Incorporate training into demonstration projects and early product purchases [1; σ]

19. Concern over long-term equipment investment risk [1; Π]

a. Pass legislation to allow fuel cell assets to stay with the property (e.g., AB 811)

20. Develop a strategy for ensuring sufficient skilled labor for the fuel cell industry [1; σ, χ]

a. Develop certification program for fuel cell trades people [1; σ, χ]

b. Develop information to highlight career opportunities in the fuel cell industry

c. Industry development barriers due to shortage of advanced skills and training [1; χ]

2. Fuel Cell Technology Specific Developments

3. Technology Integration Development

21. Adjust regulatory framework and policies for DG integration into the distribution network [3c, 1a2; Lopes 2007, χ]

22. Need national or statewide grid interconnection standards [3c; ξ , DG DOE 1999]

a. Uniformity among codes and standards [1; ξ]

b. "Plug and Play" interconnection standards [1; ξ]

4. Fuels

23. Institute regulations, codes and standards [4; α, σ, χ, Γ, ω, Θ, Harris 2006]

a. Ensure fair treatment to stationary hydrogen customers from utility

b. Develop hydrogen codes and standards to ensure safety [4a; α, ω, Γ]

i. Qualification of liquid and gaseous hydrogen [4a; Θ]

ii. Safety installation and operation standards for hydrogen conversion systems

iii. Product safety codes for hydrogen devices

iv. Allow composite tanks as ground storage [4a; Harris 2006]

v. Expedite ASME to establish the code [4a; Harris 2006]

c. National and state policies for the expansion of hydrogen conversion device use

d. Establish consistent hydrogen technology policies [4a; α]

i. Come from policy makers not knowledgeable about hydrogen

ii. Conflicting or inconsistent regulations on all levels

iii. Current policies fail to capture true costs and impacts of our energy choices

iv. Public policy makers need to establish regulations that support hydrogen systems

v. Consistent and sustainable policies

24. Customer awareness and acceptance of hydrogen and alternative fuels once cost and performance issues are met [4a, 4b; α]

25. Economic strategy for progression from current fuel to an alternative fuel future (e.g., hydrogen) [4a, 4b, 1; α]

26. Low alternative fuel demand inhibits large production capacity [4; β]

a. Industry will not commit to large-scale research and production if there is no market for their product [4; α]

27. Institute hydrogen codes and standards [4a; τ, Γ, π]

a. Stimulate safe use, delivery and production of hydrogen

b. Include hydrogen in fuel gas codes [4a; π]

28. Explore possible hydrogen market opportunities [4a; δ, Π]

a. Use as a home fuel (e.g., hot water, space heating and cooking)

b. Use as a transportation fuel

29. Industry-government cost sharing programs for hydrogen with additional support from universities [4a; α]

30. Hydrogen market analyses [4a; α]

a. Need to provide understanding of potential for fuel cells and hydrogen combustion engines

b. Cost-competitive hydrogen conversion device development is hindered by market and institutional barriers

c. Financial risk compounded by competing technologies

d. Need to include externality costs (e.g., pollution, economic instability)

e. Profitability of business models for distributed energy systems and CHP

f. Substantial cost reductions

g. Value proposition for hydrogen over fossil fuels

31. Community acceptance of hydrogen amidst conflicting local, state and national interests [4a; α]

    a. Consumer confidence

    b. End-user expectation satisfaction

32. Determination of the social cost of alternative fuels [4a, 4b; α, Θ]

    a. Cost of pollutant emissions (e.g., CO_2, H_2, SO_x, NOx) [4a, 4b; α, Θ]

    b. Defined value for carbon

    c. Most benefits of fuel cell vehicles are societal in nature (e.g., emissions, energy security)

33. Hydrogen transportation technologies competition from hybrid electric and gasoline vehicles [4a; α]

34. Hydrogen infrastructure deployment strategy [4a1; α]

35. Addressing the hydrogen economy, chicken and egg dilemma [4a; α]

    a. Investments to achieve low costs

    b. Development of the market

36. Creation of a coalition to influence U.S. energy policy [4a; α, θ]

    a. Encourage regional partnerships and initiatives

    b. Establish hydrogen advocacy coalition

        i. Creation of public policies

        ii. Educational curricula

        iii. Removal of key market and regulatory barriers

        iv. Support public policies that encourage hydrogen technologies

    c. Organize informal caucuses

    d. Support continuous technology improvement

37. Access to accurate and objective hydrogen information [4a2; α , π]

    a. "Like all fuels, hydrogen can be handled and used safely with appropriate sensing; handling and engineering measures"

    b. Fear can come from lack of understanding

    c. Misinformation can cause unnecessary fear of hydrogen

d. Misconceptions about hydrogen can hinder its widespread acceptance

38. Long-term resource and education commitment for all levels [4a2, 4b; α, σ, δ, ξ, π, Θ]

    a. Need to personalize the environmental situation and solution strategies [4a2; α]

        i. Consumers might think that there is no apparent need for change

    b. Not everyone recognizes and understands the value of hydrogen as an energy alternative [4a2; α]

        i. Current hydrogen uses (highlight market readiness where applicable [4a2; δ])

        ii. Future hydrogen uses

        iii. Advantages of hydrogen

        iv. Relation to renewable resources

        v. Storage and safety concerns

    c. Develop hydrogen education and outreach program

        i. Should be done soon

        ii. Should include public relations and advertising campaigns (traveling hydrogen exhibits; online hydrogen databases and information centers; internet marketing materials and compact discs)

    d. Education target audiences (education for most influential audiences is a higher priority) [4a2; δ, ξ, Θ]

        i. Consumers (residential, commercial, industrial)

        ii. Industry

        iii. Media

        iv. Multilateral institutions (World bank, development banks)

        v. Non-governmental organizations

        vi. Professional and trade associations

        vii. Public policy makers (federal, state, local)

        viii. Research and development community

        ix. Students and educators

            1. Kindergarten to grade 12

2. Vocational
3. Four-year engineering
4. Advanced-degree students
    a. Hydrogen fellowship program for graduate-level interest

e. Hydrogen education packages
    i. Demonstration hardware
    ii. Experiments
    iii. Lessons plans
    iv. Videos

f. Participating organization
    i. Education agencies and boards
    ii. National Science Teachers Association
    iii. Textbook publishing companies
    iv. U.S. Department of Education

g. Product recognition tag would be beneficial (e.g., energy star)

h. Incorporate training into demonstration projects and early product purchases [4a2; σ]

i. Provide training on hydrogen for emergency responders and code officials [4a2; π]

39. Need coordinated national program to advance storage materials for hydrogen [4a4; α]

40. Fuel quality specifications [4; ξ]

41. Fuel delivery system right-of-way [4; π]

5. Other

42. Creation of emission standards [5; θ]
    a. CARB 2007 Emission standards

43. Reconciliation of simultaneous consumer desire for clean environment and affordable energy [5; α]

44. Reduce sales cycles by issuing requests to suppliers with pre-approved funds [5; Harris 2006]

a. Requests for quotation

b. Requests for proposal

45. Establish and maintain national energy policy priorities [5; τ]

Appendix D: List of Projects

Below are the tables containing all of the projects explored for this analysis and tables of additional comments from the participants for the surveys. Each project is separated into its respective category. Table 38 serves as an example for how the project tables will appear. The first two columns, the *Category* column and the project number (#) column uniquely determine a particular project. From questions in the survey specifically concerning cost and duration the *Average Project Cost* and *Average Project Duration* columns were determined. Similarly, the *Average Project Score* is an average of the score assigned to that project for every survey. The *Title* column contains a description for that particular project. Following the *Title* column are four columns that rank this project among other projects in its category and among all projects. The *Category Rank* column represents the rank of this project within its category (i.e., Balance of Plant in this case) and *Overall Rank* represents this project's rank among all projects evaluated. The *Cost Rank* and *Duration Rank* represent this particular project's rank among all other projects for cost and duration, respectively.

Table 39 introduces a more detailed description of each project. These descriptions were included in the surveys and are included now to prevent confusion about what is meant by each project. Finally, Table 40 presents an example of how the accompanying comments will be shown for each project. During the survey process stakeholders left comments to further describe their reasoning or to make an additional point, comments are included after the table of projects for each technology category.

Table 38: Project Table Example

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Balance of plant	2	3.67	3.33	65%	Further develop catalyst manufacturing technology (e.g., for use in reformers, fuel cells)	1	50	135	182

Table 39: Description Table Example

Project Number	Project Description
1	To establish public and consumer acceptance as well as stimulate demand for grid supporting fuel cell systems it is critical that more demonstration projects be pursued, with emphasis placed on those projects that are nearing commercialization…

Table 40: Comment Table Example

Category	#	Comments
Balance of plant	2	Standardizing and developing a GT that SOFC and MCFC can use can be a huge benefit - Standardizing and quality control standards are necessary

I. Market Applications Project Tables

1. Grid Support

1.1 Grid Support Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Grid support	2	6.82	3.69	84%	Augment deployment activities for grid supporting fuel cell systems	1	7	222	206
Grid support	1	6.73	3.46	84%	Intensify demonstration efforts for grid supporting fuel cell systems	2	8	220	195
Grid support	7	3.11	2.15	76%	Explore the effects of and need for reactive power and ancillary service support for grid supporting fuel cell applications	3	20	121	61
Grid support	6	6.64	2.99	73%	Transmission Integrated Grid Energy Resource (TIGER) station development and deployment	4	23	214	156
Grid support	5	6.02	3.49	73%	Develop and demonstrate grid supporting fuel cell power systems that operate on landfill gas	5	25	203	197
Grid support	8	6.07	3.92	63%	Provide development and deployment opportunities for integrated gasification fuel cell (IGFC) systems for central power generation	6	58	204	227
Grid support	4	2.75	2.81	60%	Explore the effects of replacing current grid support systems with fuel cells	7	71	104	135
Grid support	9	1.51	1.38	52%	Develop a value proposition for grid supporting fuel cells given competition with the current grid generation mixture in California	8	117	24	12
Grid support	11	1.89	2.57	48%	Explore the capability for hydrogen co-production from hydro-electric power plants	9	144	55	104
Grid support	3	1.94	2.47	46%	Further identify and develop markets for fuel cell grid support	10	154	56	97

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Grid support	10	6.60	3.92	46%	Further development and deployment activities for carbon capture and sequestration (CCS) with fuel cells in grid support applications	11	156	213	227

1.2 Grid Support Description Table

Project Number	Project Description
1	To establish public and consumer acceptance as well as stimulate demand for grid supporting fuel cell systems it is critical that more demonstration projects be pursued, with emphasis placed on those projects that are nearing commercialization. These projects can be used to garner real-world data that is essential to further product development and continue fuel cell technology validation for grid supporting applications. Demonstration sites provide an integral initial outlet for manufacturers to pursue high-volume production. As an example state owned and operated organizations and utilities represent optimum demonstration sites for new and emerging technologies.
2	Deployment of fuel cell grid supporting systems extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell products in California's grid supporting environment. Also, the products and services introduced should be supported for the life of the equipment.
3	Several markets have already been identified for fuel cell grid support applications, but in the early stages of product commercialization it is important that a variety of different markets be explored and developed. The introduction of new markets will serve to stimulate product development and production. Findings in one particular market can potentially provide benefit beyond just that market. In addition, an exploration of the current and future status for the technology will be invaluable in determining the most appropriate markets for each grid supporting fuel cell technology application.
4	When replacing the current energy generation systems with fuel cell based energy generation systems, it is essential that the consequences be evaluated and well understood. A feasibility study of this type can identify the best implementation strategy and targets that need to be reached to accelerate fuel cell system integration into the electrical distribution network.

5	Additional development and further demonstrations should be performed for fuel cell applications operating on landfill gas. This technology presents a unique synergy with the use of a waste product to generate useful work. Typically at landfill sites there is not a great need for electricity; therefore, the issue of exporting electricity from landfills to the electrical distribution network should be addressed during this project.
6	The TIGER station concept will provide electricity generation to specific areas thereby preventing the need for additional electrical transmission and distribution equipment. An exploration of the benefits of adding such a station along with identification of particularly applicable areas will be a critical step in pursuing grid support using fuel cell technology. When installed, these stations will provide a unique market opportunity for fuel cell systems and alternative options for utilities beyond purchasing additional transmission and distribution equipment.
7	To provide additional benefits to the utility, the electricity generation devices should be able to produce premium filtered and conditioned power. An exploration of reactive power and ancillary service requirements and opportunities will prove vital to the interconnection of fuel cell systems and the electricity distribution network.
8	Fuel cell operation with gasification technology expands the fuel flexibility of fuel cells; however, continued development and deployment for gasification technology and the integration of the two systems is needed to progress this technology to the commercialization phase. Gas separation and clean-up technology for fuels like coal synthesis gas are two key areas where gasification systems could benefit from developments. With superior fuel flexibility and a low emission signature from gasified fuels, IGFC technology can have a large impact on the central electricity generation mixture. In addition, system operation data from demonstrations and other deployment activities will prove invaluable for further system refinement.
9	A study comparing the value of fuel cells to the value of competition in the grid support sector will provide insights into the reasons to pursue fuel cells for grid support applications. Establishing the current status and all of the possible value that fuel cells have to offer in this market area is essential for market growth of fuel cells in this area. The value proposition for each fuel cell market will be dramatically different and therefore must be conducted for each market area.
10	The IPCC 2007 report reasoned that of the greenhouse gasses carbon dioxide has the greatest effect on global climate change due to the its large flux into the atmosphere and its long residence time. Since continued climate change is likely to have many negative impacts on the earth, it is vital that something be done to mitigate the release of carbon dioxide into the atmosphere. Carbon capture and sequestration presents an opportunity to reduce the amount of carbon products released into the atmosphere while a solution can be implemented to address the source of the carbon emissions. Due to the electrochemical operation of fuel cells, the fuel and oxidant streams remain separate, thereby simplifying the separation process for any of the constituent exhaust components. This is especially true for stationary grid supporting systems where an appropriate sink for the carbon dioxide can be found (underground reservoir, ocean, biogenic process, etc.). Development and deployment of this technology can provide a significant reduction of carbon dioxide emissions into the atmosphere and the continual need for more power generation will establish an increasing

	need for deployment activities.
11	To provide an alternative fuel to fossil-based fuels for power generation systems that fuel must be produced efficiently and cost effectively. Hydro-electric power plants present a possible opportunity for co-production of hydrogen and electricity. Conducting an analysis of the capability and amenability of hydro-electric plants to co-produce hydrogen will be an important step in exploring alternative fuel production for fuel cells in grid support applications.

1.3 Grid Support Comment Table

Category	#	Comments
Grid Support	3	This should be done if there are grid supporting markets that are unmet or inadequately met in California.
Grid Support	4	The effects will be good – Don't need environmental analysis
Grid Support	5	Since this technology has been tested before ensure that installations are unique and beneficial as demonstration sites.
Grid Support	5	Won't get the volume fuel cells need, but great application
Grid Support	6	Great early application. Tiger stations should be LOAD FOLLOWING and provide phase compensation (i.e., active power filtering).
Grid Support	8	Long ways away. Very challenging.
Grid Support	9	Project should consider CCHP.
Grid Support	11	Do not generate hydrogen from electricity - INEFFICIENT use electricity directly!!!!!
Grid Support	All	Investigate SOFCs for hydrogen/electricity co-production
Grid Support	All	Connections with renewable energies such as solar- and wind-power generations have to be systematically studied.
Grid Support	All	Long-term with stable manner is required to pursue the research of this area.

2. Distributed Generation and Combined Heat and Power

2.1 Distributed Generation and CCHP Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
DG/CCHP	4	7.72	3.32	85%	Augment deployment activities for fuel cell CCHP systems	1	5	237	180
DG/CCHP	3	7.79	3.26	83%	Increase fuel cell CCHP system demonstrations	2	12	238	175
DG/CCHP	5	7.05	3.10	79%	Intensify validation and demonstration efforts for using DG/CCHP fuel cells at DC data centers	3	18	225	161
DG/CCHP	12	1.30	1.30	78%	Develop a value proposition for fuel cell systems in the DG/CCHP market in California	4	19	13	8
DG/CCHP	2	3.07	2.44	74%	Grid connectivity of fuel cell CCHP and sale of electricity to the grid	5	22	120	94
DG/CCHP	10	6.25	3.25	72%	Intensify demonstration efforts for fuel cell and absorption chiller systems	6	28	206	173
DG/CCHP	7	2.30	2.27	71%	Simplify DG/CCHP system siting processes and requirements	7	33	87	71
DG/CCHP	1	2.20	2.43	70%	Determination of critical fuel cell DG/CCHP installation locations and corresponding design requirements (e.g., thermal and electrical profiles)	8	36	84	89
DG/CCHP	8	2.20	2.44	59%	Explore the optimum design for fuel cell CCHP and co-production systems in various applications	9	75	83	95
DG/CCHP	13	1.85	2.69	58%	Explore the requirements and the current feasibility of introducing dynamic fuel composition changes	10	78	53	125
DG/CCHP	14	1.85	1.82	58%	Modeling and analysis of fuel cell CCHP systems	11	82	54	26
DG/CCHP	6	2.43	2.86	52%	Characterize and optimize thermal and electrical profiles for use in DG/CCHP applications	12	112	90	148

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
DG/CCHP	11	6.53	3.79	47%	Design a fuel cell system and an absorption chiller system specifically for hybridization with each other	13	149	212	216
DG/CCHP	9	7.67	3.92	42%	Design and development of absorption chiller cycles and component configurations	14	176	230	227

2.2 Distributed Generation and CCHP Description Table

Project Number	Project Description
1	To stimulate better system design and expand the number of demonstration projects in the DG/CCHP area it is vital that two issues be addressed. The first issue is to locate both general areas (ex. office buildings, hotels) and specific areas (ex. Irvine waste water treatment plant) that are amenable to DG/CCHP applications. Once these locations have been identified it will be beneficial to characterize the design requirements for those locations. This information can greatly aid in furthering fuel cell DG/CCHP deployment activities.
2	As with other distributed energy generation technologies grid connection and use issues are of concern for fuel cell combined cycle systems. When designing one of these systems it is important that either electricity can be sold back to the grid if there is no energy storage capability or that the system is designed below the base load of its application. Developing products that can be easily integrated into the electrical distribution network is essential to furthering the distributed power generation market.
3	The combination of a fuel cell and a heat recovery unit increases the system efficiency while providing useful product(s) from previously wasted streams. To establish market presence, and gain public and consumer acceptance for DG/CCHP fuel cell systems it is critical that more demonstration projects be pursued. An emphasis should be placed on those projects that are nearing commercialization. These projects can be used to garner real-world data that is essential to further product development and continued fuel cell technology validation in the DG/CCHP market. Demonstration sites provide an integral initial outlet for manufacturers to pursue high-volume production. While the DG/CCHP market is growing and electricity distribution infrastructure is adapting to the resulting changes, state owned and operated organizations as well as the utilities represent

	optimum demonstration sites for these technologies.
4	Deployment of fuel cell combined cycle and co-generation systems extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell products in California's DG commercial environment. Also, the products and services introduced should be supported for the life of the equipment.
5	DC data centers represent a unique opportunity to showcase fuel cell performance and availability. Fuel cells used in DC data centers can provide advantages over many of the currently used technologies including: a higher electricity to heat ratio, DC power without costly inversion and conversion technologies, and lower pollutant emissions. Effort should be directed at providing safe, secure, reliable power while stimulating public and consumer acceptance of fuel cell technologies.
6	When designing CCHP systems the proper mating of the different technologies is essential to achieve the optimum performance over the life of the system. In order to do this, it is necessary to understand the available applications for CCHP technology and how these systems will be integrated. Also, knowledge about the transient response of CCHP equipment will prove helpful in system optimization. Well integrated and high performance distributed generation technologies are be more effective at competing with current technologies.
7	The process to install a DG scale fuel cell system is more complex than the installation of similar competing technologies. Standardization of the siting requirements and siting processes will greatly simplify the installation and operation protocol for DG/CCHP fuel cell systems. As more systems are deployed and confidence in the safety of the technology is instilled the process of siting DG/CCHP fuel cell systems will change.
8	Understanding the extent to which a particular fuel cell system can practice co-generation for varying conditions will greatly aid in fuel cell system design and selection. Also, understanding and characterizing the value of different products formed during co-generation will prove invaluable in determining the appropriate proportion of products to be created (how much heating/cooling is required, when can the excess energy be used to generate hydrogen, etc.). This information can be used to further optimize co-generation systems.
9	There is a need for additional research on absorption chilling cycles. The double and triple effect chillers shows promising results in terms of achieving similar performance to that of conventional electric chillers; however, the best order and number of components for these systems has not yet been established. Both modeling absorption chiller cycles and experimental testing will aid in further development of the chilling sector.
10	The combination of a fuel cells and an absorption chiller provide a system mating that provides a unique set of products (electricity and cool gas or liquid). With very few operational installations this combination of technologies does not have the proven reliability that other competing technologies enjoy. The installation of several of these systems will provide the much needed reliability assurance and data to aid in the further development and

	implementation of fuel cell and absorption chilling systems.
11	Finding the appropriate fuel cell and absorption chiller system designs can prove difficult for several reasons. First, a fuel cell's unique electrical to heat generation ratio establishes a distinctly new set of design parameters that must be considered when determining the fuel, power and cooling capacity for the system. In addition to the fuel cell and absorption chiller, there are other components like a desiccant dehumidifier or a cooling storage unit that can be included to increase the yield or efficiency of the system, but their introduction increases the complexity and maintenance required for that system. Finally, there are no absorption chillers specifically designed for use with fuel cells. Creating these combined cycle systems will be greatly simplified if there is more collaboration between fuel cell companies and the absorption chiller manufacturers.
12	A study comparing the value of DG/CCHP fuel cell systems to the value of similarly sized and matched competition will provide insights into the reasons to pursue fuel cells for DG/CCHP applications. Determining the current status and all of the possible value that fuel cells have to offer the DG/CCHP market area is essential for the market growth of fuel cells. The value proposition for each fuel cell market will be dramatically different and therefore must be conducted for each market area.
13	Knowing the effects and the ability of current fuel cell systems to operate on not only a variety of fuels but to dynamically change the fuel composition would expand the available operating conditions and marketability of DG/CCHP fuel cell systems. This study should explore techniques for transitioning between fuels, understanding of the effects on system performance and control strategies to optimize performance on dynamic fuel composition changes.
14	System modeling provides a unique opportunity to explore the potential for fuel cell combined cycle systems without completely designing and constructing the system. The modeling results will serve to discriminate between the values of different combined cycle system technologies and to highlight the benefit of employing a fuel cell combined cycle approach.

2.3 Distributed Generation and CCHP Comment Table

Category	#	Comments
DG/CCHP	1	Can be conducted in conjunction with specific companies' equipment to increase the cost sharing.
DG/CCHP	1	It seems to me that demonstration projects will also be very important, especially to gain design experience and learn how to optimize these new systems. However, it seems as though these projects are often already carried out, without much government involved required; thus, while it's important to keep the momentum going, I'm not sure how much extra push government agencies need to give. (Though, I could also see it as being entirely possible that the addition of more government support could be a "tipping point").

Category	#	Comments
DG/CCHP	2	The description and title seem a bit at odds. The title says "policies" but the description seems to look towards creating "products" rather than working with government and utilities to establish policies. I rated this project based on the idea that it is with regard to the former, making policies to more easily integrate DG/CCHP.
DG/CCHP	3	I believe that this technology has been demonstrated previously so the focus should be more on deployment and demonstrations for additional technology improvements.
DG/CCHP	3	I'm a little confused about how this differs from question 3. They seem to be very similar to me; thus I have rated them similarly.
DG/CCHP	4	This is the next step for DG/CCHP equipment manufacturers that have already demonstrated their products. Must ramp up manufacturing!
DG/CCHP	5	I think data centers are an excellent place for CCHP as well- there is a constant demand for cooling that can be met by sizing the unit to produce enough waste heat to drive a chilling cycling, using the power to support the data center, and presumably exporting the rest to the grid for additional support.
DG/CCHP	5	This is a unique application for FC DG/CCHP equipment.
DG/CCHP	5	This seems to be too specialized, and a bit against the idea of DG/CCHP, since it is deemphasizing the use of the waste heat. In addition, it seems that the most valuable use of the heat would be for Air Conditioning in these data centers, which would require an adsorption chiller. This brings in another budding technology that the public is not familiar with and could cause confusion as to whether or not is required for the FC, and will also inevitable raise the cost of any projects, which the public will view as negative.
DG/CCHP	6	For me this is a critical part that has to be done.
DG/CCHP	6	Thermal energy storage should be added to this project. Thermal energy storage may play a critical roll in future CHP deployment
DG/CCHP	6	While this seems like a good idea over all, it seems like it's more of a refining project, and other projects should deserve more concentrated attention than this one.
DG/CCHP	7	This seems like a "no-brainer." It seems like something that is very important, almost required, for success, and only really requires an investment of time to work between state agencies to establish policies and codes. The effect will then be broad and far-reaching.
DG/CCHP	8	A very important project too.
DG/CCHP	8	I don't think that the state should necessarily conduct this project.

Category	#	Comments
DG/CCHP	8	This seems like it would just be a part of any of the other design projects listed above. I do not believe it requires a separate project specifically for this step in the design project.
DG/CCHP	9	I don't think that the state should necessarily conduct this project.
DG/CCHP	9	This project seems like it will be very useful for certain applications and FC's; however, at the same time, it is akin to trying to develop both the FC and AC markets and technologies at the same time. Neither of these will be an inexpensive venture on their own, let alone together. I would be concerned about the cost-benefit ratio of this project. Perhaps it would be a good idea to be earmarked for a time when the AC market and technology seems to have had significant developments; thus, all that may be needed right now is to keep an eye on that market.
DG/CCHP	11	A single demonstration project of this type may prove useful to encourage the AC technology to develop more and in a direction towards FC use. However, I would not recommend many projects of this type.
DG/CCHP	11	I don't think that the state should conduct this project.
DG/CCHP	13	If there are few applications specifically suited for California then this could be a good DOE project as well. I believe that it would provide valuable FC functionality especially as more alternative fuels are used.
DG/CCHP	13	Important for opportunity and biomass fuels that have been critical in early fuel cell deployment
DG/CCHP	13	Seems like it's not a bad idea, but perhaps a little too much like "icing on the cake" to be pursued in the near-term. It should be pursued after many of the other projects are able to successfully demonstrate FC DG-CCHP in general.
DG/CCHP	14	I don't think that the state should necessarily conduct this project.
DG/CCHP	All	Any type of action related with cost reduction must be also addressed. (i.e., materials recycling).
DG/CCHP	All	Need to change public perception of the safe use and deployment of fuel cells/technology.
DG/CCHP	All	Educate people about the benefits and safety of fuel cells and the technology.

Category	#	Comments
DG/CCHP	All	There is a general difference between industrial and residential CHP. It is better from a thermodynamic point of view to avoid residential heating by better insulation and heat recovery and by using solar power for hot water and cooling (if possible). Finally the utilization time is usually low. In general industrial CHP is the much better solution (reaction entropy) and a high utilization time. Thus minimize heat losses and utilize heat recovery of the site/house first before installing CHP to supply "fresh" heat. Thermodynamically spoken the highest value is the production of power, thus the first priority is to maximize electric efficiency. Delivering reaction entropy for a chemical process (utilizing the FC waste heat) is also a good choice. Be careful with funding of operating plants, in Germany the funding of government only increased the prize of solar panels.
DG/CCHP	All	There are still fundamental issues with the performance, manufacturing, and stability of each of the fuel cell types that still need to be addressed. The given survey questions indicate that there are units that are a reasonable number of systems that are near commercialization for DG/CCHP applications. It is primarily molten carbonate systems that have been fielded commercially, targeted for specialized applications that can shoulder costs above competing energy technologies. Additional fundamental research is needed in addition to the more applied engineering that is the focus of this set of survey questions.
DG/CCHP	All	Should the state be funding additional fundamental research, or the applied research and demonstration activities that are the focus of this survey? What should the expectations be for return on investment in these technologies?
DG/CCHP	All	I think you have captured this wrt CHP/DG opportunity identification. If a database of Power, Heating and Cooling profiles at promising locations is made available, it will help CHP/DG manufacturers identify specific opportunities in California better. I am convinced (based on instinct- not documented facts) that there are a lot more opportunities for helping minimize energy consumption that are going waste because people haven't matched customer requirements with product attributes.

3. Fuel Cell – Gas Turbine Hybrid

3.1 Fuel Cell – Gas Turbine Hybrid Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
FC-GT Hybrid	10	7.69	3.83	91%	Intensify demonstration efforts for fuel cell - gas turbine hybrid systems	1	2	236	218
FC-GT Hybrid	13	1.03	1.83	82%	Develop a value proposition for fuel cell systems in the FC-GT hybrid market in California	2	14	4	27
FC-GT Hybrid	11	7.40	3.76	81%	Augment deployment activities for FC-GT hybrid systems	3	16	229	213
FC-GT Hybrid	12	6.27	3.71	72%	Explore operation of a fuel cell - gas turbine hybrid system on varying fuel compositions	4	27	207	207
FC-GT Hybrid	3	8.22	3.81	70%	Redesign gas turbines to be properly mated with fuel cells	5	34	239	217
FC-GT Hybrid	1	5.98	3.32	61%	Explore and optimize fuel cell - gas turbine system configurations	6	64	202	181
FC-GT Hybrid	2	5.40	3.71	55%	Explore the compatibility of fuel cell - gas turbine systems with other advanced technologies	7	94	187	207
FC-GT Hybrid	6	3.97	3.17	51%	Explore fuel cell - gas turbine systems for feed forward actions, soft shutdown, startup and load upset	8	122	154	168
FC-GT Hybrid	5	4.17	3.31	51%	Investigate effects and techniques for load following a fuel cell - gas turbine hybrid system	9	124	157	178
FC-GT Hybrid	7	4.37	3.47	46%	Investigate interaction of hybrid systems with one another and the grid	10	160	167	196
FC-GT Hybrid	14	3.93	3.25	36%	Explore the additional requirements and resulting benefits from operating gas turbines in fired or non-fired scenarios	11	208	153	174
FC-GT Hybrid	4	2.73	3.17	35%	Develop accurate equipment and equipment integration models	12	209	103	168

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
FC-GT Hybrid	9	3.21	3.29	25%	Establish understanding of cause and prevention methods for stall in a fuel cell - gas turbine hybrid system	13	230	125	177
FC-GT Hybrid	8	5.67	3.42	21%	Explore availability, lifetime and performance of fuel cell - gas turbine hybrid system components	14	237	190	194

3.2 Fuel Cell – Gas Turbine Hybrid Description Table

Project Number	Project Description
1	There are many different configurations that can be explored when developing fuel cell – gas turbine hybrid technology. These include general system configuration, component selection, design parameter selection, etc. In order to further the development of fuel cell – gas turbine technology it is critical that characterization of different system configurations be pursued. In this way, optimum configurations for different conditions can be explored. The results of this analysis can be used to design optimum hybrid systems that are particular to California's conditions.
2	To enhance the value proposition for fuel cell – gas turbine hybrid systems it is vital that their compatibilities with advanced technologies be explored. If hybrid systems are compatible with technologies like coal gasification, carbon sequestration, co-generation, etc. then they can provide more value on account of their versatility. Hybrid system flexibility can be explored both theoretically and experimentally through the use of modeling tools and experimental equipment, respectively.
3	Proper mating between the fuel cell and turbo machinery is essential to achieving maximum performance characteristics; however, there are no turbines or compressors designed specifically for use with fuel cells. The optimum operating range for the individual components in a fuel cell – gas turbine hybrid cycle can be very different from those of each separate system. As an example, for a fuel cell – gas turbine hybrid system where the gas turbine acts as balance of plant for the fuel cell, it is most important that the operating constraints of the fuel cell be met first and then the maximum power be drawn from the turbine. Identifying the modifications needed for optimum hybrid system operation and redesigning that equipment accordingly will prove invaluable in developing fuel cell – gas turbine hybrid systems.

4	System models can provide a great deal of understanding about how a system operates and give indications of key optimization areas. When developing system models to simulate system behavior access to design data is critical. Some of the most important data for exploring dynamic response in fuel cell – gas turbine hybrid systems are turbine and compressor maps. Integrating component design data into the models provides a level of verification for the models. Providing access to information of this kind can provide quicker and more complete system optimization in the form of parallel development. Developing accurate models for fuel cell – gas turbine hybrid systems will provide better understanding of the system and the potential for further system optimization. System equipment models should be constructed for steady state and dynamic operation.
5	For certain applications including peak-shaving and other variable power demand scenarios, it is essential that a fuel cell – gas turbine hybrid system be able to operate at a variety of load levels. This provides additional flexibility that expands the possible applications of fuel cell – gas turbine hybrid systems. Determining the load following capabilities of hybrid systems will include an exploration of appropriate system designs, component selections, control strategies, etc.
6	Appropriate dynamic operations and control during soft shutdown, startup and load upset are critical to addressing fuel cell – gas turbine hybrid system challenges. Unique actions may need to be taken during these dynamic events to ensure proper system operation. An exploration of system operation and control will establish the optimum conditions and control strategy for accommodating different dynamic situations.
7	Grid interaction with fuel cell – gas turbine hybrid systems is of great importance especially as more systems are commissioned. Exploring the effects of inserting hybrid systems into the grid will include evaluating topics like the power profile from the hybrid system, power signature (phase angle, voltage, harmonics), equipment availability, equipment maintenance requirements, etc. This investigation is critical for utility acceptance and will provide information that can be used to enhance the design of fuel cell – gas turbine hybrid systems.
8	There are many components required for the operation of a fuel cell – gas turbine hybrid system. Fuel cell – gas turbine hybrid systems present unique operation challenges that must be met by balance of plant equipment. The first step to developing improved hybrid components is establishing a benchmark for current component performance, lifetime, cost, etc. Next, an analysis should be undertaken to establish areas where improvements should be pursued. Lastly, actions should be taken to address the areas that were selected for improvement.
9	If the flow of air into the compressor is interrupted and no measures are taken to address this interruption, the compressor will stall. Stall can have a catastrophic impact on the turbo machinery and should be avoided. There are current prevention methods for compressor stall including design changes that allow for operation in the desired region of the compressor map and the use of bleed off valves. When gas turbine systems are combined with fuel cells, additional complexity for stall avoidance is introduced. The integration of fuel cells and gas turbine equipment for hybrid systems will require concentration on topics like system redesign and control strategy adjustments to avoid turbo machinery damage due to stall. Thus gaining an understanding of the causes and methods to prevent stall in hybrid systems is vital for successful operation.

10	To establish public and consumer acceptance as well as stimulate demand for fuel cell – gas turbine hybrid systems it is critical that more demonstration projects be pursued, with emphasis placed on those projects that are nearing commercialization. These projects can be used to garner real-world data that is essential to further product development and continue technology validation for fuel cell hybrid applications. Demonstration sites provide an integral initial outlet for manufacturers to pursue high-volume production. As an example state owned and operated organizations represent optimum demonstration sites for new and emerging fuel cell – gas turbine hybrid technologies.
11	Deployment of fuel cell – gas turbine systems extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell – gas turbine products for power generation in California. Also, the products and services introduced should be supported for the life of the equipment.
12	A fuel cell – gas turbine hybrid system that can operate effectively on different fuel compositions can be utilized for a variety of applications with minimal redesign. An exploration of the effects of operating a fuel cell – gas turbine hybrid system on different fuel compositions is vital to establish hybrid system fuel flexibility. Both fuel cells and gas turbines exhibit fuel flexibility so this analysis must focus on optimum hybrid system operation on a variety of fuels. Examples of fuel compositions for which hybrid system operation should be explored include blending hydrogen with other fuels, and biofuels.
13	A study comparing the value of FC-GT hybrid systems to the value of similarly sized and matched competition will provide insights into the reasons to pursue fuel cells for hybrid applications. Determining the current status and all of the possible value that fuel cells have to offer is essential for the market growth of fuel cells. The value proposition for each fuel cell market will be dramatically different and therefore must be conducted for each market area.
14	Additional benefits can be realized by changing the time that the gas turbine for a FC-GT hybrid system is fired. Determining the optimum firing strategy has the potential to cause emissions reductions (i.e., noise, criteria pollutant), economic savings and affect equipment lifetime. Firing strategies may also be specific to parameters like location, ambient conditions and legislation.

3.3 Fuel Cell – Gas Turbine Hybrid Comment Table

Category	#	Comments
FC-GT Hybrid	1	To cover all topics, and likely others that arise, a $10M project is needed and maybe more. Some should be possibly done independent of a full operable hybrid system. For others, enough basic system studies have already been done, and a full operable hybrid is needed.

Category	#	Comments
FC-GT Hybrid	1	Again, enough system studies have been done on this. A demonstrated hybrid system is needed. The $5M given is for a very small scale demonstration, just to show the functional integration. From that, full systems with expected efficiencies can be pursued.
FC-GT Hybrid	1	Could prove important for future use of FC-GT technology as well as all other technologies (e.g., carbon sequestration).
FC-GT Hybrid	1	Maybe not critical for early commercialization, but can be very important to broaden scope of the technology
FC-GT Hybrid	2	Should be addressed by an industry partner not necessarily the state.
FC-GT Hybrid	2	This seems like it would be a great project to pursue to open up this part of the gas turbine market and help hybrid systems be as effective as possible. However, gas turbine development has traditionally not be an inexpensive venture, and it seems that this one would not be either. I also wonder whether gas turbine development optimized for fuel cells will end up becoming too specified itself (i.e., for MCFC vs. SOFC, for internal vs. external reforming unit, for hydrogen vs. hydrocarbon fuel, etc...). This could dramatically increase the cost.
FC-GT Hybrid	2	While gas turbine technology is mature, it is expensive to design turbines, and it may be very configuration dependant. Given that the configuration is yet to be defined, caution is needed in pursuing this project so that it has broad impact when completed.
FC-GT Hybrid	3	Critical to understanding how these systems can be best operated. Would be beneficial to develop models to determine how FC-GT systems would best be put into California's electrical distribution network whereas fundamental system modeling should be left to industry and interested universities.
FC-GT Hybrid	3	Models already exist. Verifying them is the real issue. I agree that it is important to simultaneously do modeling while full demonstration systems are being pursued...both as input to the system design, and as follow-on model verification.
FC-GT Hybrid	3	This may meet with a lot of resistance from the current part manufacturers who seem to enjoy keeping this kind of information as proprietary.
FC-GT Hybrid	4	Early hybrid system will use natural gas. Natural gas is primarily used for load following. Hence load-following hybrid fuel cells on natural gas could be very attractive. Systems being currently developed can benefit rapidly from load following hybrid systems
FC-GT Hybrid	4	I think having a hybrid system operate at steady state would be a valid place to begin. I don't think it is time yet to consider load following requirements (except to the extent that typical perturbations need to be mitigated!)
FC-GT Hybrid	4	Thought should be given to providing the additional load-following functionality but the first step should be to develop highly efficient low cost FC-GT systems.

Category	#	Comments
FC-GT Hybrid	5	This seems to just be a subset of the above project.
FC-GT Hybrid	5	This work should be part of the demonstration work described above. Some independent work can be pursued as part of dynamic modeling where such controls are studied.
FC-GT Hybrid	5	Time frame is too far out - should be addressed by industry(s)
FC-GT Hybrid	6	This is a much-needed, though expensive, venture.
FC-GT Hybrid	6	I believe this is the kind of thing that these markets will identify and stress themselves as the fuel cell market expands. I don't see a need for the fuel cell market to pursue this project itself.
FC-GT Hybrid	6	It is critical to develop the balance of plant. However, industry should have experience with BOP and I do not feel this needs state funding.
FC-GT Hybrid	7	It is too early yet to concern ourselves with these. Let's get something serious demonstrated and operable first. Besides, much of these are 'basic engineering and design' issues. We first need to settle on the initial, leading, configuration that demonstrates hybrid systems.
FC-GT Hybrid	8	Causes for stall are sufficiently understood. This project should focus on mitigation strategies. Most likely they will be PREVENTION, if not ways to swiftly achieve component isolation.
FC-GT Hybrid	8	Only if fuel cell manufactures have this problem. Solutions exist, it is just a matter of how much techniques need to be developed.
FC-GT Hybrid	8	Another much-needed, though expensive, venture.
FC-GT Hybrid	9	Hybrid technology has already been demonstrated. If additional demonstrations are undertaken ensure that they are unique and beneficial (product development, novel FC-GT technology).
FC-GT Hybrid	9	We don't need to identify the 100% optimal first application. Just pick any application where it is reasonable to expect that hybrids will be used. It is simply important that hybrids move off of ground-zero.
FC-GT Hybrid	10	I'm not sure if the technology is developed enough yet to make this successful.
FC-GT Hybrid	10	Need demonstration first.
FC-GT Hybrid	10	Too early.

Category	#	Comments
FC-GT Hybrid	11	It is not important that a single design be demonstrated to have fuel flexibility at this point. We just need to get ONE hybrid system out on the market and get its 'experience'. The earlier we do that, the sooner we will move into other apps. Note, other work is going on that looks at fuel flex issues any way.
FC-GT Hybrid	11	Need to demonstrate on Natural gas first, then consider this.
FC-GT Hybrid	11	There are many applications where the most-desired (for the fuel cell's operation) fuel will not be available or cost-effective. Proving the ability (and improving the performance) of a fuel cell on these other fuels is critical, especially for early adoption.
FC-GT Hybrid	12	This project will have only some California specific implications and should be considered for federal research as well.
FC-GT Hybrid	12	This work should be a quick lead-in for the other projects. Perform a quick study to identify a viable first generation hybrid system. That gets that fully funded and out the door.
FC-GT Hybrid	12	Not enough impact for the effort at this time.
FC-GT Hybrid	12	To cover all topics, and likely others that arise, a $10M project is needed and maybe more. Some should be possibly done independent of a full operable hybrid system. For others, enough basic system studies have already been done, and a full operable hybrid is needed.
FC-GT Hybrid	13	Again, enough system studies have been done on this. A demonstrated hybrid system is needed. The $5M given is for a very small scale demonstration, just to show the functional integration. From that, full systems with expected efficiencies can be pursued.
FC-GT Hybrid	14	Could prove important for future use of FC-GT technology as well as all other technologies (e.g., carbon sequestration).
FC-GT Hybrid	All	Projects to improve fuel cell efficiency and endurance and develop low cost balance of plant(BOP) equipment
FC-GT Hybrid	All	The risk and the cost are due to the needed hardware
FC-GT Hybrid	All	In a FC/GT hybrid systems comprising both a turbine and a fuel cell operating at elevated temperature, unexpected materials stability issues will likely arise. Just as there is a need to explore the operation on alternative fuels, there is great need for evaluating the performance and stability of fuel cell materials sets when the FC is mated with a gas turbine.
FC-GT Hybrid	All	Again, there needs to be considerable attention paid to the core constituent materials and the impacts of using these materials sets in a FC/GT hybrid system.

4. Materials Handling

4.1 Materials Handling Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Materials handling	10	4.03	2.85	68%	Explore available methods and effectiveness of those methods to produce renewable fuel for use in materials handling applications	1	42	156	146
Materials handling	2	3.67	2.40	61%	Intensify fuel cell forklift and other lift demonstration efforts	2	68	135	81
Materials handling	3	3.33	2.43	61%	Augment deployment activities for fuel cell based lift systems (e.g., forklift, scissors lift)	3	69	132	90
Materials handling	4	5.28	2.72	56%	Develop and demonstrate fuel cell systems for auxiliary power units (e.g., ships, tractor trailers, recreational vehicles)	4	88	184	126
Materials handling	5	5.28	2.72	54%	Augment deployment activities for fuel cell powered auxiliary power units	5	107	184	126
Materials handling	8	2.67	2.64	49%	Develop a strategy for successful transition from current materials handling systems to fuel cells and fuel infrastructure	6	133	95	121
Materials handling	7	5.67	3.85	49%	Augment deployment activities for fuel cell powered locomotive systems	7	138	190	223
Materials handling	6	4.67	3.85	48%	Develop and demonstrate fuel cell systems to provide power for locomotives	8	139	171	223
Materials handling	11	1.64	2.41	44%	Investigate fuel provision and infrastructure opportunities for materials handling applications	9	171	42	82
Materials handling	13	3.83	3.10	37%	Design, develop, demonstrate and deploy fueling infrastructure for fuel cells supporting the materials handling sector	10	197	152	162

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Materials handling	1	1.15	1.50	36%	Identify and develop markets for materials handling applications using fuel cells	11	204	9	14
Materials handling	14	0.95	1.14	31%	Develop a value proposition for fuel cell systems in the materials handling market in California	12	218	3	7
Materials handling	9	1.67	2.00	29%	Explore fuel cell systems supporting materials handling applications design for operation on particular fuels	13	221	44	50
Materials handling	12	1.47	2.42	27%	Determine the compatibility of current and future fuel storage techniques for the materials handling fuel cells sector	14	227	22	88

4.2 Materials Handling Description Table

Project Number	Project Description
1	Many markets have already been identified for materials handling applications utilizing fuel cells, but in the early stages of product commercialization it is important that a variety of different markets be explored and developed. The introduction of new markets will serve to stimulate product development and production. Findings in one particular market can potentially provide benefit beyond just that market. In addition, an exploration of the current and future status for the technology will be invaluable in determining the most appropriate markets for each materials handling technology using fuel cells.

2	A major category for materials handling is forklift and other lift applications. The pursuit of more demonstration projects in the fuel cell forklift area will establish public and consumer acceptance for the technology. These projects can be used to gather real-world data that is essential to further product development while providing needed goods movement services. Demonstration and other deployment activities provide an integral outlet for manufacturers to pursue high-volume production, preferably for technologies that are nearing commercialization.
3	Deployment of fuel cell lift systems extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell lift products in California's materials handling environment. Also, the products and services introduced should be supported for the life of the equipment.
4	One major category for materials handling applications is for ship auxiliary power units. The pursuit of more demonstration projects in the fuel cell auxiliary power unit area will establish public and consumer acceptance for the technology. These projects can be used to gather real-world data that is essential to further product development and continue validation for fuel cell auxiliary power units. Demonstration and other deployment activities provide an integral outlet for manufacturers to pursue high-volume production, preferably for technologies that are nearing commercialization.
5	Deployment of fuel cell based auxiliary power units (APUs) extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell APUs in California's materials handling environment. Also, the products and services introduced should be supported for the life of the equipment.
6	A major category for materials handling applications is for main and/or auxiliary power of locomotives. The pursuit of more demonstration projects in the fuel cell powered locomotive area will elucidate the technology requirements while establishing public and consumer acceptance for the technology. These projects can be used to gather real-world data that is essential to further product development and continue validation for fuel cell locomotives. Demonstration and other deployment activities provide an integral outlet for manufacturers to pursue high-volume production.
7	Deployment of locomotives powered by fuel cell systems extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell powered locomotive products in California's materials handling environment. Also, the products and services introduced should be supported for the life of the equipment.
8	Currently, the materials handling power systems market is dominated by fossil-based fuel combustion engines (ex. propane) and battery power. It is vital for the continued growth, health, and development of materials handling power market that alternatives to fossil-based fuels are utilized. Fuel cells offer clean, quiet, and potentially more efficient power generation but in order to introduce a complete solution it must first be established that fuel cell based materials handling technology provides benefits over current technology including battery power. In addition, fuels for fuel cell based materials handling systems must have the potential to be produced renewably to achieve long-term market acceptance. An important step toward

	achieving that goal is to identify available alternative fuels that can be used by fuel cell based materials handling equipment and develop a plan to address technical challenges with increasing the production and use of those fuels. The importance of forward thinking in product development and installation will be invaluable for the future of materials handling fuel cell system commercialization.
9	Once potential fuels for materials handling systems using fuel cells are identified, it will be important to determine which fuel will provide the most benefit. For example, some fuels will require reforming but are easier to store than other fuels that may not require reforming. Given the unique requirements for materials handling applications, characterizing the performance and requirements for different fuels will provide great insight into the benefits and shortcomings of the use of those fuels.
10	In order to transition from current fuels for materials handling power generation applications to renewable fuels, technically and economically sound renewable fuel production methods must be explored. Development of current renewable fuel production techniques and the introduction of new fuel production techniques may be required to address the fuel supply issues for materials handling power applications. This will involve exploration of a range of different feedstocks including but not limited to biomass, solar energy, and waste streams.
11	Depending on the type of materials handling technology that is used, different fuel delivery and distribution systems will be required. Exploring the requirements for the provision of different fuels will be critical in establishing the necessary infrastructure to support fuel cell based materials handling applications. Determining the extent to which current infrastructure can be used and the need for unique delivery methods are very important topics to be explored in this project. Other topics of interest include the sale of these fuels, delivery methods, safety during transport and distribution, and component standardization.
12	Materials handling fuel cell power applications will require a method for storing their fuel. Exploring the viability of current storage techniques and the potential of future fuel storage techniques is essential to developing materials handling products that are superior to the current technology. This can include many different aspects of the storage device like the storage media, packaging, integration, etc.
13	Depending on the applications that are pursued for fuel cell based materials handling power generation, the fueling infrastructure will look distinctly different. For example the infrastructure deployment strategy for fueling a forklift will be very different than that required for fueling a tractor trailer auxiliary power unit. Thus there are fueling infrastructure challenges that will need to be addressed for each unique materials handling application. Identifying these challenges and addressing them is essential for growth in the materials handing sector.
14	A study comparing the value of materials handling fuel cell systems to the value of similarly sized and matched competition will provide insights into the reasons to pursue fuel cells for materials handling applications. Determining the current status and all of the possible value that fuel cells have to offer the portable market area is essential for the market growth of fuel cells. The value proposition for each fuel cell market will be dramatically

	different and therefore must be conducted for each market area.

4.3 Materials Handling Comment Table

Category	#	Comments
Materials handling	3	Fork lifts often operate non-stop and can utilize the attributes of FCs over batteries. Scissor lifts remain stationary for relatively long periods while the platform is used. Consequently, the promotion of FCs over lead acid batteries in scissor lifts seems to be unreasonable.
Materials handling	4	Though FCs may offer unique advantages for some APU devices, simple electrification of ports and truck stops can achieve lower emissions and GHGs at lower costs to CA.
Materials handling	5	Operate when the vehicle is stationary (overnight truck stop, port), so why use an expensive, sophisticated mobile device? The exception may be tractor-trailer refrigeration.
Materials handling	6	Due to the size of California's shipping industry FC locomotives provide a unique opportunity.
Materials handling	6	With congestion, gas prices, etc., trains will take on a greater transportation role. Trains engines are dirty. FC's need to be ready as train usage ramps up.
Materials handling	7	Important. A good future goal. But a relatively long time away.
Materials handling	8	We don't need to spend money to develop a transition strategy. Forklifts are a purely practical device (as opposed to a car that is often purchased on appearance, cache, etc.). As such, businesses will readily adopt any technology, FC or otherwise, that saves them or makes them money.
Materials handling	9	The project earlier prescribed renewable fuel. Now we're talking about reformation? Stick to batteries and propane. I don't want my tax dollars going towards a fuel with no environmental benefits. If industry wants the 24-7 operation capability of FCs using fossil fuel, let them pay for the R&D.
Materials handling	10	Renewable fuels specifically for materials handling should not necessarily be funded, but general renewable fuels research that may be applied to materials handling is a valuable endeavor.

Category	#	Comments
Materials handling	All	FCs for forklifts have been eagerly pursued by FC manufacturers because they see it as a near term market. This is good to establish FC technology in the marketplace, but does little to help Californians, unless the manufacturers are based here. In general, FC forklifts replace battery forklifts. This is not an environmental advantage. Let the manufacturers and users foot the bill for improved 24-7 operation and potentially lower manufacturing costs. On the other hand, FC trains or ships (propulsion) would be tremendously beneficial to CA residents.
Materials handling	All	Effective fuel processing schemes to generate syngas for fuel cell use. Gauge contaminant effects and tolerance
Materials handling	All	See comments in Episodic Survey re: metric for funding
Materials handling	All	Incentives (with enforceable penalties) provide strong technology development drivers. I do not believe that standards will have any impact on commercial viability and adoption of FC technologies.

5. Episodic Project

5.1 Episodic Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Episodic	9	6.43	3.37	76%	Development of regenerative fuel cell systems for episodic power applications	1	21	211	191
Episodic	8	1.35	1.35	69%	Develop a value proposition for fuel cell systems in the episodic market in California	2	38	14	9
Episodic	2	4.59	2.61	69%	Develop and demonstrate fuel cell systems for backup power applications	3	39	169	120
Episodic	5	5.57	2.85	64%	Augment deployment activities for fuel cell based peak shaving systems	4	53	188	147

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Episodic	7	1.99	1.91	59%	Explore the environmental effects of replacing current episodic systems with fuel cell systems	5	74	76	46
Episodic	6	1.63	1.96	57%	Further identify and develop episodic power markets	6	87	40	48
Episodic	3	5.04	2.78	56%	Augment deployment activities for fuel cell backup power systems	7	91	181	132
Episodic	4	5.79	2.98	52%	Develop and demonstrate fuel cell systems as peak shaving units	8	111	201	155
Episodic	1	3.67	2.00	27%	Develop and optimize fuel processing units for episodic power applications	9	226	134	50

5.2 Episodic Description Table

Project Number	Project Description
1	Episodic fuel cell power generation systems have unique fuel processing requirements due to the nature of how they are operated. Two general issues should be addressed to further fuel processor development for episodic applications. First, determination of the appropriate fuel(s) for varying applications will be a critical step in preparing for system optimization. Optimizing the fuel processor for episodic systems will improve system performance making fuel cells for episodic power more attractive
2	One major category of episodic power is backup power. The pursuit of more demonstration projects in the fuel cell backup power area will establish public and consumer acceptance for the technology and increased demand for fuel cell backup power systems. Demonstration project provide an integral initial outlet for manufacturers to pursue high-volume production, preferably for technologies that are nearing commercialization. These projects can be used to garner real-world data that is essential to further product development while providing the needed backup services. As an example state owned and operated organizations represent optimum demonstration sites for new and emerging technologies.
3	Deployment of fuel cell backup power systems extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell products in California's episodic power market. Also, the products and services introduced should be supported for the life of the equipment.

4	A major category of episodic power is peak power demand shaving. The pursuit of more demonstration projects in the peak shaving fuel cell area will establish public and consumer acceptance for the technology. These projects can be used to gather real-world data that is essential to further product development while providing the needed peak shaving services currently provided by natural gas and some hydroelectric plants. Demonstration projects provide an integral initial outlet for manufacturers to pursue high-volume production, preferably for technologies that are nearing commercialization. As an example state owned and operated organizations represent optimum demonstration sites for new and emerging technologies.
5	Deployment of fuel cell peak shaving systems extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell products in California's episodic power market. Also, the products and services introduced should be supported for the life of the equipment.
6	Markets have already been identified for episodic fuel cell applications, but in the early stages of product commercialization it is important that different and potentially beneficial markets be explored and developed. The introduction of new markets will serve to stimulate product development and production. In addition, an exploration of the current and future status for the technology will be invaluable in determining the most appropriate markets for each episodic fuel cell technology application.
7	Fuel cells typically produce power cleaner, quieter and more efficiently than competing combustion technology, but how significant is this advantage and to what extent do the benefits extend to the episodic power area. To verify the environmental benefits of using fuel cells in episodic systems it is necessary to explore the environmental effects from operating various types of episodic technology for different episodic applications. A comparison between competing technologies including combustion engines, fuel cells, batteries, etc. should be conducted to identify the areas where fuel cells will provide the most benefit considering both current and future technology development.
8	A study comparing the value of episodic fuel cell systems to the value of similarly sized and matched competition will provide insights into the reasons to pursue fuel cells for episodic applications. Determining the current status and all of the possible value that fuel cells have to offer the episodic market area is essential for the market growth of fuel cells. The value proposition for each fuel cell market will be dramatically different and therefore must be conducted for each market area.
9	Fuel cells can be used in many different hybrid configurations. One of the promising applications for fuel cell hybrid systems in episodic power applications is regenerative systems. Regenerative systems use a fuel cell to make power during certain times and use solar or wind power to regenerate the hydrogen consumed during the fuel cells operation. These systems can have relatively high capacity factors while operating on an intermittent power source.

5.3 Episodic Comment Table

Category	#	Comments
Episodic	4	Replacing natural gas peak shaving plants with higher efficiency fuel cell plants presents an interesting opportunity especially for California. It still remains to be seen the effectiveness (economic and performance) of fuel cell peak-shaving plants versus natural gas. I think that there are other areas where the funding can be better served. Competing against grid equipment is difficult due to its high efficiency and large scale.
Episodic	6	This could prove useful but should be done by companies rather than the state unless a specific market need is not being met or explored.
Episodic	7	Establishing environmental benefit for FC in episodic applications might help to meet some state requirements while providing a niche market for FCs.
Episodic	9	Regenerative systems are a great idea but can be economically preclusive as they increase the payback period of the equipment. Episodic could provide a good test bed for this since it is operated intermittently; however, no reliability can be sacrificed.
Episodic	All	Electric storages as batteries and super-capacitors combined with FC

6. Portable

6.1 Portable Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Portable	1	3.23	2.54	73%	Intensify demonstration efforts for portable power applications	1	24	126	101
Portable	2	2.79	2.66	71%	Augment deployment activities for portable fuel cell power systems	2	32	105	123
Portable	8	1.98	2.42	57%	Determine the compatibility of current and future fuel storage techniques for portable fuel cell power applications	3	84	58	84
Portable	3	1.77	2.45	56%	Further identify and develop markets for portable power	4	89	49	96
Portable	5	3.99	2.81	56%	Explore portable power fuel cell systems design for operation on particular fuels	5	93	155	135
Portable	7	2.11	2.48	51%	Investigate fuel provision and infrastructure opportunities for portable fuel cell power applications	6	127	79	98
Portable	10	1.03	1.03	49%	Develop a value proposition for fuel cell systems in the portable power market in California	7	135	4	2
Portable	4	3.01	2.64	48%	Develop portable fuel cell sector vertical market integration	8	140	118	122
Portable	6	1.67	2.60	46%	Explore available methods and effectiveness of those methods to produce renewable fuel for use in portable power applications	9	158	43	118
Portable	9	3.11	2.29	29%	Explore technology paradigms and systems integration for fuel supply devices in portable applications	10	220	122	72

6.2 Portable Description Table

Project Number	Project Description
1	To establish public and consumer acceptance as well as stimulate demand for portable fuel cell systems it is critical that more demonstration projects be pursued, with emphasis placed on those projects that are nearing commercialization. These projects can be used to garner real-world data that is essential to further product development and continue fuel cell technology validation for portable applications. Demonstration sites provide an integral initial outlet for manufacturers to pursue high-volume production. As an example state owned and operated organizations represent optimum demonstration sites for new and emerging portable fuel cell technologies.
2	Deployment of portable fuel cell systems extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of portable fuel cell products in California's portable power market. Also, the products and services introduced should be supported for the life of the equipment.
3	Several markets have already been identified for portable fuel cell applications, but in the early stages of product commercialization it is important that a variety of different markets be explored and developed. The introduction of new markets will serve to stimulate product development and production. Findings in one particular market can potentially provide benefit beyond just that market. In addition, an exploration of the current and future status for the technology will be invaluable in determining the most appropriate markets for each portable fuel cell technology application.
4	In order to increase market penetration of portable fuel cells it is essential that portable fuel cell equipment be compatible with current devices. This will involve communication and collaboration with the portable equipment supply chain in an effort to ensure that portable fuel cell systems are standardized according to previously developed portable systems.
5	Once potential fuels for portable fuel cells are identified, it will be important to determine which fuel will provide the most benefit. For example, some fuels will require reforming but are easier to store than other fuels that may not require reforming. Characterizing the performance and requirements for different fuels will provide great insight into the benefits and shortcomings of those fuels for various portable fuel cell applications.
6	In order to transition from current fuels for portable power generation applications to renewable fuels, technically and economically sound renewable fuel production methods must be explored. Development of current renewable fuel production techniques and the introduction of new fuel production techniques will be required to address the fuel supply issues for portable power applications. This will involve exploration of a range of different feedstocks including but not limited to biomass, solar energy, and waste streams.

7	Depending on the type of portable fuel cell technology that is used different fuel delivery, and distribution systems will be required. Exploring the requirements for the provision of different fuels will be critical in establishing the necessary infrastructure to support portable fuel cell applications. Determining the extent to which current infrastructure can be used and the need for unique delivery methods are very important topics to be explored in this project. Other topics of interest include the sale of these fuels, delivery methods, safety during transport and distribution, and component standardization.
8	Portable fuel cell power applications will require a method for storing their fuel. Exploring the viability of current storage techniques and the potential of future fuel storage techniques for portable fuel cell power generation is essential for developing portable fuel cell products. This can include many different aspects of the storage device like the storage media, packaging, integration, etc.
9	Many issues arise when dealing with the distribution of fuels for portable applications. Examining where the current fuel distribution technology is trending toward and continuing development and standardization of this technology will be instrumental in providing a complete solution for portable fuel cell applications.
10	A study comparing the value of portable fuel cell systems to the value of similarly sized and matched competition will provide insights into the reasons to pursue fuel cells for portable applications. Determining the current status and all of the possible value that fuel cells have to offer the portable market area is essential for the market growth of fuel cells. The value proposition for each fuel cell market will be dramatically different and therefore must be conducted for each market area.

6.3 Portable Comment Table

Category	#	Comments

Category	#	Comments
Portable	4	Product compatibility should be done by manufacturers. The compatibility requirements could be developed by the state.
Portable	6	Renewable fuels could be better used for other markets than portable power (e.g., grid support, DG/CCHP).
Portable	8	Fuel selection and storage for portable applications are important concerns but is not necessarily a California specific problem.
Portable	9	Standardization work could be done by the state.
Portable	All	Fuel cells that can directly oxidize fuels such as methane, propane, gasoline and diesel (with out a fuel processor) for power production.
Portable	All	This will be strongly supported by the military market. there are developments on the market therefore it is questionable to increase funding
Portable	All	Quite a bit of work has been done to explore possibilities for portable power FC devices. DOD is fielding an SOFC system running on propane, and many direct methanol systems have developed and demonstrated. A vision of new opportunities needs to be laid out. Putting limited funding into this area after the substantial previous investment federal government and industrial entities does not seem to offer great promise. However, incentives may provide a needed driver for new technologies (regulations on sale and recovery of batteries, etc).

7. Transportation

7.1 Transportation Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Transportation	8	6.40	4.05	72%	Intensify development and demonstration of hydrogen fueling stations	1	29	208	233
Transportation	9	6.40	4.25	70%	Augment deployment activities highlighting hydrogen fueling stations	2	35	208	241
Transportation	6	3.27	3.22	65%	Engage in demonstrations to highlight hydrogen-fueled vehicles	3	49	127	172
Transportation	3	6.77	3.87	64%	Increase demonstration projects for heavy duty on-road fuel cell vehicles	4	57	221	225
Transportation	4	6.66	3.91	51%	Increase deployment activities for heavy duty on-road fuel cell vehicles	5	123	215	226
Transportation	7	5.00	3.92	51%	Augment deployment activities highlighting hydrogen-fueled vehicles	6	125	178	227
Transportation	14	2.73	2.55	47%	Establish the vehicle-to-grid impacts for fuel cell and fuel cell hybrid vehicles	7	148	102	103
Transportation	2	6.68	4.07	46%	Increase deployment activities for light duty on-road fuel cell vehicles	8	159	219	235
Transportation	1	6.41	3.77	45%	Increase demonstration projects for light duty on-road fuel cell vehicles	9	164	210	214
Transportation	5	6.11	4.42	37%	Design fuel cell vehicle including storage technology to achieve appropriate range (ex. 200-250 miles)	10	200	205	242
Transportation	10	2.89	2.85	34%	Establish an implementation plan to achieve optimum hydrogen vehicle and station distribution	11	211	109	145
Transportation	16	2.17	0.92	24%	Explore the benefits of fuel cell - battery hybrid systems in transportation applications	12	231	82	1
Transportation	11	2.84	2.58	24%	Further develop and explore the effectiveness of long distance hydrogen transport and storage	13	234	107	105

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Transportation	13	1.51	3.33	23%	Explore the effect of emissions trading on the fuel cell transportation sector	14	236	25	182
Transportation	15	1.98	1.03	12%	Develop a value proposition for fuel cell systems in the transportation market in California	15	246	59	2
Transportation	12	1.67	2.42	5%	Identify and further develop markets for on-road transportation	16	250	46	84

7.2 Transportation Description Table

Project Number	Project Description
1	A major category for transportation fuel cells is light duty on-road vehicle applications. The pursuit of more demonstration projects in the transportation fuel cell area will establish public and consumer acceptance for the technology. These projects can be used to gather real-world data that is essential to further product development for fuel cell powered light duty on-road vehicles. Demonstration and other deployment activities provide an integral outlet for manufacturers to pursue high-volume production, preferably for technologies that are nearing commercialization. Pursuing fuel cell demonstration projects will require simultaneous development of a fueling strategy the extent of which will vary significantly depending on the choice of fuel. In addition, state owned and operated fleets represent potential demonstration sites for new and emerging light duty on-road vehicle technologies.
2	Deployment of light duty on-road transportation vehicles extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell products in California's commercial transportation environment. Also, the products and services introduced should be supported for the life of the equipment.
3	Another major category for transportation fuel cells is heavy duty on-road vehicle applications (e.g., buses, trucks). The pursuit of more demonstration projects in the transportation fuel cell area will establish public and consumer acceptance for the technology. These projects can be used to gather real-world data that is essential to further product development for fuel cell powered heavy duty on-road vehicles. Demonstration and other deployment activities provide an integral outlet for manufacturers to pursue high-volume production, preferably for technologies that are nearing commercialization. Pursuing fuel cell demonstration projects will require simultaneous development of a fueling strategy the extent of which will vary significantly depending on the choice of fuel. In addition, state owned and operated fleets represent optimum demonstration sites for new and emerging heavy duty on-road vehicle technologies.
4	Deployment of heavy duty on-road transportation vehicles extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell products in California's commercial transportation environment. Also, the products and services introduced should be supported for the life of the equipment.
5	To increase the market acceptance of fuel cell on-road vehicle technology it is critical that fuel cell vehicles have similar or superior performance characteristics when compared to the current technology, internal combustion engines. For fuel cell vehicle systems to achieve a similar driving range as competing technologies it is necessary to do two things. First, identify the desired driving range and second, explore redesign and

	development options to allow fuel cell vehicles to achieve the desired driving range.
6	Hydrogen-fueled fuel cell vehicles present a clean and efficient alternative to current transportation systems. The pursuit of demonstration projects in the hydrogen-fueled fuel cell vehicle area will establish public and consumer acceptance for the technology. In addition, demonstration and other deployment activities provide an integral outlet for manufacturers to pursue high-volume production, preferably for technologies that are nearing commercialization. State owned and operated fleets represent optimum demonstration sites for new and emerging hydrogen-fueled fuel cell vehicle technologies.
7	Deployment of hydrogen-fueled vehicles extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fuel cell products in California's commercial transportation environment. Also, the products and services introduced should be supported for the life of the equipment.
8	Intensifying demonstration projects for hydrogen supply stations will establish public and consumer acceptance for the technology. These projects will provide much needed data that is essential to further product development for hydrogen fuel delivery and supply. Some of the pertinent data will include, pumping capacity needs, system losses, and station safety. Pursuing hydrogen station demonstration projects will be most effective with the simultaneous implementation of hydrogen fueled vehicles.
9	Deployment of hydrogen fueling stations extends beyond alpha and beta testing, which would be considered a demonstration activity, and focuses more on commercially viable, high-volume production. This project should result in an increase in the number of fueling stations in California's commercial transportation environment. Also, the products and services introduced should be supported for the life of the equipment.
10	An exploration of the best locations to introduce fuel cell vehicles and refueling stations presents an interesting technical challenge. Stations must be located so that all local hydrogen vehicles can be fueled conveniently. Another issue is with the use of portable hydrogen distribution stations. These stations do not convey the idea of a permanent solution to the transportation fuel challenges but can be effective in providing convenient access to hydrogen fueling. The development of a plan to optimize the distribution and location of hydrogen vehicles and stations, both portable and permanent, in California will prove invaluable to the future of the fuel cell based transportation sector.
11	In addition to providing clean and efficient fuel conversion and production technology, it is essential that fuel delivery techniques be evaluated. The importance of addressing the technical challenge of transporting large amounts of hydrogen efficiently will become more pronounced as the demand for hydrogen increases. Thus providing solutions to long distance transport and storage of hydrogen will provide a vital step toward widespread fuel cell vehicle commercialization.
12	Many markets have already been identified for on-road transportation applications utilizing fuel cells, but in the early stages of product

	commercialization it is important that a variety of different markets be explored and developed (economy car, SUV, crossover, etc.). The introduction of new markets will serve to stimulate product development and production of fuel cells. Findings in one particular market can potentially provide benefit beyond just that market. In addition, an exploration of the current and future status for the technology will be invaluable in determining the most appropriate markets for each fuel cell based transportation technology.
13	Before replacing the current energy generation systems used to power the electricity grid with fuel cell based energy generation systems, it is essential that the consequences be evaluated. A feasibility study of the effects of emissions trading on the transportation sector can identify the best implementation strategy and targets that need to be reached to accelerate fuel cell transportation systems integration into the current transportation portfolio. The implementation of emission regulations and an emissions trading structure will provide additional incentives for purchasing cleaner, low emission technologies like fuel cell vehicles.
14	Understanding and anticipating the effects of the introduction of fuel cell and fuel cell hybrid vehicles onto the distribution network for charging is a critical issue that needs to be addressed before an increase in market penetration of fuel cell vehicles can be realized. Conducting a detailed vehicle-to-grid impact analysis will provide the needed information and understanding of fuel cell vehicle effects to further optimize fuel cell vehicle design and control. Included in a vehicle-to-grid analysis will be an exploration of grid connection and recharging strategies. Development of advanced vehicle recharging strategies will prove essential for optimizing the vehicle-to-grid interconnection, especially as the number of on-road fuel cell vehicles increases.
15	A study comparing the value of transportation fuel cell systems to the value of similarly sized and matched competition will provide insights into the reasons to pursue fuel cells for transportation applications. Determining the current status and all of the possible value that fuel cells have to offer the transportation market area is essential for the market growth of fuel cells. The value proposition for each fuel cell market will be dramatically different and therefore must be conducted for each market area.
16	The synergy of a fuel cell – battery hybrid system could address the efficiency and power demand requirements that prevent fuel cell transportation systems from providing the necessary performance at a similar or lower cost as current transportation power systems. An analysis of varying system configurations will prove invaluable in optimizing a fuel cell – battery hybrid system. These configurations can include adjusting the size of the fuel cell and the size of the battery. Also evaluating the consequences of connecting to the grid for charging the batteries or generating hydrogen with an electrolyzer would provide valuable insight into the benefits of fuel cell – battery hybrid systems.

7.3 Transportation Comment Table

Category	#	Comments

Category	#	Comments
Transportation	2	I think stationary fuel cell research has a higher benefit to cost ratio and should be addressed before or in concert with transportation.
Transportation	3	Heavy duty vehicle emissions are consistently ignored, yet contribute significantly to overall emissions. Any route to address this should be pursued.
Transportation	4	I don't think heavy duty FC applications are near the "deployment" stage. If I'm wrong, then by all means, fund it!
Transportation	5	200 mile range is already being achieved, though this may not be enough for market acceptance. The goal must be significantly higher (350-400 miles) for consideration.
Transportation	5	This should be conducted by the automotive manufacturers.
Transportation	7	Must be developed in conjunction with filling stations.
Transportation	7	This is similar to a previous question on light duty FC vehicles. What is the difference? You're putting me in double-jeopardy here. I fear my answers won't be identical to those above and I'll look like a liar!
Transportation	9	Criteria in current phase should not be related to renewables
Transportation	10	Given that the technology will continue to develop, be improved upon, best if not investing solely in permanent stations but mobile ones as well in order to keep costs as low as possible.
Transportation	10	Market may decide.
Transportation	12	This is brand strategy of each car manufacturer.
Transportation	13	This is something the state should pursue, though it should be technology neutral and not unduly favor FCs.
Transportation	15	I think this is an important goal for the state, energy companies, and manufacturers as they pursue one technology over another. But, in the end, I don't think consumers will care. It is up to OEMs (perhaps due to state mandates) to produce the cleanest, most efficient vehicles. SUV sales demonstrate that simply knowing the facts between vehicles will not sway the marketplace.
Transportation	16	FC plug-ins appear to be the ultimate environmental personal transportation choice (unless "super" batteries are developed in the near term) and should be pursued accordingly.

Category	#	Comments
Transportation	16	This should be left to the car manufacturer. Anyone knowledgeable in the field should be able to understand the differences without the help of a study.
Transportation	All	Manufacturing R&D. This is essential to ultimately lower FC stack cost and could help establish knowledge base/manufacturing capability in CA.
Transportation	All	Addressing on-board reforming of transportation fuels
Transportation	All	Aviation and space fuel cells may fall into this category and may help in the acceptance of other transportation-based fuel cells, as well as provide benefits to their vehicles. While there are not many feasible aviation applications, there are some that fit well with fuel cells and hybrids.
Transportation	All	Many of the proposed projects are being conducted or has been conducted by DOE, CaFCP, CAH2Net, UC Davis, esp. question #7. Also, national labs and OEMs are working on storage so may not need to focus there (question 5).
Transportation	All	There is a need for nuanced emission regulation framework that balances CO2 and local emission concerns on a W2W basis. I think more work can be done to optimize the return from specific regulations.

8. Market Cross-Cutting

8.1 Market Cross-Cutting Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Market cross-cutting	4	2.00	2.03	62%	Establish a study that evaluates the needs and opportunities for implementing subsidies, buy-downs, other incentives and mandates to support fuel cell development and commercialization	1	60	77	52
Market cross-cutting	12	3.60	3.13	59%	Establish a study that develops a strategy for a California state-wide transition to greater use of alternative fuels in fuel cell power systems	2	73	133	166
Market cross-cutting	3	1.63	2.76	55%	Develop appropriate fuel cell system standards, policies and codes	3	97	41	131
Market cross-cutting	13	2.87	2.52	55%	Conduct a study to determine how fuel cell technology can be used to enable more significant use of intermittent renewable power generation	4	98	108	100
Market cross-cutting	14	2.15	2.05	54%	Explore the potential for fuel cell systems to reduce criteria pollutants and greenhouse gas emissions throughout California	5	103	80	53
Market cross-cutting	9	1.54	2.42	54%	Conduct a socio-economic study of fuel cell technologies to aid in market and policy development	6	106	34	84
Market cross-cutting	1	5.67	3.40	48%	Support development of technical capabilities and expanded relationships between fuel cell original equipment manufacturers (OEMs), installation and service companies, parts suppliers, and systems integrators in California (i.e., supply chain)	7	142	198	192
Market cross-cutting	2	5.67	3.77	46%	Development of fuel cell system subcomponent supply chain	8	155	198	215

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Market cross-cutting	11	1.98	2.58	45%	Develop labor training programs to ensure stable, skilled workforce to support the developing fuel cell community	9	161	59	105
Market cross-cutting	7	1.95	2.41	43%	Establish a study to identify fuel cell system equipment requirements that would accommodate the widest range of market applications	10	173	57	83
Market cross-cutting	10	1.35	1.67	33%	Adjust intellectual property provisions to stimulate cooperative fuel cell research, development and demonstration	11	214	14	23
Market cross-cutting	8	1.67	1.83	19%	Fund the development and application of a single fuel cell system or system component to multiple markets	12	240	44	29

8.2 Market Cross-Cutting Description Table

Project Number	Project Description
1	With the advent of new fuel cell technology, the growth and development of industry to support systems development, integration, installation, and service is required. A holistic solution for the successful commercialization of fuel cells will include the coincident development of supporting companies and technology and the appropriate support infrastructure. This infrastructure should include: OEMs, installation companies, maintenance and service companies, parts supplies, etc. Projects that propose to develop an integrated approach to supply chain development will be supported.
2	With the advent of new fuel cell technology, the growth and development of industry to support systems development, integration, installation, and service is required. The supply chain infrastructure may include: OEMs, installation companies, maintenance and service companies, parts supplies, etc. This project specifically supports the purchase and technology development associated with major system components that need to be produced at higher volumes and lower costs. Companies that can contribute directly to the supply chain in a manner that enhances the California fuel cell market and enhances relationships within the supply chain will preferentially be supported for this type of project. Identification of the specific subcomponent that should be supported is required when scoring this category.
3	Development of appropriate standards, policies and codes for fuel cell technology applications will prove invaluable as a first step toward commercialization. State, national and international codes and standards harmonization is important to the successful advance of fuel cell system integration into the many applications. The completion of new codes and standards should allow for transparent installation and operation protocols that can be integrated into the design of fuel cells. Complete and consistent regulations will stimulate investment interest by reducing the risk on investors and insurers involved in fuel cell installations.
4	The government will play an essential role in providing initial support for fuel cell technologies approaching commercialization. Government incentives can stimulate product production while full-scale manufacturing volumes are achieved. In addition, mandates can be used to preferentially select the technologies that provide the most benefit currently and the most potential in the future. A study that explores the extent to which incentives and mandates should be implemented for California fuel cell applications will aid in presenting a clear message concerning the resources that the government or ratepayers can supply to further fuel cell system deployment. Some of the possible selection criteria include: environmentally sound technology, energy security, and amenability to renewable fuels.
5	This project would establish a subsidy program funded by California ratepayers through the Public Interest Energy Research (PIER) program for specific fuel cell applications. The terms and conditions of the subsidy program will be established in this project. Identification of the specific application for this subsidy is required when scoring this category.

6	This project would establish a buy-down program funded by California ratepayers through the PIER program for specific fuel cell applications. The terms and conditions of the buy-down program will be established in this project. The government should consider the purchase and installation of fuel cell systems in government-owned properties and partial purchase of similar installations on private property. Identification of the specific application for this buy-down program is required when scoring this category.
7	Study the fuel cell performance characteristics that will enable a single fuel cell system or system component to be used in a wide variety of applications. The results of this study will guide and enable the standardization of manufacturing processes and supply chain simplification for achieving high-volume manufacturing while meeting the requirements of multiple applications. Identification of the specific markets to which a single fuel cell system or component could be applied in a cross-cutting manner is required when scoring this project.
8	A project that demonstrates the feasibility of using a single fuel cell system or system component in multiple applications presents unique opportunities for achieving higher product volumes and more robust systems. Identification of the multiple markets and single fuel cell system or component is required when scoring this project.
9	Studying the socio-economic implications of the introduction of fuel cells into the current energy market is essential to aid in fuel cell deployment. This study will determine the specific steps that should be taken to facilitate the public acceptance of fuel cell systems in various markets. The study will also determine the potential impact that fuel cell development and installation throughout California will have on job creation, economic health and competitiveness. The results of the study should be disseminated appropriately.
10	State funding agencies should revise the standard terms and conditions associated with research, development and demonstration agreements to enable the participation of modern research and development entities that require reasonable retention of intellectual property to remain viable in the marketplace. This project will explore possible revisions to intellectual property provisions and other terms and conditions that could be modified within the current policy framework to streamline contracting procedures and enable broader participation of companies, institutes, etc. in PIER fuel cell research, development and deployment projects.
11	This project will support labor training programs for jobs that support the fuel cell community including technicians, service providers, fuel cell manufacturing. California community colleges and state universities with a mission that includes job training programs and experience in developing job training programs in new fields will be solicited for developing this program.
12	Currently, central power generation is heavily dependent upon fossil fuels to operate reliably and provide the power demand profile that consumers request. It is vital for the continued growth, health, and development of the energy sector that alternatives to fossil-based fuels become increasingly utilized throughout the state. An important first step toward that goal is to identify the available alternative fuels and develop a plan to increase the use of those fuels. Thus the importance of forward thinking in product development and installation will be invaluable for the future of fuel cell system

	commercialization.
13	The equipment to generate renewable energy, particularly from wind and solar, has a much lower and more variable capacity factor than those systems that operate on constant fuel streams. This presents interesting challenges with respect to energy storage and time of use. Several examples of fuel cell technology with the potential to address intermittent renewable power generation include: reversible fuel cells, fuel cell hybrid systems and co-production systems. Further exploration into the potential of these and other related fuel cell technologies is an essential step toward establishing energy stability from intermittent sources.
14	This study will analyze the contributions that fuel cells in various applications can make toward meeting state policies and goals regarding greenhouse gas and criteria pollutant emissions reductions. Compared with current energy generation technologies, fuel cell systems typically have lower criteria pollutant emissions. Thus, fuel cell systems, if installed in areas of criteria pollutant non-attainment, will provide notable air quality improvement. The extent to which the air quality will be impacted by these changes is important to future policy developments, support and siting of fuel cell installations throughout California. In addition, this study will explore the possible contribution of fuel cell installations toward meeting the state's goals for reducing greenhouse gas emissions. Calculating differences between emissions from various energy technologies and those from fuel cell systems and comparing them under different operating conditions like power setting, fuel input, etc. will elucidate the value of fuel cells for reducing greenhouse gas emissions.

8.3 Market Cross-Cutting Comment Table

Category	#	Comments
Market cross-cutting	1	Many DG/Renewable Energy groups have lobbied policymakers in Sacramento for similar support on the basis of "green collar" job creation within the state. This same rhetoric should be employed for the fuel cell industry in an effort to secure tax breaks or other subsidies that will result in the development of more California-based jobs among installers / service providers.

Category	#	Comments
Market cross-cutting	2	As members of the California Manufacturers and Technology Association (CMTA), we have insight into the challenges faced by manufacturing organizations operating in California. Despite the benefits to the fuel cell industry, there is not a sufficiently compelling economic argument to support the idea of sub-assembly manufacturing within California. Moreover, California is probably the worst location for basing any manufacturing process due to excessive regulatory and financial burdens imposed on these types of organizations.
Market cross-cutting	3	Essential step toward commercialization but typically not as technical as the other projects, more legislative.
Market cross-cutting	3	Examples of these standards can already be seen in the California Rule 21 interconnection protocols and CARB 07 certification process. Without these types of standards, deployment of fuel cells would not be moving forward as it currently is. Nevertheless, Rule 21 standards are developed by a loosely organized body that receives sporadic and limited funding from the CPUC and CARB 07 has many flaws that are egregiously exploited by local air districts. Funding a more robust and comprehensive group that would elevate these types of standards would greatly facilitate additional fuel cell deployments throughout the state.
Market cross-cutting	5	The DOE or other governmental agency could assist with this project.
Market cross-cutting	5	While the current SGIP incentives enable "behind the fence" sales of fuel cells on a small scale, larger multi-MW systems will require a different approach if they are to succeed in California. Deployments of these larger systems would be best stimulated by a dedicated feed-in tariff. Significant examples of these market opportunities can be seen with landfill-gas-to-energy or gas utility pressure let-down station applications. The current regulatory environment and limits of the SGIP are preventing these and other large scale fuel cell deployments as there is no mechanism to pay the system operator for the electrical output of the fuel cells. As a feed-in tariff pays based on performance of the system, it is a safer alternative for ratepayers and would be easier to justify to policymakers.
Market cross-cutting	6	Look to local and federal government for buy-down assistance.
Market cross-cutting	7	All current fuel cell manufacturers have clearly demonstrated that they are more product-focused rather than market-focused. A brief consultation with any leading business school will emphatically state that a company must take a market-focused approach in order to succeed or survive. Any effort that focuses more attention on what the market may actually need, as opposed to what manufacturers want to build will be of great benefit to the industry. Identifying broad ranges of components or applications will further reinforce this market-focused initiative.

Category	#	Comments
Market cross-cutting	8	The previous project and questions demonstrate the need to bring a market-focused approach to the fuel cell industry. This idea is contrary to that approach and further encourages the existing status quo among fuel cell manufacturers wherein they rely on a product-focused method. The market must dictate what fuel cell systems should be built with less consideration given to standardization of a model or type of fuel cell plant. This drive toward standardization would further inhibit the growth of new fuel cell deployments.
Market cross-cutting	9	Current political discourse regarding energy policy within Sacramento is overwhelmingly dominated by large players in the solar and wind sectors. Whereas fuel cells can offer greater benefits than these other technologies, their prominence within California needs to be enhanced. A successful socio-economic study would result in the inclusion of fuel cells along with any other discussion that would ordinarily include wind and solar energy. Beginning with policy makers and working down toward end users and community groups, an educational initiative would greatly facilitate fuel cell deployments - especially among public sector users.
Market cross-cutting	10	Applies especially to the PIER program.
Market cross-cutting	11	The ability to create or bring jobs in California further stimulates the interest among policy makers to support other fuel cell incentives and subsidies. While pundits could label this job creation effort as political pandering, it is also essential to getting legislative support for many of the other funding requests the industry will be proposing. Ultimately, unless there is some offer of job creation - all the other project funding options will lack sufficient support in Sacramento.
Market cross-cutting	12	One common criticism of the use of hydrogen energy sources is their current reliance on natural gas as a feedstock. Despite significant efforts to deploy large stationary fuel cells using renewable fuels, the broader spectrum of pundits clings to the anti-hydrogen agenda on the basis of the natural gas dependency. Any effort that enhances the uses and applications for fuel cells using renewable or alternative feed stocks is of significant importance to the future of the technology. When entered into the public consciousness, fuel cells must have an association with renewable or alternative fuels in order to succeed.
Market cross-cutting	13	As with other proposed initiatives, fuel cells need to be more closely associated with renewable power in order to gain greater support among policy makers. Any integration of fuel cells into other renewable energy sectors will further enhance this alignment.
Market cross-cutting	13	This will be essential to meet the RPS and AB32 goals for California.
Market cross-cutting	13	With emerging renewable penetration, fuel cells will have to be integrated with renewable resources. Fuel cell's role in renewable grid of the future is critical.

Category	#	Comments
Market cross-cutting	14	Consistent with AB32 early action items and existing CARB doctrine, fuel cells are already seen as a method to reduce GHG emissions and offset criteria pollutants. What is needed from an initiative such as this is a greater effort to overcome regulatory barriers that currently inhibit fuel cell market growth. Air districts have held fuel cell projects for ransom in order to extract fees from project developers and the IOU's use their political force to inhibit the growth of DG. An overhaul of air permitting requirements and the implementation of a dedicated feed-in tariff would be the best results for this project.
Market cross-cutting	14	Understanding FC emissions issues is important but unfortunately provides little economic benefit. Without the motivation from AB32 it might be difficult to fund projects with predominantly societal benefits (clean air, clean water, etc.)
Market cross-cutting	All	The overall tone of the survey causes some concern. The questions and other text are biased toward the assumption that fuel cells are not yet commercialized in California. This attitude is deleterious to the existing industry and any suggestion that fuel cells are not yet commercialized should be eliminated. Along the way to deploying every new fuel cell in California, significant efforts are made to convince the end users that fuel cells are, in fact, fully commercialized and ready for use today. While it is not surprising to confront this sort of skepticism among potential end users, it is alarming - to say the least - to note this lack of confidence in fuel cell commercialization among the ranks of the NFCRC. I would certainly expect more of a reinforcement of fuel cells current commercial status among the more informed leaders of the NFCRC.

II. Fuel Cell Technology Specific Development Project Tables

9. Solid Oxide Fuel Cell

9.1 Solid Oxide Fuel Cell Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
SOFC	12	5.00	2.90	83%	Establish an understanding for SOFC internal reforming mechanisms and develop technique for effective use of internal reforming	1	9	179	149
SOFC	11	1.98	2.33	80%	Develop and demonstrate SOFC degradation mitigation techniques	2	17	59	75
SOFC	1	3.00	3.83	71%	Development of SOFC electrocatalysts	3	30	111	219
SOFC	9	1.60	2.58	71%	Develop understanding and novel methods for better SOFC electrode and electrode-electrolyte interface performance	4	31	35	105
SOFC	5	7.67	3.61	69%	Develop intermediate temperature SOFCs	5	37	230	202
SOFC	10	6.67	2.43	65%	Design of high-temperature SOFC cells and stacks for better integration with other system components	6	51	216	91
SOFC	2	3.67	3.40	54%	Address development barriers of particular concern to tubular SOFCs	7	100	135	193
SOFC	4	1.98	3.71	52%	Explore novel material sets for SOFCs	8	115	59	209
SOFC	13	1.79	1.98	51%	Examine the purity requirements for inputs into SOFC systems	9	129	50	49
SOFC	6	1.60	2.43	50%	Improve operation of fuel cell interconnects at high temperatures	10	130	35	91
SOFC	3	4.67	3.63	50%	Improve high-temperature fuel cell materials processing and assembly	11	132	171	203
SOFC	7	1.79	2.55	48%	Develop better performing high-temperature fuel cell seals	12	143	50	102

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
SOFC	8	1.60	1.83	39%	Explore the effects of material impurities on SOFC electrolyte fabrication and performance	13	193	35	29

9.2 Solid Oxide Fuel Cell Description Table

Project Number	Project Description
1	Further development of electrocatalysts for SOFCs is essential for moving SOFC technology toward commercialization. The electrochemical reactions that generate power through electrical and ionic flow occur on the electrocatalyst sites. During operation SOFC performance can be degraded which can eventually lead to failure as a result of coarsening when the electrocatalyst's material properties change or when impurities are introduced into the fuel or oxidant streams. It is necessary to develop more robust electrocatalyst by either improving the current materials or changing the catalyst material set. This project should explore the deficiencies of current electrocatalysts and methods to overcome those deficiencies.
2	Tubular SOFCs experience particular performance hurdles that are not experienced by other types of SOFCs (e.g., planar, monolithic). Addressing tubular SOFC's low power density, material costs and fabrication process represent several of the critical issues that need to be addressed with tubular fuel cells to achieve SOFC commercialization.
3	Operation at high-temperatures presents an environment that is particularly challenging for the operation of SOFC materials. Issues with coefficient of expansion, coating materials and processes, and mixing methods are augmented by the high-temperatures. It is necessary to address these and other issues related to high temperature material processing and assembly in order to increase SOFC performance and lifetime while reducing system costs.
4	There is a need to explore new and unique materials sets that can overcome the issues inherent to current materials sets. Specific barriers to better SOFC performance like material conductivity and coefficient of expansion mismatch can be addressed by developing new material sets for use in SOFCs.
5	In response to many of the issues resulting from operation at high-temperature there is a significant amount of interest in developing SOFCs that operate at intermediate temperatures (600-800ºC). Specifically, this will allow the use of cheaper and possibly better performing materials (e.g., metallic interconnects).
6	Solid oxide fuel cell interconnects must be able to provide structural stability to the fuel cells while also providing a pathway for the conduction of electricity. Based on the operating conditions fuel cell interconnects can have stringent design requirements (e.g., thermal expansion, conductivity). Further optimizing the material sets as well as the design are important steps toward increasing SOFC performance.

7	High-temperature fuel cell seals must meet strict requirements for mechanical properties thermal expansion and cycling as well as electrical and chemical properties (e.g., conduction, reaction with cell components). Improving the performance, lifetime, and manufacturability of SOFC seals represents an integral step on the path to commercialization for this technology.
8	When producing the electrolyte for SOFCs preventing material impurities is desirable to increase performance, lifetime, etc., but it is important to know the extent to which these impurities affect the fuel cell. Determining which material impurities should be avoided and how dramatically they affect the fuel cell can provide better optimization for performance, cost, reliability and lifetime.
9	When developing electrodes for SOFCs, there are many items that must be considered to increase the durability and performance of these systems. Degradation, surface structure engineering, and material conduction properties are several of the important features that must be better understood to increase the performance of electrodes and electrode-electrolyte interfaces and thereby increase the performance of SOFCs.
10	The physical features like shape, weight and volume of fuel cells must be optimized for integration into stacks and further integration into fuel cell systems. By adjusting these physical properties to span a single or multiple application requirements there is significant potential for performance increases and cost reductions for SOFCs.
11	Degradation is one of the critical issues preventing longer operation lifetimes for SOFCs. There is a need to quantify and qualify the effects of degradation on fuel cells and fuel cell systems. This process should include short-term/predictive tests and longer-term tests. If system degradation effects can be identified and alleviated then fuel cells lifetimes can be lengthened and the value proposition for SOFC systems can be greatly improved.
12	One of the unique features for SOFCs is there ability to reform fuels in the cell flow channel. Internal fuel reformation is predominantly a result of the increased temperatures in SOFCs allowing the fuel to be separated into its constituent components. This property allows for SOFCs to operate on a variety of different fuels while removing the need for external reforming equipment; however, the introduction of internal reforming into SOFC systems also introduces new obstacles for SOFC control and performance (e.g., extent of reaction, coking, increased polarizations, additional degradation). Thus, there is a need to develop an understanding and techniques to perform internal reforming in SOFCs in an effort to address the aforementioned obstacles.
13	In SOFCs changes in the fuel or oxidant composition and other system inputs can have an effect on the system performance. Exploring the extent to which a fuel cell can operate on impure or contaminated inputs is essential to increasing the versatility, durability and reliability of SOFCs.

9.3 Solid Oxide Fuel Cell Comment Table

Category	#	Comments
SOFC	2	Microtubular designs could be a good direction to go for this project.
SOFC	3	I don't think the state should have to fund manufacturing. Companies planning on making money should invest
SOFC	3	This seems like a very all-inclusive and broad project for SOFC development. It may be worth the investment, but care should be taken to properly manage such a large project.
SOFC	4	State shouldn't have to fund basic materials research, should be federal entity.
SOFC	6	With the advent of intermediate- and low-temperature SOFCs, this may become a moot point. This type of investigation should be held off until more fundamental development on the development of SOFC materials for lower temperature operation is completed.
SOFC	7	Important project but not really state project
SOFC	7	This one may be unnecessary depending on the success of other projects (thermal mismatch, low-temp SOFC, etc...). Its effectiveness will depend on these more fundamental projects' success.
SOFC	9	This is an area that is receiving a lot of attention lately and is largely not well-understood. The methods for studying this and carrying out this project are much less expensive than many other projects that require full stack or system production. Thus, its benefit-to-cost seems particularly attractive.
SOFC	10	The technology is developing so much right now and at such a nascent stage of stack development that I feel this exercise reaches too far into the future. The market still seems to need to define a baseline or standard before this type of optimization can occur.
SOFC	11	This is an area of research with surprisingly little information. SOFC market acceptance could be greatly bolstered by accurate information on degradation, especially as regards coking and catalyst deactivation.

10. Molten Carbonate Fuel Cell

10.1 Molten Carbonate Fuel Cell Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
MCFC	9	1.22	1.60	62%	Examine the purity requirements for inputs into MCFC systems	1	63	10	20
MCFC	1	3.67	2.58	57%	Improve high-temperature fuel cell materials processing and assembly	2	85	135	105
MCFC	8	1.51	1.83	56%	Establish an understanding for MCFC internal reforming mechanisms and develop techniques for effective use of internal reforming	3	90	25	29
MCFC	5	3.67	2.21	54%	Optimize MCFC stack for longer lifetime	4	102	135	62
MCFC	3	1.98	2.58	52%	Address MCFC electrode and electrode-electrolyte interface development barriers	5	118	59	105
MCFC	2	1.51	2.21	48%	Develop better performing high-temperature fuel cell seals	6	145	25	62
MCFC	7	2.67	2.21	46%	Develop and demonstrate MCFC degradation mitigation techniques	7	157	95	62
MCFC	4	0.80	2.21	41%	Explore the effects of material impurities on electrolyte fabrication and performance	8	185	2	62
MCFC	6	4.33	1.35	40%	Design of high-temperature MCFC cells and stacks for better integration with other system components	9	186	160	9

10.2 Molten Carbonate Fuel Cell Description Table

Project Number	Project Description

1	Operation at high-temperatures presents an environment that is particularly challenging for the operation of MCFC materials. Issues with firing temperatures and durations, coating materials and processes, and mixing methods are augmented by the high-temperatures. It is necessary to address these and other issues related to high temperature material processing and assembly in order to increase MCFC performance and lifetime while reducing system costs.
2	High-temperature fuel cell seals must meet strict requirements for mechanical properties thermal expansion and cycling as well as electrical and chemical properties (e.g., conduction, reaction with cell components). Improving the performance, lifetime, and manufacturability of MCFC seals represents an integral step on the path to commercialization for this technology.
3	When developing electrodes for MCFCs, there are many items that must be considered to increase the durability and performance of these systems. Degradation like corrosion or chemical dissolution, and material conduction properties are several of the important features that must be better understood to increase the performance of electrodes and electrode-electrolyte interfaces and thereby increase the performance of MCFCs.
4	When producing the electrolyte for MCFCs preventing material impurities is desirable to increase performance, lifetime, etc., but it is important to know the extent to which these impurities affect the fuel cell. Determining which material impurities should be avoided and how dramatically they affect the fuel cell electrolyte can provide better optimization for performance, cost, reliability and lifetime.
5	Lengthening the operational lifetime of MCFC stacks has the potential to greatly increase the value proposition for MCFCs. Molten carbonate fuel cell stack lifetime can be increased by techniques including decreasing stack degradations (e.g., corrosion and erosion as well as carbonate depletion) and introducing better stack monitoring and control equipment. These are issues that, if addressed, will aid in further commercialization of MCFC technology.
6	The physical features like shape, weight and volume of fuel cells must be optimized for integration into stacks and further integration into fuel cell systems. By adjusting these physical properties to span a single or multiple application requirements there is significant potential for performance increases and cost reductions for MCFCs.
7	Degradation is one of the critical issues preventing longer operation lifetimes for MCFCs. There is a need to quantify and qualify the effects of degradation on fuel cells and fuel cell systems. This process should include short-term/predictive tests and longer-term tests. If system degradation effects can be identified and alleviated then fuel cells lifetimes can be lengthened and the value proposition for MCFC systems can be greatly improved.
8	One of the unique features for MCFCs is there ability to reform fuels in the cell flow channel. Internal fuel reformation is predominantly a result of the increased temperatures in MCFCs allowing the fuel to be separated into its constituent components. This property allows for MCFCs to operate on a

	variety of different fuels while removing the need for external reforming equipment; however, the introduction of internal reforming into MCFC systems also introduces new obstacles for control and performance (e.g., extent of reaction, coking, increased polarizations, additional degradation). Thus, there is a need to develop an understanding and techniques to perform internal reforming in MCFCs in an effort to address the aforementioned obstacles.
9	In MCFCs changes in the fuel or oxidant composition and other system inputs can have an effect on the system performance. Exploring the extent to which a fuel cell can operate on impure or contaminated inputs is essential to increasing the versatility, durability and reliability of MCFCs.

10.3 Molten Carbonate Fuel Cell Comment Table

Category	#	Comments
MCFC	5	This is crucial since replacement of stack represents a big portion of total expenses. By enlarging its lifetime, costs get diluted and as a result they drop.
MCFC	6	I think MCFC are quite well designed already. Research has been done during past decades and MTU came up with HotModule which is quite optimal. I would move funds towards other issues.
MCFC	9	This research is very important especially for biogas fueled MCFC projects which may vary in composition.
MCFC	All	Fuel Cell Energy has this technology commercially available. The state needs to understand where the technology could play a roll of meeting the states energy demand in the future, and how much the price of the technology can decrease. If the technology is critical to the state, then some demonstration/deployment resources to mature the technology is needed. This could be in the form of incentives.

11. Proton Exchange Membrane Fuel Cell

11.1 Proton Exchange Membrane Fuel Cell Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
PEMFC	5	5.67	2.96	69%	Development and optimization of PEMFC electrocatalysts	1	40	190	151
PEMFC	1	1.41	2.13	48%	Optimize PEMFC gas diffusion layer	2	141	18	57
PEMFC	6	1.60	1.83	48%	Explore ion transport dependencies to improve PEMFC performance	3	147	35	29
PEMFC	11	3.67	1.83	46%	Develop and demonstrate PEMFC degradation mitigation techniques	4	152	135	29
PEMFC	13	1.41	1.60	46%	Develop control and system management strategies for PEMFC systems	5	152	18	20
PEMFC	9	2.67	2.21	45%	Develop alternative fuel reformers for integration into PEMFCs	6	166	95	62
PEMFC	2	2.47	2.73	44%	Optimize PEMFC membrane materials and operation	7	169	92	128
PEMFC	10	4.67	2.58	41%	Design of high-temperature (>100ºC) PEMFC stack with respect to system requirements	8	183	171	105
PEMFC	12	1.75	1.51	41%	Examine the purity requirements for inputs into PEMFC systems	9	184	47	15
PEMFC	3	1.41	3.33	40%	Develop MEA designs and processing techniques for platinum recycling	10	188	18	182
PEMFC	7	1.51	1.51	37%	Develop better performing PEMFC seals	11	198	25	15
PEMFC	8	4.67	1.83	36%	Optimize PEMFC bipolar plates	12	205	171	29
PEMFC	4	3.67	2.96	35%	Explore the effects of material impurities on PEMFC fabrication and performance	13	210	135	151

11.2 Proton Exchange Membrane Fuel Cell Description Table

Project Number	Project Description
1	The gas diffusion layer of PEMFCs has many materials related issues that can be refined to increase the overall performance of PEMFCs. For example, the pore structure, conductivity and material selection are areas that could benefit from further optimization.
2	For PEMFC systems membrane optimization represents a key area needing improvement. Exploring alternative membrane materials like hydrocarbon, or PBI that allow for higher operating temperatures and reduce the concern for water management issues are of particular interest. Also, further development of current membrane materials can provide performance improvement and cost reductions for PEMFC systems.
3	Given the limited supply of platinum on the planet, it is essential that platinum recycling and reprocessing techniques be pursued. Appropriate recycling techniques for the platinum catalyst are critical for reaching sustainable high-volume production of PEMFCs.
4	When producing PEMFCs preventing material impurities is desirable to increase performance, lifetime, etc., but it is important to know the extent to which these impurities affect the fuel cell. Determining which material impurities should be avoided and how dramatically they affect the fuel cell can provide better optimization for PEMFC performance, cost, reliability and lifetime.
5	Further development of electrocatalysts for PEMFCs is essential for moving that technology further toward commercialization. The electrochemical reactions that generate power through electrical and ionic flow occur on the electrocatalyst sites. During operation PEMFC performance can be degraded which can eventually lead to failure as a result of impurity introduction into the fuel or oxidant streams. It is necessary to develop more robust and lower cost electrocatalysts by either improving the current materials (i.e., increase material performance, reduce catalyst loading) or changing the catalyst material set. This project should explore the deficiencies of current PEMFC electrocatalysts and methods to overcome those deficiencies.
6	In an effort to increase PEMFC performance developing an understanding of the relationship between system parameters like temperature, humidity and acidity and ion transport through the cell is important. This study could be conducted for various system configurations and materials set selections.
7	Seals for PEMFC systems must survive for the life of the stack including through multiple thermal cycles. Additionally, issues like degradation (e.g., pinholes, tearing) that lead to seal failure can be exacerbated by humid conditions and thermal cycling. Further development of PEMFC seals can extend their range of operating conditions and potentially increase stack performance and lifetime.

8	As with optimizing other components in PEMFCs, bipolar plates present an opportunity to increase system performance while driving the system cost down. Determining the appropriate material and design requirements and validating those findings for bipolar plates has the potential to improve the value proposition for PEMFCs.
9	In part, because of the operating temperatures, external reforming must be used for fuels other than hydrogen when operating PEMFCs. Thus to operate on fuels, other than hydrogen, fuel reformers must be developed. Reforming technology for many different fuel types exists; however, to increase PEMFC system performance, optimization and integration of fuel reformers with PEMFCs is essential.
10	The physical features like shape, weight and volume of fuel cells must be optimized for integration into stacks and further integration into fuel cell systems. By adjusting these physical properties to span a single or multiple application requirements there is significant potential for performance increases and cost reductions for PEMFCs.
11	Degradation is one of the critical issues preventing longer operation lifetimes for PEMFCs. There is a need to quantify and qualify the effects of degradation on fuel cells and fuel cell systems. This process should include short-term/predictive tests and longer-term tests. If system degradation effects can be identified and alleviated then fuel cells lifetimes can be lengthened and the value proposition for PEMFC systems can be greatly improved.
12	In PEMFCs, changes in the fuel or oxidant composition and other system inputs can have an effect on the system performance. Particularly, fuel impurities (e.g., carbon monoxide) in PEMFCs have a dramatic effect on performance and can lead to stack failure. Exploring the extent to which a fuel cell can operate on impure or contaminated inputs is essential to increasing the versatility, durability and reliability of PEMFCs.
13	Developing optimum control and management strategies for PEMFC systems represents an opportunity to increase system performance and flexibility. Two examples of areas of particular importance for PEMFC systems are water management (e.g., humidification and water flow) since the typical operating conditions are below the boiling point of water and thermal management systems.

11.3 Proton Exchange Membrane Fuel Cell Comment Table

Category	#	Comments
PEMFC	1	For the most part, I feel GDL development/research has been neglected. These materials are unstable over time and stability needs to be improved.
PEMFC	2	Membranes are the major failure mode in fuel cells. Low humidity operation is not a real benefit to system integrators because you still need to provide humidification. Better goal is operation at ambient RH conditions, i.e., no additional humidification to the incoming gas streams.
PEMFC	3	Larry Shore of BASF (formerly Englehard) has had quite a bit of success in a DOE program on recycling Pt from MEAs. Not sure if additional research is needed. Here is a link to Shore's most recent presentation ...http://www.hydrogen.energy.gov/pdfs/review08/fcp_2_shore.pdf
PEMFC	5	There is quite a bit of literature (DOE, USFCC, JARI, SAE, ISO) on the impact of air and fuel impurities on Pt or PtRu catalysts. I would not suggest funding this portion of the proposed project.
PEMFC	9	Could look at fuel reformation for fuels or fuel blends found in California.
PEMFC	9	There are commercially available fuel cell systems today that operate on reformed methanol. Wouldn't be that difficult to switch to ethanol or bio-derived fuels
PEMFC	10	Manufacture must consider this. No need for state funding.
PEMFC	10	Need to complete high temperature membrane development first or link it to high temperature membrane development. PEM won't last long above 100°C. PBI is an alternative that could work today, but it is unstable over time. I haven't seen many hydrocarbon membranes that can operate in this temperature region.
PEMFC	11	There has been a lot of recent work on degradation, but a lot of work still remains. Understanding failure modes is key to improving the lifetime and thus the economic viability of fuel cells. USFCC, JARI and DOE have published on this subject.
PEMFC	12	I would not fund this topic as it is over funded in my mind by the industry. There are standards now for fuel quality and the impact of air contaminants is well known. See DOE, USFCC, JARI, SAE, ISO for documents.

Category	#	Comments
PEMFC	13	Thermal management is the more interesting topic. Low humidity operation is of no benefit. Humidification should either be 0% or 100%. If it's anything in between you still have to provide extra cost to humidify, so you might as well operate at 100% which yields better performance and durability.
PEMFC	All	Develop PEMFC backup systems that operate on renewable, easily stored fuels (e.g., renewable methanol or ethanol).
PEMFC	All	Need to look at easy, low cost manufacturing process. Manufacturing costs are quite high and the process is complex which inhibits production. Development of on-line QC is needed. Methods to shorten fuel cell stack/system conditioning and leak checking are needed.

12. Phosphoric Acid Fuel Cell

12.1 Phosphoric Acid Fuel Cell Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
PAFC	5	1.03	1.03	68%	Develop and demonstrate PAFC degradation mitigation techniques	1	41	4	2
PAFC	2	1.51	2.58	51%	Development and optimization of PAFC electrocatalysts	2	128	25	105
PAFC	1	1.03	3.33	36%	Explore the effects of material properties on PAFC fabrication and performance	3	207	4	182
PAFC	3	0.56	1.03	32%	Develop better performing PAFC fuel cell seals	4	217	1	2
PAFC	4	3.67	1.83	24%	Design of PAFC cells and stacks for better integration with other system components	5	233	135	29

12.2 Phosphoric Acid Fuel Cell Description Table

Project Number	Project Description
1	When producing PAFCs materials optimization is desirable to increase performance, lifetime, etc. Determining which materials can be used, the purity of those materials and how each materials set should be optimized for operation in PAFCs can provide better optimization for PAFC performance, cost, reliability and lifetime.
2	Further development of electrocatalysts for PAFCs is essential for moving that technology further toward commercialization. The electrochemical reactions that generate power through electrical and ionic flow occur on the electrocatalyst sites. During operation PAFC performance can be degraded which can eventually lead to failure as a result of impurity introduction into the fuel or oxidant streams. It is necessary to develop more robust and lower cost electrocatalysts by either improving the current materials (i.e., increase material performance, reduce catalyst loading) or changing the catalyst material set. This project should explore the deficiencies of current PAFC electrocatalysts and methods to overcome those deficiencies.

3	Seals for PAFC systems must survive for the life of the stack including through multiple thermal cycles. Additionally, issues like degradation that lead to seal failure can be exacerbated by humid conditions and thermal cycling. Further development of PAFC seals can extend their range of operating conditions and potentially increase stack performance and lifetime.
4	The physical features like shape, weight and volume of fuel cells must be optimized for integration into stacks and further integration into fuel cell systems. By adjusting these physical properties to span a single or multiple application requirements there is significant potential for performance increases and cost reductions for PAFCs.
5	Degradation is one of the critical issues preventing longer operation lifetimes for PAFCs. There is a need to quantify and qualify the effects of degradation on fuel cells and fuel cell systems. This process should include short-term/predictive tests and longer-term tests. If system degradation effects can be identified and alleviated then fuel cells lifetimes can be lengthened and the value proposition for PAFC systems can be improved.

13. Direct Methanol Fuel Cell

13.1 Direct Methanol Fuel Cell Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
DMFC	2	4.33	1.83	59%	Development and optimization of DMFC electrocatalysts	1	76	160	29
DMFC	1	4.33	2.83	57%	Address DMFC membrane concerns	2	83	160	137
DMFC	6	1.98	2.83	43%	Develop and demonstrate DMFC degradation mitigation techniques	3	175	59	137
DMFC	4	3.67	1.83	16%	Design of DMFC stack with respect to cellular phone system requirements	4	243	135	29
DMFC	3	3.67	2.58	8%	Design of DMFC stack with respect to laptop system requirements	5	248	135	105
DMFC	5	1.98	2.58	7%	Design of DMFC stack with respect to other portable electronics system requirements	6	249	59	105

13.2 Direct Methanol Fuel Cell Description Table

Project Number	Project Description
1	Addressing the issues hindering better membrane performance and lifetime in DMFCs can improve the value proposition of this technology. Some of the issues being considered are materials selection and processing related while others are related to the operation of the fuel cell and the concern of reactant cross-over across the membrane.
2	Further development of electrocatalysts for DMFCs is essential for moving that technology further toward commercialization. The electrochemical reactions that generate power through electrical and ionic flow occur on the electrocatalyst sites. During operation DMFC performance can be degraded which can eventually lead to failure as a result of impurity introduction into the fuel or oxidant streams. It is necessary to develop more robust and lower cost electrocatalysts by either improving the current materials (i.e., increase material performance, reduce catalyst loading) or changing the catalyst material set. This project should explore the deficiencies of current DMFC electrocatalysts and methods to overcome those deficiencies.
3	The physical feature requirements like shape, weight and volume for DMFCs should be optimized for integration into specific applications. By adjusting these physical properties to be matched with laptop computer requirements new markets for DMFC technology can be explored, thereby improving the value proposition for DMFCs.
4	The physical feature requirements like shape, weight and volume for DMFCs should be optimized for integration into specific applications. By adjusting these physical properties to be matched with cellular phone requirements new markets for DMFC technology can be explored, thereby improving the value proposition for DMFCs.
5	The physical feature requirements like shape, weight and volume for DMFCs must be optimized for integration into specific applications. By adjusting these physical properties to be matched with the requirements of portable electronics new markets for DMFC technology can be explored, thereby improving the value proposition for DMFCs.
6	Degradation is one of the critical issues preventing longer operation lifetimes for DMFCs. There is a need to quantify and qualify the effects of degradation on fuel cells and fuel cell systems. This process should include short-term/predictive tests and longer-term tests. If system degradation effects can be identified and alleviated then fuel cells lifetimes can be lengthened and the value proposition for DMFC systems can be greatly improved.

14. Fuel Cell Cross-Cutting

14.1 Fuel Cell Cross-Cutting Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Fuel cell system cross-cutting	14	2.47	1.79	82%	Develop dynamic models to aid in improving fuel cell and fuel cell system performance	1	13	92	25
Fuel cell system cross-cutting	8	7.67	2.43	81%	Explore fuel cell synergies with other energy conversion equipment and energy storage devices	2	15	230	91
Fuel cell system cross-cutting	11	5.00	3.83	65%	Conduct a study to characterize fuel cell system degradation mechanisms and mitigation strategies	3	48	179	219
Fuel cell system cross-cutting	6	4.60	3.11	62%	Develop strategies for optimization and control of fuel cell performance during dynamic operations	4	61	170	163
Fuel cell system cross-cutting	2	2.67	1.51	61%	Explore techniques to increase profitable operation during pre-large-scale manufacturing	5	66	95	15
Fuel cell system cross-cutting	3	3.67	2.58	60%	Further develop manufacturability of fuel cells and fuel cell systems	6	70	135	105
Fuel cell system cross-cutting	13	1.60	2.13	59%	Develop steady state models to aid in improving fuel cell and fuel cell system performance	7	77	35	57
Fuel cell system cross-cutting	9	2.67	3.63	55%	Explore the prospects of remanufacturing, recycling, reprocessing and requalifying fuel cell systems	8	95	95	203
Fuel cell system cross-cutting	1	1.75	2.21	52%	Improve fuel and air flow design and manifolding	9	118	47	62
Fuel cell system cross-cutting	21	2.26	2.84	49%	Explore and address fuel cell system durability and lifetime for stationary/continuous fuel cell power applications	10	134	86	144

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Fuel cell system cross-cutting	5	3.67	2.60	49%	Optimize fuel cell performance during startup and shutdown	11	137	135	118
Fuel cell system cross-cutting	16	4.33	1.67	48%	Explore the economic and environmental dispatch of fuel cell systems	12	146	160	23
Fuel cell system cross-cutting	10	1.51	1.83	45%	Address remote monitoring, control and maintenance of fuel cell systems	13	163	25	29
Fuel cell system cross-cutting	19	3.31	2.92	44%	Reduce parasitic losses for fuel cell inverter/converter components	14	170	131	150
Fuel cell system cross-cutting	7	3.31	4.23	43%	Explore the opportunities and consequences of fuel cell system exhaust capture, separation and carbon sequestration	15	174	130	239
Fuel cell system cross-cutting	15	1.27	1.83	40%	Develop fuel cell sub-models for integration into canned software packages	16	189	12	29
Fuel cell system cross-cutting	18	3.81	3.11	39%	Reduce parasitic losses for SOFC and MCFC balance of plant components	17	192	151	164
Fuel cell system cross-cutting	17	2.97	2.80	36%	Reduce parasitic losses for PEMFC and PAFC balance of plant components	18	206	110	133
Fuel cell system cross-cutting	4	1.98	2.83	34%	Develop methods for accelerated fuel cell materials and design selection processes	19	213	59	137
Fuel cell system cross-cutting	20	2.47	2.38	26%	Reduce parasitic losses for air handling and management balance of plant components	20	228	91	80
Fuel cell system cross-cutting	12	1.51	1.51	14%	Develop sensors and instrumentation necessary to support fuel cell and fuel cell system operation	21	245	25	15

14.2 Fuel Cell Cross-Cutting Description Table

Project Number	Project Description
1	Designing how the fuel and air will flow through the cell and stack can have an effect on losses (e.g., parasitic, overpotentials) as well as the performance of the cell. An exploration of the effects of flow design on fuel cell performance and cost parameters should be conducted.
2	Pre-large-scale manufacturing profitability not only instills confidence in consumers about fuel cell technology, but also provides additional time and funds for the product manufacturers to optimize their product. Profitable pre-large-scale manufacturing also gives an indication of how well fuel cell technology will compete with other technologies once it is expanded to higher volume manufacturing.
3	In order to further reduce fuel cell system costs and to increase market penetration of fuel cell technology large-scale manufacturing of fuel cells must be pursued. Increasing the manufacturability of fuel cells and fuel cell systems includes topics regarding continuous manufacturing, modeling and optimization of manufacturing processes, effects of manufacturing parameters on performance and quality control.
4	The time required to design and develop fuel cells systems has the potential to be reduced if appropriate accelerated testing methods are developed. This could require new procedures and testing equipment.
5	Startup and shutdown represent unique challenges for fuel cells. Additional equipment may be required to generate enough heat to initiate startup (e.g., freezing ambient conditions) and shutdown must be controlled appropriately to avoid damage to the fuel cell stack or system components. Further development of the startup and shutdown process for fuel cells is critical to increase system performance parameters like durability, reliability and lifetime.
6	This project will explore operation of fuel cell systems over a variety of operating conditions and with variable system requirements (e.g., electrical load demand, heat load demand). Enabling fuel cell systems to operate effectively over a variety of conditions increases their market appeal. Strategies for optimizing the load-following characteristics of fuel cell systems will be explored in this project.
7	Fuel cells present a unique opportunity for exhaust separation since the fuel and oxidant streams are isolated from each other. Additionally, the size and modularity of fuel cells may have an effect on the feasibility of exhaust capture, separation and sequestrations. This project would determine how well suited fuel cells are to exhaust capture, separation and carbon sequestration activities.

8	The purpose of this project is to explore how the effect of hybridizing fuel cell systems will affect their performance and their suitability for different applications. There are many different hybrid options to consider including hybridization with batteries, capacitors, turbines, renewables and other fuel cells.
9	Given the limited supply and/or difficulty to acquire certain materials, it is essential that recycling, reprocessing and requalifying techniques be pursued. These techniques are critical for reaching sustainable high-volume production of fuel cells.
10	Operating fuel cell systems remotely is of interest because multiple systems can be simultaneously controlled and monitored reducing personnel requirement and increasing safety since on-site visits will be less frequent. Exploring and developing capabilities to remotely control, monitor and maintain (if possible) fuel cells is the goal of this project.
11	This study should explore the degradation mechanism that affect fuel cell performance and develop strategies to reduce or remove the effect of these losses. By decreasing the effect of degradation on fuel cells has the potential to increase both fuel cell lifetime and performance thereby improving the value proposition for fuel cell systems.
12	Sensors and other instrumentation play an essential role in providing feedback to fuel cells and fuel cell systems to allow for control. Optimizing these sensors can further improve the ability to control fuel cell systems and potentially increase performance. Some of the instrumentation would include hydrogen and flammable gas sensors, high-temperature resistant sensors, and flow sensors.
13	The development of steady state models can be used to predict and improve fuel cell performance. This information is vital when developing fuel cell products. Some of the characteristics that should be included in the model(s) are chemical, electrochemical and thermodynamic properties and system integration and control.
14	Dynamic fuel cell models should be employed when developing new fuel cell systems or when further optimizing current systems. Exploring the dynamic effects of various stimuli on fuel cell performance, lifetime and reliability is an essential step toward understanding the flexibility of fuel cell systems. Modeling of fuel cell systems presents a cost-effective strategy for testing many scenarios without engaging in superfluous experiments. Some of the characteristics that should be included in the model(s) are chemical, electrochemical and thermodynamic properties and system integration and control.
15	Typically software packages do not contain any information specifically regarding fuel cells (e.g., COMOSL, ASPEN). The development of modeling tools for use in “canned” software packages has the potential to simplify fuel cell modeling process and standardize fuel cell modeling strategies and terminology. Some of the characteristics that should be included in the model(s) are chemical, electrochemical and thermodynamic properties and system integration and control.

16	Economic dispatch seeks to identify the lowest cost, most reliable option for generating power and similarly environmental dispatch seeks to determine the cleanest power generation option. The goal of this project is to explore and characterize fuel cell system's economic and environmental benefits. This should be completed with consideration for the current power generation technologies.
17	In order to better compete with other energy conversion technologies PEMFC and PAFC balance of plant (BOP) development should address the parasitic losses of the fuel cell system components. Parasitic losses for fuel cell system components are of particular importance due to the high level of integration required for these systems. Some examples of areas that could benefit from PEMFC and PAFC BOP technology improvements include: thermal management system, fuel reactors, systems integration and control systems.
18	In order to better compete with other energy conversion technologies SOFC and MCFC balance of plant (BOP) development should address the parasitic losses of the fuel cell system components. Parasitic losses for fuel cell system components are of particular importance due to the high level of integration required for these systems. Some examples of areas that could benefit from SOFC and MCFC BOP technology improvements include: fuel processing, heat exchangers, ejectors and compressors/blowers.
19	Electricity inversion and conversion equipment is critical to fuel cell system operation. There are still improvements that can be made to reduce losses and optimize inverter/converter performance.
20	Minimizing losses from fuel cell BOP air handling and management equipment will increase the performance of fuel cell systems. Several of the components to consider in this analysis are blowers, compressors and manifolding, filtering, and exhausting strategies.
21	Fuel cell system durability and lifetime are often mentioned as barriers to fuel cell commercialization. The goal of this project is to determine how significant lifetime and durability issues are to the commercial viability of fuel cells and what can be done to address lifetime and durability issues for fuel cells. Some of the criteria to be evaluated in the explored include stack concerns, maintenance items for BOP and load changes.

14.3 Fuel Cell Cross-Cutting Comment Table

Category	#	Comments
Fuel cell system cross-cutting	1	Important topic don't think state should fund
Fuel cell system cross-cutting	3	Again I think industry should take lead for this. If volume is there industry can invest if need to develop. State should help in developing markets not manufacturing.

Category	#	Comments
Fuel cell system cross-cutting	3	The state could become especially involved in the standardization process. Many of the manufacturing processes could be used for other processes apart from making FCs as well.
Fuel cell system cross-cutting	4	do not believe that major breakthroughs can be made on this in short term
Fuel cell system cross-cutting	4	These methods have multi-faceted use (beyond FC) but it is not really a state project.
Fuel cell system cross-cutting	5	Especially in area of diverse weather, and disturbance rejection. Siemens 220 kW was hugely affected by ambient temperature fluctuation. Hardware and control need to be specially developed to reject ambient and fuel disturbances.
Fuel cell system cross-cutting	5	This project is important for FC operation throughout the country but California has predominantly moderate ambient conditions.
Fuel cell system cross-cutting	6	Load following can great improve the marketability of fuel cells. Fuel cells are generally more expansive and generally use natural gas. Fuel cell attractiveness would greatly improve with transient performance, that can be achieved in SOFC, PEM, MCFC, PAFC, and DMFC.
Fuel cell system cross-cutting	6	One of the profound results would be what kind of equipment modifications are required to achieve different amounts of controllability.
Fuel cell system cross-cutting	8	Fuel cells will likely become mature in the next 10 years in the same time that renewable penetration will take place. Understanding fuel cell in context of a renewable energy infrastructure is critical.
Fuel cell system cross-cutting	9	Companies often do not conduct this type of life cycle analysis. However the state can provide support in this type of analysis. Not manufacturer dependent.
Fuel cell system cross-cutting	10	Grid communication will be critical in the future, especially for fuel cells in distributed generation. This research is not only germane to fuel cells but any distributed generation where a dedicated staff may not be needed.
Fuel cell system cross-cutting	12	Not necessarily the job of the state.
Fuel cell system cross-cutting	13	Industry already has system they plan to go commercial. Important research but not for commercialization

Category	#	Comments
Fuel cell system cross-cutting	14	Only in the sense to develop controls for (1) load following and (2) disturbance rejection. Modeling methodology already developed. Key now is to use available models for further research (e.g., CONTROLS!!! and thermal integration in DG).
Fuel cell system cross-cutting	16	Need to establish role of fuel cells, to focus research money to make the most impact.
Fuel cell system cross-cutting	17	Again system specific - Industry not state.
Fuel cell system cross-cutting	17	Should be predominantly completed by companies not the state.
Fuel cell system cross-cutting	19	Inverters exist, but special opportunity to use active power filters integrated with the inverter to improve grid power quality with distributed generation. VERY IMPORTANT.
Fuel cell system cross-cutting	20	Should be conducted by someone other than the state.
Fuel cell system cross-cutting	21	Especially in terms of SYSTEM CONTROLS. Materials very optimized system controls not very optimized. Possible to operate system to improve durability and lifetime. Step needs to be take before mass commercialization. Control methods to be further developed for specific systems can be developed with state funding.
Fuel cell system cross-cutting	21	The state can explore the mechanisms but it would be much more difficult for the state to address degradation issues.

III. Technology Integration Development Project Tables

15. Balance of Plant

15.1 Balance of Plant Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Balance of plant	2	3.67	3.33	65%	Further develop catalyst manufacturing technology (e.g., for use in reformers, fuel cells)	1	50	135	182
Balance of plant	4	3.67	2.58	64%	Develop BOP components for dynamic operation to support economic dispatch	2	54	135	105
Balance of plant	14	6.67	3.71	57%	Development of advanced hydrogen separation membranes	3	86	216	209
Balance of plant	6	5.67	1.83	50%	Simplify fuel processor system complexity	4	131	190	29
Balance of plant	8	7.00	2.83	47%	Deploy multiple distributed fuel reforming systems	5	150	223	137
Balance of plant	3	3.00	2.33	41%	Optimize major BOP components and instrumentation (e.g., sensors, controls) to improve performance and economics	6	180	111	75
Balance of plant	13	8.33	3.83	41%	Development of advanced oxygen separation membranes	7	182	240	219
Balance of plant	12	1.51	2.58	40%	Develop a better understanding of BOP and fuel cell system interconnections	8	187	25	105
Balance of plant	5	3.00	2.33	39%	Development and integration of heat exchangers	9	191	111	75
Balance of plant	7	5.67	3.33	38%	Development and demonstration of small reformers for distributed hydrogen production	10	196	190	182
Balance of plant	1	4.33	3.33	37%	Develop advanced material treatment methods to expand BOP operation range and lifetime	11	202	160	182

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Balance of plant	10	1.98	1.83	29%	Explore the prospects of recycling, reprocessing, remanufacturing and requalifying BOP equipment	12	222	59	29
Balance of plant	11	1.98	1.51	21%	Develop more efficient and effective humidifiers and condensers	13	238	59	15
Balance of plant	9	1.98	1.03	19%	Improve BOP sensors, controls and instrumentation	14	239	59	2

15.2 Balance of Plant Description Table

Project Number	Project Description
1	The operating conditions for BOP components can vary significantly based on their application. These components need to be protected from high-temperatures or high humidity conditions. The purpose of this project is to explore and develop treatment methods that can increase the longevity and available operating range for BOP components by methods like advanced heat-treatment or surface treatment.
2	Catalyst technology needs further development to increase the manufacturing and assembly flexibility for catalyst applications. Developing more precise control of catalyst application can increase the performance of catalyst coated systems while reducing the catalyst loading and system cost.
3	This project will focus on identifying and addressing BOP performance and cost issues. For example component standardization quality control and integration represent issues where work can be done to improve not only the performance of fuel cell systems but also the economics of these systems.

4	In addition to developing load following and other dynamic operation flexibility for fuel cells BOP components need to be built and controlled properly to achieve the highest performance at lowest cost. In addition to load following, BOP components should be capable of multiple startups and shutdowns at various ambient conditions.
5	Heat exchangers are essential for system integration and recycle of heat. Thus driving down the cost of heat exchangers and increasing their effectiveness can have a positive impact on the cost and performance of the system.
6	Currently steam methane reformation, water gas shift and other CO removing reactors are separated. These systems require a certain degree of complexity to accommodate the different operating conditions of the reactors. If the reformation process could be simplified and/or combined there is potential for improvement of the system. Another concern for current fuel processing technology is the time delay for fuel demand changes. Better development and control of fuel processing systems could result in more favorable dynamic performance and prevent damage to the system under extreme dynamic operations.
7	A major category within BOP is fuel processing and reforming technology. The pursuit of more demonstration projects in the fuel processing and particularly small reformers area can be used to determine operational reliability, efficiency and lifetime as well as establish public and consumer acceptance for the technology. These projects can be used to gather real-world data that is essential to further product development while providing distributed hydrogen production for use with a variety of applications. Demonstration and other deployment activities provide an integral outlet for manufacturers to pursue high-volume production.
8	Deployment of fuel reforming systems should extend beyond alpha and beta testing, which would be considered a demonstration activity, and focus more on commercially viable, high-volume production. This project should result in an increase in the number of fuel reforming products for use with fuel cells and other technologies. Also, the products and services introduced should be supported for the life of the equipment.
9	Sensors and other instrumentation play an essential role in providing feedback for control of BOP components. Optimizing these sensors can further improve the ability to control BOP systems and potentially increase performance. Developing sensors and instrumentation that can function at the various operating conditions in the BOP system presents a challenge but provides potential for system improvement.
10	The BOP contains many different components that after the system is decommissioned must be disposed of. In an effort to make BOP components more economically competitive and more environmentally sustainable recycling, reprocessing, remanufacturing and requalifying of BOP equipment should be further explored.
11	Humidifier and condenser technology could benefit from additional development for use in fuel cell applications. Fuel cells have particular operating conditions for which they operate optimally and designing humidifiers and condensers to meet these operating conditions while decreasing their

	losses represents and opportunity to increase system performance.
12	Integrating fuel cells with all of the BOP components necessary for optimal operation is an area of particular concern. An exploration of BOP to fuel cell system trade-offs and potential impacts resulting from the interconnection of these systems will provide a better understanding of how best to integrate these two systems. The goal of this project is to establish that understanding and to aid in further development of BOP systems for integration with fuel cells.
13	Some BOP equipment like gasifiers for example require that the oxygen be separated from the air for use in the gasifier. This represents an efficiency loss for the gasification system. Developing highly efficient oxygen separation membrane will benefit any process needing an oxygen stream for optimum operation.
14	The development of highly efficient hydrogen separation membrane will allow for higher performance of technologies like co-generation systems that need to separate a hydrogen stream or wish to store pure hydrogen. Current hydrogen separation technology does not provide the performance desired and could benefit from further development.

15.3 Balance of Plant Comment Table

Category	#	Comments
Balance of plant	1	One good thing about BOP improvements is that they can extend to many different applications beyond just FCs.
Balance of plant	3	Standardizing and developing a GT that SOFC and MCFC can use can be a huge benefit - Standardizing and quality control standards are necessary
Balance of plant	4	There should be a focus on performance improvement first and then on load-following BOP equipment. Provision for load-following during the initial design should be considered as it has marked benefits.
Balance of plant	5	Can help meet efficiency and performance goals but is not the responsibility of the state.
Balance of plant	7	Would provide an excellent tool for a distributed hydrogen generation infrastructure but must overcome cost, efficiency (due to equipment size) and economies of scale issues. Also, what would the hydrogen be used to operate?!
Balance of plant	8	What would the hydrogen be used to fuel? The reforming systems need to be developed and deployed in concert with the generation technology otherwise they will be no more than a source of data for research rather than a useful part of the energy portfolio.

16. Energy Storage

16.1 Energy Storage Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Energy storage	8	7.10	4.06	64%	Develop improved reversible SOFC technology for energy storage	1	52	226	234
Energy storage	3	3.13	3.14	63%	Explore the integration of fuel cells and energy storage systems with intermittent, distributed photovoltaic power systems	2	59	123	167
Energy storage	4	3.04	3.05	62%	Explore the integration of fuel cells and energy storage systems with intermittent, centralized wind power systems	3	62	119	159
Energy storage	1	2.33	1.92	61%	Explore hybridizing fuel cells with electrical energy storage devices (e.g., batteries, capacitors)	4	65	88	47
Energy storage	9	4.33	2.96	56%	Further development of high-performance batteries and ultracapacitors for use in hybrid applications	5	92	160	151
Energy storage	6	1.22	2.73	53%	Conduct fuel cell - energy storage system modeling	6	109	10	128
Energy storage	7	5.76	4.12	52%	Develop improved reversible PEMFC technology for energy storage	7	113	200	238
Energy storage	2	1.51	2.21	43%	Explore energy storage charging and discharging strategies to optimize grid connecting hybrid systems	8	172	25	62
Energy storage	10	1.35	1.83	41%	Development of novel thermal storage materials (e.g., phase change)	9	180	14	29
Energy storage	5	3.13	3.27	37%	Explore the interaction of fuel cells and energy storage systems with other intermittent renewable power systems	10	199	123	176

16.2 Energy Storage Description Table

Project Number	Project Description
1	Fuel cells if hybridized with electrical energy storage devices can provide many synergistic improvements like higher efficiency and power density than fuel cells could provide alone. Exploring the requirements to combine fuel cells and electrical storage devices and the benefits associated with operating them in a hybrid configuration can expand the marketability of fuel cells to previously unavailable applications and further enhance performance for current fuel cell applications.
2	Charging and discharging strategies are an important topic to explore when considering their interaction with the grid. The purpose of this project is to explore the charging and discharging strategy of energy storage systems hybridized with fuel cells.
3	Integrating fuel cells with intermittent power systems like distributed photovoltaic units presents a unique opportunity to reduce the variability of photovoltaic units. This project will explore how best to integrate and control the two systems for optimum performance.
4	Integrating fuel cells with intermittent power systems like centralized wind power presents a unique opportunity to reduce the variability of wind power generators. This project will explore how best to integrate and control the two different systems for optimum performance.
5	Integrating fuel cells with intermittent renewable power systems presents a unique opportunity to reduce the variability of those renewable sources. This project will explore how best to integrate and control the two different systems for optimum performance.
6	Developing models that characterize fuel cell – energy storage hybrids can aid in the improvement of these systems. Models can be used to garner a better understanding of the system requirements and how to optimize that system.
7	Reversible PEMFC systems act like a typical power generator when supplying power and as an energy storage device while operating in reverse. These fuel cells have a great deal of flexibility in controlling their supply and demand for electricity. The development of this technology would allow fuel cells to be used in new markets.
8	Reversible SOFC systems act like a typical power generator when supplying power and as an energy storage device while operating in reverse. These fuel cells have a great deal of flexibility in controlling their supply and demand for electricity. The development of this technology would allow fuel cells to be used in new markets.
9	Improving the performance of batteries will further increase the performance of fuel cell – battery hybrid systems. Additional performance

	characteristics could be improved by better integration of the two systems.
10	Another way to store energy is with thermal storage materials. These materials offer an alternative technique to storing energy from fuel cells and can also be used simultaneously with other heat sources.

16.3 Energy Storage Comment Table

Category	#	Comments
Energy storage	1	Electrical energy storage always adds cost and complexity. Fuel cell systems should be able to perform without need of electrical energy storage.
Energy storage	2	This project is many years away and the development of these fuel cell - energy storage systems needs to occur first.
Energy storage	3	The integration of fuel cells with photovoltaic and thermal energy storage is important (i.e., the integration of fuel cells, PV, and air conditioning with thermal energy storage). Again electric storage does not make sense.
Energy storage	3	This project would be amenable to California with its large solar resource. The technology could be explored now but the practicality of this application will not be evident for several years if at all. The issue right now is that FCs need to operate at full power or their payback period is increased and with high capital costs plaguing FCs part-load operation is seldom an attractive option.
Energy storage	4	Any current fuel cell project has a time to payoff >3 years.
Energy storage	4	This project would be amenable to California with its large wind resource. The technology could be explored now but the practicality of this application will not be evident for several years if at all. The issue right now is that FCs need to operate at full power or their payback period is increased and with high capital costs plaguing FCs part-load operation is seldom an attractive option.
Energy storage	5	The technology could be explored now but the practicality of this application will not be evident for several years if at all. The issue right now is that FCs need to operate at full power or their payback period is increased and with high capital costs plaguing FCs part-load operation is seldom an attractive option.
Energy storage	7	I think resources could better be used elsewhere. We should first develop the technology to take advantage of the current electrical infrastructure. Reversible FCs seem more for remote and off-grid applications.
Energy storage	7	Reversible fuel cells are expensive, and very low efficiency systems

Category	#	Comments
Energy storage	8	I think resources could better be used elsewhere. We should first develop the technology to take advantage of the current electrical infrastructure. Reversible FCs seem more for remote and off-grid applications.
Energy storage	8	Reversible fuel cells are expensive, and very low efficiency systems
Energy storage	9	Does not significantly help FC technology and marketability.
Energy storage	9	Reversible fuel cells are expensive, and very low efficiency systems
Energy storage	10	Research in the integration of thermal energy storage is important too. The technology will be important but I do not think it will be critical for initial commercialization.
Energy storage	All	The integration of fuel cells with THERMAL energy storage for both (1) combined heat and power and (2) dispatchable air conditioning loads. The integration of fuel cells with thermal energy storage is more important then electric storage.

17. Grid Level Distributed Generation Connectivity

17.1 Grid Level Distributed Generation Connectivity Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Grid-DG connectivity	6	3.00	2.33	86%	Analyze different control strategies and arrangements for optimum grid connections and interactions between customers and the utilities.	1	4	111	75
Grid-DG connectivity	7	3.27	2.73	84%	Design and develop a smart controller to autonomously connect DG systems to the electricity distribution network and develop corresponding metering technology and controls to interface with DG systems	2	6	128	128
Grid-DG connectivity	1	1.03	1.83	83%	Exploration of contractual ancillary service arrangements between customers and the utility.	3	10	4	27
Grid-DG connectivity	9	2.67	2.32	73%	Streamline DG equipment interconnection process set forth by the utility	4	26	101	73
Grid-DG connectivity	3	2.23	2.07	67%	Explore the practicalities and consequences of supplying reactive power to the electrical distribution network from distributed sources	5	43	85	54
Grid-DG connectivity	2	2.16	2.42	64%	Develop technology to provide ancillary power filtering, line switching, etc. to the electrical distribution network (i.e., power electronics)	6	55	81	84
Grid-DG connectivity	8	2.36	2.23	58%	Explore the reliability and safety of connecting DG equipment with the electrical distribution network	7	80	89	69
Grid-DG connectivity	4	1.98	1.35	51%	Explore the benefits and drawbacks of reducing short-term load variability on the electrical distribution network	8	126	59	9
Grid-DG connectivity	11	1.51	2.80	42%	Establish either statewide or national DG-grid interconnection codes, policies and standards.	9	177	23	134

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Grid-DG connectivity	12	4.33	2.83	30%	Develop advanced fuel cell power inversion and conversion technologies	10	219	160	137
Grid-DG connectivity	5	3.00	2.33	27%	Explore the benefits and drawbacks of long-term reduction of load variability on the electrical distribution network	11	225	111	75
Grid-DG connectivity	10	1.98	1.83	15%	Evaluate the need and location for additional electrical transmission lines in California taking into account growing energy demand and aging equipment	12	244	59	29

17.2 Grid Level Distributed Generation Connectivity Description Table

Project Number	Project Description
1	There is some concern on how best to implement ancillary services. Currently the distributed generation supplier does not benefit from phase angle adjustment, power factor correction, etc. that is then exported to the grid. These are services for which there is no reimbursement on the small scale but there is an efficiency loss to the system. It would be beneficial to the customers and the utility to explore how ancillary services should be integrated into the grid.
2	There is need for further development of ancillary grid service technology. Ancillary services like power filtering, VAR support and line switching are often not integrated into distributed-scale power generation equipment. These services can provide benefits for the generation equipment and the electrical distribution network.
3	Currently the electrical distribution network supplies most of the reactive power to out of phase equipment. The purpose of this project is to explore how reactive power could be supplied by distributed power generation sources and the consequences resulting from the supply of that reactive power.
4	Electrical power dynamics occur very quickly and must be analyzed around the microsecond scale. The goal of this project is to explore how short-term load variability can be attenuated and the benefits and costs for pursuing lower load variability. Concern should be given to issues like electricity waveforms, harmonics and interferences.
5	Diurnal and seasonal variations apply a highly variable load to the electrical distribution network. There is potential to have this variable load reduced through the use of energy storage and generation controls techniques. This could result in the construction of less distribution network infrastructure and better use of the current infrastructure.
6	Developing a robust control strategy for the connection of DG systems with the electricity distribution network in addition to the corresponding infrastructure could increase DG penetration into the grid. This could greatly simplify the process to connect DG equipment to the grid, which can be complicated and often not allowed. Also, it is important that a rate structure be developed for the sale of electricity to the grid.
7	The goal of this project is to better integrate DG systems with the electrical distribution network. One critical area that needs to be addressed is with the control and communication between the generation equipment and the grid. Developing autonomous smart controllers to optimally control DG systems can potentially provide benefit to the utility with regard to the dispatch of power and benefit to the power generation equipment owner with

	regard to issues like optimum payback, safety and simplicity.
8	There are concerns that if DG equipment is connected to the grid utility personnel are at risk when they perform grid diagnostic or repair operations. For example, during a power outage the utility personnel repairing the grid will be in danger if all the DG equipment still operating is not switched to island mode. An exploration of the reliability and safety issues affecting the integration of DG equipment onto the grid is an essential step toward increasing the deployment of DG-grid connected equipment.
9	Currently the process to have DG systems connected to the grid can be challenging and restrictive. The goal of this project is to work in conjunction with the utility(s) to standardize and streamline the process for connecting DG equipment to the grid. This work represents a key step for removing barriers to DG-grid connected equipment deployment.
10	Understanding where additional electrical infrastructure will be installed is critical for developing the “smart grid” or grid of the future. When planning for future electrical infrastructure it is important to include new electrical distribution paradigms into this thinking (e.g., DG fuel cells, distributed solar power).
11	Integrating DG equipment with the electrical distribution network can be difficult in part since codes and standards for this equipment vary throughout California and the entire United States. Educating codes and standards officials about DG system requirements and developing uniform codes, policies and standards for DG systems is important for the future implementation of this technology.
12	For successful connection of fuel cells with the electrical distribution network it is essential that their output power be adjusted to the power required by the distribution network. This can be accomplished with the use of inversion and conversion technologies. Further development of these technologies can provide better system performance and better integration with DG equipment and the grid.

17.3 Grid Level Distributed Generation Connectivity Comment Table

Category	#	Comments
Grid-DG connectivity	4	How significantly will this affect fuel cells?
Grid-DG connectivity	4	If achieved, this would effectively turn DG into a local UPS that would protect equipment!

Category	#	Comments
Grid-DG connectivity	5	How significantly will this affect fuel cells?
Grid-DG connectivity	5	While improving the utilization of the existing infrastructure would be important, I think the most important benefit from this is allowing higher renewable penetrations. This isn't really a direct fuel cell benefit, since they are roughly dispatchable
Grid-DG connectivity	6	Analysis must include customer acceptance and flexibility aspects of control technology.
Grid-DG connectivity	7	Must ensure customer acceptance and system stability. Use of technology extends beyond FC connectivity.
Grid-DG connectivity	10	Again: very valuable in general, but NOT for fuel cells.
Grid-DG connectivity	10	How significantly will this benefit fuel cells?
Grid-DG connectivity	11	This is a subset of "streamline grid-DG interconnection" project but very important.
Grid-DG connectivity	12	Inverter/converter technology exists it just needs to be improved. Also, how significantly benefit FCs.

IV. Fuel Project Tables

18. Hydrogen Fuel

18.1 Hydrogen Fuel Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Hydrogen Fuel	8	2.47	2.13	67%	Explore the flexibility of industrial processes for supplying hydrogen fuel at large volumes	1	44	92	57
Hydrogen Fuel	13	3.00	1.83	67%	Increase public awareness, understanding and acceptance of hydrogen technologies	2	45	111	29
Hydrogen Fuel	24	9.67	3.33	66%	Design, develop and optimize high-pressure hydrogen gas storage technologies	3	46	247	182
Hydrogen Fuel	2	5.26	3.32	61%	Support demonstration of renewable hydrogen production and delivery	4	67	183	179
Hydrogen Fuel	20	5.10	3.55	58%	Improve gas separation and purification technology	5	79	182	198
Hydrogen Fuel	21	1.41	1.60	58%	Conduct a life-cycle analysis for hydrogen production technologies and distribution methods	6	81	18	20
Hydrogen Fuel	6	4.87	2.13	55%	Improve design and integration of hydrogen delivery components	7	96	176	57
Hydrogen Fuel	1	2.81	3.12	54%	Determine the effects of fuel variation on conversion technologies	8	99	106	165
Hydrogen Fuel	5	3.67	2.08	54%	Optimize hydrogen combustion and after-treatment strategies for engine and turbine designs	9	101	135	56
Hydrogen Fuel	12	2.05	2.07	53%	Explore the needs and opportunities for governmental mandates and financial incentives for hydrogen production, delivery and storage	10	108	78	55

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Hydrogen Fuel	4	4.25	2.99	52%	Support California state policies and goals for introducing hydrogen infrastructure as required by funding demonstration and deployment projects	11	110	158	157
Hydrogen Fuel	3	7.00	4.08	52%	Support demonstration of ultra-low criteria pollutant and greenhouse gas emissions hydrogen production and delivery	12	114	223	236
Hydrogen Fuel	22	3.27	3.93	52%	Explore the available capacity and practicality of hydrogen production from a nuclear energy generation plant's product heat	13	116	128	231
Hydrogen Fuel	19	7.38	4.83	52%	Development of carbon dioxide capture and sequestration technologies for use with hydrogen production streams	14	120	227	244
Hydrogen Fuel	11	1.84	2.68	51%	Harmonization of hydrogen regulations, codes, policies and standards	15	121	52	124
Hydrogen Fuel	23	8.33	3.58	49%	Explore cost reduction and optimization techniques for hydrogen production (e.g., reforming, electrolyzing)	16	136	240	200
Hydrogen Fuel	14	5.63	3.60	45%	Expand hydrogen technology original equipment manufacturers (OEMs), service companies, parts suppliers, and systems integrators in California (i.e., supply chain)	17	162	189	201
Hydrogen Fuel	15	8.33	4.58	45%	Advance gasification technology for hydrogen fuel	18	165	240	243
Hydrogen Fuel	9	1.98	1.41	45%	Conduct a life-cycle analysis for different fuel delivery alternatives	19	167	59	13
Hydrogen Fuel	28	5.67	3.93	45%	Develop an understanding for the interaction between hydrogen and other materials	20	168	190	231
Hydrogen Fuel	26	9.00	4.83	42%	Design, develop and optimize solid state hydrogen storage technology	21	179	245	244
Hydrogen Fuel	30	5.67	3.03	39%	Explore opportunities for bulk hydrogen storage	22	190	190	158

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Hydrogen Fuel	29	4.95	3.55	38%	Exploration of novel hydrogen storage and distribution techniques	23	194	177	199
Hydrogen Fuel	10	2.67	2.58	38%	Develop and standardize hydrogen fuel quality specifications	24	195	95	105
Hydrogen Fuel	7	9.67	4.23	37%	Create hydrogen pipeline demonstration projects	25	201	247	240
Hydrogen Fuel	25	7.67	3.71	34%	Design, develop and optimize liquid hydrogen storage technology	26	212	230	209
Hydrogen Fuel	16	7.67	3.83	33%	Advance electrolysis technology for hydrogen fuel	27	215	230	219
Hydrogen Fuel	27	9.00	4.83	32%	Design, develop and optimize chemical hydride storage technology	28	216	245	244
Hydrogen Fuel	17	9.67	4.83	25%	Advance thermochemical hydrogen production technology	29	229	247	244
Hydrogen Fuel	18	8.33	3.33	17%	Advance gas to liquid production/conversion technologies for hydrogen	30	242	240	182

18.2 Hydrogen Fuel Description Table

Project Number	Project Description
1	When designing an energy conversion device it is important that the composition and flow rate of the inlet fuel stream be determined, especially for fuel cells. Variations in the composition or the flow rate can dramatically affect the performance and lifetime of conversion equipment. Variations can be realized through dynamic or steady state changes in the fuel production, or delivery equipment as well as design or operational changes in the conversion equipment. Given the effect of these changes it is critical that the available fuel stream and the desired fuel stream be characterized and matched properly.
2	The goal of this project is to demonstrate techniques for producing hydrogen renewably. Finding ways to generate the fuels renewably represents a large step toward sustainable fuel production. These fuels can be used with fuel cells and other power generation devices to demonstrate generation of renewable power.

3	This project seeks to highlight and support hydrogen production and delivery technology that can achieve ultra-low criteria pollutant and greenhouse gas emissions. An example of such technology is a high-temperature fuel cell that diverts some of the fuel stream to the co-production of hydrogen.
4	The purpose of this project is to support hydrogen production, storage, transmission, delivery and dispensing infrastructure based on California's state policies and goals. Engaging in these projects will aid in expanding the implementation of hydrogen infrastructure while pursuing California's more unified goals for hydrogen technology.
5	Developing hydrogen combustion technology provides an initial outlet for high-volume hydrogen production. In this way, hydrogen combustion and after-treatment technology has the potential to act as a bridge to hydrogen production for fuel cell technology while providing performance and emissions improvements for engine and turbine technology.
6	There is a need to further develop, standardize and integrate components for hydrogen delivery and dispensing. Thoroughly exploring the alternatives for hydrogen delivery and dispensing technologies now can identify the optimum alternative while allowing for early component standardization. Also, development of the components to be used for hydrogen delivery and dispensing is critical to ensure safe, reliable operation and to provide a competitive product.
7	Hydrogen presents unique challenges when considering its delivery in pipelines. Funding demonstration projects for hydrogen pipelines will stimulate the growth and development of this technology and can be integrated into areas where it can be immediately used (e.g., industrial processing, fueling stations).
8	There are specific industrial processes used to generate hydrogen and in addition there may be synergies with other industrial processes that can produce hydrogen as a byproduct or a waste stream. The goal of this project is to explore the availability and practicality of industrial processes to supply hydrogen fuel, especially at large volumes.
9	To aid in the design selection of hydrogen delivery technologies a life-cycle analysis should be performed on different fuel delivery alternatives. Life-cycle analyses present a more holistic view of the consequences for using a given technology. Some of these alternatives include: tube-trailer, pipeline, distributed production, locomotive transport.
10	It is important for manufacturers of fuel cell technology and other hydrogen technologies that fuel quality specification be developed. This will increase the flexibility of hydrogen fuel by allowing the manufacturers of hydrogen fueled technologies to design their devices to operate optimally on the given fuel specification. Additionally, hydrogen production will be simplified since there will be more standardized fuel specifications.
11	The goal of this project is to establish uniform hydrogen regulations, codes, policies and standards either throughout California or throughout the

	United States. This will require education of policy and codes and standards makers about hydrogen safety and operation; however, developing realistic and consistent regulations, codes, policies and standards is essential for the widespread implantation of hydrogen fuel and hydrogen technologies.
12	The government will play an essential role in providing initial support for hydrogen technologies approaching commercialization. Government incentives can stimulate product production while full-scale manufacturing volumes are achieved. In addition, mandates can be used to preferentially select the technologies that provide the most benefit currently and the most potential in the future. A study that explores the extent to which incentives and mandates should be implemented for California hydrogen production, delivery and storage applications will aid in presenting a clear message concerning the resources that the government or ratepayers can supply to further hydrogen technology deployment.
13	Customer awareness, understanding and acceptance of hydrogen technology is paramount to their introduction into the current fueling system. The goal of this project is to increase customer and public confidence and understanding of hydrogen technologies. One example that can be used to address these issues is to develop accurate and objective information about hydrogen technology for dissemination to the public.
14	With the advent of new hydrogen production, storage, delivery and dispensing technology, the growth and development of industry to support systems development, integration, installation, and service is required. A holistic solution for the successful inclusion of hydrogen fuel into the fueling portfolio will include the coincident development of supporting companies and technology and the appropriate support infrastructure. This infrastructure should include: OEMs, installation companies, maintenance and service companies, parts supplies, etc. Projects that propose to develop an integrated approach to supply chain development will be supported.
15	The goal of this project is to further develop gasification technology for the production of hydrogen fuel. Improvements in gasification of feedstocks like coal and coke to produce hydrogen can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of hydrogen fuel production methods is essential to lower the cost of hydrogen fuel to that of competing fuels.
16	The goal of this project is to further develop electolysis technology for the production of hydrogen fuel. Improvements in electrolysis to produce hydrogen can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of hydrogen fuel production methods is essential to lower the cost of hydrogen fuel to that of competing fuels.
17	The goal of this project is to further develop thermochemical technologies for producing hydrogen fuel. Improvements in thermochemical hydrogen production technologies can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of hydrogen fuel production methods is essential to lower the cost of hydrogen fuel to that of competing fuels.

18	The goal of this project is to further develop gas to liquid conversion technologies for the production of hydrogen fuel. Improvements in gas to liquid technologies to produce hydrogen can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of hydrogen fuel production methods is essential to lower the cost of hydrogen fuel to that of competing fuels.
19	When hydrogen is produced from carbon containing compounds typically carbon dioxide will be released. The purpose of this project is to identify critical hydrogen production areas that are particularly amenable to carbon capture and sequestration (e.g., fuel cell co-production, industrial processing). In addition, further development of carbon separation and sequestration technologies can be pursued.
20	The goal of this project is to improve gas separation and purification processes and technology for different components (e.g., carbon dioxide, hydrogen). Gas separation technology is available but can benefit from simplification and power consumption reductions. Additionally, to aid in this effort modeling of separation and purification processes can be pursued.
21	To aid in the design selection of hydrogen production technologies a life-cycle analysis should be performed on different hydrogen production alternatives. Life-cycle analyses present a more holistic view of the consequences for using a given technology.
22	Nuclear power generators are uniquely suited for generating hydrogen because of the large amount of product heat that they generate. The goal of this project is to identify the available capacity for hydrogen production at nuclear power plants and explore the practicalities of generating hydrogen using this technique.
23	The purpose of this project is to identify cross-cutting hydrogen production issues that have the potential to reduce costs or further optimize hydrogen production methods. For example, addressing the degradation mechanisms for hydrogen production equipment or optimizing a BOP component for hydrogen production systems are actions that can positively affect several hydrogen production technologies.
24	High-pressure hydrogen gas storage systems, though commercially available can benefit from further design, development and optimization. For instance, the inclusion of embedded sensors, resistance to impact and system packaging represent areas where advancements could be made for hydrogen gas storage systems. The goal of this project is to advance hydrogen gas storage technologies making them more competitive with current energy storage techniques.
25	Liquid hydrogen storage systems, though commercially available can benefit from further design, development and optimization. Currently liquid storage systems can benefit from reductions to hydrogen boil-off and better containment insulation. The goal of this project is to advance liquid hydrogen storage technologies making them more competitive with current energy storage techniques.
26	Solid state hydrogen storage systems, though commercially available can benefit from further design, development and optimization. There is a need

	to develop advanced materials and further material reaction and regeneration technology. This and other developments that reduce the cost and increase the efficiency and energy density of solid state storage technologies are particularly desirable. The goal of this project is to advance solid state hydrogen storage technologies making them more competitive with current energy storage techniques.
27	Chemical hydride hydrogen storage systems can benefit from further design, development and optimization. There is a need to develop advanced materials and further material reaction and regeneration technology. This and other developments that reduce the cost and increase the efficiency and energy density of chemical hydride storage technologies are particularly desirable. The goal of this project is to advance chemical hydride storage technologies making them more competitive with current energy storage techniques.
28	The purpose of this project is to explore the properties of hydrogen and how it reacts to the presence of other materials, especially materials that it will typically come in contact with like storage tank materials, fuel cell materials and balance of plant components. This study should explore long-term and short-term hydrogen materials testing. Additionally, this project should include determining the best techniques to reduce negative interactions with hydrogen (e.g., embrittlement).
29	There may be unique opportunities for storing and distributing hydrogen both for low-volume hydrogen distribution and as hydrogen distribution becomes more widespread. The purpose of this project is to explore various hydrogen storage and distribution techniques that can be used as hydrogen distribution volumes increase. Exploring distribution and storage techniques like reversible and regenerative hydrogen storage materials and fill-in place storage devices should be included in this project.
30	The goal of this project is to identify and explore opportunities to store large amounts of hydrogen while maintaining easy availability and reducing storage losses. Bulk hydrogen storage has the potential to increase the flexibility of hydrogen production at hydrogen production facilities by optimizing the operation times for hydrogen production (e.g., base hydrogen production on electricity rate schedule). An example of bulk hydrogen storage is inserting hydrogen underground in a similar manner as carbon sequestration.

18.3 Hydrogen Fuel Comment Table

Category	#	Comments
Hydrogen Fuel	1	Benefits question involves diverse group of stakeholders (society, CA ratepayers, business/investors) and the actual benefit to each stakeholder group can be different. Consider in future survey design addressing each stakeholder group independently.
Hydrogen Fuel	2	There are commercial ways to make hydrogen from renewable energy -- electrolysis using wind, solar, hydro, burned biomass. The development of various alternate technologies (photolysis, etc) is high cost, high risk, long term.

Category	#	Comments
Hydrogen Fuel	2	Very vague. There are many techniques for generating renewable hydrogen. This project could be separated into several smaller projects. Make sure that equipment is available to use the generated hydrogen (FC, turbine, etc.).
Hydrogen Fuel	3	Good as demonstration but technology must stand on its own economically in order to be competitive.
Hydrogen Fuel	4	Need to see much greater details before support offered.
Hydrogen Fuel	5	Indirectly related to fuel cells (FC in hybrid and with post combustion strategies).
Hydrogen Fuel	8	Can be explored by the state but implementation should be pursued by the industry.
Hydrogen Fuel	9	Project can be very location specific so it would be good that the state pursues this project to help guide hydrogen sector development.
Hydrogen Fuel	10	Excellent outlet for the state to help guide the development of its hydrogen sector.
Hydrogen Fuel	14	Allow free market competition to prevail.
Hydrogen Fuel	14	Can lower equipment and installation costs but can be difficult to stimulate the supply chain.
Hydrogen Fuel	15	Funding for project should be provided at the federal level.
Hydrogen Fuel	15	State shouldn't shoulder all technology development costs. Should aid with some development but predominantly demonstrations and deployment.
Hydrogen Fuel	16	Hydrogen production via electrolysis consumes large amounts of electricity and there's no clear line of sight in achieving a large step change in efficiency. Survey feedback comment: Please consider revising 1st question of survey with a 4th option of No, this project is not worth consideration, and instead of skipping to next section, allow respondents provide feedback on why a specific initiative is not worth considering.
Hydrogen Fuel	16	Low temperature electrolysis is a pretty well-developed technology -- gains will be incremental. High temperature electrolysis is highly developmental, much work remains to be done.
Hydrogen Fuel	16	State shouldn't shoulder all technology development costs. Should aid with some development but predominantly demonstrations and deployment. Electrolysis will have to compete with SMR for hydrogen generation.

Category	#	Comments
Hydrogen Fuel	17	State shouldn't shoulder all technology development costs. Should aid with some development but predominantly demonstrations and deployment.
Hydrogen Fuel	18	Converting fuels to liquid has an extreme cost penalty, especially when compared to the cost of current liquid fuels.
Hydrogen Fuel	19	California's amenability to CCS and the potential of CCS (uptake, leak rate, etc.) should first be explored before large investments are made in the technology.
Hydrogen Fuel	19	Fossil-based production of hydrogen needs to be phased out.
Hydrogen Fuel	20	Fossil-based production of hydrogen needs to be phased out.
Hydrogen Fuel	22	Project should be predominately funded at the federal level.
Hydrogen Fuel	22	To explore the POTENTIAL is cheap and easy and worthwhile. To IMPLEMENT this would be a major development effort.
Hydrogen Fuel	23	There is federally-funded work in this area.
Hydrogen Fuel	24	Project should be funded at the federal level.
Hydrogen Fuel	25	Funding required at federal level.
Hydrogen Fuel	25	LH2 technology is commercial for large scale storage. LH2 for vehicles doesn't make a lot of sense.
Hydrogen Fuel	26	There are large federal programs in this area.
Hydrogen Fuel	28	Funding should be provided at the federal level.
Hydrogen Fuel	30	I assume this is a paper study.

19. Opportunity Fuel

19.1 Opportunity Fuel Project Table

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Opportunity fuels	13	6.67	2.83	100%	Support multiple demonstrations of similar fuel cell technologies applied to opportunity fuels	1	1	216	137
Opportunity fuels	14	8.67	3.71	91%	Support greenhouse gas and emissions reduction through multiple demonstration projects in non-attainment areas that use opportunity fuels	2	3	244	209
Opportunity fuels	16	7.38	3.19	83%	Increase deployment activities for systems operating on landfill and digester gas	3	11	228	170
Opportunity fuels	2	4.44	3.22	59%	Improve and optimize production methods for methane containing opportunity and renewable fuels	4	72	168	171
Opportunity fuels	4	1.98	2.49	54%	Advance gas cleanup and purification processes for digester gas use in fuel cell systems	5	104	59	99
Opportunity fuels	3	1.98	2.96	54%	Advance gas cleanup and purification processes for landfill and biomass gas use in fuel cell systems	6	105	59	151
Opportunity fuels	5	3.70	3.07	47%	Identify promising fuel production methods that can be integrated with opportunity fuels	7	151	150	160
Opportunity fuels	7	7.67	4.08	42%	Advance gasification fuel production technology	8	178	230	236
Opportunity fuels	12	5.34	3.65	36%	Expand opportunity fuel technology original equipment manufacturers (OEMs), service companies, parts suppliers, and systems integrators in California (i.e., supply chain)	9	203	186	205
Opportunity fuels	1	1.98	1.83	28%	Establish fuel quality specifications for different opportunity fuels to allow for product standardization	10	223	59	29

Category	#	Average Project Cost (million $)	Average Project Duration (years)	Average Project Score	Title	Category Rank	Overall Rank	Cost Rank	Duration Rank
Opportunity fuels	6	3.67	4.83	27%	Advance biological fuel production technology	11	224	135	244
Opportunity fuels	11	1.35	2.83	24%	Explore the flexibility of industrial processes for supplying opportunity fuels at large volumes	12	232	14	137
Opportunity fuels	9	3.00	4.83	23%	Advance solar photolysis fuel production technology	13	235	111	244
Opportunity fuels	15	5.67	3.33	17%	Explore methods to address the temporal availability barriers for opportunity fuels	14	241	190	182
Opportunity fuels	8	9.67	4.83	9%	Advance thermochemical fuel production technology	15	247	247	244
Opportunity fuels	10	9.67	4.83	0%	Advance gas to liquid fuel production technologies	16	251	247	244

19.2 Opportunity Fuel Description Table

Project Number	Project Description
1	It is important for manufacturers of fuel cell technology and other technologies that operate on similar fuels that fuel quality specification be developed. This will increase the flexibility of opportunity fuels by allowing the manufacturers of opportunity fueled technologies to design their devices to operate optimally on a given fuel specification. Additionally, opportunity fuel production will be simplified since there will be more standardized fuel specifications.
2	The goal of this project is to further develop fuel production technology for methane containing opportunity and renewable fuels. Improvements in the production of these types of fuels can increase performance, lifetime and reliability of the systems that operate these fuels, making them more versatile and economically attractive. Further development of methane containing opportunity and renewable fuel production methods is essential to

	lower the cost of these fuels to that of competing fuels.
3	Landfill gas and biomass gas contain contaminants and toxic components that need to be removed for optimum performance with fuel cell systems. Some of these components include sulfur, siloxanes, chlorine, mercury, and arsenic. Fuel cell systems will experience reduced performance and potentially fail if operated on contaminated fuels. Thus it is important that the gas be cleaned and purified before being used in fuel cell systems. The purpose of this project is to explore and develop cleanup and purification technology to reduce the harmful contaminants and toxics present in landfill and biomass gases.
4	Digester gas contains contaminants that need to be removed for optimum performance with fuel cell systems. Some of these components include sulfur, siloxanes, and chlorine. Unlike landfill gas and biomass gas, digester gas typically has fewer toxic contaminants. Fuel cell systems will experience reduced performance and potentially fail if operated on contaminated fuels. Thus it is important that the gas be cleaned and purified before being used in fuel cell systems. The purpose of this project is to explore and develop cleanup and purification technology to reduce the harmful contaminants present in digester gas.
5	There are many methods to produce fuels from opportunity fuels. The purpose of this study is to identify and explore the feasibility of using opportunity fuels with different production methods. Also, the flexibility of each fuel production process should be explored.
6	The goal of this project is to further develop biological fuel production technology. Improvements in biological production technologies can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of biological fuel production methods is essential to lower the cost of opportunity fuels to that of competing fuels.
7	The goal of this project is to further develop gasification technology for utilizing opportunity fuels. Improvements in gasification technologies can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of opportunity fuel production methods is essential to lower the cost of opportunity fuels to that of competing fuels.
8	The goal of this project is to further develop thermochemical technologies for utilizing opportunity fuels. Improvements in thermochemical technologies can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of opportunity fuel production methods is essential to lower the cost of opportunity fuels to that of competing fuels.
9	The goal of this project is to further develop photolysis technologies for producing fuels. Improvements in photolysis technologies can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of opportunity fuel production methods is essential to lower the cost of opportunity fuels to that of competing fuels.

10	The goal of this project is to further develop gas to liquid conversion technologies to convert opportunity fuels into liquid fuels. Improvements in gas to liquid technologies can increase performance, lifetime and reliability of these systems, making them more versatile and economically attractive. Further development of fuel production methods is essential to lower the cost of hydrogen fuel to that of competing fuels.
11	There may be synergies with industrial processes that can produce opportunity fuels as a byproduct or a waste stream of their process. The goal of this project is to explore the availability and practicality of industrial processes to supply opportunity fuel, especially at large volumes.
12	With the advent of opportunity fuel technologies, the growth and development of industry to support systems development, integration, installation, and service is required. A holistic solution for the successful inclusion of opportunity fuels into the fueling portfolio will include the coincident development of supporting companies and technology and the appropriate support infrastructure. This infrastructure should include: OEMs, installation companies, maintenance and service companies, parts supplies, etc. Projects that propose to develop an integrated approach to supply chain development will be supported.
13	The goal of this project is to test the performance of opportunity fuels in specific applications. The applications should include fuel cell technologies and other power generation technologies. These demonstrations can be used to garner real-world data that is essential to further product development for fuel cells and other power generation technologies that can operate on opportunity fuels.
14	To establish greenhouse gas and emissions reduction potential for technologies operating on opportunity fuels in non-attainment areas it is critical that more demonstration projects be pursued, with emphasis placed on those technologies that are nearing commercialization. These demonstrations can be used to garner real-world data that can be used to compare performance of power generation equipment fueled with opportunity fuels to that of conventional fuels. Demonstration sites provide an integral initial outlet for manufacturers to pursue high-volume production. As an example state owned and operated organizations and utilities represent optimum demonstration sites for new and emerging technologies.
15	Some opportunity fuels are only available during certain times throughout the year. The purpose of this study is to explore the possible methods to increase the flexibility of using such seasonal fuels. Some examples are blending one or more seasonal fuel feedstock with one or more fuel feedstock that is available year-round to reduce the impact of one particular feedstock on the availability of the fuel. There is also an interest in exploring power generation equipment operation on dynamic fuel compositions, because the composition of many opportunity fuels will vary not only throughout the year but throughout the day.
16	Deployment of power generation systems operating on landfill and digester gas should be pursued with a focus on commercially viable, high-volume production methods. This project should result in an increase in the use of landfill and digester gas fueled products throughout California. Also, the

	products and services introduced should be supported for the life of the application (e.g., equipment life, landfill life).

19.3 Opportunity Fuel Comment Table

Category	#	Comments
Opportunity fuels	1	Standardization of fuel specifications represent an optimal project for the state because it is state specific and the government should be more objective in their review of different technologies than any given company or industry.
Opportunity fuels	2	There are many benefits but the availability of these fuels is limited, thereby lowering the benefit to cost ratio.
Opportunity fuels	3	Important project but the results will be specific to applications for which there is a limited supply (e.g., landfills, farms)
Opportunity fuels	3	Not sure opportunity fuels will provide the volume needed for FC commercialization.
Opportunity fuels	4	Available number of applications is limited to the number of areas needing gas digestion (waste water treatment plants, farms, etc.)
Opportunity fuels	10	It is difficult for gas to liquid conversion technology to compete with currently used liquid fuels (high cost and low efficiency). This has a profound effect on my benefit to cost ratio selection.
Opportunity fuels	11	Opportunity fuels are very location specific and will vary significantly from area to area making them difficult to conduct general analysis and development for the technology.
Opportunity fuels	14	More as advertising
Opportunity fuels	15	One of the key issues is with developing opportunity fuel markets!!
Opportunity fuels	16	Offer initial market applications that can greatly benefit the development of the technology. How large and how continuous is the need for landfill and digester gas installations?
Opportunity fuels	All	One general comment is that many of these projects would be beneficial but depending on the market size and sustainability may or may not be wise investments. Do opportunity fuels represent a niche market or is the market large enough for companies to specialize in fuel cells operated on opportunity fuels?

Appendix E: List of Prioritized Projects by Score, Cost and Duration

Rank	Score		Cost		Duration		Rank
	#	Category	#	Category	#	Category	
1	13	Opportunity fuels	3	PAFC	16	Transportation	1
2	10	FC-GT Hybrid	4	MCFC	5	PAFC	2
3	14	Opportunity fuels	14	Materials handling	10	Portable	3
4	6	Grid-DG connectivity	1	Grid-DG connectivity	3	PAFC	4
5	4	DG/CCHP	13	FC-GT Hybrid	9	Balance of plant	5
6	7	Grid-DG connectivity	5	PAFC	15	Transportation	6
7	2	Grid support	10	Portable	14	Materials handling	7
8	1	Grid support	1	PAFC	12	DG/CCHP	8
9	12	SOFC	1	Materials handling	8	Episodic	9
10	1	Grid-DG connectivity	9	MCFC	4	Grid-DG connectivity	10
11	16	Opportunity fuels	6	Energy storage	6	MCFC	11
12	3	DG/CCHP	15	Fuel cell system cross-cutting	9	Grid support	12
13	14	Fuel cell system cross-cutting	12	DG/CCHP	9	Hydrogen Fuel	13
14	13	FC-GT Hybrid	8	Episodic	1	Materials handling	14
15	8	Fuel cell system cross-cutting	10	Energy storage	2	Fuel cell system cross-cutting	15
16	11	FC-GT Hybrid	10	Market cross-cutting	12	PEMFC	16

Rank	Score		Cost		Duration		Rank
17	11	SOFC	11	Opportunity fuels	7	PEMFC	17
18	5	DG/CCHP	21	Hydrogen Fuel	11	Balance of plant	18
19	12	DG/CCHP	1	PEMFC	12	Fuel cell system cross-cutting	19
20	7	Grid support	13	PEMFC	9	MCFC	20
21	9	Episodic	3	PEMFC	21	Hydrogen Fuel	21
22	2	DG/CCHP	12	Materials handling	13	PEMFC	22
23	6	Grid support	11	Grid-DG connectivity	16	Fuel cell system cross-cutting	23
24	1	Portable	9	Grid support	10	Market cross-cutting	24
25	5	Grid support	8	MCFC	14	Fuel cell system cross-cutting	25
26	9	Grid-DG connectivity	2	PAFC	14	DG/CCHP	26
27	12	FC-GT Hybrid	2	MCFC	1	Grid-DG connectivity	27
28	10	DG/CCHP	10	Fuel cell system cross-cutting	13	FC-GT Hybrid	28
29	8	Transportation	2	Energy storage	13	Hydrogen Fuel	29
30	1	SOFC	12	Balance of plant	2	DMFC	30
31	9	SOFC	7	PEMFC	8	MCFC	31
32	2	Portable	13	Transportation	6	Balance of plant	32
33	7	DG/CCHP	12	Fuel cell system cross-cutting	6	PEMFC	33
34	3	FC-GT Hybrid	9	Market cross-cutting	11	PEMFC	34

Rank	Score		Cost		Duration		Rank
35	9	Transportation	9	SOFC	10	Fuel cell system cross-cutting	35
36	1	DG/CCHP	13	Fuel cell system cross-cutting	10	Energy storage	36
37	5	SOFC	6	SOFC	15	Fuel cell system cross-cutting	37
38	8	Episodic	6	PEMFC	8	SOFC	38
39	2	Episodic	8	SOFC	8	PEMFC	39
40	5	PEMFC	6	Episodic	10	Balance of plant	40
41	5	PAFC	3	Market cross-cutting	1	Opportunity fuels	41
42	10	Materials handling	11	Materials handling	4	PAFC	42
43	3	Grid-DG connectivity	6	Portable	8	Market cross-cutting	43
44	8	Hydrogen Fuel	9	Materials handling	4	DMFC	44
45	13	Hydrogen Fuel	8	Market cross-cutting	10	Grid-DG connectivity	45
46	24	Hydrogen Fuel	12	Transportation	7	Episodic	46
47	5	Market cross-cutting	1	Fuel cell system cross-cutting	1	Energy storage	47
48	11	Fuel cell system cross-cutting	12	PEMFC	6	Episodic	48
49	6	Transportation	3	Portable	13	SOFC	49
50	2	Balance of plant	13	SOFC	9	Materials handling	50
51	10	SOFC	7	SOFC	1	Episodic	51
52	8	Energy storage	11	Hydrogen Fuel	4	Market cross-cutting	52

Rank	Score		Cost		Duration		Rank
53	5	Episodic	13	DG/CCHP	14	Market cross-cutting	53
54	4	Balance of plant	14	DG/CCHP	3	Grid-DG connectivity	54
55	2	Grid-DG connectivity	11	Grid support	12	Hydrogen Fuel	55
56	6	Market cross-cutting	3	Grid support	5	Hydrogen Fuel	56
57	3	Transportation	7	Market cross-cutting	8	Hydrogen Fuel	57
58	8	Grid support	8	Portable	13	Fuel cell system cross-cutting	58
59	3	Energy storage	11	SOFC	6	Hydrogen Fuel	59
60	4	Market cross-cutting	4	Opportunity fuels	1	PEMFC	60
61	6	Fuel cell system cross-cutting	3	Opportunity fuels	7	Grid support	61
62	4	Energy storage	4	SOFC	5	MCFC	62
63	9	MCFC	3	MCFC	1	Fuel cell system cross-cutting	63
64	1	FC-GT Hybrid	4	Grid-DG connectivity	2	MCFC	64
65	1	Energy storage	11	Market cross-cutting	7	MCFC	65
66	2	Fuel cell system cross-cutting	9	Hydrogen Fuel	9	PEMFC	66
67	2	Hydrogen Fuel	6	DMFC	2	Energy storage	67
68	2	Materials handling	4	Fuel cell system cross-cutting	4	MCFC	68
69	3	Materials handling	10	Balance of plant	8	Grid-DG connectivity	69
70	3	Fuel cell system cross-cutting	1	Opportunity fuels	6	Market cross-cutting	70

Rank	Score		Cost		Duration		Rank
71	4	Grid support	11	Balance of plant	7	DG/CCHP	71
72	2	Opportunity fuels	9	Balance of plant	9	Portable	72
73	12	Market cross-cutting	10	Grid-DG connectivity	9	Grid-DG connectivity	73
74	7	Episodic	15	Transportation	5	Market cross-cutting	74
75	8	DG/CCHP	5	DMFC	6	Grid-DG connectivity	75
76	2	DMFC	7	Episodic	11	SOFC	76
77	13	Fuel cell system cross-cutting	4	Market cross-cutting	3	Balance of plant	77
78	13	DG/CCHP	12	Hydrogen Fuel	5	Balance of plant	78
79	20	Hydrogen Fuel	7	Portable	5	Grid-DG connectivity	79
80	8	Grid-DG connectivity	14	Market cross-cutting	20	Fuel cell system cross-cutting	80
81	21	Hydrogen Fuel	2	Grid-DG connectivity	2	Materials handling	81
82	14	DG/CCHP	16	Transportation	11	Materials handling	82
83	1	DMFC	8	DG/CCHP	7	Market cross-cutting	83
84	8	Portable	1	DG/CCHP	2	Grid-DG connectivity	84
85	1	MCFC	3	Grid-DG connectivity	8	Portable	85
86	14	Balance of plant	21	Fuel cell system cross-cutting	9	Market cross-cutting	86
87	6	Episodic	7	DG/CCHP	12	Transportation	87
88	4	Materials handling	1	Energy storage	12	Materials handling	88

Rank	Score		Cost		Duration		Rank
89	3	Portable	8	Grid-DG connectivity	1	DG/CCHP	89
90	8	MCFC	6	DG/CCHP	3	Materials handling	90
91	3	Episodic	20	Fuel cell system cross-cutting	8	Fuel cell system cross-cutting	91
92	9	Energy storage	14	Fuel cell system cross-cutting	10	SOFC	92
93	5	Portable	8	Hydrogen Fuel	6	SOFC	93
94	2	FC-GT Hybrid	2	PEMFC	2	DG/CCHP	94
95	9	Fuel cell system cross-cutting	2	Fuel cell system cross-cutting	8	DG/CCHP	95
96	6	Hydrogen Fuel	9	Fuel cell system cross-cutting	3	Portable	96
97	3	Market cross-cutting	8	Materials handling	3	Grid support	97
98	13	Market cross-cutting	7	MCFC	7	Portable	98
99	1	Hydrogen Fuel	9	PEMFC	4	Opportunity fuels	99
100	2	SOFC	10	Hydrogen Fuel	13	Market cross-cutting	100
101	5	Hydrogen Fuel	9	Grid-DG connectivity	1	Portable	101
102	5	MCFC	14	Transportation	7	SOFC	102
103	14	Market cross-cutting	4	FC-GT Hybrid	14	Transportation	103
104	4	Opportunity fuels	4	Grid support	11	Grid support	104
105	3	Opportunity fuels	2	Portable	9	SOFC	105
106	9	Market cross-cutting	1	Hydrogen Fuel	4	Balance of plant	106

Rank	Score		Cost		Duration		Rank
107	5	Materials handling	11	Transportation	3	Fuel cell system cross-cutting	107
108	12	Hydrogen Fuel	13	Market cross-cutting	1	MCFC	108
109	6	Energy storage	10	Transportation	3	MCFC	109
110	4	Hydrogen Fuel	17	Fuel cell system cross-cutting	2	PAFC	110
111	4	Episodic	6	Grid-DG connectivity	11	Market cross-cutting	111
112	6	DG/CCHP	1	SOFC	10	PEMFC	112
113	7	Energy storage	13	Hydrogen Fuel	12	Balance of plant	113
114	3	Hydrogen Fuel	3	Balance of plant	10	Hydrogen Fuel	114
115	4	SOFC	5	Balance of plant	11	Transportation	115
116	22	Hydrogen Fuel	5	Grid-DG connectivity	3	DMFC	116
117	9	Grid support	9	Opportunity fuels	5	DMFC	117
118	1	Fuel cell system cross-cutting	4	Portable	5	Fuel cell system cross-cutting	118
119	3	MCFC	4	Energy storage	6	Portable	119
120	19	Hydrogen Fuel	2	DG/CCHP	2	Episodic	120
121	11	Hydrogen Fuel	7	Grid support	8	Materials handling	121
122	6	FC-GT Hybrid	9	Portable	4	Portable	122
123	4	Transportation	3	Energy storage	2	Portable	123
124	5	FC-GT Hybrid	5	Energy storage	11	Hydrogen Fuel	124

Rank	Score		Cost		Duration		Rank
125	7	Transportation	9	FC-GT Hybrid	13	DG/CCHP	125
126	4	Grid-DG connectivity	1	Portable	4	Materials handling	126
127	7	Portable	6	Transportation	5	Materials handling	127
128	2	PAFC	7	Grid-DG connectivity	7	Grid-DG connectivity	128
129	13	SOFC	22	Hydrogen Fuel	6	Energy storage	129
130	6	SOFC	7	Fuel cell system cross-cutting	2	PEMFC	130
131	6	Balance of plant	19	Fuel cell system cross-cutting	3	Market cross-cutting	131
132	3	SOFC	3	Materials handling	3	Episodic	132
133	8	Materials handling	12	Market cross-cutting	17	Fuel cell system cross-cutting	133
134	21	Fuel cell system cross-cutting	1	Episodic	11	Grid-DG connectivity	134
135	10	Portable	2	Balance of plant	4	Grid support	135
136	23	Hydrogen Fuel	4	Balance of plant	5	Portable	136
137	5	Fuel cell system cross-cutting	2	Materials handling	13	Opportunity fuels	137
138	7	Materials handling	3	Fuel cell system cross-cutting	1	DMFC	138
139	6	Materials handling	1	MCFC	8	Balance of plant	139
140	4	Portable	2	SOFC	6	DMFC	140
141	1	PEMFC	5	Hydrogen Fuel	4	Fuel cell system cross-cutting	141
142	1	Market cross-cutting	5	MCFC	12	Grid-DG connectivity	142

Rank	Score		Cost		Duration		Rank
143	7	SOFC	5	Fuel cell system cross-cutting	11	Opportunity fuels	143
144	11	Grid support	11	PEMFC	21	Fuel cell system cross-cutting	144
145	2	MCFC	4	PEMFC	10	Transportation	145
146	16	Fuel cell system cross-cutting	6	Opportunity fuels	10	Materials handling	146
147	6	PEMFC	4	PAFC	5	Episodic	147
148	14	Transportation	4	DMFC	6	DG/CCHP	148
149	11	DG/CCHP	3	DMFC	12	SOFC	149
150	8	Balance of plant	5	Opportunity fuels	19	Fuel cell system cross-cutting	150
151	5	Opportunity fuels	18	Fuel cell system cross-cutting	5	PEMFC	151
152	13	PEMFC	13	Materials handling	9	Energy storage	152
153	11	PEMFC	14	FC-GT Hybrid	3	Opportunity fuels	153
154	3	Grid support	6	FC-GT Hybrid	4	PEMFC	154
155	2	Market cross-cutting	5	Portable	4	Episodic	155
156	10	Grid support	10	Materials handling	6	Grid support	156
157	7	MCFC	5	FC-GT Hybrid	4	Hydrogen Fuel	157
158	6	Portable	4	Hydrogen Fuel	30	Hydrogen Fuel	158
159	2	Transportation	5	Market cross-cutting	4	Energy storage	159
160	7	FC-GT Hybrid	2	DMFC	5	Opportunity fuels	160

Rank	Score		Cost		Duration		Rank
161	11	Market cross-cutting	1	DMFC	5	DG/CCHP	161
162	14	Hydrogen Fuel	9	Energy storage	13	Materials handling	162
163	10	Fuel cell system cross-cutting	16	Fuel cell system cross-cutting	6	Fuel cell system cross-cutting	163
164	1	Transportation	6	MCFC	18	Fuel cell system cross-cutting	164
165	15	Hydrogen Fuel	1	Balance of plant	1	Hydrogen Fuel	165
166	9	PEMFC	12	Grid-DG connectivity	12	Market cross-cutting	166
167	9	Hydrogen Fuel	7	FC-GT Hybrid	3	Energy storage	167
168	28	Hydrogen Fuel	2	Opportunity fuels	6	FC-GT Hybrid	168
169	2	PEMFC	2	Episodic	4	FC-GT Hybrid	169
170	19	Fuel cell system cross-cutting	6	Fuel cell system cross-cutting	16	Opportunity fuels	170
171	11	Materials handling	3	SOFC	2	Opportunity fuels	171
172	2	Energy storage	6	Materials handling	6	Transportation	172
173	7	Market cross-cutting	10	PEMFC	10	DG/CCHP	173
174	7	Fuel cell system cross-cutting	8	PEMFC	14	FC-GT Hybrid	174
175	6	DMFC	6	Market cross-cutting	3	DG/CCHP	175
176	9	DG/CCHP	6	Hydrogen Fuel	5	Energy storage	176
177	11	Grid-DG connectivity	29	Hydrogen Fuel	9	FC-GT Hybrid	177
178	7	Opportunity fuels	7	Transportation	5	FC-GT Hybrid	178

Rank	Score		Cost		Duration		Rank
179	26	Hydrogen Fuel	12	SOFC	2	Hydrogen Fuel	179
180	10	Energy storage	11	Fuel cell system cross-cutting	4	DG/CCHP	180
181	3	Balance of plant	3	Episodic	1	FC-GT Hybrid	181
182	13	Balance of plant	20	Hydrogen Fuel	24	Hydrogen Fuel	182
183	10	PEMFC	2	Hydrogen Fuel	2	Balance of plant	183
184	12	PEMFC	4	Materials handling	3	PEMFC	184
185	4	MCFC	5	Materials handling	7	Balance of plant	185
186	6	MCFC	12	Opportunity fuels	1	Balance of plant	186
187	12	Balance of plant	2	FC-GT Hybrid	1	PAFC	187
188	3	PEMFC	5	Episodic	13	Transportation	188
189	15	Fuel cell system cross-cutting	14	Hydrogen Fuel	15	Opportunity fuels	189
190	30	Hydrogen Fuel	5	PEMFC	18	Hydrogen Fuel	190
191	5	Balance of plant	6	Balance of plant	9	Episodic	191
192	18	Fuel cell system cross-cutting	7	Materials handling	1	Market cross-cutting	192
193	8	SOFC	28	Hydrogen Fuel	2	SOFC	193
194	29	Hydrogen Fuel	30	Hydrogen Fuel	8	FC-GT Hybrid	194
195	10	Hydrogen Fuel	7	Balance of plant	1	Grid support	195
196	7	Balance of plant	8	FC-GT Hybrid	7	FC-GT Hybrid	196

Rank	Score		Cost		Duration		Rank
197	13	Materials handling	15	Opportunity fuels	5	Grid support	197
198	7	PEMFC	1	Market cross-cutting	20	Hydrogen Fuel	198
199	5	Energy storage	2	Market cross-cutting	29	Hydrogen Fuel	199
200	5	Transportation	7	Energy storage	23	Hydrogen Fuel	200
201	7	Hydrogen Fuel	4	Episodic	14	Hydrogen Fuel	201
202	1	Balance of plant	1	FC-GT Hybrid	5	SOFC	202
203	12	Opportunity fuels	5	Grid support	9	Fuel cell system cross-cutting	203
204	1	Materials handling	8	Grid support	3	SOFC	204
205	8	PEMFC	5	Transportation	12	Opportunity fuels	205
206	17	Fuel cell system cross-cutting	10	DG/CCHP	2	Grid support	206
207	1	PAFC	12	FC-GT Hybrid	12	FC-GT Hybrid	207
208	14	FC-GT Hybrid	8	Transportation	2	FC-GT Hybrid	208
209	4	FC-GT Hybrid	9	Transportation	14	Opportunity fuels	209
210	4	PEMFC	1	Transportation	14	Balance of plant	210
211	10	Transportation	9	Episodic	4	SOFC	211
212	25	Hydrogen Fuel	11	DG/CCHP	25	Hydrogen Fuel	212
213	4	Fuel cell system cross-cutting	10	Grid support	11	FC-GT Hybrid	213
214	10	Market cross-cutting	6	Grid support	1	Transportation	214

Rank	Score		Cost		Duration		Rank
215	16	Hydrogen Fuel	4	Transportation	2	Market cross-cutting	215
216	27	Hydrogen Fuel	13	Opportunity fuels	11	DG/CCHP	216
217	3	PAFC	10	SOFC	3	FC-GT Hybrid	217
218	14	Materials handling	14	Balance of plant	10	FC-GT Hybrid	218
219	12	Grid-DG connectivity	2	Transportation	1	SOFC	219
220	9	Portable	1	Grid support	11	Fuel cell system cross-cutting	220
221	9	Materials handling	3	Transportation	13	Balance of plant	221
222	10	Balance of plant	2	Grid support	16	Hydrogen Fuel	222
223	1	Opportunity fuels	3	Hydrogen Fuel	7	Materials handling	223
224	6	Opportunity fuels	8	Balance of plant	6	Materials handling	224
225	5	Grid-DG connectivity	5	DG/CCHP	3	Transportation	225
226	1	Episodic	8	Energy storage	4	Transportation	226
227	12	Materials handling	19	Hydrogen Fuel	8	Grid support	227
228	20	Fuel cell system cross-cutting	16	Opportunity fuels	7	Transportation	228
229	17	Hydrogen Fuel	11	FC-GT Hybrid	10	Grid support	229
230	9	FC-GT Hybrid	8	Fuel cell system cross-cutting	9	DG/CCHP	230
231	16	Transportation	5	SOFC	22	Hydrogen Fuel	231
232	11	Opportunity fuels	9	DG/CCHP	28	Hydrogen Fuel	232

Rank	Score		Cost		Duration		Rank
233	4	PAFC	7	Opportunity fuels	8	Transportation	233
234	11	Transportation	25	Hydrogen Fuel	8	Energy storage	234
235	9	Opportunity fuels	16	Hydrogen Fuel	2	Transportation	235
236	13	Transportation	10	FC-GT Hybrid	3	Hydrogen Fuel	236
237	8	FC-GT Hybrid	4	DG/CCHP	7	Opportunity fuels	237
238	11	Balance of plant	3	DG/CCHP	7	Energy storage	238
239	9	Balance of plant	3	FC-GT Hybrid	7	Fuel cell system cross-cutting	239
240	8	Market cross-cutting	23	Hydrogen Fuel	7	Hydrogen Fuel	240
241	15	Opportunity fuels	15	Hydrogen Fuel	9	Transportation	241
242	18	Hydrogen Fuel	13	Balance of plant	5	Transportation	242
243	4	DMFC	18	Hydrogen Fuel	15	Hydrogen Fuel	243
244	10	Grid-DG connectivity	14	Opportunity fuels	19	Hydrogen Fuel	244
245	12	Fuel cell system cross-cutting	26	Hydrogen Fuel	26	Hydrogen Fuel	245
246	15	Transportation	27	Hydrogen Fuel	27	Hydrogen Fuel	246
247	8	Opportunity fuels	24	Hydrogen Fuel	6	Opportunity fuels	247
248	3	DMFC	7	Hydrogen Fuel	17	Hydrogen Fuel	248
249	5	DMFC	17	Hydrogen Fuel	9	Opportunity fuels	249
250	12	Transportation	8	Opportunity fuels	8	Opportunity fuels	250

Rank	Score		Cost		Duration		Rank
251	10	Opportunity fuels	10	Opportunity fuels	10	Opportunity fuels	251

Appendix F: Commercialization Barrier Data

Weighted Criteria Values	Markets								Fuel Cell Types						Related Technology			Fuels			
Data	Market cross-cutting	DG/CCHP	FC-GT Hybrid	Grid support	Materials handling	Episodic	Portable	Transportation	Fuel Cell cross-cutting	SOFC	MCFC	PEMFC	PAFC	DMFC	Balance of plant	Energy storage	Grid-DG connectivity	Hydrogen Fuel	Opportunity fuels	Grand Total	Rank
Average of Cost Reduction	0.0	2.5	4.2	3.1	1.9	2.7	1.2	3.9	3.7	6.0	4.7	4.7	2.5	1.2	6.8	2.4	3.3	3.5	4.2	3.3	8
Average of Cost / Value to Customer	3.9	9.5	8.5	8.6	7.8	9.5	6.9	6.4	6.6	7.5	6.7	5.1	4.2	4.1	5.4	6.1	13.1	8.9	13.2	7.7	1
Average of Durability	0.0	0.5	2.9	0.0	0.0	1.5	0.0	2.6	4.2	8.6	4.2	5.1	5.7	4.0	1.8	3.7	2.4	1.8	3.5	2.6	12
Average of Reliability	0.0	2.5	5.4	5.4	3.8	5.6	3.6	7.7	5.1	3.6	2.1	1.9	3.2	2.0	1.5	5.0	8.3	2.9	3.5	3.8	4
Average of Efficiency	0.0	3.1	7.2	0.9	0.9	6.9	0.0	3.6	3.8	9.8	2.2	5.2	2.9	2.3	2.7	6.2	2.4	2.9	2.8	3.4	7
Average of Transient Operation	1.8	2.2	1.9	2.1	0.0	2.8	1.2	0.0	3.8	1.2	0.0	1.9	0.0	0.0	2.8	7.4	4.3	1.1	0.0	1.9	20
Average of Power and Energy Density	0.0	0.0	1.0	0.0	0.9	0.0	3.1	1.3	2.8	0.0	0.0	3.3	1.7	5.1	1.1	3.5	0.0	0.7	0.0	1.2	22
Average of Control	1.8	4.1	6.4	5.6	1.8	1.5	3.0	2.7	4.6	3.8	2.4	3.7	1.8	0.9	2.6	8.6	7.9	2.3	5.0	3.8	5
Average of Size and Weight	0.0	0.0	1.9	0.0	0.9	0.0	4.4	1.3	1.7	2.5	1.1	0.0	0.5	3.3	0.7	2.2	0.0	1.9	0.0	1.1	23
Average of Manufacturing	1.0	0.8	2.0	1.2	1.9	1.3	3.1	3.7	3.0	5.9	3.3	3.3	4.9	3.2	5.4	2.4	2.4	3.0	2.4	2.7	11
Average of Maintenance	1.0	2.9	2.5	3.4	3.8	2.7	0.0	6.4	1.6	2.4	1.1	0.0	3.0	0.0	2.3	0.0	1.0	2.2	4.6	2.2	19
Average of Installation / Commissioning	1.9	4.8	2.5	6.9	5.5	3.8	0.8	3.9	0.8	1.1	1.2	0.0	0.0	0.0	0.8	0.0	3.5	0.5	4.6	2.4	16

Average of Decommissioning / Recycling	0.9	0.7	0.0	0.0	3.7	1.2	3.0	0.0	1.4	0.0	0.0	1.4	1.0	1.2	1.1	0.0	1.0	0.0	0.0	0.8	24
Average of Certification	2.9	3.4	1.2	1.2	1.1	4.0	2.1	5.2	1.4	0.0	1.2	0.0	0.0	0.0	0.8	0.0	7.7	3.6	4.6	2.3	18
Average of System Integration	4.7	8.5	11.1	9.6	4.7	5.7	8.2	5.1	6.8	4.7	2.4	0.9	1.0	0.5	5.0	6.1	7.4	3.0	7.3	5.7	2
Average of Safety	1.8	0.5	1.0	0.0	4.7	1.4	5.2	5.4	0.0	0.0	0.0	0.9	0.0	0.5	0.0	1.1	5.8	1.9	0.0	1.6	21
Average of Public Awareness / Acceptance	4.6	2.7	3.1	1.7	3.1	3.9	5.1	7.8	2.5	0.0	0.0	0.0	0.0	0.0	0.8	2.5	5.5	4.2	3.2	2.8	10
Average of Customer requirements	2.8	7.1	5.1	5.2	5.8	6.7	6.1	7.9	6.6	2.5	2.2	0.9	0.5	0.5	1.1	1.1	7.4	5.4	6.0	4.6	3
Average of Market size	3.0	3.6	3.5	2.2	1.9	3.9	3.8	4.9	1.5	0.0	0.0	0.0	0.0	0.0	1.6	0.0	7.1	2.3	1.4	2.3	17
Average of Number of markets	3.7	4.4	3.0	0.0	0.9	4.3	5.8	1.3	1.0	0.0	0.0	0.0	0.0	0.0	2.2	5.0	4.6	1.7	5.5	2.4	14
Average of Energy independence	2.9	2.3	1.0	4.7	2.3	1.5	0.0	7.5	0.0	0.0	0.0	0.0	0.0	0.0	0.8	3.8	2.4	4.7	9.7	2.4	15
Average of Energy security	1.9	3.1	3.3	6.1	1.1	4.2	0.8	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.8	3.8	8.3	2.4	7.3	2.5	13
Average of Environmental impact	2.8	4.4	4.2	5.2	5.8	6.6	0.8	3.9	3.5	0.0	0.0	0.0	0.0	0.0	0.8	4.9	3.4	3.5	8.8	3.2	9
Average of Emissions	3.7	4.4	4.7	5.0	8.8	6.7	0.8	7.5	3.5	0.0	0.0	0.0	0.0	0.0	0.0	5.0	3.4	5.2	8.8	3.7	6
Count of Market Transforming	3	3	0	0	0	2	0	1	2	1	0	2	0	0	1	1	2	3	0	21	
Sum of Evaluated Criteria	6	11	7	7	6	5	6	5	8	6	5	5	5	5	6	5	7	10	6	121	
Count of Projects	14	14	14	11	14	9	10	16	21	13	9	13	5	6	14	10	12	30	16	251	

Average Grand Total	2.0	3.3	3.6	3.3	3.1	3.7	2.9	4.2	2.9	2.5	1.5	1.6	1.4	1.2	2.0	3.4	4.7	2.9	4.4
Rank	15	8	5	7	9	4	12	3	10	13	17	16	18	19	14	6	1	11	2