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Exploration and Prioritization of Fuel Cell Commercialization Barriers for Use in the Development of a Fuel Cell Roadmap for California

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Barriers to fuel cell commercialization are often introduced as general challenges, such as cost and durability, without definition of the terms and usually without prioritizing the degree to which each of these barriers hinder the development of fuel cell technology. This work acts to objectively determine the importance of technology barriers to fuel cell commercialization and to develop a list of appropriate actions to overcome these barriers especially as they relate to the California market. Using previous fuel cell roadmaps and action plans along with feedback from the fuel cell community, benchmarks (i.e., the current technology status), and milestones (i.e., the desired technology status) for fuel cell technology are explored. Understanding the benchmarks and milestones enables the development of a list of fuel cell commercialization barriers. These barriers or gaps represent issues, which if addressed will enhance the market feasibility and acceptance of fuel cell technologies. The research process determined that the best technique to address these barriers, and bridge the gaps between fuel cell benchmarks and milestones, is to develop specific research projects to address individual commercialization barriers or collections of barriers. This technique allows for a high resolution of issues while presenting the material in a form that is conducive to planning for organizations such as industry, regulatory bodies, universities, and government entities that desire to pursue the most promising projects. The current analyses resulted in three distinct research and development areas that are considered most important based on the results. The first and most important research and development area is associated with technologies that address the connection and interaction of fuel cells with the electric grid. This R&D area is followed in importance by the production, use, and availability of opportunity fuels in fuel cell systems. The third most important category concerned the development and infrastructure required for transportation related fuel cell systems. In each of these areas the fuel cell community identified demonstration and deployment projects as the most important types of projects to pursue since they tend to address multiple barriers in many different types of markets for fuel cell technology. Other high priority types of projects are those that addresses environmental and grid-related barriers. The analyses found that cost/value to customer, system integration, and customer requirements were the most important barriers that affect the development and market acceptance of fuel cell technology. [DOI: 10.1115/1.4000689]

Keywords: fuel cell, commercialization, barriers, benchmarks, milestones, surveys, roadmap, technology gap, technology issues

1 Introduction

In the face of rising energy demand, changing environmental conditions, and dwindling natural resources, something must be done to reduce fossil fuel use and eventually transition from the use of nonrenewable resources to renewable and sustainable forms of energy conversion. Fuel cells are an energy conversion technology that has the potential to provide cleaner, higher efficiency, more scalable, quieter, and more fuel flexible operation than the current market leading technologies such as reciprocating engines and gas turbines [1–3]. The introduction of this technology into

the energy conversion portfolio can facilitate reductions in the use of nonrenewable feedstock due in part to their higher efficiency and scalable operation and fuel flexibility features [1].

Even though fuel cell technology possesses the aforementioned benefits, it has yet to achieve significant market penetration. This has been generally attributed to things such as high market entry costs, lack of compatible infrastructure, and general unfamiliarity with the technology [2]. The purpose of this work is to identify the barriers hindering further fuel cell commercialization and to recommend actions that should be taken to overcome these barriers, thereby driving fuel cell technology development and acceptance. Thorough development of a plan that considers a large cross-section of scientific and technology hurdles together with the current energy technology landscape, competitive technologies, and distribution grid needs for fuel cells were accomplished to provide the most profound impact on fuel cell commercialization.

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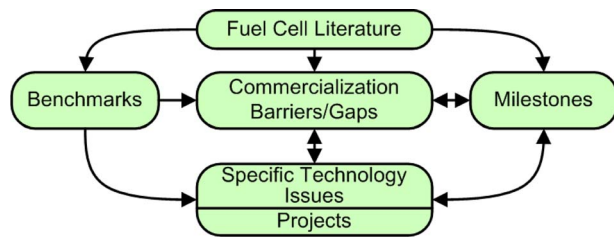


Fig. 1 Methodology for bridging the technology gap

Many different entities have developed planning documents to guide technology development and R&D investment for the fuel cell sector. There have been several international efforts made to develop fuel cell roadmaps and action plans with documents coming from Europe [4], United Kingdom [5], Canada [6], Japan [7,8], and the United States [9–26]. Additional resources used in the current effort to develop a California roadmap and action plan include Refs. [27–46]. Many resources including these plans tend to each provide a relatively narrow perspective of the status and barriers hindering fuel cell development and oftentimes focus heavily on the political and social barriers and other market-related aspects of fuel cell commercialization. This work draws information from all of the aforementioned literature and the fuel cell community to develop a more complete perspective of the status and needs for fuel cells that focus on technical barriers. This is accomplished by identifying and prioritizing technology development issues and compiling them into a fuel cell technology roadmap, which may be used by interested parties to drive the development and market acceptance of fuel cell technology. Thus, this work relies heavily on the review of current fuel cell literature and cooperation and feedback from fuel cell stakeholders, regulatory bodies, and government entities including the California Energy Commission (CEC), and the Public Interest Energy Research program; industry partners including the California Stationary Fuel Cell Collaborative (CaSFCC) industry advisory panel, fuel cell companies, and university researchers. Due to space constraints, the current paper only presents the fuel cell technology roadmap while the action plan is available in the draft report to the CEC [47].

2 Approach

Conducting a literature review of all pertinent fuel cell roadmaps and other planning documents was the first step for identifying pinch-points and barriers to successful commercialization of fuel cell technology. Based on the information gained, the most attractive methodology for characterizing commercialization barriers, establishing the needs to address those barriers, and hastening further fuel cell market acceptance is as follows.

The first step is to establish the current status of fuel cell technology (benchmarks) and the desired status and goals for the technology (milestones). Based on the fuel cell literature and stakeholder feedback, a general list of fuel cell technology benchmarks and milestones was developed. The goal in identifying these benchmarks and milestones is to objectively determine the significance of each and to develop a method to effectively bridge the gap between them. This can be accomplished by developing a list of specific technology issues based on the benchmarks, barriers, and milestones. These issues are intended to include every aspect of fuel cell technology development that were found in literature and that the fuel cell community could identify as important to address. These issues range from materials development issues, to marketing and policy issues, to installation and decommissioning issues, and are used to formulate a list of projects that can be pursued to achieve the desired technology milestones while addressing fuel cell commercialization barriers. An illustration of the general methodology used is presented in Fig. 1.

Several things are important to be noted 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. This means that discrepancies may arise between the previously perceived milestones and the practical or optimal milestones based on the findings of this work. 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 for addressing 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 included projects.

Public review and feedback plays an integral role in the conduct of this work, ensuring that a good cross-section of stakeholders in the fuel cell community is used to establish the results. Several review mechanisms were integrated into this work. Review and participation opportunities were provided to the fuel cell community through several survey tools and workshops administered by the National Fuel Cell Research Center (NFCRC). 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 milestones.

3 Benchmarks and Milestones

Identifying the benchmarks and milestones for fuel cell technology is an essential first step in the development of a roadmap and action plan and will greatly aid in the selection and timing of appropriate markets and tasks to pursue. In addition, determining the general 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 significantly between sources and (2) many sources containing values must be checked and researched, which is time consuming and often results in only a few insights. As a result the list of benchmarks and milestones is useful for determining the commercialization barriers but does not reflect a comprehensive set of the technology improvements required to further develop fuel cell technology.

Benchmarks and milestones are drawn from reference documents, insights from fuel cell manufacturers, academic, national laboratory, and agency experts and members of the fuel cell community. Each performance metric associated with both benchmarks and milestones is categorized as follows: availability, capacity factor, cost, degradation, efficiency, emissions, energy density, incentives, life, noise, power, sales volume, sensors, size and weight, transient response, and others. A complete list of the benchmarks and milestones can be found in the more detailed draft report to the CEC [47].

Benchmarks have been established for many specific types of fuel cell technologies, including especially solid oxide fuel cell (SOFC) and proton exchange membrane fuel cell (PEMFC), and for the performance of sensors, component lifetime and cost issues. There were significantly more milestones than benchmarks identified from 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., membrane electrode assembly (MEA) and bipolar plates). Additionally, there are several milestones for market-related features such as distributed generation (DG) and grid support. The collection of these technology evaluation metrics is essential to developing a list of the commercialization barriers hindering fuel cell development and commercial use.

4 Commercialization Barriers

The fuel cell industry is currently in various states of commercialization depending on the type of technology and application.

Table 1 Fuel cell commercialization barriers

Group	Barrier		Description
Cost	Cost reduction	A	Direct reduction in system or component cost
	Cost/value to customer	B	Increase the value of the technology by methods other than direct system or component cost reductions
Performance	Durability	C	Measure of system degradation and lifetime
	Reliability	D	Measure of availability and capacity factor
	Efficiency	E	Measure of system or component efficiency
	Transient operation	F	Performance measure of the ability to perform dynamic operations
	Power and energy density	G	Measure of system or component power, power density, and energy density
	Control	H	A measure of the ability to control a system to desired customer specifications with minimal additional equipment
Manufacturing Operation	Size and weight	I	A measure of the volume, shape, mass and weight of a system
	Manufacturing	J	Relating to how systems or components are manufactured
	Maintenance	K	Frequency and severity of system maintenance
	Installation/commissioning	L	Whatever is required to prepare a system for installation and for its initial startup
	Decommissioning/recycling	M	Includes what is required to shutdown, remove and recycle a system
	Certification	N	Requirements for systems to pass inspection and be approved for installation
Safety Marketing	System integration	O	Concerns how and the extent to which a systems can be combined and integrated
	Safety	P	Issues where safety is of particular concern
	Public awareness/acceptance	Q	Public familiarity and interaction with new technologies and any implications stemming from the introduction of new technologies
	Customer requirements	R	Regarding specifications unique to the customer that must be considered
	Market size	S	Directly cause an increase in the size of a particular market by increasing volume or increasing demand
	Number of markets	T	Directly introduce fuel cell technology to new markets not previously pursued
Other	Energy independence	U	Concerns sovereignty and independence of energy supply
	Energy security	V	Concerns the safety and stability of generation equipment and fuel supply. Includes daily and long-term energy supply
	Environmental impact	W	The effect of non-GHG and criteria pollutant emissions on the environment
	Emissions	X	Relating predominantly to GHG and criteria pollutant emissions

Some technologies are in the research and development stage while other technologies are pressing toward different levels of commercial market penetration. From review of fuel cell literature and feedback from the community, the list of most pertinent commercialization barriers is presented in Table 1 along with a short description of each barrier. Understanding of the scope of each barrier is essential to understanding the results of this study.

The barriers are grouped into subsets based on similar properties. These groups of barriers include cost, performance, manufacturing, operation, safety, marketing, and others. Each of the barriers is assigned a letter designation that is used for identification. Projects are evaluated for their ability to address each barrier. An analysis of the type and quantity of barriers associated with the highest ranking projects shows the relative significance of each barrier and the extent to which each project can address specific commercialization barriers.

5 Technical Issues and Projects

Using all of the information gathered from literature and from fuel cell stakeholders, a detailed outline of specific issues hindering fuel cell technology development was generated. This outline acts as an intermediate step to formulating and organizing the list of projects. Discretizing the fuel cell technology barriers into a list

of projects provides two major benefits, (1) this technique potentially allows for a high resolution of barriers for each project while (2) presenting the material in a form that is conducive for use by research funding bodies to pursue research or solicit proposals for one or more of the project areas. The complete list of technology issues and projects is available in the more detailed draft report to the CEC [47].

A total of 251 projects have been identified, which have been organized into four main categories and 19 subcategories. The categories were selected so as to contain a similar magnitude of data and prevent overlap between categories. A brief description for each technology category is provided below.

5.1 Market Applications. Market cross-cutting: The technology barriers for fuel cell market development include many issues that are specific to a single market; however, there are also many issues that are similar for all fuel cell markets. The fuel cell market cross-cutting development category represents the barriers to fuel cell development that are common among several of the fuel cell markets.

5.1.1 Grid Support. Fuel cell systems in grid supporting applications could supplement or replace current power generation equipment and delay system upgrades. As competition for limited fuel reserves increases, the need for operation on renewable fuels and higher efficiencies becomes essential. Grid supporting fuel cells offer a solution to both of these issues.

5.1.2 Distributed Generation and Combined Cooling, Heating, and Power (DG-CCHP). The current energy distribution paradigm involves predominantly central generation without heat recovery followed by transmission, distribution and sale to the customer. Distributed generation with cogeneration systems represents a transition from central generation to the generation of power, heating, and cooling near the point of use.

5.1.3 Fuel Cell—Gas Turbine (FC-GT) Hybrid. Hybrid systems rely on the synergy of integrated constituent components to achieve better performance and efficiency than either system could provide separately. Gas turbines with their proven track record, high availability, and ability to provide balance of plant (BOP) services to a fuel cell, complement the low pollutant emissions, and high efficiency of fuel cells.

5.1.4 Transportation. With the vast majority of on-road transportation vehicles operating on fossil fuels, there is a tremendous opportunity to provide cleaner, more efficient, fuel flexible transportation solutions using fuel cells and fuel cell hybrid systems, which also includes concerns for component and infrastructure development.

5.1.5 Materials Handling. The materials handling area includes equipment that is used to transport and manipulate materials. Examples include forklifts, other lifts, tractor trailers, ships, and locomotives. Current materials handling technology predominantly relies on fossil-fuel-based combustion devices or batteries for power.

5.1.6 Episodic. A power generation system that is designed to be used periodically under particular conditions is considered to be episodic. The goal of episodic power equipment is to compensate for grid or primary power instability and demand changes. The two main examples are backup power and peak shaving power.

5.1.7 Portable. The portable power 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. Some examples of portable power applications include many electronic devices (e.g., laptops and cell phones) and remote area power generators.

5.2 Fuel Cell Technology Specific Development

5.2.1 Fuel Cell Cross-Cutting. The cross-cutting development category represents the barriers to fuel cell development that are similar among the many types of fuel cells.

5.2.2 Fuel Cell Specific Categories. Five types of fuel cells are individually explored for this analysis. They include solid oxide (SOFC), molten carbonate (MCFC), proton exchange membrane (PEMFC), phosphoric acid (PAFC), and direct methanol fuel cells (DMFC). Projects that address a technical need that is specific to a particular fuel cell type are included in these categories.

5.3 Technology Integration Development

5.3.1 BOP. Balance of plant (BOP) is the term used to describe the components not included in the fuel cell stack such as pumps and blowers, hoses and valves, and many other components that support the operation of the fuel cell stack.

5.3.2 Energy Storage. Energy storage technology includes typical forms of energy storage such as batteries and capacitors but also explores less common forms of energy storage such as reversible fuel cells and thermal storage using salts and phase change materials and how they interact with fuel cells.

5.3.3 Grid Level and Distributed Generation Connectivity. It is insufficient to develop technology that can generate electricity with high efficiency and ultra low emissions without considering

where and how interconnection can be established with the electric grid. There are many grid-related issues that challenge or augment the attractiveness of fuel cell implementation for both the consumer and the electric utility. These issues are included in this category

5.4 Fuels

5.4.1 Hydrogen. Given the availability, price volatility, and the growing environmental concerns over the current energy carriers it is critical to transition toward a renewable, domestically produced, cheaper, and more sustainable fuel. Hydrogen has the potential to address many of the current energy carrier issues but will require additional research, development, and deployment activities to compete with the current technologies.

5.4.2 Opportunity Fuels. Opportunity fuels represent the fuels that result as a byproduct of another activity (e.g., landfill gas, digester gas, bioderived fuels, and industrial waste gases). This category concerns use of such fuels in fuel cell systems.

6 Technology Surveys

Once the list of projects is created, it must be refined and reviewed by stakeholders in the fuel cell community. Review and refinement were accomplished in a multistage process that included (1) an April 3, 2008 workshop in Sacramento, (2) completion of an invitation only industry survey by April 25, 2008, (3) development of a second web-based survey that was refined according to feedback from the first survey participants, (4) administration of the second web-based survey completed by August 15, 2008, (5) analysis of the first two surveys, (6) a second workshop at the NFCRC on August 27, 2008, (7) revision of the web-based survey based on feedback from the first two surveys and the two workshops, and (8) administration of the final on-line survey, completed on October 10, 2008, by a broad cross-section of the fuel cell community including the United States Fuel Cell Council members, California Hydrogen Business Council, CaSFCC members, and others.

The evaluation criteria used in all three surveys was very similar. For the final survey, the questions asked along with a criteria weight value are shown in Table 2. The funding value was not used for evaluation of the score but rather for development of cost information about each project for the action plan. Each project score was based on the average of the weighted responses from each participant. The weight for each criterion was determined from the feedback and review process.

Table 3 contains information about the number of projects within each category and survey participation for each technology category. The highest ranking projects are separated into four priority groups. A natural break in the scores separates the critical priority projects (top 21) from the high priority projects (next 47), the medium priority projects (next 53), and the low priority projects (all remaining). The overall column denotes the average and total values for all 251 projects while the highest priority column presents the average and total values for the critical, high, and medium priority projects. See the CEC draft report [47] for more detailed information on these projects.

Ideally, several dozens or even hundreds of individuals would have been surveyed for each project but due to the highly technical nature of the current material and the relative small size of the fuel cell community such high participation was not possible; thus, even though the scoring analyses generate exact values to several significant digits, caution must be used when attempting to compare project parameters that are numerically close.

7 Results

By collecting and averaging the surveys, the overall average project score was determined. Figure 2 presents the resulting scores for each of the 251 projects. The relative value of project categories, range of scores, and deviation are provided. The green

Table 2 Final survey evaluation criteria

Evaluation criteria	Description	Weight
Funding value required	What is this projects need for funding?	
Cost sharing potential	What is the potential for cost-sharing on this project?	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?	23
Benefits	How significant are the benefits for this project? (for society, California ratepayer, business/investors)	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)	22
Goals	To what extent are national or state goals met by pursuing this project?	10
Time to payoff	How long until this project enhances the economic viability of this technology?	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)	5

bar at the top of each category is the maximum project score, the red bar at the base of each category is the minimum project score, and the orange bar near the middle of each category is the average project score. Each blue bar represents the score for a particular project and the orange horizontal line spanning all categories presents the average score of all projects.

8 Commercialization Barrier Analysis

The list of fuel cell commercialization barrier criteria (Table 1) was applied to each of the highest ranking projects to determine the extent to which each project will address the criteria. The reason for this analysis is to provide a detailed description and validation for claims that cost, performance, marketing, etc. are the major barriers to fuel cell commercialization. Often these general terms are used with little to no further description of their meaning. This analysis provides verification for why certain barriers are more significant than others.

Each project was assigned the appropriate set of criteria that it addressed, then the values were ranked to determine, which commercialization barriers were deemed by survey participants to be the most important. The barrier criteria for each project are weighted by the score for that project. This step effectively integrates the importance of different projects into the criteria ranking process. This analysis was conducted once for each technology category and once including all projects. Table 4 presents the results of these analyses. More detailed information can be found in the draft report to the CEC [47].

This analysis makes it 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 by each project.

From this analysis, the cost/value to customer is found to be the most important criteria to consider when determining what results will be achieved if the highest ranked projects are pursued. The

Table 3 Project count and participation

Technology categories	Identified projects	Average participation		Total participation	
		Overall	Highest priority	Overall	Highest priority
Grid support	11	14.4	16.3	158	114
DG/CCHP	14	20.1	22.2	282	244
FC-GT hybrid	14	15.3	18.9	214	132
Transportation	16	12.9	15.2	207	76
Materials handling	14	13.1	17.3	183	104
Episodic	9	10.7	10.3	96	52
Portable	10	10.1	11.8	101	71
Market cross-cutting	14	14.5	16.2	203	97
SOFC	13	7.4	7.3	96	44
MCFC	9	5.2	5.2	47	26
PEMFC	13	6.2	5.8	81	29
PAFC	5	2.2	2.2	11	11
DMFC	6	3.3	3.4	20	17
Fuel cell cross-cutting	21	7.7	7.3	161	58
BOP	14	4.9	4.8	69	29
Energy storage	10	8.9	9.4	89	47
Grid-DG connectivity	12	10.6	12.6	127	88
Hydrogen	30	10.3	10.2	310	102
Opportunity fuels	16	8.2	9.8	132	59
Total	251	10.3	11.6	2587	1400

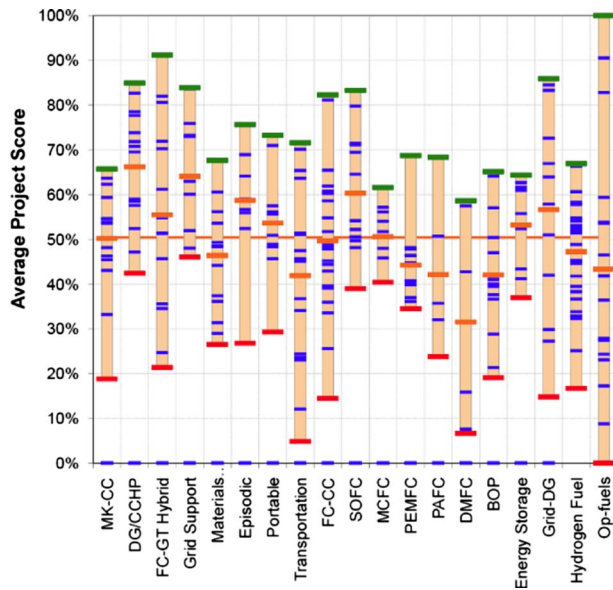


Fig. 2 Project score distributions

system integration ranks second while satisfying unique customer requirements ranks third. Two cost terms are included in the list of barriers/gaps. The cost reduction term is ranked eighth. This is a unique finding in that when the term “cost” is used, the value to the customer is considered much more important than a simple cost reduction.

When considering fuel cell performance characteristics the highest ranking criteria are reliability, control, efficiency, and durability. There is a large break between these features and the next highest ranked performances are criteria, transient operation, power and energy density, and size and weight. Manufacturing was ranked near the middle at 11th while safety was ranked near the bottom at 21st. Most of the operation criteria (excluding system integration) were ranked low including installation/commissioning, certification, maintenance, and decommissioning/recycling. 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 14th, respectively. There was some surprise with the market size criterion with a rank of 17th. This result is caused by the fact that there were only a limited number of projects that directly addressed 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 13th and 15th.

Table 4 Commercialization barrier analysis

Groups	Rank of Groups	Barriers	Rank of Barriers	DG/CCHP	FC-GT Hybrid	Grid Support	Materials Handling	Episodic	Portable	Transportation	Market Cross-cutting	SOFC	MCFC	PEMFC	PAFC	DMFC	Fuel Cell Cross-cutting	Balance of Plant	Energy Storage	Grid-DG Connectivity	Hydrogen Fuel	Opportunity Fuels			
Cost	1 st	Cost Reduction	8		9							4	2	4	7	8	9	1				8			
		Cost / Value to Customer	1	1	2	2	2	1	2	6	3	3	1	2	3	2	2	2	3	4	1	1	1		
Performance	6 th	Durability	12									2	3	3	1	3	6								
		Reliability	4	5	6	8	7	9	3			8	9	9	4	7	4			8	2				
		Efficiency	7	3			2					1	7	1	6	6	8	6	6	3					
		Transient Operation	20												8			7	5	2					
		Power and Energy Density	22											6	9	1									
		Control	5	8	4	5						7	5	5	8			5	7	1	4			9	
		Size and Weight	23					7				9					4								
Manufacturing	4 th	Manufacturing	11									5	4	7	2	5		2				9			
Operation	5 th	Maintenance	19			8		6							5			8							
		Installation / Commissioning	16	4		3	5																		
		Decommissioning / Recycling	24														8								
		Certification	18							9	8											5	6		
		System Integration	2	2	1	1	6	6	1	1	1	6	5					1	4	4	6			5	
Safety	7 th	Safety	21			6	5	8													9				
Markets	2 nd	Public Awareness / Acceptance	10					6	2	2													5		
		Customer Requirements	3	3	6	7	3	3	3	1	9	9	8				2				6	2	7		
		Market Size	17	9					8	6												8			
		Number of Markets	14	5			8	4	5										9	6				8	
Other	3 rd	Energy Independence	15						4	7													4	2	
		Energy Security	13			4	9														2			5	
		Environmental Impact	9	6	8	8	3	5												9		7	3		
		Emissions	6	6	7	9	1	3		4	4									6		3	3	3	

Table 5 Technology category analysis

Technology categories	Rank based on project score and barriers	Rank based on project score only
Grid-DG connectivity	1	1
Opportunity fuels	2	2
Transportation	3	13
FC-GT hybrid	4	6
Episodic	5	4
Grid support	6	7
DG/CCHP	7	5
Energy storage	8	9
Fuel cell cross-cutting	9	3
Materials handling	10	8
Hydrogen fuel	11	12
Portable	12	11
Solid oxide fuel cells	13	10
BOP	14	15
Market cross-cutting	15	16
Molten carbonate fuel cells	16	14
Proton exchange membrane fuel cells	17	17
Phosphoric acid fuel cells	18	18
Direct methanol fuel cells	19	19

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 4 contains the technology specific category analyses. The first, second, and third most important barriers for each category are highlighted in progressively lighter shades of green. Cells that are left blank signify that the particular technology category had a rank of above ninth. The general order of the barriers for each of the four main technology categories is similar to that for all of the projects. Cost/value to customer is clearly the highest ranked barrier receiving the highest rank for many of the technology categories.

As an example, 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 ranking seventh and tenth while the latter two categories ranked 18th and 19th.

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

9 Technology Category Analysis

Based on the scores of each project and the extent to which commercialization barriers are addressed one can determine which technology categories are the most promising to pursue. Two columns are presented in Table 5 to convey this information. The middle column depicts the rank of each category when the score and extent to which commercialization barriers are addressed is included while the last column 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 middle 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 while 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 projects within that category have to fuel cell development and acceptance in California. As a result, the middle column of Table 5 is used to develop the technology roadmap for California.

Table 6 presents the first ten projects from the list of critical priority projects. This list presents the most important group of projects along with the type of information that was determined for each category. The projects listed in Table 6 are a representative set of the types of projects that are included in the following analyses.

10 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 independently from the score 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 sufficient solution to the related issues will result in extreme benefit.

Twenty-one projects were selected from the list of 251 total projects. Table 7 contains the top 11 market transforming projects sorted with the highest scoring project at the top.

11 Keyword Analysis to Identify Important Types of Projects

In addition to reviewing the project scores, the importance of several specific keywords included in the surveys was explored. Searches were made for certain keywords in the project descriptions and average scores were compared against other keyword groups. This analysis provides insight into the general needs for fuel cell technology (i.e., not specific to only a single one of the 19 technologies outlined)

Table 8 shows the results in order of descending average score. The project type description column is used to convey the scope of the projects included in each key word search. The last three columns contain statistical information resulting from the analysis. The count is the number of projects included in the analysis. The 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 (in the 12th row) is one where all of the projects are included and can be used as a standard of comparison for all of the resulting values. Several unique findings result from this analysis.

Since the average score for all of the projects is 50%, no conclusions can be drawn for those projects that have scores close to 50%; however, the top three scores are markedly higher than the fourth score and they also have 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. With an average score of 63%, deployment and demonstration projects are on average much more highly ranked than other types of projects. Having 48 projects that contributed to this group adds to the confidence in the conclusion. Tied for second with scores of 61% are projects considering environmental and grid-related issues and 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 is 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 group had a higher standard deviation than the other two project types meaning that there

Table 6 Critical Priority Projects

Category	Avg. score (%)	Project descriptions (critical priority projects)	Rank	Barriers Addressed						
				Cost	Performance	Manufacturing	Operation	Safety	Marketing	Other
Opportunity fuels	100	Support multiple demonstrations of similar fuel cell technologies applied to opportunity fuels	1	B	CDH		KLNO		QRT	VWXU
FC-GT hybrid	91	Intensify demonstration efforts for fuel cell—gas turbine hybrid systems	2	B	DEH		KLO			X
Opportunity fuels	91	Support greenhouse gas and emissions reduction through multiple demonstration projects in nonattainment areas that use opportunity fuels	3	B	H		KLNO		QRT	VWXU
Grid-DG connectivity	86	Analyze different control strategies and arrangements for optimum grid connections and interactions between customers and the utilities.	4	AB	CDEFH	J	LNO		QRST	VWXU
DG/CCHP	85	Augment deployment activities for fuel cell CCHP systems	5	AB	D	J	KLNO		QRS	VWX
Grid-DG connectivity	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	6	AB	CDEFH	J	LNO		QRST	VWXU
Grid support	84	Augment deployment activities for grid supporting fuel cell systems	7	AB	DH	J	KLNO		RS	VWX
Grid support	84	Intensify demonstration efforts for grid supporting fuel cell systems	8	B	DH		KLO			W
SOFC	83	Establish an understanding for SOFC internal reforming mechanisms and develop technique for effective use of internal reforming	9	AB	EHI		O		R	
Grid-DG connectivity	83	Exploration of contractual ancillary service arrangements between customers and the utility.	10	B	DH		NO	P	QRST	V

Table 7 Market transforming projects

Category	Avg. score (%)	Project descriptions	Rank
Grid-DG connectivity	86	Analyze different control strategies and arrangements for optimum grid connections and interactions between customers and the utilities.	4
DG/CCHP	85	Augment deployment activities for fuel cell CCHP systems	5
Grid-DG connectivity	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	6
DG/CCHP	74	Grid connectivity of fuel cell CCHP and sale of electricity to the grid	22
DG/CCHP	71	Simplify DG/CCHP system siting processes and requirements	33
SOFC	69	Develop intermediate temperature SOFCs	37
PEMFC	69	Development and optimization of PEMFC electrocatalysts	40
Episodic	64	Augment deployment activities for fuel cell based peak shaving systems	53
Market cross-cutting	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	60
Energy storage	62	Explore the integration of fuel cells and energy storage systems with intermittent, centralized wind power systems	62
Fuel cell cross-cutting	60	Further develop manufacturability of fuel cells and fuel cell systems	70

Table 8 Results from keyword analysis

Rank	Project type description	Count	Score (%)	StDev
1	Technology demonstration and deployment projects	48	63	0.16
2	Environmental issues (i.e., criteria pollutants and GHGs)	5	61	0.17
3	Grid related issues	24	61	0.19
4	Electrode and electrolyte related issues	8	56	0.13
5	Technology modeling and analysis projects	14	55	0.12
6	Fuel reforming technology (e.g., internal reforming and SMR)	8	54	0.14
7	Manufacturing related issues	5	54	0.15
8	Renewable energies and alternative fuels	10	54	0.10
9	Value propositions	7	53	0.25
10	Hybrid systems	13	52	0.15
11	Codes, policies, and standards issues	5	51	0.05
12	Baseline analysis including all projects	251	50	0.18
13	General technology optimization issues	24	50	0.14
14	Performance characteristics	17	49	0.15
15	Electricity and fuel storage issues	23	47	0.15
16	Carbon sequestration	3	47	0.04
17	Market issues (e.g., studies, integration, and valuation)	15	46	0.22
18	Fuel production and use issues	44	45	0.18
19	Explore material and fuel impurity requirements	6	44	0.10
20	Component design, development, and performance	40	43	0.15

was more disagreement between the scores while the material and fuel impurity group had a 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.

12 Roadmap Development

The first step in developing a roadmap was to explore the current status and goals within the fuel cell sector. Currently, the major fuel cell areas being explored in California can be separated into two groups, R&D, and market development. The work being done by the automobile manufacturers and by universities, government organizations, national laboratories, and other companies in the transportation area is characterized primarily as R&D. Market development, on the other hand, is quite active in the distributed generation, materials handling, and backup power applications. These activities establish the current status for fuel cell research and development in California.

Based on the analyses conducted for this work the structure established by the commercialization barriers along with the benchmarks and milestones can be used to develop appropriate goals for performance, cost, markets, etc. If commercialization barriers are overcome, fuel cells can produce unique business opportunities and make significant contributions to meeting California's energy and environmental goals.

Using the benchmarks and milestones, commercialization barriers and the results from the technology barrier/gap analysis, the project analysis, and feedback from the fuel cell community as inputs, a draft fuel cell roadmap is developed. The roadmap outlines the general path that the fuel cell community believes will provide the most beneficial results for overcoming commercialization barriers. Figure 3 presents the fuel cell technology roadmap, followed by a description of the top three categories and the reasons for their positioning. In the center section of the roadmap, a general time-scale is introduced and below it is a prioritized list of the technology categories in order of importance. Additionally, the width of each bar represents the average duration for projects within that category. The order was established from stakeholder feedback and relative dependencies of one category on another.

13 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. 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 on 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 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 often scored among the highest ranking projects. Thus the use of these opportunity fuels for power and heat generation with fuel cells is considered quite promising and worthy of investment. The duration of this category is relatively long, likely due to the large number of demonstration and deployment projects 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 to guide the development of transportation technologies.

14 Conclusions and Recommendations

The draft roadmap presented herein is meant to provide guidance such as a compass, pointing technology research efforts in the direction of where the fuel cell community believes the research can do the most benefit. An action plan has been developed, based on the roadmap presented, which is available in the draft report to the CEC [47]. In addition, a more detailed commer-

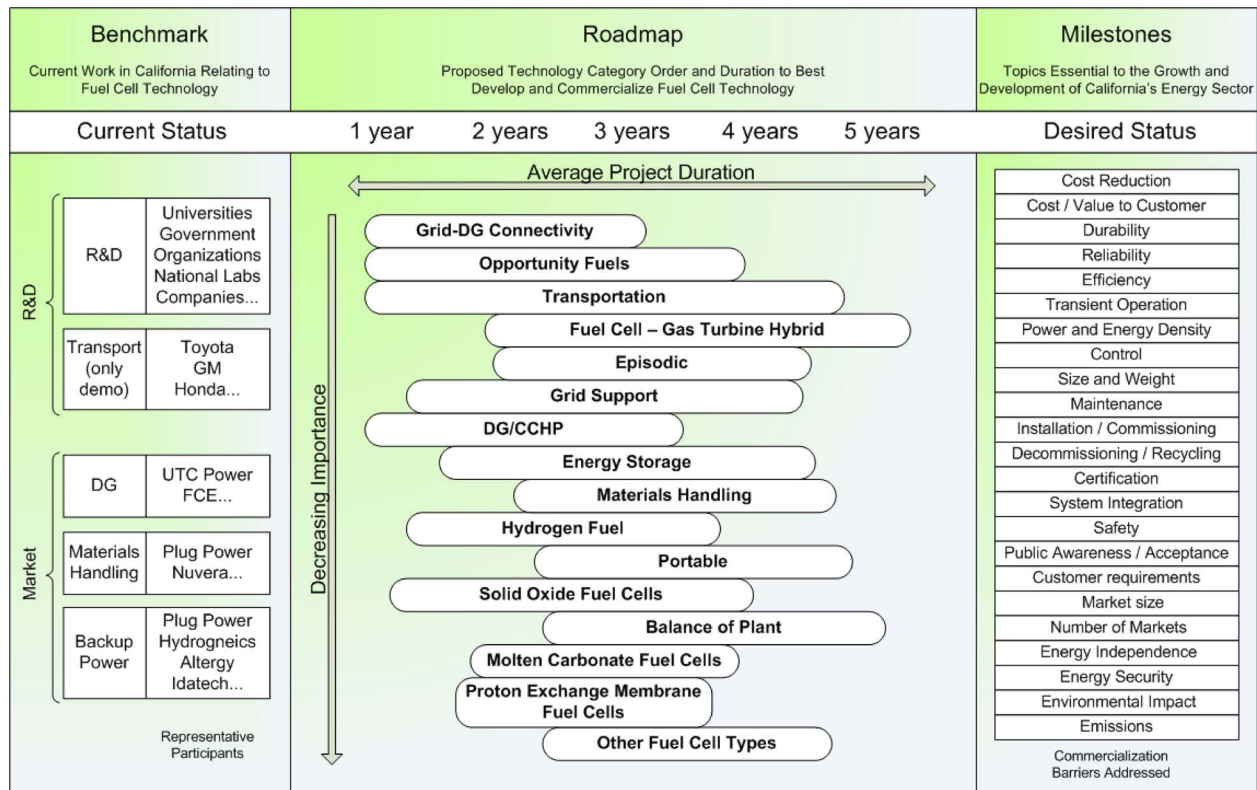


Fig. 3 Fuel cell roadmap

cialization barrier analysis is presented in the action plan, thereby establishing a detailed strategy to bridge the gap between fuel cell technology benchmarks and milestones.

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. Based on 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 that the results from all of these analyses be considered concurrently. The results from this work are posed as specific to California because of the nature of the questions and the majority of participants surveyed; however, due to the focus on technology barriers, it is possible to extend these results to cover the broader fuel cell community. Figure 4 shows the most important results from the three main analyses. The figure illustrates that all analyses rely on the reviewed literature and feedback from fuel cell stakeholders. Also, to conduct the commercialization barrier analysis the list of benchmarks and milestones were used and lastly, in conducting the project type analysis and when determining the importance of the types of projects and technology categories, the complete list of projects and the market transforming projects were used.

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 followed by customer requirements.

The most important technology category to pursue is the 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 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 and third highest ranking technology categories are the opportunity fuels and transportation 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

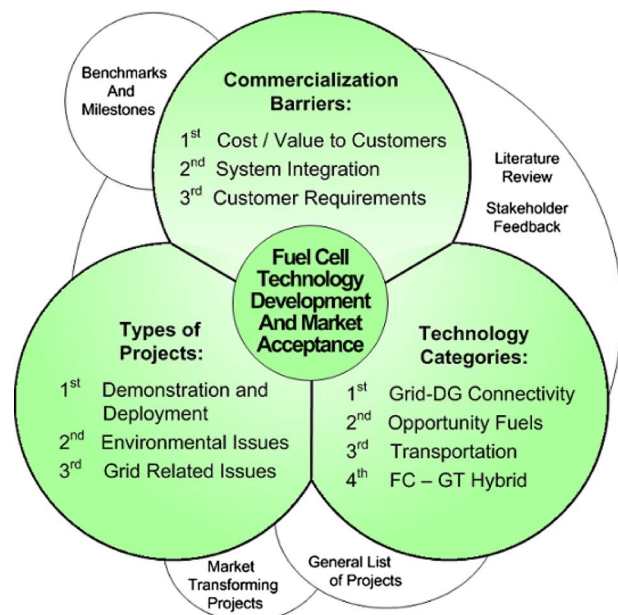


Fig. 4 Summary of findings

important project types. 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 analyses. These major findings are recurring themes from the survey results, all analyses of the results, and are oftentimes reiterated by stakeholder feedback and comments.

- There is a great need to pursue grid-connected fuel cell R&D that addresses **electrical distribution network issues**. This sentiment was echoed by the high average score and rank for the grid-DG connectivity category and the project type 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 (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 are demonstration or deployment of 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 one project.
- The **development and commercialization** of fuel cell technology is often associated with a timeframe. Fuel cells are currently penetrating the distributed power generation materials handling and backup power markets but with limited market penetration. It is recommended that the concept of “time to commercialization” be replaced with, “remaining barriers to commercialization.” Thus instead of speculating a number of years that are required for widespread market penetration and cost-competitiveness a set of technology and political barriers should be used to better express the status of the technology. This will provide a more tangible picture of the needs for fuel cells and can be used to establish a more informed and explicit time estimate. This will also avoid raising unachievable expectations.
- The **opportunity fuels** category was ranked as the second most important technology category and contained the highest and second highest ranking projects. Opportunity fuels have the potential to increase the sustainability of power generation while addressing climate concerns. Additionally, the importance of this area was explicitly noted in the comments from fuel cell stakeholders and should not go without notice.

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