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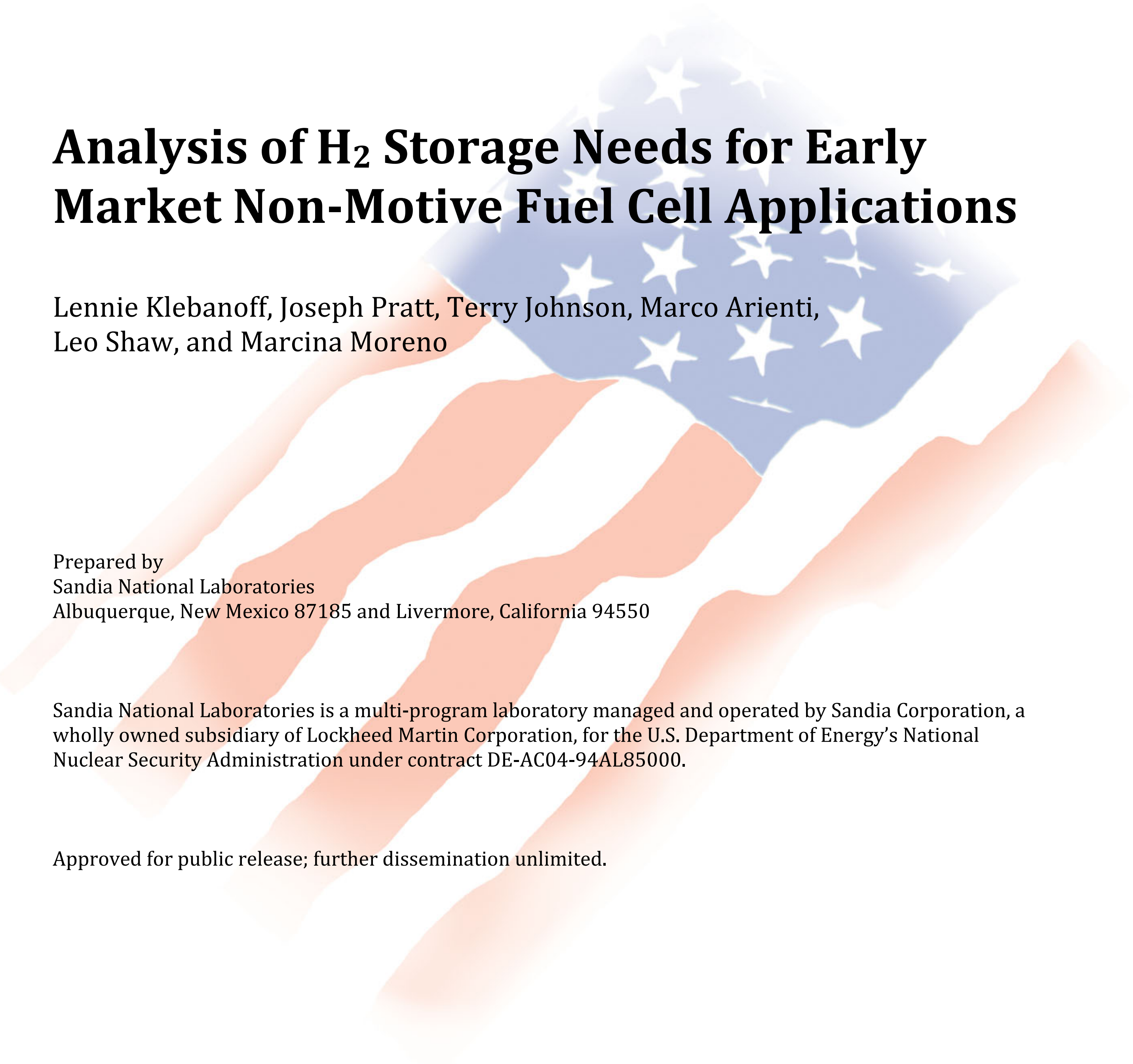

Analysis of H_2 Storage Needs for Early Market Non-Motive Fuel Cell Applications

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Abstract

Hydrogen fuel cells can potentially reduce greenhouse gas emissions and the United States' dependence on foreign oil, but issues with hydrogen storage are impeding their widespread use. To help overcome these challenges, this study analyzes opportunities for their near-term deployment in five categories of non-motive equipment: portable power, construction equipment, airport ground support equipment, telecom backup power, and man-portable power and personal electronics.

To this end, researchers engaged end users, equipment manufacturers, and technical experts via workshops, interviews, and electronic means, and then compiled these data into meaningful and realistic requirements for hydrogen storage in specific target applications.

In addition to developing these requirements, end-user benefits (e.g., low noise and emissions, high efficiency, potentially lower maintenance costs) and concerns (e.g., capital cost, hydrogen availability) of hydrogen fuel cells in these applications were identified. Market data show potential deployments vary with application from hundreds to hundreds of thousands of units.

Acknowledgements

The authors would like to thank the Department of Energy's Fuel Cell Technologies Program, Ned Stetson, Carol Read, and Scott McWhorter in particular, for funding this project and providing their enthusiastic support and valuable feedback throughout.

Torsten Erbel (Multiquip), Roger Hoosen (SFO), Russ Saunders (Saunders Electric), and Kevin Kenny (Sprint) gave informative presentations at the End User Workshop in Livermore and we are grateful for their special contributions in making that workshop a success.

Our collaborations with NREL and PNNL were especially fruitful and helped with the overall effectiveness of this project. At NREL, thank you to Jennifer Kurtz for leading the collaboration work and Chris Ainscough for the introduction to the Kano methodology, leadership in developing the questionnaires, and effort in co-planning the workshop at the Military Alternatives conference. At PNNL, thank you to Ewa Ronnebro for leading that side of the collaboration effort.

We want to thank all of those who attended our workshop, those who we interviewed in person or over the phone, and those who gave us their input via questionnaire. These data form the backbone of our study and this work would be incomplete without their willing participation. Most of these people are listed in the References, but others are not included in that list. In particular, L. Shaw also wishes to acknowledge Phil Robinson of Protonex for answering questions about the company's products, and Christian Böhm and Saskia Guderian of SFC Energy for providing photos of their JENNY product. L. Klebanoff wishes to thank Dana Mauch from Peterson Power for information on the air compressors.

Finally we want to thank those at Sandia who assisted with this project, including Julie Hillskemper for providing data on selected products and Karen McWilliams for preparing the final report for publication.

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Executive Summary

Efforts to reduce greenhouse gas emissions and the United States' dependence on foreign oil have led to the research and development of a variety of alternative energy solutions. Of particular interest is the hydrogen fuel cell, a device that produces electricity from the electrochemical reaction of hydrogen gas with oxygen. Challenges with hydrogen storage, however, are affecting near-term, widespread deployment of such fuel cell technologies.

The U.S. Department of Energy (DOE) has recently expanded the scope of its fuel cell technology interests to include applications of fuel cells for non-motive early market equipment. Examples of non-motive equipment included portable power generators, air compressors, airport luggage belt loaders (an example of aviation ground support equipment (GSE)) and backup power systems for cell phone towers. Additionally, DOE is interested in how fuel cells might be used as power sources in "man-portable" electronic systems and in exploring the hydrogen storage issues that arise when considering using fuel cells for man-portable electronics.

The primary objective of this study is to identify non-motive equipment technology suitable for powering via fuel cells, including technology currently being pursued for fuel cell conversion as well as technology that would be new to fuel cell introduction. Other objectives include the following:

1. Develop a list of developers and users for the non-motive equipment referred to above.
2. Identify the energy storage and power requirements of non-motive technology compatible with fuel-cell-based power, thereby enabling a determination of hydrogen storage needs for future fuel-cell-based operation.
3. Identify other requirements of such equipment (for example operational temperature, noise) to put into overall context the requirements that would be placed on a hydrogen fuel-cell based piece of equipment.

In the course of achieving the above objectives, non-motive equipment market information was often gathered, and it is also presented in this report.

The approach taken was to engage end users, technical experts, and mass manufacturers in the following areas: construction equipment, portable power, telecommunications, aviation ground support, and man-portable power and consumer electronics. These representatives originated from DOE's contacts as well as Sandia contacts developed in the course of ongoing work in the hydrogen technology arena. The primary means of interaction with these stakeholders was through an "End User" workshop hosted by Sandia National Laboratories, Livermore, California on February 8, 2011, but extensive communication also occurred through other workshops, personal interviews, phone calls, email, and web-based questionnaires.

Through interactions and analyses, eleven applications spanning these five categories were identified:

- Construction: lighting, scissor lifts, air compressors
- Aviation ground support: ground power unit, boom lift

- Telecommunications: backup power
- Portable power: small (< 10 kW) generators, large (> 10 kW) generators
- Man-portable power and consumer electronics: military power supplies, consumer power supplies, laptop computers.

Market analyses show that the markets for these different applications vary. The construction equipment applications have a market estimated to be in the hundreds of thousands per year, while aviation ground support equipment may be just in the hundreds or low thousands. Hydrogen fuel cell telecom backup power stations are already being deployed and the U.S. currently has 3.7 megawatts of fuel cells at about 1,300 sites. The portable power generator market is nearly 1 million units per year. The power supply market for the military is estimated to be in the hundreds or low thousands per year, but those for consumers may be in the millions.

Hydrogen power systems are attractive to end users in each of these applications. When competing with diesel- or gasoline-powered generators, the zero emissions and low noise of the hydrogen fuel cell systems stand out among all categories of end users. The reason for this is it would enable users to operate the equipment in places where emissions are not tolerated (such as indoors) or where emissions are heavily regulated. Users of power generation equipment (the telecom backup and portable generator markets) also noted the load-following capability of the hydrogen fuel cell system to be a significant benefit when compared to the existing units that waste fuel when idling. Finally, the potentially lower maintenance cost of hydrogen fuel cell power systems was another cited benefit, as for example, no oil changes or engine rebuilds are needed.

Some concerns about hydrogen fuel cell systems were also identified. All of the markets are capital cost-sensitive, with customers demanding a payback in just 2 to 5 years. This may not be an issue in portable power: with its large potential market the cost of a hydrogen fuel cell system could be comparable to existing gasoline or diesel units provided the projected production volume targets are met. Another concern with hydrogen fuel cell systems is the availability and supply of hydrogen. This concern was cited by end users in the telecom backup industry as a secondary concern, but it was a primary concern for those in the portable power and consumer electronics market. Those in consumer electronics feel strongly that a device that requires the consumer to manually refuel it with hydrogen, in its current state of availability, will not be sufficiently successful in the marketplace to justify developing such a product, even though there may be no other barriers to commercialization. The portable power and consumer electronics market has further concerns about the air-breathing behavior requirements of fuel cells that preclude them from inclusion in many devices, the additional heat generation, and the size to compete with batteries for all but specialized applications. However, the size issue of hydrogen fuel cell systems may not deter those in the other four market categories, where much of this equipment does not impose unmanageable volume or weight restrictions.

In addition to the market information, the benefits, and end user concerns expressed above, this report also details the technical specifications of each of the eleven applications, enabling the determination of requirements for a hydrogen fuel cell system that could fulfill the same function and still be accepted—or perhaps embraced—by the end user. These requirements are summarized in Table 1.

Table 1. Summary requirements for hydrogen fuel-cell-powered versions of the non-motive applications studied in this work.

	Requirements		Restrictions						
Application	Rated Output Power	Run Duration Per Fill/Charge	Energy Storage System Volume[1]	Energy Storage System Weight[1]	Refuel/ Recharge Time	Operating Conditions - Temperature	Operating Conditions - Weather[2]	Noise level[3]	Emissions[4]
Small Generator	4.5 kW (5.0 kW max)	8.1 hr @ rated load, 11.2 hr at 50% load	26 L	22 kg	0.6 min	-30 C to 40 C	Extreme	< 72 dB	Meets or exceeds EPA requirements
Medium Generator	20 kW	10 hr @ 100% load, 20 hr @ 50% load	71 L	59 kg	1.7 min	-25 C to 50 C	Extreme	< 63 dB	Meets or exceeds EPA requirements
Large Generator	100 kW	8.6 hr @ 100% load, 15.4 hr @ 50% load	264 L	220 kg	6.3 min	-25 C to 50 C	Extreme	< 68 dB	Meets or exceeds EPA requirements
Ground Power Unit	100 kVA	10 hr @ full load	302.5 L	252 kg	7.3 min	-25 C to 50 C	Extreme	< 85 dB	Meets or exceeds EPA requirements
Mobile Light	6 kW	66 hr @ 75% power	123.7 L	104 kg	10 min	-25 C to 50 C	Extreme	< 73 dB	Meets or exceeds EPA requirements. Indoor use desirable
Air Compressor	97 kW	8.7 hr @ full load	230.0 L	199 kg	15 min	-30 C to 50 C	Extreme	< 76 dB	Meets or exceeds EPA requirements
Scissor Lift	600 W (average), 1800 W maximum	8 hr	52.7 L	112.3 kg	8 hr	-20 C to 50 C	Primarily indoor	Not Available	Acceptable for indoor use
Telecom Backup	5 kW (most common)	> 8 hr (min FCC req.)	1220 L	409 kg	40-45 min	-40 C to 45 C	Extreme	53 dBA @ 1 meter	Must meet local requirements
Military Personnel Battery	30 W nominal and 85 W for short bursts	> 15 hr	0.65 L	1.02 kg	Cartridge swap	MIL-STD-810 (-31 °C to 49 °C)	Extreme (MIL-STD-810)	Negligible	Warm air or none
Consumer Battery Charger	2.5 W	40 hr to 100 hr @ rated power	0.28 L	0.285 kg	Cartridge swap	-10 C to 45 C	Not designed for weather exposure	Negligible	Warm air or none
Specialized Laptop Computer	8 W (idle) to 35 W (heavy use)	8 hr to 24 hr at heavy use	0.774 L	0.475 kg	Cartridge swap	MIL-STD-810 (-31 C to 49 C)	MIL-STD-810, IP65 enclosure	Negligible	Warm air or none

Table notes: 1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware. Restrictions on size assume the storage of enough energy to meet the rated output power for the required run duration; if more energy is stored these restrictions may be relaxed. 2. Extreme weather conditions include rain, snow, hail, ice, blowing sand, blowing water, dirt, mud, dust, high elevation, salt air, and humidity extremes. 3. All noise levels when operating at rated load, at a distance of 5 m unless stated otherwise. 4. EPA requirements: *Phase 3* for gasoline engine replacement (http://www.epa.gov/otaq/equip-ld.htm), *Tier 3* for diesel engine replacement (http://www.epa.gov/nonroad-diesel/regulations.htm).

Acronyms

CARB	California Air Resources Board
d-SLR	Digital single lens reflex
DMFC	Direct methanol fuel cell
DOD	(U.S.) Department of Defense
DOE	(U.S.) Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
FCHEA	Fuel Cell and Hydrogen Energy Association
GPU	Ground power unit
GSE	Ground support equipment
ID	Illumination dynamics
LHV	Lower heating value
MQ	Multiquip
NREL	National Renewable Energy Laboratory
PEM	Proton exchange membrane
PNNL	Pacific Northwest National Laboratory
SFO	San Francisco International Airport

1 Introduction

Efforts to reduce greenhouse gas emissions and the United States' dependence on foreign oil have led to the research and development of a variety of alternative energy solutions. Of particular interest is the hydrogen fuel cell, a device that produces electricity from the electrochemical reaction of hydrogen gas with oxygen. Producing only water, this clean technology shows much promise as a viable alternative to petroleum-based power and indeed in some specific applications has already found implementation. Challenges with hydrogen storage, however, are affecting near-term, widespread deployment of such fuel cell technologies.

Historically, DOE has funded a great deal of work in hydrogen storage R&D focused on light-duty vehicle applications. However, recently DOE expanded the scope of its fuel cell technology interests to include applications of fuel cells for both motive equipment beyond light-duty vehicles as well as non-motive early market equipment. For this study, non-motive equipment is defined as equipment that is not driven directly by a human being (i.e., does not possess a steering wheel). The equipment is either stationary or, if portable, carried or towed by a person or vehicle. Examples of non-motive equipment include portable power generators, air compressors, airport luggage belt loaders (an example of aviation ground support equipment (GSE)) and backup power systems for cell phone towers. Additionally, DOE is interested in how fuel cells might be used as power sources in "man-portable" electronic systems and in exploring the hydrogen storage issues that arise when considering using fuel cells for man-portable electronics.

1.1 Objective

The objectives of this study can be summarized as follows:

1. Identify non-motive equipment technology suitable for powering via fuel cells, including technology currently being pursued for fuel cell conversion as well as technology that would be new to fuel cell introduction.
2. Develop a list of developers and users for the non-motive equipment in #1 above.
3. Identify the energy storage and power requirements of non-motive technology compatible with fuel cell based power, thereby enabling a determination of hydrogen storage needs for future fuel-cell-based operation.
4. Identify other requirements of such equipment (for example operational temperature, noise) to put into overall context the requirements that would be placed on a hydrogen fuel-cell-based piece of equipment.

The hydrogen storage needs for non-motive uses of fuel cells are anticipated to be different than the well-known hydrogen storage needs for light-duty vehicle applications. In order for DOE to understand the eventual hydrogen storage needs for non-motive fuel cell use, it is important to understand what the highest-priority pieces of equipment are in the non-motive equipment realm that might best be suited for conversion to fuel cell power (objective #1). Specific information is needed to enable the development of quantitative DOE targets for hydrogen storage for non-motive equipment. Additionally, it is vital to fully understand who is currently developing and commercializing such equipment (objective

#2) and what the current operational demands are for energy storage and power delivery (objective #3). It is also important to understand the “real world” environments of how this non-motive equipment is actually used (objective #4) to better understand the overall system demands on a hydrogen fuel-cell-based piece of non-motive equipment. In the course of achieving objectives 1 through 4, in many cases non-motive equipment market information was gathered, and is therefore also presented in this report.

To achieve these objectives, the investigators engaged end users, technical experts, and manufacturing experts in various non-motive equipment categories, identified the highest-priority pieces of equipment in each one of those categories that might best benefit by conversion to a “clean energy technology” such as hydrogen fuel cells, and captured in detail the current energy storage and use specifications. By understanding the current specifications for energy storage and power output, DOE can better understand what the goals of a substitute hydrogen-based technology would be, and in particular, where the hydrogen storage performance gaps truly are if hydrogen-fueled fuel-cell-based non-motive equipment were to meet or exceed the capabilities of the current equipment.

1.2 Scope of This Study

This report builds off an earlier 2007 DOE-funded study conducted by Battelle entitled, “Identification and Characterization of Near-Term Direct Hydrogen Proton Exchange Membrane Fuel Cell Markets.”[1] In that earlier study, Battelle examined likely near-term “pre-automotive” markets for proton exchange membrane (PEM) fuel cells in the power range of 1 to 250 kW. The report identified two near-term markets for PEM Fuel cells, namely “Specialty Vehicle Applications,” and “Backup Power Applications.” Within the specialty vehicle category, Battelle identified forklifts within distribution centers and airport GSE as being the most promising. Within backup power, the Battelle report identifies telecommunications (i.e., cell phone towers) as being the most promising for the early introduction of fuel cells. Applications below 1 kW and Department of Defense (DOD) applications for PEM fuel cells were excluded from the scope of the Battelle work.

At the request of DOE, investigators engaged the end user and technical expert communities for both backup power for telecommunications and airport GSE applications of “non-motive” equipment use of fuel cells. This engagement was motivated in part by the prior findings of the Battelle study; however, this study also went beyond the original Battelle study in investigating the applicability of fuel cells and stored-energy requirements for power applications below 1 kW. DOD end users were engaged as a potential market and the scope was broadened to include possible use of fuel cells in construction equipment, “man-carry” portable electronics, and in portable power systems. Any application that could be considered as primarily “motive” (in the sense that its primary purpose is transportation or if it has a steering wheel and is “self propelled” at significant speeds) was excluded. A separate study of motive equipment is being conducted concurrently by the National Renewable Energy Laboratory (NREL).

The consumer electronics and man-portable power generation areas are defined as pertaining to fuel cell systems primarily targeting small-scale use. Specifically, “man-portable” refers to devices capable of being carried, worn, or held in-hand by an individual. Such devices generally have power ratings less than 100 W, with certain systems tailored to military applications having ratings around 300 W. Because of the size and portability constraints of these applications, the upper limit of fuel cell power explored in this part of the study was approximately 500 W.

The purpose of this study was to solicit and capture feedback from end users and technical experts in these diverse communities and understand the energy storage needs for specific pieces of non-motive equipment. Care was taken to not allow the investigators' technical biases to intrude on the process. This report therefore reflects the input provided by the end user and technical user community. No judgments were made on the veracity of the feedback beyond investigators' judgment regarding whether the particular piece of feedback comes from a source "in the know" on a particular topic. In addition, market data were examined where possible to put the feedback from the end users in context. In some applications, fuel cells are already being considered for deployment, and that activity is captured. In other applications, no fuel-cell-related activities are presently occurring, but specific equipment and applications that could benefit from fuel cell introduction are identified, and current specifications for energy storage and use are given.

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2 Method

This section describes the overall approach and information gathering methods including the workshops that were held, questionnaires and analysis methods that were used, interviews, and collaborations with other National Lab partners.

2.1 Approach

In the early phase of this work, the approach taken was to engage end users, technical experts, and mass manufacturers in the following areas: construction equipment, portable power, telecommunications, aviation, and consumer electronics. These representatives originated from DOE's contacts as well as Sandia contacts developed in the course of ongoing work in the hydrogen technology arena. The primary means of interaction with these stakeholders was through an "End User" workshop hosted by Sandia National Laboratories, Livermore, California on February 8, 2011, but extensive communication also occurred through other workshops, personal interviews, phone calls, email, and web-based questionnaires.

In general, interactions with the end users revolved around finding qualitative and quantitative answers to the following six questions about the equipment identified for analysis:

1. What equipment (typically based on diesel fuel, batteries, or other energy technology) would benefit technically and in a business sense if based on a clean, non-polluting, efficient energy technology?
2. Who is using this equipment?
3. How is the equipment currently being used?
4. What are the environmental and worksite requirements that the current technology must meet?
5. What are the performance requirements of the current equipment with regard to stored energy, power output, duration, so as to better understand the needs of the new clean technology?
6. What is the cost sensitivity?
7. What works well now with the current technology, what works poorly, what could be improved?

In order to eliminate bias from the feedback process, these end user communities were engaged not with the technology of hydrogen fuel cells in mind, but rather with the possibility of replacing fossil-fuel based and battery technology with a "clean non-polluting" energy technology based on hydrogen that also improved thermal efficiency. However, the topic at hand—namely, fuel cell technology—occasionally found its way into the discussions because in a number of cases, fuel cells were already in the process of being applied to the specific activity, for example in telecom backup power and mobile lighting. In these cases, the discussion considered what could be improved with the fuel cell implementation. However, engagement with construction equipment, portable power, GSE and telecom backup personnel went beyond areas where fuel cells are currently being used. At the instruction of

DOE, the energy storage of a clean alternative technology was treated as a “black box,” and essentially no discussions of hydrogen storage technology were held.

2.1.1 Man-Portable Power and Consumer Electronics

A different approach was taken for the “man–portable and consumer electronics” applications. This market was engaged primarily through one-on-one interviews, teleconferences, and emails using Sandia’s existing contacts as well as those provided by DOE and those developed during investigators’ research in this area. The approach to this portion of the project was as follows:

1. Identify categories of common portable electronics used today.
2. Compile major brand names and companies who produce each product.
3. Search for any active research, patents, news articles, and reports involving fuel cells in these products or by these companies.
4. Talk to both fuel cell manufacturers and to consumer electronics companies to assess the status and potential of fuel cells and of hydrogen in these products.
5. Gather information on the markets of existing and potential products that would benefit from hydrogen fuel cell use, regardless of whether or not fuel cells had actually started to be used in that realm.
6. Select the categories with the most potential for near-term fuel cell deployment and the highest impact of deployment.
7. Determine the technical specifications of the energy storage systems for products in the selected categories.
8. Determine the requirements a hydrogen system would need in order to compete with currently available energy storage technology.

A variety of methods were used to find active fuel cell research, including searches in scholarly journals and academic databases. The filing of patents related to fuel cells served as an indicator of active research within a particular electronics category. Internet searches for relevant news articles and press releases were also employed. Several companies were contacted directly via email about their existing products and the potential they saw in the industry. These contacts generally had expansive knowledge about the industry’s direction and major areas of focus.

Using the volume and extent of active research, the current value and volume of the market, and the existence of devices already containing fuel cell components, three markets were selected for further investigation. Sample products in each market were then chosen and their technical specifications and performance requirements were used to determine the requirements that a fuel cell/hydrogen-powered device would need to meet to be a viable near-term option for consumers in that market.

2.2 Workshops

Three separate workshops were held over the course of this study. The primary effort was focused on the "End User Workshop on Needs of Non-Motive Power Technology," held in Livermore, CA, on February 8, 2011. Additionally, NREL's "Onboard Energy Storage Performance Needs for Fuel Cell Motive Markets" workshop was held in conjunction with the FCHEA Meeting on Feb. 16, 2011, and Sandia co-facilitated DOE's interactive workshop, "Navigating Obstacles Associated with Utilizing Hydrogen Power as an Alternative Energy Source," held on February 24, 2011, in conjunction with the Marcus Evans 6th Annual Military Energy Alternatives conference. This section gives more detail on each of those activities.

2.2.1 Sandia Workshop, Livermore, CA

An "End User Workshop on Needs of Non-Motive Power Technology" was held at Sandia's General Access Area in Livermore, CA, on February 8, 2011. The workshop agenda is given in Appendix C. The workshop was attended by representatives from the construction equipment, portable power, telecommunications, and aviation markets. In aviation, DOD representatives from Travis Air Force Base were also present. In all, 22 "end users" and 9 "technology experts" attended the workshop, and representatives from DOE, NREL, and PNNL also attended the meeting. There were a total of 40 attendees, as shown in Figure 1.

Figure 1. Workshop attendees visiting Sandia-CA on February 8, 2011.

In the morning the attendees heard fuel cell technology presentations from DOE (Scott McWhorter) and Sandia (Lennie Klebanoff). The purpose of the DOE and Sandia presentations was to educate the audience on the DOE Hydrogen and Fuel Cell Technology program and to provide the audience with the hydrogen technology background to facilitate discussions when the conversation turned to fuel cells and their benefits and limitations. The presentations specifically avoided making statements of preference for hydrogen fuel cell technology as power sources. For the remainder of the morning, the group heard presentations on uses of equipment and power in construction (Torsten Erbel, Multiquip), entertainment (Russ Saunders, Saunders Electric), telecommunications (Kevin Kenny, Sprint) and in aviation GSE (Roger Hooson, San Francisco International Airport). Figure 2 shows pictures from some of those morning lectures. The industry leaders giving presentations were also asked to lead the "break out" sessions scheduled for the afternoon, and to summarize the results of the breakout sessions later in the day.

Scott McWhorter, DOE **Russ Saunders, Saunders Electric**

Torsten Erbel, MQ **Roger Hooson, SFO** **Kevin Kenny, Sprint**

Figure 2. Several morning presentations from the End Users Workshop.

During this workshop, the attendees were surveyed with multiple questionnaires to help identify how equipment is used in their respective realms, as shown in Figure 3.

Figure 3. Workshop attendees filling out questionnaire forms.

Later in the afternoon, facilitated break-out sessions, organized and facilitated by Ricky Tam (Sandia) as well as by the project team (Lennie Klebanoff, Joe Pratt, Terry Johnson and Marcina Moreno), were held in the areas of construction equipment, portable power, aviation GSE, and telecom backup power. These were held to extract the end user requirements and identify specific pieces of equipment in each non-motive early market. It was important to identify from the workshop attendees very specific pieces of equipment so that specific hydrogen storage requirements could eventually be developed by DOE. For each breakout session, investigators sought to identify the top three pieces of equipment to target in each category, and for each one to solicit detailed information on the way it is used, the environmental (temperature) requirements, as well as the stored energy, energy densities, and required power output and duration. Figure 4 shows typical activity in the breakout sessions.

Figure 4. Kevin Kenny (Sprint) examines raw breakout session charts.

After the workshop, the results of the questionnaires were quantified using a Kano-type analysis. In addition, representatives of the four areas were contacted again to gain a quantitative understanding, for the top three selected equipment items, of how this non-motive equipment is actually used and what the demands are on the energy system.

2.2.2 NREL's FCHEA Meeting Workshop

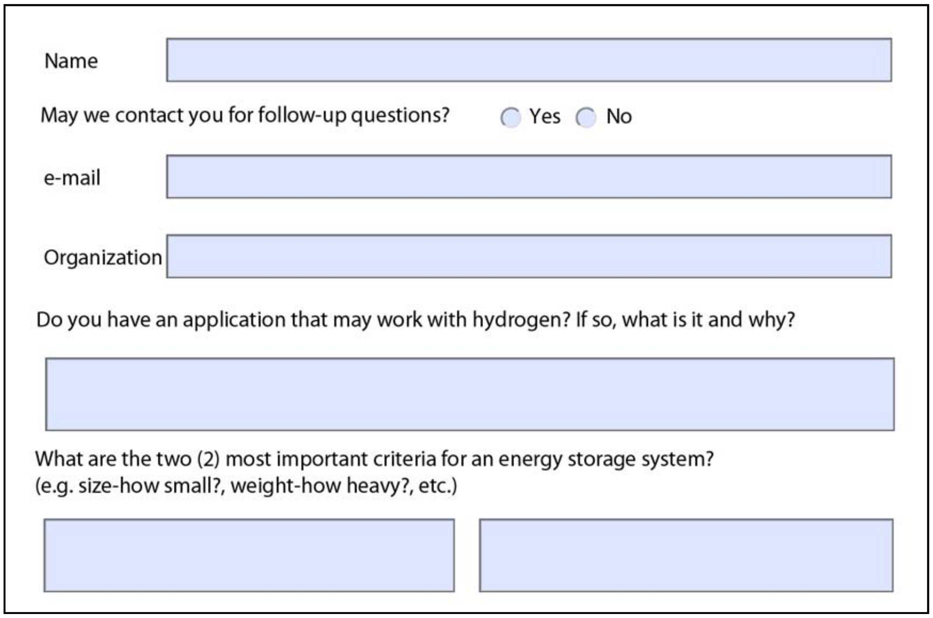
NREL was asked by DOE to complete a similar, parallel study in which they focused on motive equipment. They held a workshop titled, "Onboard Energy Storage Performance Needs for Fuel Cell Motive Markets," which was co-located with the Fuel Cell and Hydrogen Energy Association (FCHEA) Meeting on February 16, 2011, in National Harbor, MD. While the workshop was focused on motive applications, it was thought that some of the attendees may also be involved in non-motive applications of fuel cells or hydrogen, which is the reason Sandia attended. Unfortunately there were no attendees of this nature. So, while the workshop was beneficial from many perspectives, it did not yield any information for this particular "non-motive" equipment study. For more information on this motive technology workshop, the reader is referred to the NREL study.

2.2.3 DOE's Military Alternatives Conference Workshop

Sandia and NREL were facilitators for an interactive workshop held as part of the 6th Annual Military Energy Alternatives Conference on February 24, 2011, in Washington, D.C., titled, "Navigating Obstacles Associated with Utilizing Hydrogen Power as an Alternative Energy Source." There were 25–30 participants, including 11 from the military (U.S. and Canada), two from DOE laboratories (excluding the facilitators), and the remainder from companies that market or provide technologies or services to the military. The outline of the 90-minute workshop was as follows:

1. Presentation from Dr. Ned Stetson of DOE on the basics of fuel cells and hydrogen.
2. Hand out pre-printed note cards (see Figure 5) with focus questions.

3. Break into two groups: motive and non-motive applications.
4. After filling out the cards, go through the room one-by-one to compile and discuss responses.
5. Group vote on the needs of the top three equipment types and discussion.



Name

May we contact you for follow-up questions? ○ Yes ○ No

e-mail

Organization

Do you have an application that may work with hydrogen? If so, what is it and why?

What are the two (2) most important criteria for an energy storage system?
(e.g. size-how small?, weight-how heavy?, etc.)

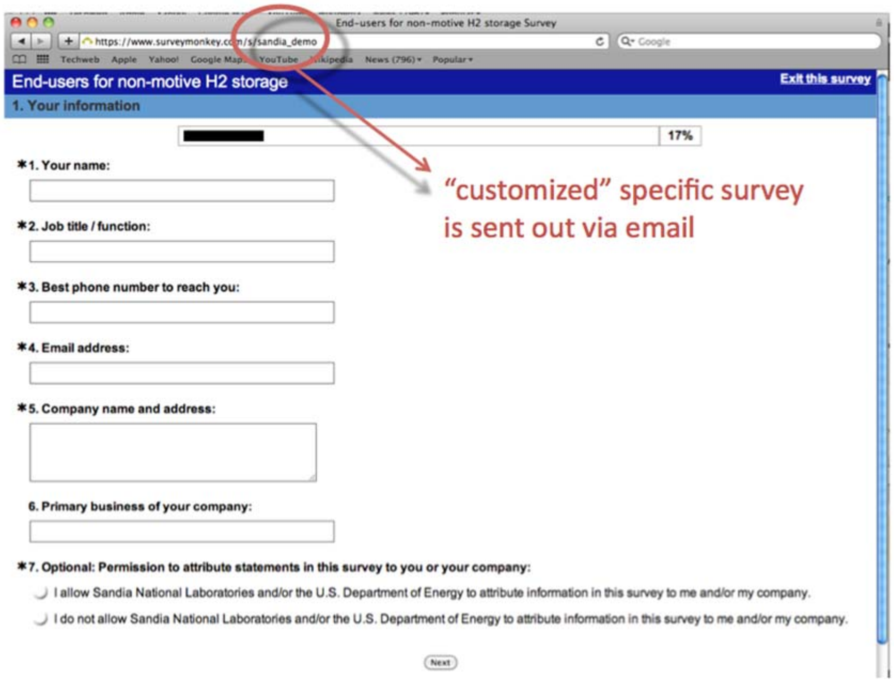
Figure 5. Note card with focus questions, given to participants at DOE's Military Energy Alternatives conference workshop. The completed note cards have been cataloged by NREL and the information from them is shown in Appendix A.

About 90% of the participants attended the non-motive application side of the workshop. Of these, 11 expressed an interest in stationary, large-scale base power, which is outside the scope of this study. Four were interested in remote or backup power, and six were interested in portable power. Only one participant was interested in something other than a power generator: a pump. Due to these concentrated interests, this workshop was helpful in gathering more needs on the portable power generators section of this study, and also indicated that portable power may be a well-received early market opportunity within the DOD. More details on the results from this workshop can be found in Section 3.4).

2.3 Questionnaires/Surveys

The questionnaires presented to workshop attendees and others from the database who could not attend the workshops were developed with a Kano Analysis in mind. The purpose of the questionnaires was to allow a broader range of feedback on how equipment is used in these various markets.

The questionnaires were also developed as online surveys (see Figure 6) to target specific sub-groups (mobile vs. ground support equipment, for instance) amongst end users and hydrogen storage manufacturers. The end users contacted for the survey were requested to enter data that identify a specific piece of equipment in terms of power requirement and utilization. Multiple surveys could be filled by the same end user for different types of equipment. The core of the survey consisted of 18 Kano questions (see explanation below) concerning equipment footprint, temperature range of operation, cost of maintenance, emission constraints, etc. Each Kano pair was completed by one or several follow-up questions to quantify the feedback about performance. The survey concluded with open-ended questions in which the end user could list desired performance improvements or technical barriers that, if removed, would enable a broader/more efficient utilization. Data were collected in a spreadsheet of which a portion is shown in Figure 7.



End-users for non-motive H2 storage

1. Your information

*1. Your name:

*2. Job title / function:

*3. Best phone number to reach you:

*4. Email address:

*5. Company name and address:

6. Primary business of your company:

*7. Optional: Permission to attribute statements in this survey to you or your company:

○ I allow Sandia National Laboratories and/or the U.S. Department of Energy to attribute information in this survey to me and/or my company.

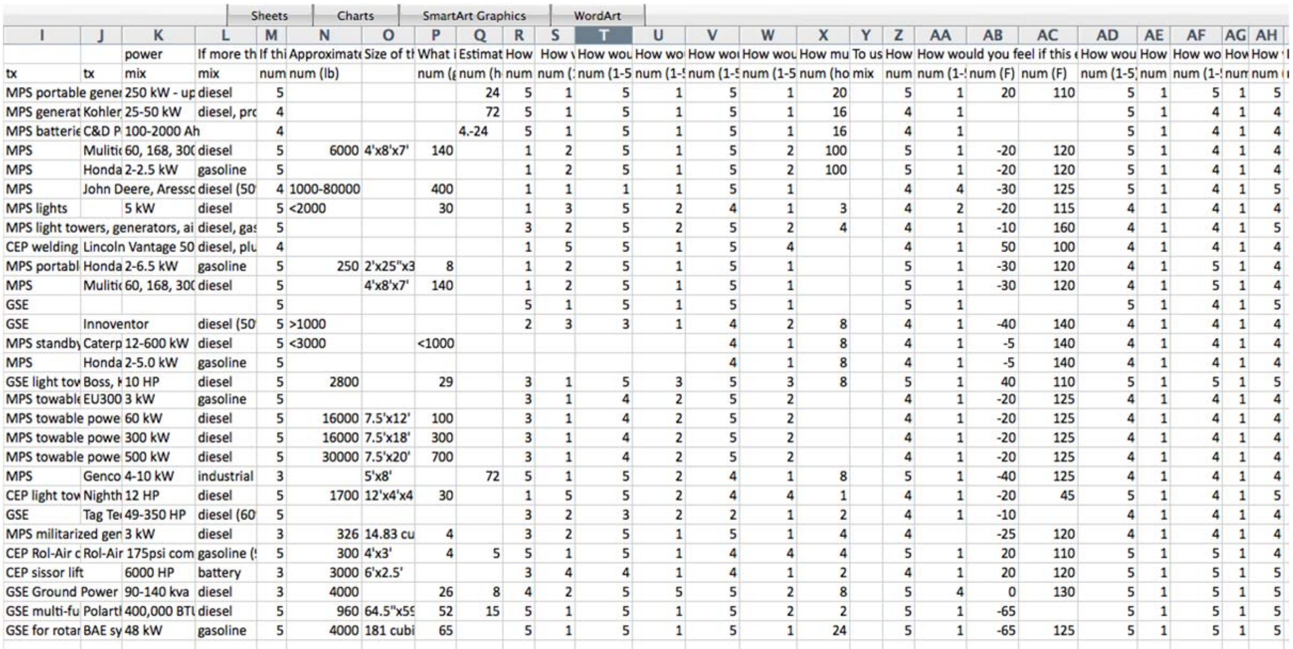
○ I do not allow Sandia National Laboratories and/or the U.S. Department of Energy to attribute information in this survey to me and/or my company.

"customized" specific survey is sent out via email

Figure 6. Online version of the end user questionnaire showing the header page.

A second questionnaire was prepared for hydrogen storage manufacturers (compressed H_2 at 350 bar; compressed H_2 at 700 bar; cryocompressed; liquid; metal hydride; chemical hydride; and sorbent) and expert users or researchers in the field. This group was asked to rate system gravimetric and volumetric efficiencies; refueling time; H_2 rate of delivery and availability; durability of the system; temperature operational range; H_2 purity; existence of toxic or dangerous byproducts; costs; and end-of-life disposal issues. Although it was decided in discussions with DOE that evaluation of this information should be removed from the scope of this work, the raw data from the completed surveys is given in Appendix A.

The Kano Methodology posits that: (1) Performance on product and service features is not equal in the eyes of the customers; (2) Performance on certain categories of features produces higher levels of satisfaction than on others.



I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH
		power	If more th	If thi	Approximat	Size of tl	What i	Estimat	How	How v	How wou	How wo	How wo	How wou	How mu	To us	How	How would you feel if this e			How wou	How	How wo	How	How 'I
tx	tx	mix	mix	num	num (lb)		num (g	num (h	num	num (:	num (1-5	num (1-5	num (1-5	num (1-5	num (ho	mix	num	num (1-5	num (F)	num (F)	num (1-5)	num	num (1-5	num	num (
MPS portable gener		250 kW - up	diesel	5				24	5	1	5	1	5	1	20		5	1	20	110	5	1	5	1	5
MPS generat	Kohler	25-50 kW	diesel, prc	4				72	5	1	5	1	5	1	16		4	1			5	1	4	1	4
MPS batterie	C&D P	100-2000 Ah		4				4.-24	5	1	5	1	5	1	16		4	1			5	1	4	1	4
MPS	Mulitic	60, 168, 30	diesel	5	6000	4'x8'x7'	140		1	2	5	1	5	2	100		5	1	-20	120	5	1	4	1	4
MPS	Honda	2-2.5 kW	gasoline	5					1	2	5	1	5	2	100		5	1	-20	120	5	1	4	1	4
MPS	John Deere, Aressc		diesel (50	4	1000-80000		400		1	1	1	1	5	1			4	4	-30	125	5	1	4	1	5
MPS lights		5 kW	diesel	5	<2000		30		1	3	5	2	4	1	3		4	2	-20	115	4	1	4	1	4
MPS light towers, generators, ai			diesel, ga	5					3	2	5	2	5	2	4		4	1	-10	160	4	1	4	1	5
CEP welding	Lincoln Vantage 50		diesel, plu	4					1	5	5	1	5	4			4	1	50	100	4	1	4	1	4
MPS portabl	Honda	2-6.5 kW	gasoline	5	250	2'x25"x3	8		1	2	5	1	5	1			5	1	-30	120	4	1	5	1	4
MPS	Mulitic	60, 168, 30	diesel	5		4'x8'x7'	140		1	2	5	1	5	1			5	1	-30	120	4	1	5	1	4
GSE				5					5	1	5	1	5	1			5	1			5	1	4	1	5
GSE	Innoventor		diesel (50	5	>1000				2	3	3	1	4	2	8		4	1	-40	140	4	1	4	1	4
MPS standb	Caterp	12-600 kW	diesel	5	<3000		<1000						4	1	8		4	1	-5	140	4	1	4	1	4
MPS	Honda	2-5.0 kW	gasoline	5									4	1	8		4	1	-5	140	4	1	4	1	4
GSE light tov	Boss,	10 HP	diesel	5	2800		29		3	1	5	3	5	3	8		5	1	40	110	5	1	5	1	5
MPS towabl	EU300	3 kW	gasoline	5					3	1	4	2	5	2			4	1	-20	125	4	1	4	1	4
MPS towable powe		60 kW	diesel	5	16000	7.5'x12'	100		3	1	4	2	5	2			4	1	-20	125	4	1	4	1	4
MPS towable powe		300 kW	diesel	5	16000	7.5'x18'	300		3	1	4	2	5	2			4	1	-20	125	4	1	4	1	4
MPS towable powe		500 kW	diesel	5	30000	7.5'x20'	700		3	1	4	2	5	2			4	1	-20	125	4	1	4	1	4
MPS	Genco	4-10 kW	industrial	3		5'x8'		72	5	1	5	2	4	1	8		5	1	-40	125	4	1	4	1	4
CEP light tov	Nighth	12 HP	diesel	5	1700	12'x4'x4	30		1	5	5	2	4	4	1		4	1	-20	45	5	1	4	1	5
GSE	Tag Te	49-350 HP	diesel (60	5					3	2	3	2	2	1	2		4	1	-10		4	1	4	1	4
MPS militarized gen		3 kW	diesel	3	326	14.83 cu	4		3	2	5	1	5	1	4		4		-25	120	4	1	4	1	4
CEP Rol-Air c	Rol-Air	175psi com	gasoline (	5	300	4'x3'	4	5	5	1	5	1	4	4	4		5	1	20	110	5	1	5	1	4
CEP sissor lift		6000 HP	battery	3	3000	6'x2.5'			3	4	4	1	4	1	2		4	1	20	120	5	1	5	1	5
GSE Ground Power		90-140 kva	diesel	3	4000		26	8	4	2	5	5	5	2	8		5	4	0	130	5	1	5	1	5
GSE multi-fu	Polartl	400,000 BT	diesel	5	960	64.5"x5	52	15	5	1	5	1	5	2	2		5	1	-65		5	1	5	1	5
GSE for rotar	BAE sy	48 kW	gasoline	5	4000	181 cubi	65		5	1	5	1	5	1	24		5	1	-65	125	5	1	5	1	5

Figure 7. A portion of the end user database including answers to the questionnaire.

Some features of a product are absolutely essential, whereas other features are unexpected bonuses. In addition, people's sensitivity to the features of a product can be widely disparate, forming a complex space of product features and people's reactions and desires with respect to those features.

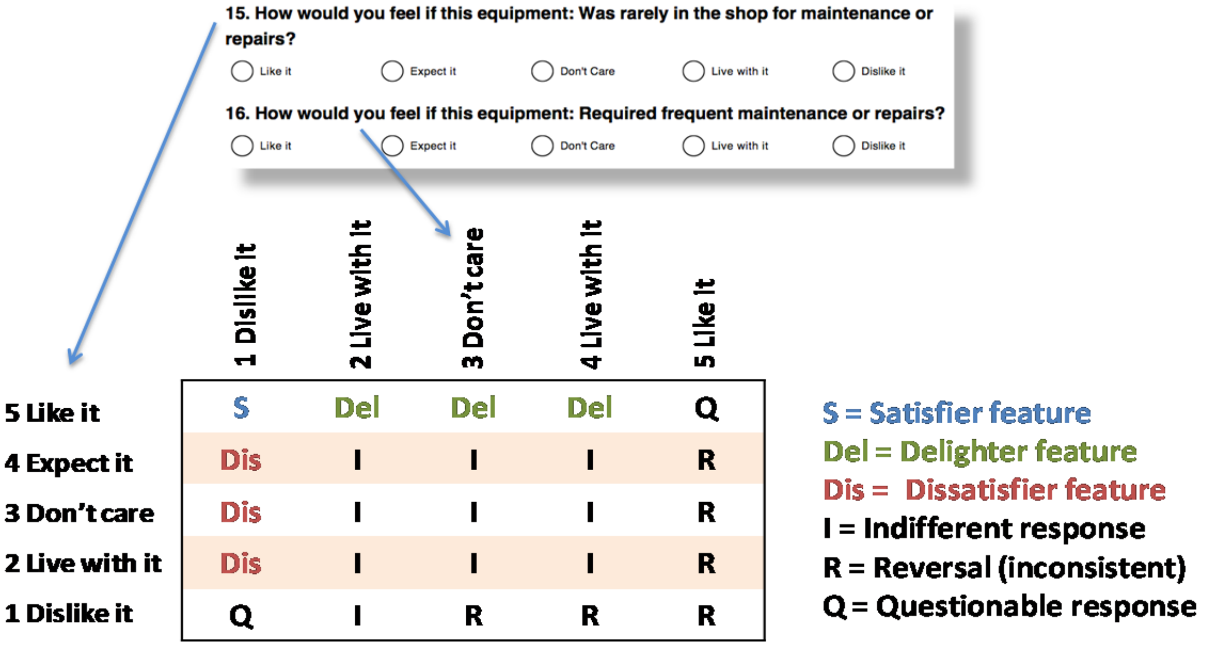
The Kano methodology attempts to tease out the more subtle information by asking a set of questions about each feature, and then characterizing that feature based on the responses. Three characterizations of features are:

- Dissatisfier—A feature that if absent, produces dissatisfaction. The customer assumes it will be there, and if it is absent a lot of dissatisfaction is generated. One could consider this a technical threshold of sorts. However, once present, a Dissatisfier feature only produces so much satisfaction. For example, people do not care that much about the ON button of a cell phone, so making a much better ON button does not produce much more satisfaction, and indeed it is hard to say what a "much better" ON button would be. A set of Kano questions, properly posed about this feature, would reveal a Dissatisfier classification based on customer responses.
- Satisfier—A feature that if absent, produces dissatisfaction. If the feature is there, the more there is, the better the satisfaction. A good example here would be the coverage area of a cell phone. If there is no coverage, customers are very unhappy. But the more coverage the better, and the happier the customer. If a Satisfier is there, the more it is there, the more satisfaction. A set of Kano questions, properly posed about the coverage area of a cell phone, would reveal a Satisfier classification based on customer responses.
- Delighter—A Delighter is a "latent" need of the customer. It is a need that the customer may not even be aware of, or is quite happy living without (until the customer becomes aware of the new capability!). A good example from the earlier days of the cell phone would be the ability to text message. Prior to text messaging, customers were happy with phones that

made phone calls. They did not miss the ability to text message because it did not yet exist. However, when the ability to text message presented itself, it became a highly desirable feature. The absence of a delighter does not cause much dissatisfaction, but its presence can cause a great deal of new satisfaction. A set of Kano questions, properly posed about the ability of a phone to text message, would, in the early days of text messaging, identify this feature as a Delighter based on customer responses. However, today the same Kano methodology would reveal text messaging to be a Dissatisfier.

To identify features that are Dissatisfiers, Satisfiers, and Delighters, paired "Functional Form" vs. "Dysfunctional Form" questions are then asked about that feature: "How would you feel if the product ***had*** feature X?" and "How would you feel if the product ***didn't have*** feature X?" The answers to both questions are one of five options, such as: "I like it" (given the number 5); "I expect it" (given the number 4); "I don't care" (given the number 3); "I can live with it" (given the number 2); "I dislike it" (given the number 1). More examples in Appendix B illustrate cases of functional and dysfunctional questions, with their corresponding Dissatisfiers and Delighters.

The results of the (x, y) scores from a Kano question can be plotted in an array, as shown in Figure 8, where the different response possibilities summarized above, and also other categories such as "indifferent" or "reversal" (inconsistent) responses are given.



15. How would you feel if this equipment: Was rarely in the shop for maintenance or repairs?

○ Like it ○ Expect it ○ Don't Care ○ Live with it ○ Dislike it

16. How would you feel if this equipment: Required frequent maintenance or repairs?

○ Like it ○ Expect it ○ Don't Care ○ Live with it ○ Dislike it

	1 Dislike It	2 Live with It	3 Don't care	4 Live with It	5 Like It
5 Like it	S	Del	Del	Del	Q
4 Expect it	Dis	I	I	I	R
3 Don't care	Dis	I	I	I	R
2 Live with it	Dis	I	I	I	R
1 Dislike it	Q	I	R	R	R

S = Satisfier feature
Del = Delighter feature
Dis = Dissatisfier feature
I = Indifferent response
R = Reversal (inconsistent)
Q = Questionable response

Figure 8. Using the Kano Survey Method to gather stakeholder feedback.

The kind of additional information that can be gained from the Kano analysis may be demonstrated by examining one of the survey questions. Let us look at how frequently a piece of equipment needs to be in the shop for maintenance. A user may be completely indifferent to this specific performance, or it may be the most important feature to him/her. The Kano analysis targets specifically this aspect by formulating the paired questions: "How would you feel if this equipment: Was rarely in the shop for maintenance or repairs?"; "How would you feel if this equipment: Required frequent maintenance or repairs?" If "I like it" is given a value of 5 and "I dislike it" a value of 1, then the two answers can be mapped to a 5x5 table (such as that in Figure 8).

The results of this particular example, summed over all equipment categories except man-portable power and consumer electronics, is shown in Figure 9. The maintenance repair period from the followup question is also shown: maintenance frequency appears to vary greatly from every several days to no more than twice per year (more than every 200 days). Several responders to the survey identified limited maintenance/repair time as a Satisfier feature with some showing it as a Dissatisfier: a new power system should have low maintenance frequency to be accepted, and the lower the frequency the happier the consumer will be. However, a non-negligible number of responders identified this feature as a strong Delighter. An outcome of the analysis should therefore be to follow up with this particular set of users to better identify their specific needs.

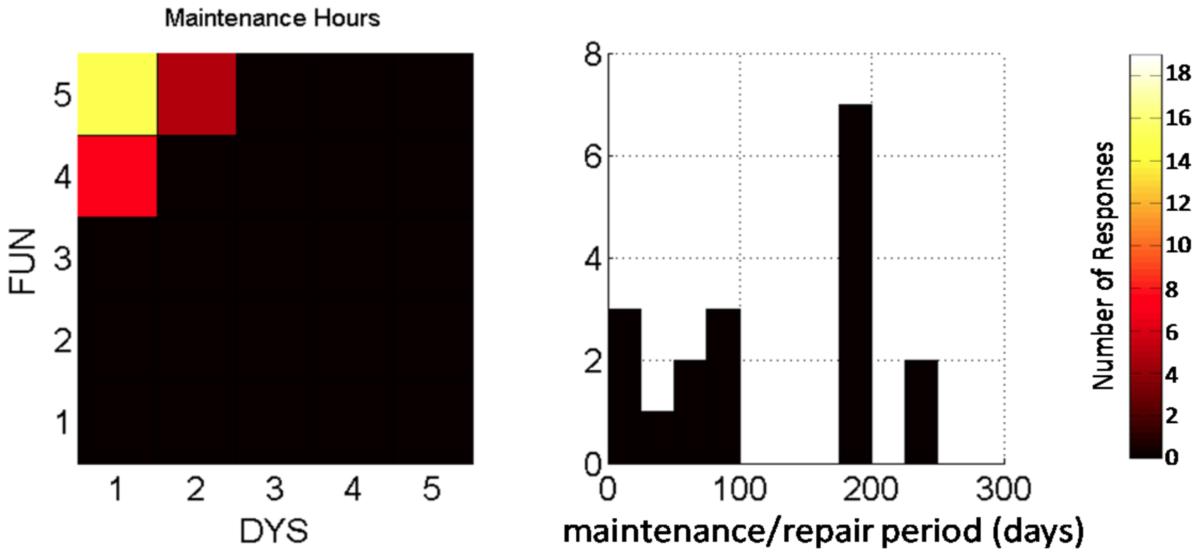


Figure 9. Kano response matrix (left) and quantification follow-up question (right) results for the question pair shown in Figure 8.

2.4 Interviews

Telephone and in-person interviews were conducted with stakeholders from every category of equipment in this study. These were especially useful in quantifying otherwise qualitative requirements. In the text of this report, information resulting from an interview is referenced and the reader can examine the references to see which companies and people were interviewed.

2.5 Other Information-Gathering Communications

Some information needed for this analysis is available in the public domain, including equipment technical specifications from company websites, technical data or market analyses published in news and journal articles, and technology innovations presented in patents. All of the relevant available information was utilized for this study and is cited in the References section.

Because of the parallels with NREL's motive equipment study, the two labs worked together in sharing information that could be relevant to each other's work. For example, a master contact list was continually updated by the labs and shared on the project website. Much of the information gathering material such as questionnaires and workshop formats was co-developed. Information that was discovered during the project that may have been useful to the NREL team was passed along to them, and vice-versa.

A third project related to this work is the development of Technology Readiness Levels (TRL) for hydrogen storage by the Pacific Northwest National Laboratory (PNNL). PNNL will be examining the TRL levels for hydrogen storage technologies that have application in motive equipment and non-motive equipment applications identified by the Sandia and NREL work. Thus, regular teleconferences were held between all three national laboratories as the work progressed.

3 Results for Non-Motive Applications

This section describes the findings for each of the five non-motive categories explored in this study:

1. Construction equipment
2. Airport ground support equipment
3. Portable power
4. Telecom backup power
5. Man-portable power and consumer electronics

A variety of specific pieces of equipment were considered for these categories. In each section below, the results of prioritizing these specific pieces in each category and the basis for doing so is described. Then the performance and current energy storage specifications of these pieces of equipment are given. These needs are combined to provide the implications for deploying a hydrogen storage system into this equipment. In other words, the current characteristics of the energy storage and use are provided; these must be met if a new hydrogen-based fuel cell technology were to meet the current specifications. Following is a discussion of the features and requirements common to all these categories.

3.1 Common Results for All Categories Revealed by Kano Methodology

While there are many differences between how and where these categories of equipment are used, the survey indicated that end users have many of the same requirements. This can be seen by examining the results of the questionnaires that were given to end users.

The questionnaires used the Kano method, as described in Section 2.3. A total of 29 questionnaires were received. The distribution of end users completing the questionnaire is given by category below:

- Construction equipment: 4
- Airport ground support equipment: 7
- Portable power: 15
- Telecom backup power: 3

The man portable power and consumer electronics category was not included in the questionnaires, as described in Section 2.1.1.

As mentioned in Section 2.3, features can be classified as follows:

- Dissatisfier (Dis): A feature that is required by the end user. The product must have this feature to be accepted.
- Satisfier (S): A feature that gives the user more satisfaction if it is present, and makes the user dissatisfied if it is absent. Satisfaction also varies linearly with the degree to which it is present or absent.

- Delighter (Del): A feature that is unexpected by the end user but provides him or her satisfaction when it is present. This may make one product more attractive than another, and there is no dissatisfaction if it is absent.
- Indifferent (Indiff): A feature that does not affect the user's satisfaction.

The questionnaires focused on what performance requirements and features the end user is looking for in a piece of equipment. In addition to the Kano responses, which are more qualitative, quantitative answers were also solicited. Table 2 shows each feature and the end user response in each category, as well as overall. The majority of features have similar responses, both qualitative and quantitative.

Figure 10 shows the combined responses (all four categories together) in graphical form. The features are loosely ranked along the horizontal axis in order from most common Dissatisfier to most common Delighter. In this way it is easier to visualize what features may be more important than others.

Considering the responses given in Table 2 and illustrated in Figure 10, conclusions about each feature are as follows:

- **Size:** The end users in each of the product categories prefer smaller volumes and lighter weights but this is not necessary. (Portable power seems to indicate that small volumes are required, but this result may have been due to a misunderstanding of the question, believing that smaller volume would imply less stored energy and less runtime. In fact, in Section 3.4 it is discussed that some portable power devices may be more tolerant to increases in volume.)
- **Operating Conditions:** The three operating condition features (extreme conditions, shock and vibration, and temperature range) were the highest-scoring Dissatisfier features. Any piece of equipment in these four equipment categories must therefore be able to withstand these tough environmental and use conditions to be accepted.
- **Fueling:** While a long runtime per full fuel tank was preferred but not required, end users felt that equipment which takes a long time to refuel may not be acceptable. In general, all pieces of equipment are expected to be refueled in 15 to 20 minutes or less. The expected runtimes per full fuel tank varied, but 10 hours was the lowest for any piece of equipment. Telecom backup equipment has the longest required run time: 72 hours.
- **Maintenance:** Of the four user categories, construction equipment users are the most lenient on maintenance requirements, while telecom backup users are the strictest. In general, all users require the system to be available when needed.
- **Personnel Training:** The responses varied, but overall end users felt that a decrease in required operator training would be an added benefit, though not required.
- **Emissions:** For either CO_2 or pollutants, all end users felt that lower emissions would be a benefit, and would prefer not to have high emissions, but it is not necessary.
- **Costs:** The end users do not expect low initial costs and would be extra-satisfied in this case, which indicates that they may be flexible on initial cost. For fuel and O&M costs end users would be happy if costs are low and unhappy if they are high. They, in general, have no expectations of scrap or residual value to the equipment when they are finished with it, but would be unhappy if they had to pay for equipment disposal.

Table 2. Summary of end user questionnaire responses by equipment category. For the features, “S” indicates a Satisfier, “Dis” indicates a Dissatisfier, “Del” indicates a Delighter, and “Indiff” indicates the end users were indifferent to this feature.

Category	Construction Equipment		Airport GSE		Portable Power		Telecom Backup Power	
Feature	Kano	Measure	Kano	Measure	Kano	Measure	Kano	Measure
Size								
Smaller volume	S	5-30 gal	S	25-65 gal	Dis	Up to 700 gal	S	
Lighter weight	S		S	1,000—4,000 lb	S	Up to 30,000 lb	S/Del	
Operating Conditions								
Operate in wide temperature range	Dis		S/Dis	-60 °C to +40 °C	Dis	-30 °C to +20 °C	Dis/S	-40 °C minimum
Withstand large shock and vibration	S		S		Dis		S	
Operate in extreme conditions	S/Dis		S/Dis		Dis		Dis	
Fueling								
Run longer between refuelings	S	15-60 hrs between refueling	S	10-30 hrs between refueling	S	15-40 hrs between refueling	S	60-70 hrs between refueling
Refuel quickly	S	< 20 minutes per refill	S/Dis	< 15 minutes per refill	Dis	< 20 min per refill	S/Dis	15 minutes per refill
Maintenance								
Low maintenance	S	50-250 days between maint.	S	50-175 days between maint.	S	25-250 days between main.	S/Dis	60 days between maint.
Nearly always available when needed	S	60%-100%	S/Dis	Nearly 100% availability	Dis	10% to 100%	Dis	100% availability
Long lasting storage system	Del	5-20 yr life	S/Del	5-20 yr life	S	10-20 yr life	S/Dis	> 20 yr life
Personnel Training								
Little operator training	Indiff.		S/Del	<25 hr/yr	Del/S	<20 hr/yr	S/Dis	< 15 hr/yr
Little additional service training	S/Del		S/Dis		Indiff.		S/Dis	
Emissions								
Little CO_2 emissions	Del/S		S		S		S/Dis	
Little pollutant emissions	S		S		S		S/Dis	
Costs								
Low initial cost	S/Del		S/Del		Del		S	
Low fuel cost	Del		S		S		S/Dis	
Low O&M cost	S	\$1k - \$2k per yr	S		S		S/Dis	
Scrap/residual value of storage system	Dis		S		Dis		Dis/Del	

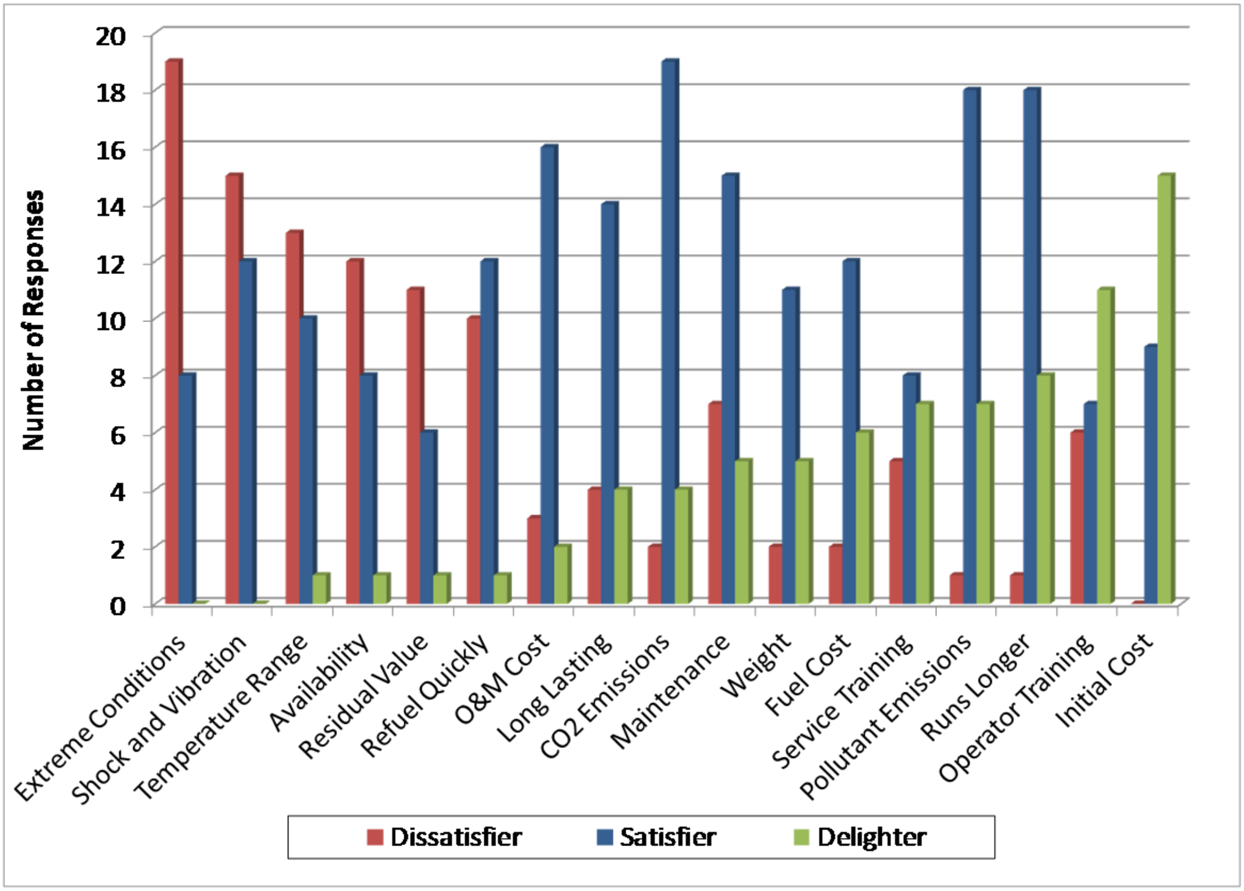


Figure 10. Graphical representation of questionnaire responses, combining data from all categories. Features (on the horizontal axis) which are predominantly Dissatisfiers (highest red bars) are towards the left, those that are mostly Satisfiers (highest blue bars) are near the middle, and those that are largely Delighters (highest green bars) are towards the right.

3.2 Construction Equipment

Construction equipment was identified as an important area for evaluation, partly in response to the positive experience Sandia has had in introducing fuel cell technology into mobile lighting. The traditional diesel-fueled mobile lights are considered general construction equipment, and it seemed likely that other pieces of general construction equipment might benefit from the attributes of fuel cell power. As a result, members of the construction equipment community (both technology providers and end users) participated in Sandia'a End User Workshop. Much broader feedback was sought from the construction equipment community than simply mobile lighting, and care was taken not to let Sandia's Fuel Cell Mobile Light experience introduce a bias towards lighting. The database captures 12 representatives from the construction equipment realm (broadly construed) and a broad range of construction equipment interests were represented.

The introductory talk on construction equipment given by Torsten Erbel of Multiquip can be summarized as follows. Erbel reviewed the types of light-duty construction equipment. Starting with portable power generators, such construction equipment includes small (1 to 180 kW) portable power generators (diesel and gasoline powered), stationary generators (both diesel and natural gas fueled), and higher-power containerized generators (500 kW to 2000 kW). Custom generators round out the portable power generators in construction equipment.

Mobile lighting is also considered "construction equipment." Typical lighting equipment used in the construction realm includes mobile light towers (diesel fueled), as well as "balloon lights," which are not mobile but rather placed at a worksite and need a source of power. Erbel also described the recent DOE- and Boeing-funded Fuel Cell Mobile Light Project that Multiquip and Sandia are collaborating on.

In the area of typical light-duty construction equipment, Erbel gave brief descriptions of "compaction equipment" (rammers, plate compactors and rollers), "dewatering equipment," which includes electric submersible pumps, centrifugal pumps, trash pumps and diaphragm pumps as well as "mixers" (concrete mixers, mortar mixers, handheld and stationary mixers). Finally, Erbel described for the workshop attendees the type of equipment used for "concrete and masonry work," which includes concrete vibrators, screeds, power trowels, saws, rebar equipment, power buggies, core drill machines, floor preparation equipment, and concrete/masonry pumps.

Overall, a very good description was given for some (but not all) of the many types of construction equipment that could be assessed to identify the top three equipment items that would best benefit by introducing a clean non-polluting energy technology. This landscape of possibilities was considered in the breakout session that followed.

3.2.1 Summary of Stakeholder Feedback

The construction equipment break out session was facilitated by Joe Pratt of Sandia. From the construction equipment breakout sessions, the top three pieces of equipment were selected by the attendees:

1. **Lighting:** Light towers, portable message boards, remote message boards, and arrow signs. These are ubiquitous items, currently diesel-powered or powered with solar/battery combinations.
2. **Scissor lifts:** Also known as aerial lift equipment, these devices extend vertically to provide elevated work platforms. The current scissor lift technology is battery-based.
3. **Air compressors:** Noisy, much room for improvement of this technology.

A key lesson from this breakout session is that construction equipment is very cost sensitive. Lifecycle costs, even project-cycle costs are considered. Furthermore, construction equipment must be very durable. The attendees indicated that because fuel cells "load follow" and only generate power to meet the load demanded, this "smart technology" aspect may be a way for a fuel cell system to gain acceptance faster.

In the first group of equipment, mobile lighting was ranked the highest by the construction equipment breakout session attendees. This piece of equipment is typical of a ~5 kW power need in the construction industry. Other items (such as portable message boards, remote message boards, arrow signs) were also listed from the workshop attendees as important for possible fuel cell application. However, feedback subsequently received from the California Department of Transportation (Caltrans) indicated that these portable message and signage items are often low-power (~200 W) solar-powered construction items. This fact was confirmed by information provided by the Federal Highway Administration. Because of the low light levels associated with many roadway signs, especially those using LEDs[2], the current strategy is to power this signage with solar energy. In other words, the low energy density required by this type of signage was a very good match to the low energy density collection of solar panels. This situation suggested these low-power signage applications were not a good fit for fuel cells and were not considered further, so the focus shifted instead to providing more detailed information about the diesel-powered mobile light systems.

It is perhaps a good indication of the breadth of the considerations that two of the three items (scissor lifts and air compressors) came not from the extensive list of construction equipment highlighted in the introductory talk by Erbel; while the Erbel talk set the stage for the construction equipment breakout session, the discussions themselves went beyond the early introduction, which is a sign of robust discussion.

The stakeholder feedback on construction equipment is summarized in Table 3.

3.2.2 Analysis of Current Market Status and Identification of High-Potential Markets

The Multiquip model LT 12D mobile light tower is used primarily in general construction applications and security lighting. Approximately 20,000 LT 12D units are sold each year in the United States. The total light tower market in the U.S. is estimated to be ~100,000 units.

Scissor lifts are primarily used in general construction applications. The U.S. Census Bureau estimated the number of units sold in the U.S. to be 96,742 (2010 data)[3], with an additional 36,000 units being imported and exported (2011 data)[4]. The battery-operated units satisfy the Tier 3 specifications for emissions.

For portable air compressors, the U.S. Census Bureau estimated the number of units sold in the U.S. to be 1,846,581 (2010 data)[5]. The biggest technical limitations of the current technology are the noise associated with the units and the tightening limits on diesel emissions placed by EPA regulations.

Table 3. Summary of stakeholder feedback for construction equipment.

Category Feature	Kano Indicator	Written Survey Preferences	Workshop and Interview Feedback
General			The new equipment's performance and specifications should be at the same level or better than the current equipment's.
Size			
Smaller volume	Satisfier	5-30 gal	
Lighter weight	Satisfier		
Operating Conditions			Most equipment is used in all conditions and all weather. Exception: Scissor lifts (indoor, hard, flat surfaces).
Operate in wide temperature range	Dissatisfier		-20 to +140 °F
Withstand large shock and vibration	Satisfier		Ability to shut down when impacted or in an earthquake.
Operate in extreme conditions	Satisfier/ Dissatisfier		Outdoor: Rain, snow, hail, salt water, dust, sand storms, mud, bullets, paintball, vandalism Indoor: quiet, no emission, no vibration, no O_2 depletion.
Fueling			
Run longer between refueling	Satisfier	15-60 hrs between refueling	Good if it can shut itself off when not needed, have load sensitivity.
Refuel quickly	Satisfier	< 20 minutes per refill	Do not like the requirement of the scissor lift to recharge every night—sometimes forget.
Maintenance			
Low maintenance	Satisfier	50-250 days between maint.	
Nearly always available when needed	Satisfier	60%-100%	Able to start even if it has been shut down for a long time.
Long lasting storage system	Delighter	5-20 yr life	
Personnel Training			Often used by low-skilled workers with minimal education. Amount of training depends on piece of equipment. Like familiarity of current equipment.
Little operator training	Indifferent		
Little additional service training	Satisfier/ Delighter		
Emissions			
Little CO_2 emissions	Dellighter /Satisfier		Receiving carbon credits to offset added cost would be a benefit.
Little pollutant emissions	Satisfier		
Costs			If increased cost, must be a specification for the project to force implementation.
Low initial cost	Satisfier/ Delighter		Lifecycle or project costs are considered more than just capital costs.
Low fuel cost	Delighter		
Low O&M cost	Satisfier	$1k - $2k per yr	
Scrap/residual value of storage system	Dissatisfier		

3.2.3 Discussion of Technical Needs for Storage

3.2.3.1 *Lighting*

A prototypical example of the mobile light, the Model LT 12D Light Tower from Multiquip Inc., is shown in Figure 11. Such lighting is used in a variety of applications, including general construction, event lighting and emergency response activities.

Figure 11. Diesel mobile light system (Multiquip LT 12D).

Ideally, a hydrogen-based technology that substitutes for the current diesel fuel mobile light must be able to meet or exceed the current operational aspects of the LT 12D in Figure 11**Error! Reference source not found.**. Discussions with Multiquip[6] revealed the following characteristics and requirements of the LT 12D:

1. Weight of LT 12D = 1550 lbs (unit weight must be kept below 3200 lbs if the unit is to be towed behind conventional pick-up trucks).
2. Volume of the LT12D cabinet that houses the power generation: length 56 in, width 33 in, height 30.5 in = 5634 in^3 = 924 L.
3. Estimate for power generation equipment weight: 750 lbs including fuel.
4. Diesel fuel tank size: 30 gallons diesel = 113.5 L.
5. Volume of fuel storage system: 32.7 gallons = 123.7 L.
6. Weight of fuel storage system (with fuel): 230 lbs = 104 kg.
7. Volume of diesel generator system: 5200 in^3 = 85.3 L.
8. Weight of diesel generator system: 187 lbs = 85 kg.
9. Operating temperature range: -15 °F to 120 °F.
10. Shock/vibration: These units are not specified for shock or vibration.
11. The diesel powered LT 12D can only be used outdoors. Indoor use is forbidden due to emissions.
12. The LT 12D system is based on a 6 kW diesel generator. Four kilowatts is used for lighting, 2 kW for auxiliary power. At three-quarter total load, the system will run for 64 hours on 30 gallons of diesel fuel.

13. There are no specifications concerning acceptable refueling time, probably because refueling with diesel fuel is so facile.

14. The most desired refueling method is to refuel the LT 12D unit in place.

15. Power rating for the diesel generator is 6 kW. The generator provides both 120 VAC and 240 VAC. Current ratings: 50 amps at 120 VAC, 25 amps at 240 VAC.

16. Stored energy (LHV) corresponding to 30 gallons of diesel fuel: 30 gallons x (128, 450 BTU/gal) = 3,853,500 BTU = 4066 MJ[7].

17. Current maintenance costs for the LT 12D[6]: Assuming it is used for 250 days a year, for eight hours per day, the total is 2000 hours of use. The estimated maintenance cost for 2000 hours of use is $4500 total. $1400 of the $4500 is labor cost. Maintenance items include an oil filter, fuel filter, fuel water separator filter, hoses, and clamps.

18. This unit meets or exceeds Tier 3 requirements on diesel engines, which is an EPA requirement.[8] This particular unit is within certification until the year 2014. By 2017, all diesel engines must be Tier 4.

19. Lifetime (cycle life): the engine itself is rated for a 10,000 hour lifetime with normal maintenance. After 10,000 hours an engine overhaul is recommended. However, anecdotal evidence suggests that the engines can run 17,000 hours without overhaul. Typically the mobile light units are held for three years and then sold or scrapped.

20. Purchase price: ~$13,000.

3.2.3.2 *Scissor Lifts*

Scissor lifts, sometimes called Aerial Work Platforms, are used extensively in industry. A picture of a mid-performance scissor lift is shown in Figure 12. A representative manufacturer for this unit is Genie Inc. The construction market is the largest market that uses such lifts.[9]

Figure 12. Photograph of the Genie GS-3232 scissor lift.

Any hydrogen-based technology that substitutes for the current battery powered scissor lift technology must typically meet or exceed the current operational aspects of the GS-3232 in this particular example. The GS-3232 was chosen as a “mid-range” example of scissor lift with regard to size and operational capabilities. Discussions with Genie[9] and their web-based product literature[10] reveal the following characteristics of the GS-3232:

1. Weight of GS-3232: 5185 lbs.
2. Dimensions of lower power system volume: 32 in W x 73 in L x 24 in H.
3. Power System: 4 batteries. Each battery 6V, 225 Ah. Typical battery would be the Trojan T-105, Wt. = 62 lbs, battery dimensions 10.375 in L x 7.125 in W x 10.875 in H, stored energy per battery = 1.35 kW-h, 6V, 225 A-hr (20 hour rate). Four batteries in the system, 0.5 typical depth of discharge, assume room temperature 77 °F operations.
4. Rated output power: 600 W (average), 1,800 W (maximum).
5. Total volume of 4 batteries: 3216 in^3, = 52.7 L.
6. Total weight of 4 batteries: 248 lbs = 112.3 kg.
7. Stored energy: 19.44 MJ.
8. Operating temperature range: Not specified for this equipment.
9. Shock/vibration: These units are not specified for shock or vibration.
10. Battery powered system can be used indoors or outdoors.
11. The unit is specified to have an 8 hour recharge time, use time ~ 8 hour shift.
12. Current maintenance costs for GS 3232: Not available.
13. Lifetime (cycle life): Not available.
14. Purchase price: purchase ~ $23,000.[11]

3.2.3.3 *Air Compressors*

Air compressors, used extensively in industrial processes, are provided in the form of both stationary air compressors and portable air compressors. The feedback received from the construction equipment breakout session specifically identified portable air compressors, so those are considered further.

In discussions with Peterson Power of San Leandro, CA,[12] a distributor of air compression equipment, a typical and popular portable air compressor was represented by the Sullair 375 H AF air compressor, shown in Figure 13 below. The Sullair 375H AF is a unit that can provide 375 cubic feet per minute (cfm) flow at a pressure of 150 psi. The unit produces high-quality air suitable for instrumentation, process equipment, and other contamination-sensitive applications. Uses on construction sites include clean compressed air for media blasting and painting/protective coating applications, as well as compressed air for jack hammers and other pneumatic tools. As far as performance specifications, it is designed to be a mid-range piece of equipment, so it was chosen as an example here to represent an average capability.

Figure 13. Diesel powered portable air compressor
(Sullair 375H AF) at Peterson Power, San Leandro, CA.

Any hydrogen-based technology that substitutes for the current diesel fuel air compressor technology must be able to meet or exceed the current operational aspects of the Sullair 375H AF in this example. Discussions with Peterson Power revealed the following characteristics of the Sullair 375H AF operation (the trailer-mounted version, identified as 375H AF DPQ (diesel portable, quiet)):

1. Working weight (with diesel fuel) of Sullair 375H AF DPQ: 4420 lbs.
2. Weight of fuel storage system (with fuel): ~440 lbs = 199 kg.
3. Weight of diesel generator system: 793 lbs = 359 kg.
4. Volume of the 375H AF DPQ cabinet that houses the equipment: length 98.8in, width 77.2 in, height 74in = 564,425 cubic inches = 9249 L.
5. Diesel fuel tank size: 56 gallons.
6. Operating temperature range (with cold weather package): -20 °F to 120 °F.
7. Shock/vibration: These units are not specified for shock or vibration.
8. The diesel powered 375H AF DPQ can only be used outdoors. Indoor use requires conduit provision for venting exhaust outside a building.
9. The 375H AF DPQ system is based on a single 97 kW diesel generator. At full load, the system will run for 8.7 hours on 56 gallons of diesel fuel.
10. There are no specifications concerning acceptable refueling time, probably because refueling with diesel fuel is so facile.
11. The most desired refueling method is to refuel the 375H AF unit in place using mobile diesel refueling equipment.

12. Stored energy (LHV) corresponding to 56 gallons of diesel fuel: 7731 MJ.
13. Volume of fuel storage system: 61 gallons = 230.0 L.
14. Volume of Diesel generator system: 18,720 in^3 = 306 L.
15. Current maintenance costs for the 375H AF: The portable air compressors are typically run constantly (for example in their use in refineries), and at least 10 to 12 hours per day, for a minimal typical run time of 4380 hours per year. Maintenance items are as follows: Every 250 hours, change compressor fluid filter, change the engine fuel filter, change the air filter elements, and change the engine oil and oil filters. After 1500 hours, the compressor fluid needs changing, and the engine coolant and axle bearings need lubrication.
16. Noise level: 76 dBa at 23 ft.
17. This unit meets or exceeds Tier 3 requirements on diesel engines.
18. Purchase price: ~$31,000 new.

3.2.4 Implications for Hydrogen Storage Technology

The current energy storage requirements for mobile lighting, scissor lifts, and air compressors indicated above give the current energy storage demands and power generation performance with regard to total energy and energy densities. For battery powered scissor lifts, these numbers also reflect the requirements for a hydrogen-based technology—for example, the combined hydrogen storage + fuel cell system. However, for the diesel-powered equipment mobile lighting and air compressors, the quantity of hydrogen stored must also consider the efficiency of the energy conversion device. For example, the thermal efficiency of the 5 kW PEM fuel cell currently being used for fuel cell mobile lighting is 47%. The diesel generators currently being used for diesel-based lighting have a thermal efficiency of ~25%. As a result, for a given required energy output, the fuel cell requires approximately half the required stored energy, which reduces the quantity of hydrogen needing to be stored.

However, the actual amount of hydrogen one might want to store on a fuel cell-based piece of equipment is *a priori* unclear and would need to be decided with consideration of a number of factors. If one is using a storage method with poor volumetric efficiency such as high-pressure tanks, then one wants to store the minimum amount of hydrogen that one can “get away with” so as not to exceed a perceived volumetric budget. On the other hand, if refueling the system is very cumbersome and inconvenient, one may want to minimize the number of refueling events, suggesting storing more hydrogen on the system. In addition, the overall efficiency of the piece of equipment needs to be considered. For example, if there are choices to be made for the weight of a scissor lift platform or the efficiency of lights used for mobile lighting, these choices affect the desired amount of hydrogen to be stored. This is only true if the “downstream” efficiencies are actually part of the piece of equipment. The downstream efficiencies do not really affect the specifications for a portable power generator, for example.

The ultimate requirements on the volumetric and gravimetric energy densities of the combined H_2 storage + fuel cell system for a piece of non-motive fuel cell equipment ultimately depends on resolving these various considerations, which is beyond the scope of this study. Future “gap” analyses of hydrogen storage that seek to quantify future improvements in hydrogen storage performance needed to enable non-motive fuel cell equipment will have to delve into the overall system considerations. However, the increased efficiency of the fuel cell certainly lowers the requirements on the stored energy density for hydrogen technology.

3.2.5 Summary Table of Technical Needs

Some of the relevant energy storage needs for these technologies are summarized below. Table 4 summarizes the energy storage requirements for each piece of equipment. It is the result of stakeholder feedback on what they require from their equipment (from the workshop, interviews, written questionnaires, and Kano analysis). In several cases, the feedback was unanimous in stating that the requirements for a hydrogen fuel-cell powered version of a piece of equipment are to match the specifications of the existing equipment, so in those instances the numbers used for the requirements are generated largely from the specifications (shown for reference in Table 5.)

Where the stakeholder feedback indicated differences between what they would like to see in fuel cell versions and the current equipment, the stakeholders' numbers are used to generate the requirements shown in the table. The stakeholder feedback is therefore the driver for developing the requirements and it was utilized without judgment. The only modifications to this feedback occurred when the feedback was ambiguous or conflicting, and in those instances investigators used their own knowledge to clarify and decide upon the most appropriate requirement.

Table 4. Energy storage requirements for a hydrogen fuel cell powered version of each piece of construction equipment studied.

Application	Mobile Light	Scissor Lift	Air Compressor
Requirements			
Rated Output Power	6 kW	600 W (average), 1800 W maximum	97 kW
Run Duration Per Fill/Charge	66 hr @ 75% power	8 hr	8.7 hr @ full load
Restrictions			
Energy Storage System Volume[1]	123.7 L	52.7 L	230.0 L
Energy Storage System Weight[1]	104 kg	112.3 kg	199 kg
Refuel/ Recharge Time	10 min	8 hr	15 min
Operating Conditions - Temperature	-25 °C to 50 °C	-20 °C to 50 °C	-30 °C to 50 °C
Operating Conditions - Weather[2]	Extreme	Primarily indoor	Extreme
Noise level[3]	< 73 dB	Not Available	< 76 dB
Emissions[4]	Meets or exceeds EPA requirements. Indoor use desirable	Acceptable for indoor use	Meets or exceeds EPA requirements

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware. Restrictions on size assume the storage of enough energy to meet the rated output power for the required run duration; if more energy is stored these restrictions may be relaxed.
2. Extreme weather conditions include rain, snow, hail, ice, blowing sand, blowing water, dirt, mud, dust, high elevation, salt air, and humidity extremes.
3. All noise levels when operating at rated load, at a distance of 5 m unless stated otherwise.
4. EPA requirements: *Phase 3* for gasoline engine replacement (http://www.epa.gov/otaq/equip-ld.htm), *Tier 3* for diesel engine replacement (http://www.epa.gov/nonroad-diesel/regulations.htm).

Table 5. Summary of technical specifications for the construction equipment.

Specification	Mobile Light	Scissor Lift	Air Compressor
Manufacturer	Multiquip	Genie	Sullair
Model	LT 12D	GS-3232	375H AF
Rated Output Power	6 kW	600 W (average), 1800 W maximum	97 kW
Run Duration Per Fill/Charge	66 hr @ 75% power	8 hr	8.7 hr @ full load
Output Power Type	Lighting, 120 VAC (50 A), 240 VAC (25 A)	DC	Mechanical
Overall Dimensions - L x W x H	56" x 33" x 30.5" cabinet only, no trailer	8' x 2'8" x 7'	98.8" x 77.2" x 74" cabinet only, no trailer
Overall Volume	5,634 in3 (924 L)	149 ft3	564,425 in3 (9,249 L)
Overall Dry (no fuel) Weight	1,550 lb	5,185 lb	4,030 lb
Fuel/Battery Type	Diesel	Lead-Acid	Diesel
Fuel Tank or Charge Capacity	30 gal (113.5 L)	4 x 225 A-hr	56 gal
Stored Energy (kW-hr)	4,066 MJ	9.7 MJ (assuming 0.5 depth of discharge)	7731 MJ
Energy Storage System Volume	123.7 L	3,216 in3 (52.7 L)	230.0 L
Energy Storage System Volumetric Energy Density	32.9 MJ/L	0.18 MJ/L	33.6 MJ/L
Energy Storage System Weight	230 lb (104 kg) with fuel	248 lb (112.3 kg)	440 lb (199 kg)
Energy Storage System Gravimetric Energy Density	39.0 MJ/kg	0.086 MJ/kg	38.8 MJ/kg
Engine/FC Model	Lombardini LDW 1003	Not Applicable	Caterpillar C4.4
Power System (Engine/FC) Weight	187 lb (85 kg)	Not Applicable	793 lb (359 kg)
Power System (Engine/FC) Volume	5,200 in3 (85 L)	Not Applicable	18,720 in3 (306 L)
Combined Energy + Power System Volume	209 L	3,216 in3 (52.7 L)	536 L
Combined Energy + Power System Volumetric Energy Density	19.4 MJ/L	0.18 MJ/L	14.4 MJ/L
Combined Energy + Power System Weight	189 kg	248 lb (112.3 kg)	558 kg
Combined Energy + Power System Gravimetric Energy Density	21.5 MJ/kg	0.086 MJ/kg	13.8 MJ/kg
Refuel/Recharge Time	10 min	8 hr	15 min
Fuel Consumption	0.47 gal/hr @ 75% load	Not Applicable	6.4 gal/hr @ full load
Emissions	Outdoor use only. Meets or exceeds EPA Tier 3 requirements.	None	Meets or exceeds EPA Tier 3 requirements
Operating Temperature Range	-15 F to 120 F	0 F to 120 F	-20 F to 120 F
Noise level	73 dB @ 23 ft	Not Available	76 dB at 23 feet
Overall Cost	$13,000	$23,000	$31,000

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
2. Power system refers to the engine that generates mechanical power, the generator to convert mechanical to electrical power, and associated hardware.

3.3 Aviation Ground Support Equipment

The feedback gained from the aviation community consisted of three components. The first was the presentation at Sandia's End User Workshop from Roger Hooson, Senior Planner for Landside Operations at the San Francisco International Airport (SFO).The second was the Aviation GSE breakout session facilitated by Lennie Klebanoff of Sandia. The third was telephone and in-person interviews with users and manufacturers of airport GSE equipment.

The talk by Hooson summarized the type of equipment typically on an airfield. For a major international airport such as SFO, the numbers and type of equipment include over 1,200 off-road vehicles, mainly airfield. These vehicles/equipment include ~ 400 baggage tractors, ~200 belt loaders, 100 aircraft pushback tractors, 90 maintenance/cabin lifts, 80 ground power units, 50 container loaders, 30 lavatory trucks, 150 forklifts, ~30 mobile light towers, ~50 boom lifts, as well as a number of specialized diesel-fueled lighting systems called light crosses (for marking a runway out of service) and light ropes. A picture of a belt loader is shown in Figure 14.

Figure 14. Example of a luggage belt loader in use at SFO.

Most of these GSE equipment items can be classified as "motive" pieces of equipment, so they fall outside the scope of this study. Hooson pointed out that all operators of equipment on the airfield, whether owned by the airline tenants or the airport facility itself, have a strong emphasis and concern about cost, and an "absolute" requirement and emphasis on reliability. Hooson mentioned that there are existing electric (battery) based pieces of GSE, and that these raise concerns about battery replacement and vehicles being stranded on the airfield due to battery discharge. This issue was specifically mentioned with regard to "boom lifts." For a clean energy technology such as that based on hydrogen fuel cells, there could be an opportunity to retrofit or "re-power" existing equipment or substitute new equipment. It was mentioned that use of propane on the airfield is discouraged due to CARB LSI rules. The airport tries to use low-emission vehicles whenever possible.

Ongoing hydrogen activity is occurring at SFO. SFO is currently constructing $5 M-plus hydrogen fueling complex using CARB, CEC, BAAQMD, San Mateo C/CAG, private sector, and airport funds. The facility will be located landside near the 101 freeway but close to airfield gates. Completion is targeted for June of 2012. Major automakers, a transit provider, and courtesy shuttle operators will recharge fuel cell and hybrid vehicles at the site. A fuel cell-based mobile lighting system will eventually use hydrogen from the facility.

3.3.1 Summary of Stakeholder Feedback

The breakout session on GSE consisted of representatives with mixed backgrounds that included hydrogen storage experts and representatives from SFO, Travis Air Force Base, Southwest Airlines, and Boeing. This group discussed the non-motive GSE that could be powered by a hydrogen fuel cell; the discussion is summarized below.

1. 2 to 10 kW power generators, the power basis for light towers, light crosses, light ropes, and hand tools. These were identified as important applications because there are so many of them. These are typically Honda gasoline generators.
2. 90 to 120 kW ground power units (GPUs) based on diesel generators and turbine systems for aircraft electrical support and engine start.
3. 400,000 BTU heater carts, used to heat the interiors of aircraft during maintenance. It is important to heat the aircraft during maintenance periods because one cannot allow condensation on the avionics during maintenance. These heater carts are important for both civilian and military aviation GSE purposes.
4. Electric boom lifts used for aircraft maintenance.
5. Walk-behind electric belt loaders for loading luggage.
6. 20-ton portable air conditioning units for cooling aircraft during maintenance.

Through further discussion, the group decided to focus on two pieces of equipment. First, it was decided that the small portable generators would be covered elsewhere (see Section 3.4). From the remaining equipment types, ground power units (GPUs) were chosen as the first application and heater carts as the next to focus on. Both of these pieces of equipment are needed because the number of aircraft being serviced at any given time on the tarmac far outnumbers available gates at airports. A great deal of servicing is therefore performed in the absence of stationary infrastructure power.

The stakeholder feedback on airport ground support equipment is summarized in Table 6.

3.3.2 Analysis of Current Market Status and Identification of High-Potential Markets

Two key pieces of knowledge gained from the Aviation GSE breakout session were that such equipment is very cost sensitive, and end users have little desire to pay extra for fuel cell versions. This group also stated that although the fuel cell life cycle savings over diesel equipment carries weight, that argument has a time horizon of five years or less.

Table 6. Summary of stakeholder feedback for airport ground support equipment.

Category Feature	Kano Indicator	Written Survey Preferences	Workshop and Interview Feedback
Size			
Smaller volume	Satisfier	25-65 gal	
Lighter weight	Satisfier	1,000—4,000 lb	
Operating Conditions			
Operate in wide temperature range	Satisfier/ Dissatisfier	-60 °C to +40 °C	-40 to 150 °F (military), -10 to +125 °F, (civilian)
Withstand large shock and vibration	Satisfier		
Operate in extreme conditions	Satisfier/ Dissatisfier		Salty air, blowing rain and ocean water, snow, cold, heat, stored unprotected outside.
Fueling			Currently, some terminals have limited capacity to charge electric equipment. Ability to run independent of the terminal's electrical supply is a benefit.
Run longer between refueling	Satisfier	10-30 hrs between refueling	At cold airports, GSE will be run 100% of the time so it does not freeze.
Refuel quickly	Satisfier/ Dissatisfier	< 15 minutes per refill	
Maintenance			
Low maintenance	Satisfier	50-175 days between maint.	
Nearly always available when needed	Satisfier/ Dissatisfier	Nearly 100% availability	May be used 24/7
Long lasting storage system	Satisfier/ Delighter	5-20 yr life	
Personnel Training			Used by service personnel (civilian) and GI's (military)
Little operator training	Satisfier/ Delighter	<25 hr/yr	Keep simple, similar as possible to existing equipment. Not too advanced, which requires trained (expensive) operators.
Little additional service training	Satisfier/ Dissatisfier		Best if can be maintained by a conventional mechanic—without a laptop, in the rain, etc.
Emissions			
Little CO_2 emissions	Satisfier		
Little pollutant emissions	Satisfier		
Costs			
Low initial cost	Satisfier/ Delighter		Lifecycle cost considered somewhat, with 5 yr or less payback
Low fuel cost	Satisfier		
Low O&M cost	Satisfier		
Scrap/residual value of storage system	Satisfier		

GPUs were considered the top piece of non-motive GSE for fuel cell replacement. Similar to the towable generators discussed in Section 3.4.3.2, these units are sold primarily with a power output of 90 to 120 kVA. One primary difference between GPUs and towable generators is the power electronics. These units are used to provide power to aircraft, which require 400 Hz, 115 or 200 VAC power. A second difference is that GPUs are typically integrated with a trailer that is made to be towed by airport handling equipment. Otherwise, the size and weight including the trailer are similar.

Market data were unavailable for GPUs, so figures for annual sales and U.S. inventory are not reported here. Generally speaking, these units are likely to be produced and sold in much smaller quantities than portable generators simply due to their specialized purpose. However, a staff member at Menzies Aviation indicated that one hundred to several hundreds of these units might be in use at each major U.S. airport.[13] That would indicate that there are many thousands of GPUs in operation in the US.

3.3.3 Discussion of Technical Needs for Storage

3.3.3.1 *Ground Power Units (GPUs)*

A picture of a typical GPU is shown in Figure 15 below. Discussion with Menzies personnel revealed that these units can be used up to 15 hours per day. However, they would be typically refueled during that time, and an 8-hour run time would be sufficient. Refueling at point of use is desirable over a central refueling facility since large airports can take a significant amount of time to traverse. It would be possible to tolerate larger and heavier GPUs based on alternative energy. The restriction on size would only be that it has to be maneuvered around aircraft. Weight is less of an issue since the tow vehicles can handle significantly more than the current units. Capital cost is probably the most critical parameter. This industry is unwilling to pay more for fuel cell technology than current technology unless mandated or if a cost of ownership model can show a short-term (within a few years) benefit.

Figure 15. TUG GP400-120 120 kVA ground power unit.

3.3.3.2 *Portable Heating Units*

The second piece of GSE that was identified through the workshop was portable heating units. These units are used to heat aircraft while on the ground when heat is not available from the engines. Portable heaters can be used for 8 to 14 hours at a time to keep aircraft warm in cold environments. The units almost universally provide 400,000 BTU/hr of heated air while operating. This heat is provided by burning diesel, kerosene, or jet fuel. A small diesel engine is used to power a fan which then produces air flow at 1500 cfm. The heaters work in temperatures as low as -54 °C and produce air at 65 °C to 135 °C.

Research and analysis on portable heating units following the Sandia workshop suggests that a fuel cell replacement may not be feasible for an aircraft portable heater because the primary output of these units is heat rather than electricity. It would make little sense to replace the small diesel engine that operates the fan with a fuel cell that requires hydrogen storage, when the unit still requires a 400,000 BTU/hr burner that is fed by a liquid hydrocarbon fuel. A catalytic hydrogen burner could conceivably be designed such that the system would run entirely on hydrogen, but that is outside the scope of the current study. Thus, detailed analysis of this GSE was determined to be unnecessary and it is not considered further.

Dipping deeper into the GSE Breakout session recommendations, the point was made that a typical civilian and military airport uses a lot of mobile lighting, including mobile light towers, light crosses, and light ropes. Light crosses and light ropes are shown in Figure 16.

Figure 16. Pictures of an aviation light cross (left), and light ropes with a portable generator (right) in use at SFO.

However, mobile lighting was partially considered in the construction equipment category via mobile light towers, and thus would be redundant here. In addition, although these are important pieces of aviation GSE, light crosses and light ropes are so specialized to the aviation industry that their market is severely limited. Therefore, the diesel power GSE lighting in Figure 16 was not considered further.

Equipment staff at SFO expressed particular concern about the performance of their existing electric boom lifts. Approximately 50 boom lifts of the type shown in Figure 17 are currently in use at SFO. Discussions with SFO staff indicate that there are problems associated with the boom lift units running out of charge on the runway and needing to be towed back into the equipment shop. Although the boom lift is "self propelled" in a sense, and could be construed as "motive equipment," its primary purpose is vertical lifting, and as such it is considered "non-motive" equipment for the purposes of this analysis.

Figure 17. Photograph of a boom lift being used at SFO.

3.3.4 Implications for Hydrogen Storage Technology

Based on the TUG GPU unit shown in Figure 15, the following energy storage density and power output are specified for this piece of equipment. In other words, if a fuel cell based unit were to meet the specifications for the current diesel technology, the following would be required by a fuel cell unit:

1. Total weight (including fuel): 6263 lbs (2841 kg).
2. Total volume = 711,942 cubic inches: 11,667 L.
3. Energy storage system weight: 381 kg.
4. Energy storage system volume: 458 L.
5. Stored energy: 14,932 MJ.
6. Volumetric energy density: 1.28 MJ/L.
7. Gravimetric energy density: 5.26 MJ/kg.
8. Volumetric energy density of storage: 32.6 MJ/L.
9. Gravimetric energy density of storage: 39 MJ/kg.
10. Output power: 96 kW.
11. Duration: 10 hours at 96 kW.
12. Required operating temperature range: -40 °F to 120 °F.
13. Cost: $57,867.

For the boom lift of Figure 17, which is typical of the JLG 450 Series, the electric power system can be characterized as follows:

1. 8 batteries. Each battery 6V, 370 Ah (20 hour rate). Typical battery would be the Trojan L16E-AC, Wt. = 100 lbs, battery dimensions 12.25 in L x 7.0in W x 16.375 in H, stored energy per battery =

2.22 kW-h. Eight batteries in the system. 0.5 typical depth of discharge (DOD). Assume room temperature 77 °F operation.

2. Total volume of 8 batteries: 11,233 in^3 = 184 L.
3. Total weight of 8 batteries: 800 lbs = 364 kg.
4. Stored energy, assuming 50% depth of discharge: 31.96 MJ.
5. Volumetric energy density of storage: 31.96MJ/184L = 0.17 MJ/L.
6. Gravimetric energy density of storage: 31.96MJ/364kg = 0.088 MJ/kg.
7. Power rating: 37 kW maximum (power rating for battery-powered boom lift not available, diesel powered boom lift has a 37 kW diesel engine), 6.7 kW average (assuming 8 hr. shift and 50% DOD).

The electric energy storage of these larger capacity batteries is very similar to the battery system on the scissor lift technology covered in the construction equipment category, so the requirements for the boom lift GSE equipment are not described further. The energy storage needs, while larger in an overall sense, have the same density requirements as the scissor lift technology in the construction equipment section. For the GSE equipment category, only the ground GPUs are discussed further.

3.3.5 Summary Table of Technical Needs

Table 7 summarizes the energy storage requirements for a typical aviation GSE ground power unit. It is the result of stakeholder feedback on what they require from their equipment (from workshops, interviews, written questionnaires, and Kano analysis). In several cases, the feedback was unanimous in stating that the requirements for a hydrogen fuel-cell powered version of a piece of equipment are to match the specifications of the existing equipment, so, in those instances, the numbers used for the requirements are generated largely from the specifications (shown for reference in Table 8). In cases where the stakeholder feedback indicated differences between what they would like to see in fuel cell versions and the current equipment, the stakeholders' numbers are used to generate the requirements shown in the table. The stakeholder feedback is therefore the driver for developing the requirements and it was utilized without judgment. The only modifications to this feedback occurred when it was ambiguous or conflicting, and in those instances investigators used their own knowledge to clarify and decide the most appropriate requirement.

While technical specifications and requirements were compiled for a heater cart application, as explained in the text (Section 3.3.3.2) it was subsequently found that this application would not be a good match for a hydrogen-powered fuel cell, so it was excluded from this summary table.

Table 7. Energy storage requirements for a hydrogen fuel cell-powered version of a typical aviation ground power unit.

Application	Ground Power Unit
Requirements	
Rated Output Power	100 kVA
Run Duration Per Fill/Charge	10 hr @ full load
Restrictions	
Energy Storage System Volume[1]	302.5 L
Energy Storage System Weight[1]	252 kg
Refuel/ Recharge Time	7.3 min
Operating Conditions - Temperature	-25 °C to 50 °C
Operating Conditions - Weather[2]	Extreme
Noise level[3]	< 85 dB
Emissions[4]	Meets or exceeds EPA requirements

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware. Restrictions on size assume the storage of enough energy to meet the rated output power for the required run duration; if more energy is stored these restrictions may be relaxed.
2. Extreme weather conditions include rain, snow, hail, ice, blowing sand, blowing water, dirt, mud, dust, high elevation, salt air, and humidity extremes.
3. All noise levels when operating at rated load, at a distance of 5 m unless stated otherwise.
4. EPA requirements: *Phase 3* for gasoline engine replacement (http://www.epa.gov/otaq/equip-ld.htm), *Tier 3* for diesel engine replacement (http://www.epa.gov/nonroad-diesel/regulations.htm).

3.4 Portable Power

Presentations in the morning of the Feb. 8 workshop gave descriptions of current portable power units. The presentation by Torsten Erbel of Multiquip covered portable power in the construction industry. The presentation by Russ Saunders of Saunders Electric covered portable power in the entertainment industry. Summarizing some of Saunders' points, there are extensive use of low power diesel and gasoline DC and AC portable power generators, for example the Honda EU 3000, which is a DC generator (3 kW) with 120 VAC inverter, or the Honda 5500 AC generator with 120/240 VAC operation. There are also significantly larger (150–180 kW) diesel generators that are critically important for the entertainment industry. Saunders highlighted two concerns regarding hydrogen fuel cell technology. The first was the required footprint. In many entertainment venues, space can be tight (see Figure 20) and footprint is critical. The second was the poor current availability of hydrogen fuel, at least the availability at 5,000 psi for use in high-pressure gas storage. Both the Erbel and Saunders presentations set the stage for a separate breakout session on portable power systems.

Table 8. Summary of technical specifications for aviation ground support equipment: Ground power units (GPU) and heater carts.

Specification	Ground Power Unit	Ground Power Unit	Heater Cart
Manufacturer	Houchin[14]	TUG[15]	Herman Nelson[16]
Model	C690	GP400-120	BT400-46
Rated Output Power	100 kVA	120 kVA	400,000 BTU/hr (117 kW)
Run Duration Per Fill/Charge	10 hr @ full load	10 hr @ full load	10 hr @ -65 F, 14 hr @ 0 F
Output Power Type	400 Hz 115/200 VAC	400 Hz 115/200 VAC	Heat
Overall Dimensions - L x W x H	145" x 69" x 70.5" with trailer	138" x 77" x 67" with trailer	68.5" x 57.5" x 44" with trailer
Overall Volume	11558 L	11667 L	2840 L
Overall Dry (no fuel) Weight	6,173 lb	5,500 lb	716 lb
Fuel/Battery Type	Diesel	Diesel	Diesel
Fuel Tank or Charge Capacity	275 L	110 gal	35 gal
Stored Energy (kW-hr)	2739.3	4147	1319.5
Energy Storage System Volume	302.5 L	458 L	146 L
Energy Storage System Volumetric Energy Density	9.05	9.05	9.05
Energy Storage System Weight	252 kg	381 kg	121 kg
Energy Storage System Gravimetric Energy Density	10.88	10.88	10.88
Engine/FC Model	Cummins QSB 160BHP	Cummins QSB 200 HP	Yanmar 6.5 HP Diesel
Power System (Engine/FC) Weight	371 kg	475 kg	40 kg
Power System (Engine/FC) Volume	512 L	739 L	72 L
Combined Energy + Power System Volume	814.5 L	1197 L	218 L
Combined Energy + Power System Volumetric Energy Density	3.36	3.46	6.05
Combined Energy + Power System Weight	623 kg	856 kg	161 kg
Combined Energy + Power System Gravimetric Energy Density	4.40	4.84	8.20
Refuel/Recharge Time	7.3 min	11 min	3.5 min
Fuel Consumption	7.3 gal/hr	11 gal/hr	3.5 gal/hr
Emissions	Must meet local requirements	Must meet local requirements	Must meet local requirements
Operating Temperature Range	-25 °C to 50 °C	-15 F to 120 F	-65°to 120°F
Noise level	85 dB @ 5m	68 dB @ 23 ft	Not Available
Overall Cost	Not Available	$57,867	$8,000

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
2. Power system refers to the engine that generates mechanical power, the generator to convert mechanical to electrical power, and associated hardware.

3.4.1 *Summary of Stakeholder Feedback*

The Feb. 8 workshop breakout session on portable power consisted of eleven people from mixed backgrounds that included hydrogen storage experts, portable power operators, representatives from Caltrans and the Connecticut DOT, and portable power providers to the broadcast and movie industry. This group first produced a list of the equipment types in this area that could be powered by a hydrogen fuel cell. The list is shown in Table 9.

Table 9. Categories of portable power equipment.

Description	Fuel	Power level
Small portable generators	Gasoline	2-10 kW
Large towable generators	Diesel	60, 90, 144, 180 200, 300, 500 kW
Light towers	Diesel	5 kW
Production light towers	Diesel	5-20 kW
Portable office trailers	Diesel	3-5 kW
Broadcast trailers	Diesel	15-20 kW
Motion picture mill	Diesel	144 kW

Through further discussion, the group decided that the portable power equipment could be condensed into two general categories: small (< 10 kW) portable gasoline-fueled generators and large, towable diesel generators (> 60 kW). The small gensets were considered very good candidates for fuel cell replacement for a number of reasons. First, these units are ubiquitous in the construction, consumer, and broadcast and movie arenas. They were considered to be, by far, the most common piece of portable power equipment. Also, these units have several limitations that could be improved by fuel cell technology. Small generators have short lifetimes, on the order of 2500 hours, and cost \$400–\$600/kW. They also require significant preventive maintenance that results in high operating costs (up to \$1400/yr). For some applications these generators are too loud, and while quieter models are available, they are more expensive and still not quiet enough. For broadcasts and on movie sets, the generators must be located far away and they require long cable runs. Operationally, the small gensets are typically operated intermittently and refueled by an operator with a handheld gasoline container. They are typically refueled once per day, and the units have to be turned off for refueling per safety regulations.

Large diesel generators were the second category identified. These units are also very common at construction sites and broadcast and movie sets. These gensets are most often towed on their own trailers that include diesel fuel tanks. They range in size from about 50 kW up to 500 kW. Large diesel generators also suffer from a number of issues that fuel cells could overcome. In addition to noise and maintenance issues like those of the small gasoline units, these units are difficult to operate at low load, where they continue to consume 30–40% of full-load fuel, resulting in poor fuel efficiency. This low-load operation results in incomplete combustion or ‘wet stacking,’ which fouls the exhaust system and requires additional maintenance. Emissions from the diesel units can also be a problem both for the environment and people nearby.

At the “Navigating Obstacles Associated with Utilizing Hydrogen Power as an Alternative Energy Source” workshop held at the 6th Annual Military Energy Alternatives Conference on February 24, 2011 (described in Section 2.2.3) the participants identified eight distinct applications in the military for portable power generators, including four in the 100 W to 5 kW range and four in the 5 kW to 100 kW range. Through an open feedback session, issues and features of military portable power units were self-identified (with no input from the facilitator) and the participants subsequently voted on their top three priorities. The features and number of votes were as follows:

1. Capital cost: 8
2. Safety: 6
3. Reliability: 5
4. Maintainability (ease of maintenance): 4
5. Capacity (longevity of operation between refueling/recharge): 4
6. Volume: 3
7. Weight: 3
8. Lifecycle cost: 2
9. Dormancy: 1
10. Environment: 1
11. Operations ease: 0
12. Lifetime: 0
13. Emissions: 0

This list helps to prioritize the needs of the military as they pertain to portable power generators. They are extremely sensitive to capital cost but insensitive to lifecycle costs, in part due to the way procurement and maintenance contracts are awarded separately. Safety was the most important performance feature, perhaps due to a perceived general concern about hydrogen. The participants did not perceive hydrogen as safe (one participant suggested he would treat H_2 as an explosive on a base) and want to make sure the new technology has enough protection to make it safe. It was also pointed out that different users may have very different requirements for the same piece of equipment. For example, users of a portable power generator on a base are more concerned about cost, but users of a portable power generator at a forward area are more concerned about reliability and size. Emissions did not play a role in determining acceptability for the military: just two participants brought up greenhouse gas/CO_2 emissions, and in the end nobody voted for emissions as a top-three priority.

The stakeholder feedback on portable power units is summarized in Table 10.

Table 10. Summary of stakeholder feedback for portable power units.

Category Feature	Kano Indicator	Written Survey Preferences	Workshop and Interview Feedback
Size			Must be transportable, moveable (on trailer) with 2 people.
Smaller volume	Dissatisfier	Up to 700 gal	
Lighter weight	Satisfier	Up to 30,000 lb	
Operating Conditions			Operating within public access. Noise requirements (< 65 dB) may require siting remotely with long cables.
Operate in wide temperature range	Dissatisfier	-30 °C to +20 °C	-28 to +125 °F
Withstand large shock and vibration	Dissatisfier		
Operate in extreme conditions	Dissatisfier		Up to 8,000 ft elevation, dust, rain, etc.
Fueling			
Run longer between refueling	Satisfier	15-40 hrs between refueling	May be limited to refueling once per day
Refuel quickly	Dissatisfier	< 20 min per refill	Diesel units can be refueled while operating, which is good. Diesel/gasoline spills are a frequent nuisance.
Maintenance			
Low maintenance	Satisfier	25-250 days between main.	Preventative maintenance (i.e., oil changes) often required. Parts store required.
Nearly always available when needed	Dissatisfier	10% to 100%	
Long lasting storage system	Satisfier	10-20 yr life	
Personnel Training			
Little operator training	Delighter /Satisfier	<20 hr/yr	"Plug and play" (anyone can operate)
Little additional service training	Indifferent		
Emissions			
Little CO_2 emissions	Satisfier		May be regulatory restrictions (CARB)
Little pollutant emissions	Satisfier		Some customers require "green" units.
Costs			
Low initial cost	Delighter		2 yr payback for lifecycle cost.
Low fuel cost	Satisfier		Poor fuel efficiency and fuel consumption at low load. Load following unit would be preferred.
Low O&M cost	Satisfier		Smaller units more expensive to maintain than larger ones.
Scrap/residual value of storage system	Dissatisfier		

3.4.2 Analysis on Current Market Status and Identification of High-Potential Markets

Following the workshops, further information was gathered on both small and large portable generators to gain a better understanding of the impact that fuel cell replacements could have in the context of the entire non-motive application space. Also, more detailed information was gathered such that specific requirements for a hydrogen storage system could be developed for these applications.

A market study by Frost and Sullivan[17] indicated that only 2% of light duty portable generators run on fuels other than gasoline. More than 40 U.S. suppliers of these generators were identified in a 2003 CPSC report.[18] Portable, light duty generators are often powered by 3600 rpm, air-cooled, twin cylinder lawnmower engines.[19] These high-rpm air-cooled engines have relatively short product lives, providing about 500 hours of use. Three firms dominate this market—Briggs and Stratton (27%), Coleman (18%), and Honda (13%)—producing about 60% of generator sales revenues in 2002.[17] According to the Frost and Sullivan study, in 2002, average retail prices of light-duty portable units were about $723 with a range of about $500 to $1500. This study also published an estimate of the number of units sold in the U.S. from 1999 to 2002, reproduced in Table 11.

Table 11. Estimated homeowner purchases of light-duty portable generators, 1999 to 2002.

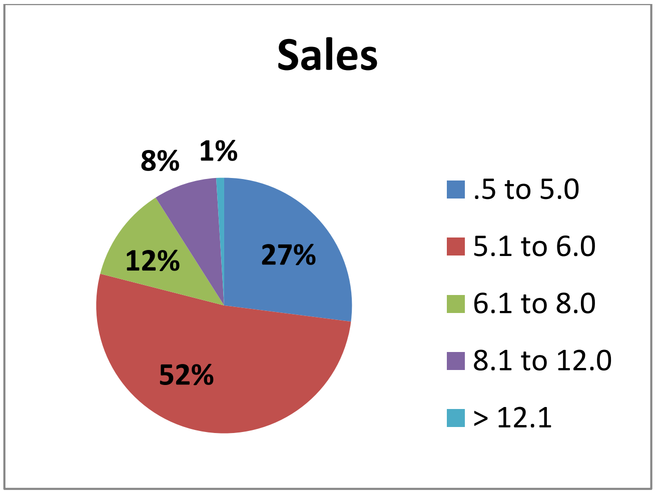
Year	Total U.S. Sales
1999	733,000
2000	288,000
2001	342,000
2002	357,000

Source: Frost & Sullivan

According to the study, homeowners are the largest end users of light-duty portable power generators, with the most popular size being 5 to 6 kW of output, accounting for about 52% of light-duty sales. According to EPRI, most residential generators operate in the 3 to 10 kW range.[18] Figure 18 below illustrates the breakdown by kilowatt output and percentage of sales.

The U.S. Environmental Protection Agency (EPA), in its work on emissions of non-road engines, developed estimates of the population of gasoline powered generators for 1998 for all end users. Table 12 shows the population of generators by power output. Note that these estimates track closely with the 2002 sales estimates from the Frost and Sullivan study and show that about half of all light-duty generators are in the 5 kW power range.

From a report by Power Systems Research based on their *OE Link*™ database, an estimate was made for the total market size for reciprocating engine powered gensets in North America to be in the range of 800,000 to 1,000,000 units per year when all power ranges and all fuel types are considered. The database tracks the production of all gensets powered by a reciprocating engine.



Source: Frost and Sullivan

Figure 18. Generator sales by kilowatt output, 2002.

Table 12. EPA estimates of the population of gasoline powered generators in 1998.

Power Range (kW)	Estimated Population	% of Total
0 to 0.6	4,052	0.12
0.6 to 1.8	100,577	2.94
1.8 to 3.6	707,572	20.66
3.6 to 6.6	1,699,093	49.61
6.6 to 9.6	375,830	10.97
9.6 to 15.0	537,782	15.70
Total	**3,424,906**	**100.00**

Table 13 shows that sales of light-duty generators (< 10 kW) in North America were about 800,000 in 2006 and 2007 and about 630,000 in 2008. These figures are comparable to the Frost & Sullivan estimate for 1999 of about 700,000 but are twice as high as their estimates for the years 2000–2002.

Overall, the market data indicate that generators in the sub-10 kW size amass annual sales in the many hundreds of thousands. Also, it seems as though the most popular generator size in this class is about 5 kW. Based on these figures and additional research (workshop, questionnaires, telephone and in-person communications), the 5 kW gasoline powered portable generator was identified as a potentially important fuel cell market.

Table 13. Production estimates of reciprocating engine powered generators in North America.

EGSA kW Range	2006	2007	2008
<10.0 kW	819,460	805,147	629,645
10.1 to 15.0 kW	77,634	82,844	68,600
15.1 to 30.0 kW	29,072	29,491	25,572
30.1 to 50.0 kW	25,175	25,531	23,466
50.1 to 150.0 kW	38,394	38,561	34,002
150.1 to 250.0 kW	9,908	9,985	8,707
250.1 to 500.0 kW	9,067	9,174	7,419
500.1 to 750.0 kW	2,580	2,646	2,180
750.1 to 1000.0 kW	1,911	1,942	1,653
1000.1 to 2000.0 kW	4,372	4,413	4,032
2000.1 to 6000.0 kW	259	261	232
Total	**1,017,832**	**1,009,995**	**805,508**

Source: PSR OE Link^{TM} database.

3.4.3 Discussion of Technical Needs for Storage

3.4.3.1 *Small (< 10 kW) Portable Generators*

To obtain more detailed information on the operating requirements of these generators, specific models were selected for consideration. Table 14 shows the specifications for two 5 kW generators from Honda.[20] The EG5000CL is from their Economy series while the EB5000X is from their Industrial series of generators. The engine in the EB model is upgraded with a digital CDI ignition system and an electronic control unit. The EB model is also mounted in a frame with wheels, which makes it easier to move around the worksite and accounts for the larger dimensions. The price for these generators was found by doing an internet search. Note that with tax, the cost per kW is about $400 for the economy unit and $500 for the industrial version. Pictures of the two units are shown in Figure 19.

Table 14. Honda 5 kW portable generators.

Specification	Small Generator	Small Generator
Manufacturer	Honda	Honda
Model	EB5000X	EG5000CL
Rated Output Power	4.5 kW (5.0 kW max)	4.5 kW (5.0 kW max)
Run Duration Per Fill/Charge	8.1 hr @ rated load, 11.2 hr at 50% load	11 hr at 50% load
Output Power Type	120/240 VAC	120/240 VAC
Overall Dimensions - L x W x H	41.9" x 27.2" x 29.2" with wheels and handles	26.8" x 22.8" x 22.6"
Overall Volume	545 L	226 L
Overall Dry (no fuel) Weight	214 lb	177 lb
Fuel/Battery Type	Gasoline	Gasoline
Fuel Tank or Charge Capacity	6.2 gal	6.3 gal
Stored Energy (kW-hr)	209.8	213.2
Energy Storage System Volume	26 L	26 L
Energy Storage System Volumetric Energy Density	8.13	8.13
Energy Storage System Weight	22 kg	22 kg
Energy Storage System Gravimetric Energy Density	10.91	10.91
Engine/FC Model	Honda iGX390	Honda GX390
Power System (Engine/FC) Weight	30.3 kg	31 kg
Power System (Engine/FC) Volume	69.3 L	76.4 L
Combined Energy + Power System Volume	95 L	102 L
Combined Energy + Power System Volumetric Energy Density	2.21	2.09
Combined Energy + Power System Weight	52 kg	53 kg
Combined Energy + Power System Gravimetric Energy Density	4.03	4.02
Refuel/Recharge Time	0.6 min	0.6 min
Fuel Consumption	0.78 gal/hr	0.78 gal/hr
Emissions	Must meet local requirements	Must meet local requirements
Operating Temperature Range	-20 F to 100 F	-20 F to 100 F
Noise level	72 dB @ rated load	73 dB @ rated load
Overall Cost	$2,484	$1,865

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
2. Power system refers to the engine that generates mechanical power, generator to convert mechanical to electrical power, and associated hardware.

Figure 19. Honda EG5000CL (left) and EB5000X (right).

3.4.3.2 *Large (> 10 kW) Towable Generators*

For larger gensets that are typically towed behind a vehicle, the sizes range from about 15 kW up to hundreds and even several thousand kW. Based on the information in Table 13 from Power Systems Research, the largest number of units sold is in the 15 kW to 150 kW power range. Workshop results indicated that the 60 kW to 100 kW range was of high importance to users. In a private communication from Torsten Erbel of Multiquip, he indicated that their most popular size was their 25 kVA models. Based on this information, two of Multiquip's generators were chosen to represent the requirements for this class of equipment, with their specifications shown in Table 15.[21]

The DCA25SSI and DCA125SSI models are from Multiquip's WhisperWatt line of generators, which include diesel fuel tanks. (A EGS1400C3 model is from the Studio Generator line which has even lower noise levels specifically for the broadcast market, but was not included here because it does not include a fuel tank, instead relying on an external fuel tank that is provided by a Multiquip trailer or tractor trailer that it is mounted on.)

Table 15. Specifications of large (> 10 kW) towable power generators.

Specification	Large Generator	Large Generator
Manufacturer	Multiquip	Multiquip
Model	DCA25SSI	DCA125SSI
Rated Output Power	20 kW	100 kW
Run Duration Per Fill/Charge	10 hr @ 100% load, 20 hr @ 50% load	8.6 hr @ 100% load, 15.4 hr @ 50% load
Output Power Type	AC: 1- and 3-phase switchable	AC: 1- and 3-phase switchable
Overall Dimensions - L x W x H	73" x 30" x 39" cabinet only, no trailer	120" x 44" x 56" cabinet only, no trailer
Overall Volume	1400 L	4845 L
Overall Dry (no fuel) Weight	1,411 lb	4,700 lb
Fuel/Battery Type	Diesel	Diesel
Fuel Tank or Charge Capacity	17 gal	63 gal
Stored Energy (kW-hr)	640.9	2375.1
Energy Storage System Volume	71 L	264 L
Energy Storage System Volumetric Energy Density	9.05	9.05
Energy Storage System Weight	59 kg	220 kg
Energy Storage System Gravimetric Energy Density	10.88	10.88
Engine/FC Model	Isuzu BV-4LE2	Isuzu 4HK1X
Power System (Engine/FC) Weight	170 kg	470 kg
Power System (Engine/FC) Volume	199 L	731 L
Combined Energy + Power System Volume	270 L	995 L
Combined Energy + Power System Volumetric Energy Density	2.37	2.39
Combined Energy + Power System Weight	229 kg	690 kg
Combined Energy + Power System Gravimetric Energy Density	2.80	3.44
Refuel/Recharge Time	1.7 min	6.3 min
Fuel Consumption	1.7 gal/hr	7.33
Emissions	Tier 3	Tier 3
Operating Temperature Range	-15 F to 120 F	-15 F to 120 F
Noise level	63 dB @ rated load @ 23 ft	68 dB @ rated load @ 23 ft
Overall Cost	$17,600	$48,338

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
2. Power system refers to the engine that generates mechanical power, generator to convert mechanical to electrical power, and associated hardware.

3.4.4 *Implications for Hydrogen Storage Technology*

3.4.4.1 *Small (<10 kW) Portable Generators*

In terms of performance requirements, the two units described above (Table 14) provide a benchmark with which to make a comparison to fuel cell portable generators. The EG5000CL economy model provides the following energy storage density and power output:

1. Weight (including fuel): 216 lbs (98 kg).
2. Volume: 13,809 cubic inches = 226 L.
3. Stored energy: 767 MJ.
4. Volumetric energy density: 3.39 MJ/L.
5. Gravimetric energy density: 7.83 MJ/kg.
6. Output power: 4.5 kW.
7. Duration: 11 hours at 2.25 kW.

To get an idea of the challenge for a fuel cell system with hydrogen storage to meet this performance, investigators identified two 5 kW fuel cells currently being produced. The specifications for these fuel cells are shown in Table 16. A company called Tropical S. A. can be found on the internet selling fuel cell power generators based on Ballard fuel cell technology.[22] The TB-5000 model generator uses a Ballard FCGen 1300 stack and produces 5 kW max power with AC and DC output. Note that while this unit is lighter, it is approximately the same size as the Honda EG5000CL, and it does not include hydrogen storage. Also listed in the table is the Altergy FPS unit.[23] These 5 kW fuel cell power generators are designed primarily for backup power applications, specifically for cell phone towers. Thus, they are sold as 24 V or 48 VDC models with no AC output. The Altergy units are larger and heavier than the Ballard-based generator and also do not include hydrogen storage.

Table 16. 5 kW fuel cell portable generators (not including H_2 storage).

Manufacturer	Tropical	Altergy
Model	TB-5000	FPS-524 or FPS-548
Engine	Ballard FCGen 1300	Altergy 5kW stack
Power Output	5000 W max	5000 W max
AC output	110/230V	N/A
DC output	12V/24V/48V	24V/48V
Starting system	Electric	Electric
H_2 required for 8 hrs @ 5 kW	3 kg	3 kg
Dimensions (L x W x H), Volume	23.6" x 21.7" x 27.5" = 230.6 L	21" x 33" x 25" = 284 L
Noise level	Not Available	< 60 dB
Dry weight	121 lbs.	179 lbs.

To operate these 5 kW fuel cell units at full power for 8 hours would require about 3 kg of hydrogen. Current hydrogen storage solutions would require, at a minimum, a 75 liter (20 gal) tank to store that amount of hydrogen. Since current 5 kW fuel cell systems are nearly as large as their gasoline generator counterparts (with fuel), a reduction in volume of both the fuel cell and the hydrogen storage system would be required to meet the energy density of current generators. The assumption is that a larger size would be unacceptable to the end user; however, that may not necessarily be the case. End users of 5 kW generators might accept a larger volume in exchange for the benefits of a fuel cell-powered unit that includes reduced noise, zero emissions, longer lifetime, low maintenance, and higher efficiency. How large is acceptable may depend on the application. For applications that use many small generators at once such as a movie set, a broadcast event, or a construction site, fitting several of them in the bed of a truck to transport to the site is important. For other applications where single units are used, size may be less of an issue.

In addition to size or energy density, cost will be a big driver for any commercial product. The 5 kW gasoline generators listed in Table 14 cost \$400 to \$500 per kW. Small fuel cells such as those in Table 16 cost nearly 10 times as much in the small quantities in which they are manufactured today. Volume manufacturing and cost reductions would have to occur before they could compete with those costs. Both the fuel cell and the hydrogen storage system costs need to be considered here. Thus, the hydrogen storage system cost could not be more than \$150/kg to compete. DOE has developed cost targets for automotive fuel cell and hydrogen storage systems that can be compared to these values. For automotive fuel cells, the 2010 and 2015 cost targets are \$45/kW and \$30/kW respectively for 500,000 units/year production.[24] For automotive hydrogen storage, the 2010 and 2015 cost targets are \$133/kg H_2 and \$67/kg H_2 respectively. If these targets were met for a 5 kW fuel cell system with a 3 kg H_2 storage system, the costs would be \$624 using the 2010 targets and \$351 using the 2015 targets. These units would be quite cost competitive compared to the Honda generators. However, these values are targets and while projections of fuel cell system costs are approaching the 2010 target,[25] hydrogen storage system cost projections range from \$267/kg H_2 to \$667/kg H_2 depending on the technology. Also, the fuel cell cost targets are for 80 kW fuel cell systems, which would benefit from an economy of scale. In addition, the targets are for very high-volume manufacturing.

3.4.4.2 *Large (> 10 kW) Towable Generators*

An example of a deployment of large towable power generators is shown in Figure 20. A truck mounted “broadcast truck” with two 175 KW 1400A movie quiet generators is shown in Figure 21. The three models outlined in Table 15 cover the most common generator power levels and provide a basis for comparison for fuel cell systems.

Figure 20. Two paralleled towable studio generators (300 kW, 2500A Movie Quiet each) in use at the 2011 Oscars by Saunders Electric. Note the space restrictions that can occur at such deployments. Photo courtesy of Saunders Electric.

Figure 21. Live broadcast truck with two 175KW-1400A Movie Quiet generators permanently mounted. Photo courtesy of Saunders Electric.

The DCA25SSI model provides the following energy storage density and power output:

1. Weight (including fuel): 1529 lbs (694 kg).
2. Volume: 85,410 cubic inches = 1400 L.
3. Stored energy: 2308 MJ.
4. Volumetric energy density: 1.65 MJ/L.
5. Gravimetric energy density: 3.33 MJ/kg.

6. Output power: 20 kW.
7. Duration: 10 hours at 20 kW.
8. Cost = \$880/kW.

In addition to information provided Saunders Electric, additional information on how these towable generators are used was obtained from Illumination Dynamics (ID)[26]. ID provides power for the broadcast industry at a variety of events. Because of noise restrictions, ID primarily uses the Studio Generator line from Multiquip. The EGS1400C3 168 kW model is the workhorse generator, but other equipment used includes 60 kW and 300 kW generators. All of the generators operated, when towed, use the MQ tandem axle trailer which is 15' X 6' and includes a 150 gallon diesel tank. Alternatively, two of these generators are put on a tractor trailer, and the trailer diesel tanks are used for fuel. ID found that having fuel separate from the generator can be desirable because it makes the system more modular.

For a fuel cell replacement, refueling will be a key issue. The current diesel fuel can be replaced while the units are operating. ID refuels their generators once or twice per day depending on the venue, and fuel delivery services which are available anywhere in the U.S. are contracted. The fuel delivery truck can pull up and refill the 150 gallon tank in 5 minutes. Although one could imagine a similar scenario for hydrogen refueling, it might be difficult to match this flexibility with a hydrogen storage system.

The information from Table 15 provides a basis for the energy density required to match current diesel generators. However, other concerns arose during discussions with ID about the acceptable weight and volume of a towable generator. One consideration with weight is that if the system and trailer are greater than 10,000 lbs, the driver needs a commercial license. For volume, the 4' X 8' footprint is somewhat of a standard for the studio generators. It allows them to be shipped easily and arranged in pairs on a tractor trailer. However, ID indicated that a larger footprint could be acceptable. In fact, a towable generator could be as large as 20'X8'X11' and as long as it was less than 10,000 lbs could be acceptable for many applications. This size would be much easier to meet for the hydrogen storage system.

3.4.5 Summary Table of Technical Needs

Table 17 summarizes the energy storage requirements for each piece of equipment. It is the result of stakeholder feedback on what they require from their equipment (from workshops, interviews, written questionnaires, and Kano analysis).

In several cases, the feedback was unanimous in stating that the requirements for a hydrogen fuel-cell powered version of a piece of equipment match the specifications of the existing equipment, so in those instances the numbers used for the requirements are generated largely from the specifications (shown in Table 14 (< 10 kW class) and Table 15 (> 10 kW class)). Where the stakeholder feedback indicated differences between what they would like to see in fuel cell versions and the current equipment, the stakeholders' numbers are used to generate the requirements shown in the table. The stakeholder feedback is the driver for developing the requirements and it was utilized without judgment. The only modifications to this feedback occurred when it was ambiguous or conflicting, and in those instances investigators used their own knowledge to clarify and decide the most appropriate requirement.

Table 17. Energy storage requirements for a hydrogen fuel cell powered version of each class of portable power generators studied.

Application	Small Generator	Medium Generator	Large Generator
Requirements			
Rated Output Power	4.5 kW (5.0 kW max)	20 kW	100 kW
Run Duration Per Fill/Charge	8.1 hr @ rated load, 11.2 hr at 50% load	10 hr @ 100% load, 20 hr @ 50% load	8.6 hr @ 100% load, 15.4 hr @ 50% load
Restrictions			
Energy Storage System Volume[1]	26 L	71 L	264 L
Energy Storage System Weight[1]	22 kg	59 kg	220 kg
Refuel/ Recharge Time	0.6 min	1.7 min	6.3 min
Operating Conditions - Temperature	-30 °C to 40 °C	-25 °C to 50 °C	-25 °C to 50 °C
Operating Conditions - Weather[2]	Extreme	Extreme	Extreme
Noise level[3]	< 72 dB	< 63 dB	< 68 dB
Emissions[4]	Meets or exceeds EPA requirements	Meets or exceeds EPA requirements	Meets or exceeds EPA requirements

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware. Restrictions on size assume the storage of enough energy to meet the rated output power for the required run duration; if more energy is stored these restrictions may be relaxed.
2. Extreme weather conditions include rain, snow, hail, ice, blowing sand, blowing water, dirt, mud, dust, high elevation, salt air, and humidity extremes.
3. All noise levels when operating at rated load, at a distance of 5 m unless stated otherwise.
4. EPA requirements: *Phase 3* for gasoline engine replacement (http://www.epa.gov/otaq/equip-ld.htm), *Tier 3* for diesel engine replacement (http://www.epa.gov/nonroad-diesel/regulations.htm).

3.5 Telecom Backup Power

Backup power for cell phone towers was identified in the Battelle Report as a high-priority market for the introduction of fuel cell technology. Indeed, in the past few years, PEM fuel cells have found their way into the cell tower backup power market by the hundreds of units. In the Feb. 8 workshop morning presentation by Kevin Kenny, a Sprint Power Network Engineer, a summary was given of the current status of the technology. A photograph of a typical cell phone tower station is shown in Figure 22.

As reviewed by Kenny, telecommunications equipment for cell phone towers consists of 4 kW to 10 kW power systems operating at either 48 VDC (majority) or 24 VDC. Typically, they are grid-operated facilities with provision made for a backup system. Local utility provides AC power to the facility, where the power plant rectifies the input AC to output DC, with the DC delivered to the internal DC bus, which then provides power to the telecom gear. There is also a battery plant in the facility that is trickle charged by the grid power. Upon loss of grid power, the battery plant provides bridge power so that power is provided seamlessly to the gear while the backup generator set turns on. Typically, the backup power is provided by a fossil fueled (predominantly diesel) generator system designed to provide 72 hr runtime.

Figure 22. Photograph of a cell phone tower.

As mentioned above, backup solutions are currently being deployed based on fuel cell technology. In 2005, Sprint began deployment of PEM fuel cells in Florida. A total of 250 units were deployed with output power ranging from 3 to 6 kW. These early deployments used relatively low-pressure (~2200 psi) hydrogen in a six-pack of "K" bottles. At these low pressures, not so much hydrogen can be stored, limiting the backup operational time to ~16 to 20 hour runtime, depending upon load. Experience with the hydrogen refueling is that it is cumbersome, with swap out of bottle required. More recently Sprint was awarded a DOE grant to deploy 260 new hydrogen fuel cell backup power systems, along with a retrofit of 70 in-service units. Sixteen medium-pressure bottles at an elevated pressure (3,000 psi) now allows for a backup run time of 72 hours.

3.5.1 Summary of Stakeholder Feedback

In this realm, the most important piece of equipment is a 5 to 30 kW backup power system. A key point regarding area is that cell phone towers are often placed in very high-density areas, making highly desirable a small footprint for a fuel cell-based backup power system.

The Kano analysis (see Section 3.1) based on the end user survey indicates strong interest in reducing the hours the equipment is in the shop, in reducing the overall weight and footprint of the equipment; and in broadening the temperature range of operability. There is very limited interest on residual value at the end of life of the storage unit.

One of the main issues raised by the end users is the difficulty to operate the equipment at low load (wet stacking is observed in portable units equipped with diesel engines). Fuel efficiency is poor, and at low load the unit continues to consume up to 30 to 40% of the fuel. Moreover, because of noise restrictions (50 to 60 db) gasoline and diesel units are difficult to use indoors. Conventional power units tend also to be dirty—fuel leaks must be treated as environmental spills. In addition, they must comply with CARB regulations for CO_2 and NO_X emissions. The maintenance cost is substantial: on average, it is estimated at \$1400 per year for high-end units and \$4500.00 per year for large units. Transport often requires 2 people to install the unit. Increased volume of the unit corresponds to increased installation cost. The Pareto diagram in Figure 23 illustrating the main priorities of end users for all the system surveyed indicates that noisy, polluting, and spill-prone equipment is of main concern.

The stakeholder feedback on telecom backup power units is summarized in Table 18.

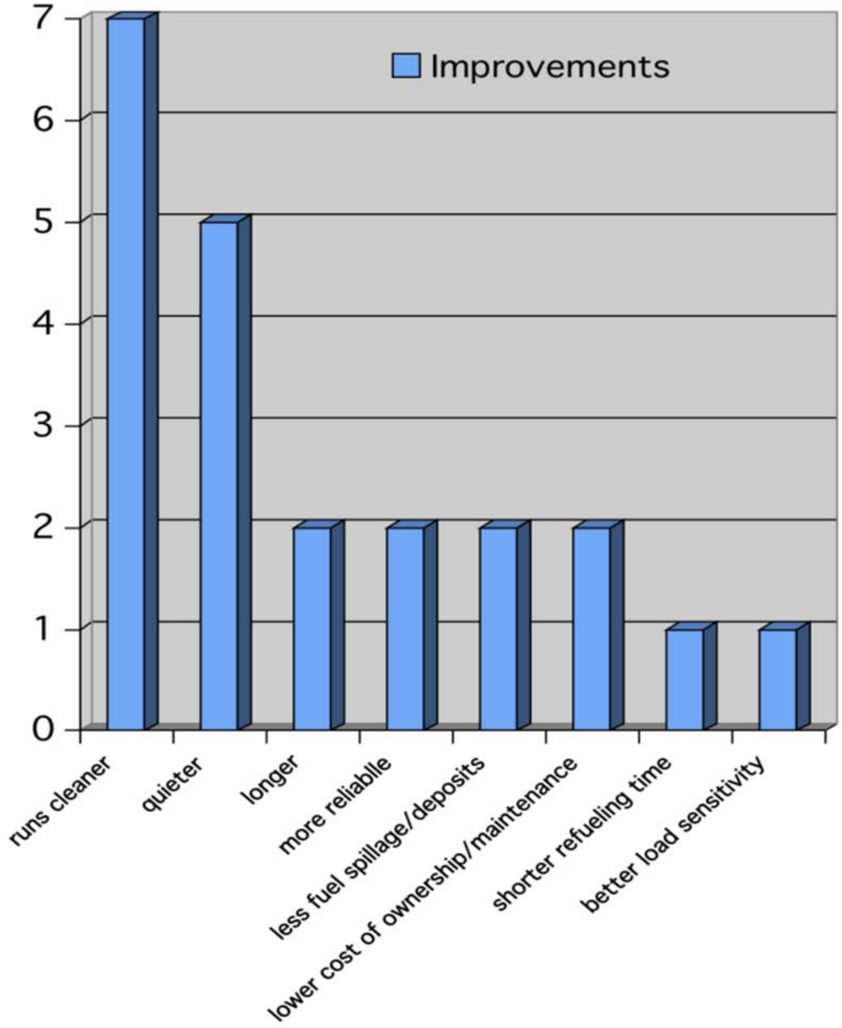


Figure 23. Question: Thinking about all the problems you have with this equipment, which ones would you like to see improved the most?

Table 18. Summary table of stakeholder feedback for telecom backup power units.

Category Feature	Kano Indicator	Written Survey Preferencess	Workshop and Interview Feedback
General			Also used for rail signals, traffic lights, building management, and emergency lighting.
Size			
Smaller volume	Satisfier		
Lighter weight	Satisfier/ Delighter		
Operating Conditions			
Operate in wide temperature range	Dissatisfier/ Satisfier	-40 °C minimum	-40 °F to +140 °F
Withstand large shock and vibration	Satisfier		
Operate in extreme conditions	Dissatisfier		Humidity, elevation dictate type of battery used.
Fueling			
Run longer between refueling	Satisfier	60-70 hrs	72 hrs
Refuel quickly	Satisfier/ Dissatisfier	15 minutes per refill	Refueling spills (diesel) are a nuisance.
Maintenance			
Low maintenance	Satisfier/ Dissatisfier	60 days between maint.	
Nearly always available when needed	Dissatisfier	100% availability	
Long lasting storage system	Satisfier/ Dissatisfier	> 20 yr life	
Personnel Training			
Little operator training	Satisfier/ Dissatisfier	< 15 hr/yr	Operators are trained and qualified, typ. electricians.
Little additional service training	Satisfier/ Dissatisfier		
Emissions			
Little CO_2 emissions	Satisfier/ Dissatisfier		
Little pollutant emissions	Satisfier/ Dissatisfier		Heavily regulated for noise, pollutants, location.
Costs			Need independent (neutral 3rd party) model to demonstrate total cost of different technologies
Low initial cost	Satisfier		Highly cost sensitive, 2-3 yr payback for lifecycle cost.
Low fuel cost	Satisfier/ Dissatisfier		
Low O&M cost	Satisfier/ Dissatisfier		
Scrap/residual value of storage system	Dissatisfier/ Delighter		

3.5.2 Analysis on Current Market Status and Identification of High-Potential Markets

A more detailed analysis is provided in the following for the model that emerged from the end user survey as one of the most used for cell tower backup: the T-2000® hydrogen fuel cell produced by ReliOn (Figure 24). In addition to accessing the technical specifications[27], investigators contacted a Network Engineer from Sprint[28] as well as a sales representative from ReliOn[29]. According to this latter source, in the U.S. 3.7 megawatts of fuel cells are currently deployed at about 1300 sites. The purchase price for the overall system is estimated to be approximately $50,000[28]. Maintenance only consists of the annual equipment inspection: a replacement of the air filter ($200) may be required. Lifetime information (cycle life) was not disclosed.

Figure 24. T-2000® hydrogen fuel cell.

3.5.3 Discussion of Technical Needs for Storage

The perceived limit to the use of PEM cells for telecom back-up is the limited extra power available for air conditioning. In those cases, a traditional power generator is preferred[28]. A second issue is the perception that, overall, the equipment is difficult to set up in an already crowded place such an urban cell tower[28]. Purchasing cost is also an issue, but it is currently offset by tax credits or other forms of financial support.

3.5.4 Implications for Hydrogen Storage Technology

Based on a phone interview with a Sprint Power Network Engineer[28], refueling consists of storing on site a number of H_2 bottles sufficient for a maximum back-up run time of 72 hours (substantially above the federal requirement for telecom back-up). In this case, and assuming a fuel-to-electric efficiency of 40%, it is estimated that 19.4 Kg of H_2 are necessary to supply 2 kW electricity for 72 hrs. This H_2 mass corresponds to 16 bottles at 3000 psi., or approximately 40 cubic feet required for energy storage.

3.5.5 *Summary Table of Technical Needs*

Table 19 summarizes the energy storage requirements for this equipment. It is the result of stakeholder feedback on what they require from their equipment (from workshops, interviews, written questionnaires, and Kano analysis). In several cases, the feedback was unanimous in stating that the requirements for a hydrogen fuel-cell powered version of a piece of equipment match the specifications of the existing equipment, so in those instances the numbers used for the requirements are generated largely from the specifications (shown for reference in Table 20). In cases where the stakeholder feedback indicated differences between what they would like to see in fuel cell versions and the current equipment, the stakeholders' numbers are used to generate the requirements shown in the table. So, the stakeholder feedback is the driver for developing the requirements and it was utilized without judgment. The only modifications to this feedback occurred when it was ambiguous or conflicting, and in those instances investigators used their own knowledge to clarify and decide the most appropriate requirement.

Table 19. Energy storage requirements for a hydrogen fuel cell-powered version of a typical aviation ground power unit.

Application	Telecom Backup
Requirements	
Rated Output Power	5 kW (most common)
Run Duration Per Fill/Charge	> 8 hr (min FCC req.)
Restrictions	
Energy Storage System Volume[1]	1220 L
Energy Storage System Weight[1]	409 kg
Refuel/ Recharge Time	40-45 min
Operating Conditions - Temperature	-40 °C to 45 °C
Operating Conditions - Weather[2]	Extreme
Noise level[3]	53 dBA @ 1 meter
Emissions	Must meet local requirements

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware. Restrictions on size assume the storage of enough energy to meet the rated output power for the required run duration; if more energy is stored these restrictions may be relaxed.
2. Extreme weather conditions include rain, snow, hail, ice, blowing sand, blowing water, dirt, mud, dust, high elevation, salt air, and humidity extremes.
3. Noise level when operating at rated load.

Table 20. Summary of technical specifications for the telecom backup application.

Specification	Telecom Backup
Manufacturer	ReliOn
Model	T-2000 Hydrogen Fuel Cell
Rated Output Power	10 kW
Run Duration Per Fill/Charge	72 hr @ 4 kW,
Output Power Type	80A @ 24VDC or 40A @ 48VDC
Overall Dimensions - L x W x H	21" x 21.5" x 26" (fuel cell indoors configuration)
Overall Volume	192 L
Overall Dry (no fuel) Weight	61 to 111 kg
Fuel/Battery Type	Hydrogen
Fuel Tank or Charge Capacity	19.4 kg (16 bottles @ 3,000 psi)
Stored Energy (kW-hr)	363 kW-hr needed for 72 hr / 647 kW-hr avaialble
Energy Storage System Volume	1000 L
Energy Storage System Volumetric Energy Density	0.363/0.647 kW-hr/L
Energy Storage System Weight	1040 kg
Energy Storage System Gravimetric Energy Density	0.349 / 0.622 kW-hr/kg
Engine/FC Model	T-2000
Power System (Engine/FC) Weight	134 to 244 lbs
Power System (Engine/FC) Volume	192 L
Combined Energy + Power System Volume	1300 L
Combined Energy + Power System Volumetric Energy Density	0.30 / 0.50 kW-hr/L
Combined Energy + Power System Weight	1200 kg
Combined Energy + Power System Gravimetric Energy Density	0.30 kW-hr/kg needed / 0.54 kW-hr/kg available
Refuel/Recharge Time	40-45 min
Fuel Consumption	30 SLPM @ 2 kW
Emissions	Water (max 30 mL/kWh)
Operating Temperature Range	-40 F to 115 F
Noise level	53 dBA @ 1 meter
Overall Cost	$50,000

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
2. Power system refers to the engine that generates mechanical power, generator to convert mechanical to electrical power, and associated hardware.

3.6 Man-Portable Power and Consumer Electronics

As described in the introduction, this study investigated the energy storage needs (and therefore the demands on a potential future hydrogen fuel cell power technology) of consumer electronics and man-portable power generation areas, primarily targeting small-scale use. Specifically, “man-portable” refers to devices capable of being carried, worn, or held in-hand by an individual. Such devices generally have power ratings less than 100 W, with certain systems tailored to military applications having ratings around 300 W. Because of the size and portability constraints of these applications, the upper limit of fuel cell power explored in this part of the study was approximately 500 W.

Common portable consumer electronics were considered for this part of the study. The following device categories considered were:

- Broadband modems (mobile)
- Camcorders
- Cellular phones
- Power supplies and charging stations
  - Consumer
  - Military
- DVD players (portable)
- Digital cameras
- External hard drives
- GPS (handheld)
- Headsets (telecommunications)
- Laptop computers
- MP3 players
- Radios (including satellite radio and two-way)
- Tablet PCs, iPads, and eReaders
- Video game systems (handheld)

The power supply category is separated into two subcategories (consumer and military) because the devices’ technical specifications are generally very different.

Several prominent companies in each category were chosen to search for active fuel cell research. Table 21 lists the companies that were examined as example manufacturers.

Table 21. A list of products considered with brand names and companies.

Product Category	Brand Names/Companies Considered
Broadband modems (mobile)	Sierra Wireless, Samsung, Novatel
Camcorders	GoPro, JVC, Flip Video, Insignia, Dynex, Sanyo
Cellular phones	Motorola, Apple, LG, Blackberry, HTC, Sony, Hitachi
Charging stations / power supplies	*Battery makers:* Duracell, Energizer, Maxwell, Panasonic, Rayovac, Sanyo, New Trent *Fuel-cell related:* mti micro (DMFC), myFC (sodium silicide), SFC Energy (methanol), Genport (H2), Jadoo (metal hydride, H2), UltraCell (methanol), Trulite, Samsung, Fuji Electric (propane, gas), Toshiba (methanol), Horizon (solid state) *Gas-powered portable generators:* All Power America, Briggs & Stratton, Eastern Tools & Equipment, Generac, Honeywell, PowerMate
Digital cameras	Nikon, Canon, Casio, Fujifilm, Olympus, Kodak, Panasonic
DVD Players (portable)	Philips, Toshiba, CyberPower, Golla
External hard drives	Iomega, LaCie, Seagate, Toshiba, Verbatim, Western Digital
GPS (handheld)	Garmin, Magellan, Bushnell, Sonocaddie
Headsets (telecomm.)	Belkin, Bose, Jawbone, Plantronics
Laptop computers	Compaq, Apple, HP, ASUS, Dell, Sony, Toshiba, Samsung
MP3 players	Apple, Zune, SanDisk, Creative, Archos
Radios (including 2-way)	Midland, Sirius, Pioneer, Sangean, Motorola, Uniden
Tablet PCs / iPads / eReaders	Amazon, Apple, Samsung, Barnes & Noble, Motorola
Video game systems (handheld)	Nintendo, Sony

3.6.1 *Summary of Stakeholder Feedback*

Several issues facing currently commercialized fuel cell systems are of interest when considering the potential for hydrogen. Much of the feedback is with regard to portable power generators for military and consumer applications. However, the information is relevant to fuel cell devices in general. This section contains the feedback received from engaging manufacturers of fuel cell and portable electronics devices.

It must be stressed that this section and the feedback below presents the opinions, perceptions, ideas, and suggestions of the people in the both the military and consumer realms with whom investigators engaged in conversation. In general, these people intimately understand the needs of their customers and strive to produce products that will meet those needs. This feedback is presented without significant editing or judgment.

3.6.1.1 *Size and Weight*

The market perception is that fuel cell systems today are difficult to miniaturize. While there have been many developments in reducing the size of the fuel cell itself, the balance of plant for the total system is a challenge.[30] There are extra size "costs" to the deployment of these systems: carrying electrical cables, fuel tubing, fuel cartridges, etc.

For the military, each of these issues ultimately affects the effective load carried by the soldier. In the goal of reducing the variety and quantity of batteries needed on the battlefield, the Army has identified the LI-145 battery (by UltraLife Corporation) as having the potential to reduce the soldiers' carried weight and to meet these goals.[31] This lithium ion battery provides benchmark gravimetric and volumetric energy densities to which current fuel cell technologies may be compared. These metrics may be used to develop the requirements for future hydrogen technologies. However, as mentioned below in the Infrastructure and Refueling section, if a fuel cell device is going to add an additional fuel logistics burden, it will not be good enough to just match the LI-145's size, but rather must be significantly smaller to still make it attractive for deployment.

The form factor of the device should also be conformal;[32] the military desires a device that can be easily and comfortably worn on the body, possibly tethered directly to the device to be recharged. An effort is proceeding now in fuel cell development towards this end.

For consumer use, the size and weight requirements depend on the application. Specifically, for integration into a device such as a laptop computer or eReader, the needed size and weight are very restrictive in order to meet the device's performance requirements.

3.6.1.2 *Device Housing*

The military has specific requirements for devices to be used by its soldiers. Rather restrictive ruggedness requirements must be met; the products surveyed in this study were often stated to meet the standards of MIL-STD 810F or G. These requirements often add extra complexity to the overall fuel cell device,[30] so the economic costs associated with stringent requirements may be an issue. For example, the small size requirements needed for military applications could only be met with an active cooling system, whereas a simpler, passive system (without cooling fans) would need to be larger.[33]

3.6.1.3 *Fuel*

Feedback received from customers in this realm reveals concerns about hydrogen fuel. The perception is that major safety issues exist with hydrogen (real and perceived) and with hydrogen supply infrastructure. Moreso for the consumer market, refueling method is also a concern.

Safety

Device and fuel safety is a primary concern for the military, and, given the dangerous environments that soldiers often face, a big problem for fuel cell systems is the potential hazards posed by the fuel. Some methanol fuel cell manufacturers have approached this issue by using methanol-water mixtures to reduce flammability risk.

Furthermore, the military is wary of any type of system requiring compressed gases or contents under high pressure.[31] The risk of explosive decompression is very real, and such a system appears unfit for military applications based on the feedback received.

In non-combat applications the threat of tank explosion is very small. Nonetheless, there is a perception of danger in compressed hydrogen storage. This concern may be alleviated somewhat through education and outreach that invite the public to experience hydrogen and fuel cells first-hand. For example, the public accepts widespread and informal use of gasoline, a highly flammable and toxic liquid, most likely due in large part to its decades of use and familiarity.

Infrastructure and Refueling

An important consideration along with fuel safety is the energy infrastructure needed to facilitate the deployment of a fuel cell system. Using methanol, propane, or hydrogen requires the creation of an energy supply chain whether for military or civilian consumers. For remote or hostile locations, there is an immense logistical challenge to supplying needed fuel. According to General David Petraeus' Operational Energy Memorandum released June 7, 2011,[34] almost 80% of ground supply movement is of fuel. A significant amount of resources is already required to secure such shipments, and many casualties are the result of such activities. There is a desire to reduce the number of these resupply convoys, to increase energy efficiency, and to reduce energy expenditure. Feedback from the customer base indicates that a fuel cell system must offer a significant increase in energy density to warrant the creation of a new logistical system to transport a new fuel,[31] assuming the infrastructure for the new fuel is feasible to begin with. The fuel type itself is not as important because there will be an additional logistical burden to supply the fuel regardless (unless it is the logistics fuel JP-8, which is used on the battlefield now). While a fuel cell's inherent high efficiency will save some fuel, this advantage is considered too small by itself to be worth the additional resupply burden of another fuel.

The widespread availability of electricity, whether at military bases, workplaces, or homes, makes simply plugging a device into a wall outlet the preferred means of obtaining more energy. For example, the military would rather have a fuel cell unit with integrated electrolyzer that can be plugged into the base grid than send hydrogen to refill metal hydride canisters at in-country bases.[36] Most consumers would rather use the grid than use and replace a disposable fuel cartridge—let alone manually refill a liquid fuel like methanol (if available),[33] and for all users, inconvenience—or the perception of inconvenience—may deter interest.

An argument could be made that disposable batteries require replacement but are still widely used. The problem for fuel cells thus comes down to the availability of the fuel. With today's technology and infrastructure, neither hydrogen nor methanol can compare to the availability of simple batteries, and for low-power applications, there is no need to develop a new power system for fuel cells when batteries suffice. Again, the fuel cell must not just meet the current technology's specification but must significantly exceed it if the fuel cell requires the user to take the additional step of refueling it.

3.6.1.4 *Energy Requirements*

For both the military and consumers, "creeping featurism" is a phenomenon where devices continually gain more and more functions and features for end user use, and it is a problem for consumer electronics designers in general.[35] The consequence of these added features is increased power consumption. Thus, there is tendency for power demands to continuously grow. While this issue may be mitigated by effecting end user changes in power consumption, it is nonetheless an issue when considering the overall energy and power requirements needed. This is particularly true for the military: overall carrying weight, and thus energy content, is becoming the factor limiting the technology they carry (see Section 3.6.3.1 and Figure 27) and is causing the DOD to decline additional capabilities that would be useful to the soldier.

3.6.1.5 *Power Requirements*

The U.S. Army is interested in two different energy platforms: soldier-wearable power in the 20 to 50 W range and squad-level power of about 300 W.[31] To this end, field-testing of various energy solutions are being conducted by the 1-16th Infantry for Operation Enduring Freedom. Several personal and squad-level power systems have been deployed in Afghanistan, including methanol fuel cell systems, solar power, propane fuel cells, and internal combustion engines. While the Army expects full feedback from soldiers in the field by the latter half of 2011, preliminary feedback is indicating that very small individual power systems (around 20 Watts) are not suited for direct use with radio equipment.[32] A spike of power around 80 to 85 W is needed during radio transmission, and the small 20 W methanol fuel cells used for this purpose were unable to provide that power. These fuel cell systems are current-limited and are meant to provide nearly constant levels of power. Such feedback indicates that these systems may be limited to constant power recharging applications unless integrated with another energy storage device such as a battery or capacitor.

Small, multipurpose fuel cell power generators in the 150 to 175 W nominal, 300 W peak range are being marketed for both military and civilian applications. The uses include medical life-support transport gurneys, portable radio relay stations for civilian services (police, fire, first responders, etc.), and indoor/outdoor power stations for consumers.

Consumer electronics such as cell phones require 5 W or less from a battery or recharger, and are often limited to 2.5 W when using USB connectors. Laptop computers require more: on the order of 30 to 75 W.

3.6.1.6 *Product Integration*

Integrating a fuel cell into a product is another challenge facing near-term application of fuel cells into consumer electronics and is the result of several issues. For example, there has been a push in the consumer electronics industry for closed-body designs—systems lacking open-air vents or ports.[35] This trend is disadvantageous for fuel cells, which require not only a fresh air supply but also a means of removing warm, humid waste air. This air-breathing characteristic of fuel cells may prevent them from being able to be integrated into any portable consumer electronics device that could be carried in a pocket or bag, such as a cell phone, tablet computer, or camera.

This is not an issue for desktop computers because they have active cooling systems necessitating an open-body design. However, even in laptops with open-body designs adding an additional heat source to the system is incredibly undesirable.[33] Also, new developments in laptop cooling may render forced air systems obsolete, and thus the opportunity provided for fuel cells in open-body laptops may also disappear.[35]

The pace of technological development is also a concern, especially for the consumer electronics industry where the turn-around time for new devices is extremely swift. The speed at which new products are introduced into the market outstrips the rate of current fuel cell development. In one case, by the time an integrated fuel cell prototype was developed for a laptop, the computer had already advanced three generations.[30]

Improvements to both the energy efficiency of consumer electronics and the energy storage capacity of batteries both lead to smaller size needs for integrated device energy storage for given run-times. As mentioned above, fuel cells already have trouble meeting these requirements; in general experts are pessimistic that they will ever be able to ("not ever ever ever ever ever," according to one executive[36]).

3.6.1.7 *Competition*

Feedback received from end users and manufacturers in the consumer electronics realm is that the large size of the consumer market does not necessarily lead to a greater opportunity for fuel cells. These devices face a large barrier of entry into the market because of the competition with typical electrochemical cells. Batteries are the most common form of energy storage for portable consumer electronics, and with the rapid progress and constant development of battery technologies, it is unlikely that they will be displaced by another technology unless the new energy source can not only match the swift pace at which batteries are improving but also improve upon some aspect of the device, such as energy density or efficiency.

Most importantly, one piece of feedback has consistently resounded from those in the fuel cell industry, and it is especially relevant to consider the fact when looking at the future of hydrogen storage. With present technology, it is difficult for a fuel cell generator to compete with grid power: energy from the grid is simply too inexpensive to compete with (it is considered free by most portable electronics consumers), and a typical consumer will always prefer a wall outlet over a portable power generator for normal consumer device recharging. When this preference cannot be met, and thus the only realistic market perceived for fuel cell-powered devices, is when grid power is not available for extended periods of time.

3.6.1.8 *End User Interest and Target Audience*

In the military, fuel cell deployment can be bolstered if there is enough of a pull from the end user. Because it is the soldiers themselves who will be using these devices, their satisfaction or dissatisfaction with a device has an impact on the usage and development of fuel cell devices. So far, none of the fuel cell sources of man-portable power have been embraced by the soldiers evaluating them,[31] although the potential of fuel cells still holds attraction to the DOD.

For consumers, while competing with grid power may be impractical with today's technology, there are opportunities in niche applications without access to the grid. Just as with other portable power sources, one of the advantages of fuel cell devices is precisely their independence from grid power. A typical consumer in conducting day-to-day activities is not always able to charge or power their electronic devices using wall outlets, and it seems that fuel cells could facilitate a greater degree of freedom and portability. In other words, fuel cell generators could function as a substitutional good in relation to grid power. However, batteries would also be a substitute, and they already facilitate "energy independence" in most all portable consumer electronics. As previously mentioned, because of the rapid progress in battery technology, it is difficult for fuel cells to compete in such an application.

It is in applications requiring energy beyond what is available in batteries that fuel cells may find much use, but this market segment is a small subset of the total consumer electronics market audience. Very few consumers are away from grid power sources for weeks at a time, and most people have access to grid power at least once a day.

In light of these issues, however, there are some consumers that fuel cells may have potential with, for both integrated device power and portable rechargers:[33]

1. Campers and other sportsmen who are away from the electric grid for extended periods of time.
2. Power users of laptops and other personal electronic devices who have a high demand for energy.
3. Consumers who are interested in reducing the environmental impact of computers because fuel cells potentially create less pollution than devices powered from the grid.
4. Professionals working remotely such as border patrol, emergency medical personnel, and trouble shooting and repair personnel.
5. Markets where there is no or unreliable electric grid power.

3.6.2 Analysis on Current Market Status and Identification of High-Potential Markets

Of the 14 product categories examined (Table 21), only four indicated active or past fuel cell research as shown in the open literature by patent filings and news articles: cellular phones, charging stations and power supplies, digital cameras (specifically d-SLRs, or digital single lens reflex), and laptop computers. (A sampling of recent patent filings by major brand names is shown in Table A-2.)

Of these four consumer electronics categories, fuel cell systems are only commercially available in portable recharging devices and power supplies. Their potential application as portable, off-grid power supplies is appealing to both consumers and the military. Portable fuel cell generators have many applications for military use, and because the U.S. military has very specific form factor and ruggedness standards and requirements, military systems constitutes its own category. All other end users would fall into the commercial category, where environmental and other requirements are typically more relaxed than those of the military. The current availability of these systems, their potential for future deployment, and end user interest in portable power generation indicate that portable power applications are an important application and require further analysis.

Additional information is needed to select which of the other groups are the most viable for fuel cell deployment in the near-term. Market data is a useful criterion for prioritization, and Figures 25 and 26 show data for 2009. The market value and volume for d-SLR cameras are a small minority of the total digital camera market. Cellular phones have an immense market volume globally, although their dominance in the U.S. is not as pronounced and they have the least market value. To give perspective, consumer electronics, which consists of audio visual equipment and video game consoles, have the greatest market value compared to both personal computers and cellular phones.

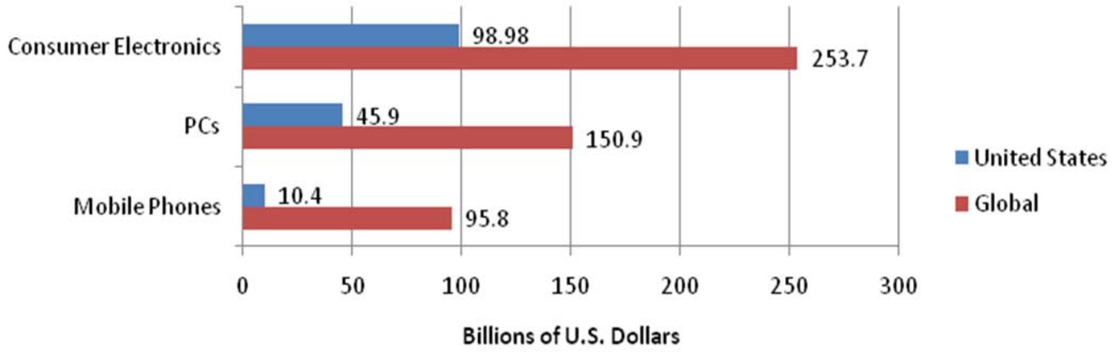


Figure 25. Market value (billions of U.S. dollars) of consumer electronics, PCs, and mobile phones for 2009. Laptop computers are about 54% of the total PC market. “Consumer Electronics” includes audio visual equipment (CD players, DVD players and recorders, hi-fi systems, home theater, in-car entertainment systems, portable digital audio, radios, televisions, and video recorders) and video game consoles (home and portable). Data from Datamonitor[37,38,39,40,41,42].

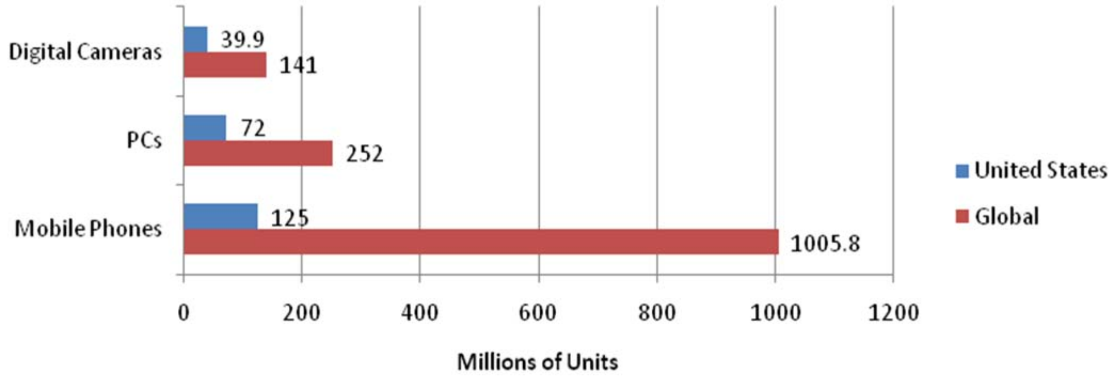


Figure 26. Market volume (millions of units sold) of digital cameras, PCs, and mobile phones for 2009. Digital SLR (d-SLR) cameras are a small portion of all digital cameras. Data from Datamonitor[37,40,39,40] digital camera data from Tarr[43].

Mobile computers (which compose 54.3% of the global PC market) have a substantial market share in portable consumer electronics as a whole. They hold an intermediate position in terms of both value and volume, and from 2009 to 2014 the global PC market is expect to grow 8.6% in value and 62.9% in volume (-7.4% in value and 43% in volume for the U.S. market).

Although future laptops might evolve into a closed body design, thereby possibly precluding fuel cell use in the future, currently laptops have open-enclosure architectures, so there is interest in the development of fuel cell systems for laptops. Laptops generally have a greater energy and power requirement and are large enough volumetrically to support a fuel cell system at today’s level of technology and miniaturization. The size of today’s cellular phones and their closed-body designs are restrictive factors for fuel cell integration. Although companies like Angstrom Power (Vancouver, Canada) have created prototype cellular phones with integrated fuel cells, there seems to be more interest in portable computing because of fuel and integration considerations (see Sections 3.6.1.3 and 3.6.1.6). Given the interest in laptop computers within the fuel cell industry along with the market's vitality, laptops are selected for further analysis, whereas cell phones are not.

In summary, portable rechargers and power generators, both military and consumer, are chosen as the most attractive target for near-term introduction of fuel cell technology because of their current availability and deployment and their veritable market potential. The third category is laptop computers because of existing R&D of integrated fuel cell systems and fuel and size requirements. While some research has been conducted in cell phones and d-SLR cameras, their size and design reduce their potential for realistic near-term deployment.

3.6.3 Discussion of Technical Needs for Storage

Because fuel cells themselves are power sources, it is not surprising that their application as a power generator is the most prominent in the market today. These fuel cell generators face perhaps the smallest barrier to entry into the market because these devices are not reinventing or even replacing conventional energy storage technologies, such as batteries. In fact, they work in concert with the existing energy storage in typical consumer electronics: these systems inherently rely on the device's batteries or other power source and are meant to be recharged. In this way, instead of competing with batteries—a highly developed and well-established multi-billion dollar industry—these fuel cell devices utilize them by coupling fuel cell-based power generation with the energy storage capacities in existing batteries. Furthermore, from an economic point of view, the cost of such fuel cell systems is distributed over all of the devices recharged, making an external rather than integrated fuel cell device more appealing to manufacture and to use.[44]

Many current fuel cell technologies used for this application rely on methanol. The simplest alcohol, methanol is a liquid at ambient conditions, dense in energy, and relatively stable. In direct methanol fuel cells (DMFCs), methanol is the fuel fed into the system, and carbon dioxide and water are released as waste products according to the follow reaction equations:

Anode: $2CH_3OH + 2H_2O \rightarrow 12H^+ + 12e^- + 2CO_2$

Cathode: $3O_2 + 12H^+ + 12e^- \rightarrow 6H_2O$

Overall: $2CH_3OH + 3O_2 \rightarrow 4H_2O + 2CO_2$

Another technology using methanol is the reformed methanol fuel cell (RMFC), developed at the Lawrence Livermore National Laboratory. This proprietary technology reforms the methanol into hydrogen gas and carbon dioxide before being fed into a so-called "high-temperature PEM" fuel cell.

Because of the carbon in the alcohol, a methanol system can be carbon neutral only if the methanol is produced renewably. However, methanol is popular because of the relative ease with which the fuel can be handled and stored, as compared to hydrogen. From an environmental standpoint, there is much opportunity for a hydrogen fuel cell to compete with methanol fuel cells because hydrogen gas is a carbon-free energy carrier.

3.6.3.1 *Military Portable Power Generators*

The modern soldier's repertoire of equipment has significantly increased overall energy demand. The storage devices needed to provide sufficient energy for individual power consumption have led to an overall increase in the weight of each soldier's load. As Figure 27 shows, the weight that an individual must carry has been correlated with an increased incidence of musculoskeletal injury, and so an effort is being made to find lightweight technologies capable of providing the requisite amount of energy and power. Furthermore, an energy solution must not only have a size that is portable, but also a form factor (shape) that does not hinder a soldier's maneuverability.

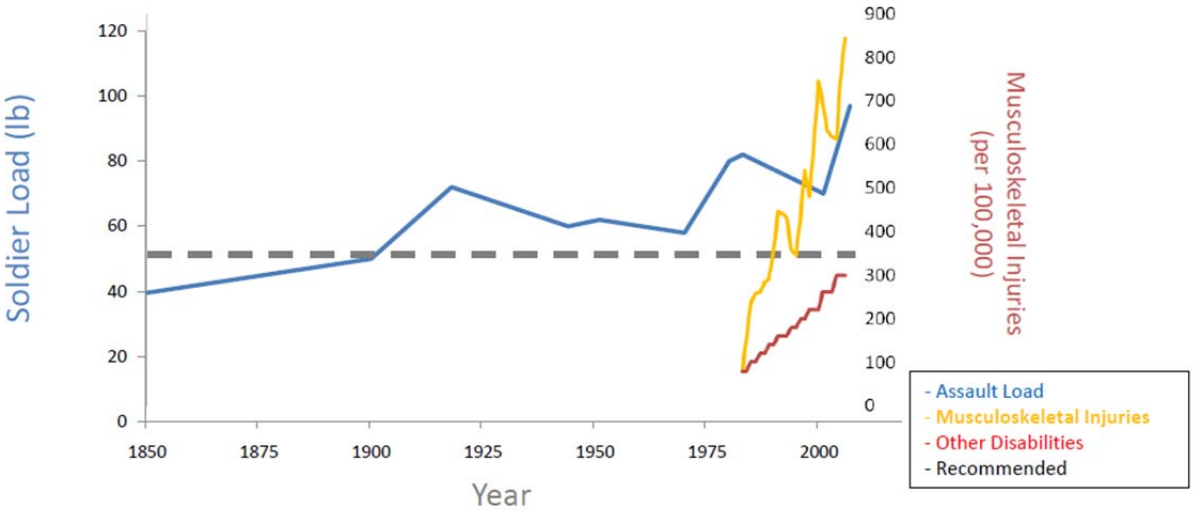


Figure 27. The increased weight of a soldier's load is correlated with an increased incidence of musculoskeletal injury. The military's goal is to reduce the weight of the equipment carried into the battlefield.[31]

Batteries are currently employed by the military to satisfy energy demand. Both primary (disposable) and secondary (rechargeable) batteries are used in the field. In the U.S. Army, soldiers typically carry a variety of primary batteries for each piece of equipment, and for those devices with secondary batteries, they carry another battery to recharge the device batteries. In this way, the versatility of the power source is necessary.

The ultimate goal for the U.S. Army is to have personal power supplies for each soldier on mission acting as continuous "battery toppers" or even to power their devices directly. This need could be met by a fuel cell in the 20 to 50 W power range for each solider. Of interim interest are 300 W systems because at the platoon level, two of these systems can provide the needed recharging power for all the platoon's batteries when the platoon is at rest. These larger systems have less restrictive requirements.

3.6.3.2 *Consumer Portable Power Generators*

The landscape of the consumer market for fuel cells is considerably different from that of the military market. The current target for portable recharging is small devices with USB connectivity, with emphasis on cellular phones and other portable electronics. The fuel cells themselves are compact and versatile. For example, each of the systems is small enough to be carried in-hand and relatively light-weight, producing 5 W of power. Replaceable fuel cartridges are the most common way to refuel these small fuel cells, but there are systems where fuel must be poured into the device. Fuel supplied via cartridges is also sold in addition to the system, but the bulk of the initial cost is in the system and not the fuel.

In competition, there are also many battery-based, grid-powered recharger systems on the market. These enable a user to be away from the grid for an extended period of time and have impressive performance, price, and size. Because of the inconvenience of refueling compared to the ease of grid-recharging, fuel cells would have to not just meet but significantly exceed the capabilities of these devices in order to compete. For example, one company surveyed offered that to overcome this inconvenience, a fuel cell device would need a runtime of more than ten-times that of an otherwise-identical grid-rechargeable device.[35] In other words, they feel a consumer would accept the effort of refueling if they only had to do it one-tenth as often. While this is just one example and may not be applicable to all devices, it highlights consumers' extreme sensitivity to any possible device inconvenience; in this case the act of plugging something into a wall outlet vs. that of finding, purchasing, and installing/refilling some kind of fuel.

3.6.4 Laptop Power

Unlike portable power generators, there are no commercially available laptop computers with integrated fuel cell systems. The lack of integration into consumer electronics reflects the current state of fuel cell development and of the impediments that block fuel cell deployment. While large electronics and computer companies have been filing patents for fuel cell-related technology, the existence of these patents suggests that at most, companies are doing research and have taken action to protect their inventions. Whether or not the subject of the patent will ultimately lead to a commercial product is unknown.

Because remote users are expected to be attracted to an integrated fuel cell system, this study specifically focused on ruggedized laptops designed specifically for this market segment. For example, Panasonic has explored the possibility of fuel cell integration with its own laptops.[30] The commercialization of such laptops indicates that the market does indeed exist, giving hope for future development of integrated fuel cells.

3.6.5 Implications for Hydrogen Storage Technology

Two prominent techniques for storing hydrogen are compressed gas and hydride storage. There are safety issues with compressing hydrogen to high pressures. The risk of stray bullets piercing the tank, for example, and other warzone hazards are of particular concern for wearing compressed hydrogen tanks in military applications. As end users, the soldiers themselves must feel comfortable carrying and using such a system. The fuel must be safe, and perhaps more importantly, it must be *perceived* as safe.

Metal and chemical hydride hydrogen storage systems show promise with regard to safety. They are often held in pressures well below those used in compressed gas and are generally stable during storage. However, metal hydrides are significantly heavier than alternative systems because a metal is used to bind and store hydrogen gas; their gravimetric energy densities are poor. Common chemical hydrides must be recharged off-board or have cartridges that are thrown away or recycled.

A major issue for both military and consumer hydrogen technology is the fuel supply. The infrastructure for hydrogen fuel is nowhere as mature as that of gasoline or grid power, and for remote users, the issue is paramount. In the battlefield, hydrogen, whether compressed or stored as a hydride, introduces a major logistical burden. For typical consumers, hydrogen can be purchased in high-pressure bottles, but is an expensive way to get the fuel with costs approaching $100/kg.

Furthermore, an important aspect of the fuel supply issue is the exact nature of the refueling process. The majority of currently available fuel cell generators use a cartridge mechanism for supplying fuel to the device, and such a system is an important consideration for developing a hydrogen infrastructure. A cartridge supply and recycle system may perhaps facilitate a greater shift towards hydrogen-based energy. By making the fuel supply in the consumer's eyes seem similar in nature to a typical battery, the refueling process is simplified, and consumer adjustment to and acceptance of the new technology should not be an issue.

As mentioned above, UltraLife's LI-145 battery is a good benchmark for evaluating the feasibility of a military battery recharger. Using its energy density, one can see how currently available portable power systems compare. Figures 28 and 29 plot gravimetric and volumetric energy densities respectively, for the entire system (storage and power generating device) from the specifications of portable generators marketed for both military and consumer use. The chart organizes the systems according to fuel source. The horizontal line on the charts is the energy density of the LI-145 battery. The charts show that fuel cell systems perform well on a gravimetric basis, with 8 of the 15 sample fuel cell systems exceeding the gravimetric energy density of the LI-145. However, only 3 of the fuel cell systems have a better volumetric energy density. All of the fuel cell systems that meet or exceed the LI-145 benchmarks are methanol-powered. It is also evident from Figure 28 that there is a trend for the larger-mass systems to have a higher gravimetric energy density: the higher mass of these systems is due to more fuel being carried while the fuel cell remains the same. This trend is not observed for volumetric energy density (Figure 29**Error! Reference source not found.**).

3.6.6 Summary

A variety of issues face hydrogen storage and hydrogen fuel cell deployment in the portable electronics industry. As an energy source, perhaps the most relevant metrics of fuel cell performance are its gravimetric and volumetric energy densities, and because the properties of the fuel are directly related to the total energy density of a system, storage is of primary concern when assessing the future of fuel cell technology. Methanol systems currently dominate this market segment because of the fuel's relatively high energy density, ease of storage, and superior safety issues.

To compete, a hydrogen system must at least achieve energy densities comparable to methanol systems. Significant increases in energy density are important for hydrogen storage development, but many other factors must be dealt with for widespread, near-term deployment of hydrogen fuel cells in man-portable electronics. Issues of safety, compactness, fuel infrastructure, energy competition, market expanse, refueling method, and public perception all affect the viability of the technology.

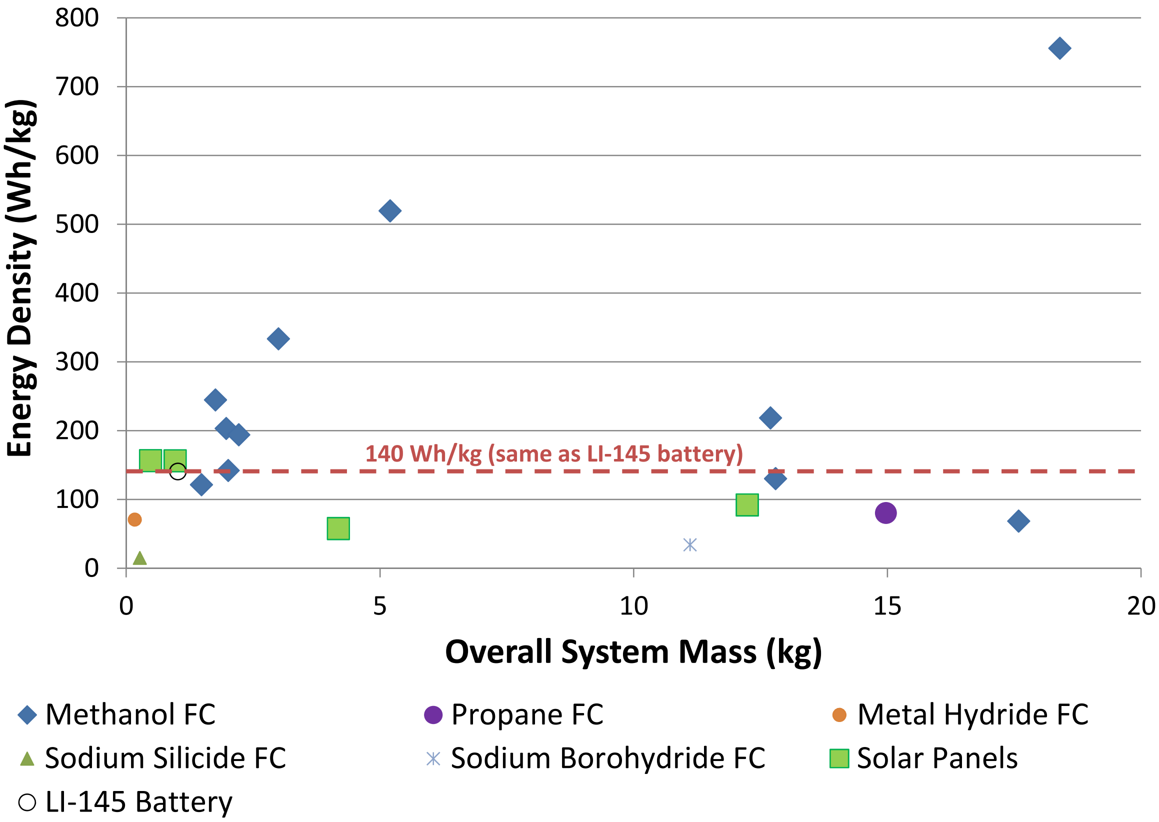


Figure 28. Gravimetric energy density of various currently available portable power systems. Data are for entire systems (power generating device, fuel storage, and full fuel). The dashed horizontal line shows the LI-145 energy density (140 Wh/kg) as a reference. Full specifications for each system shown here are listed in Table A-1.

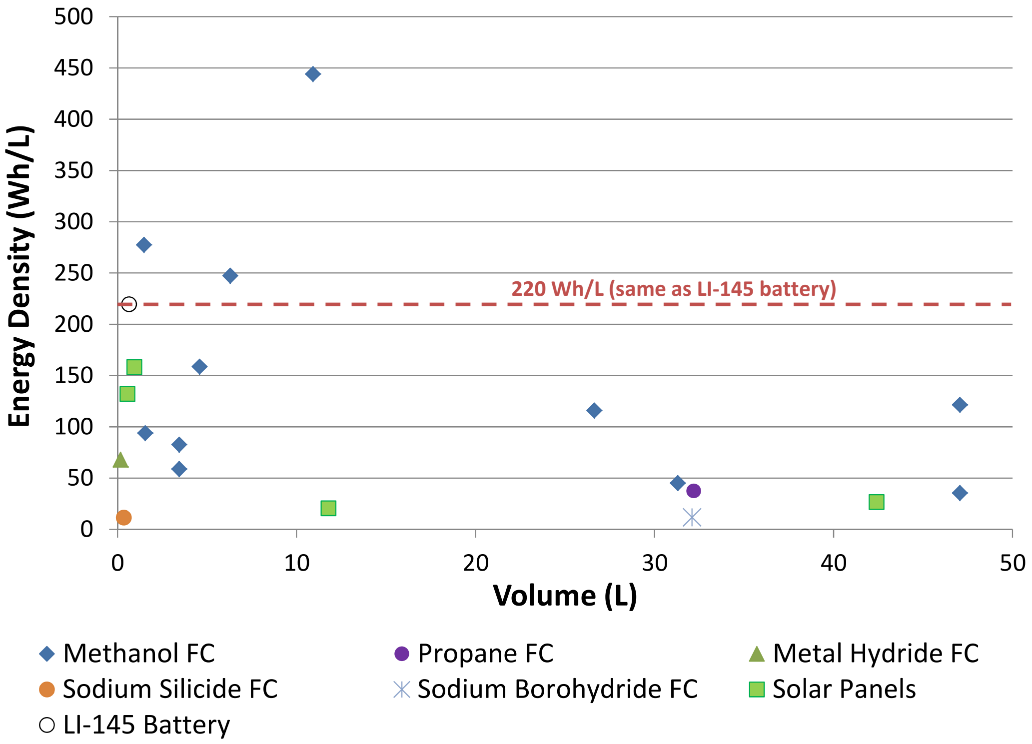


Figure 29. Volumetric energy density of various currently available portable power systems. Data are for entire systems (power generating device, fuel storage, and full fuel). The dashed horizontal line shows the LI-145 energy density (220 Wh/L) as a reference. Full specifications for each system shown here are listed in Table A-1

For the military, the higher efficiencies that fuel cells may offer over other energy sources may appear to be attractive. But from a macroeconomic level, the device must offer some strategic advantage in terms of weight or volume to be worth deployment. Thus, while fuel cell efficiency may realize some savings, this alone is not big enough of a push for widespread, near-term deployment.[31]

The inability of a practical fuel cell system to match the small size of batteries integrated into consumer electronics along with its air-breathing behavior prevent them from being integrated into nearly all of these devices. Where larger sizes and the air-breathing behavior are not an issue, the fuel cell and hydrogen storage system must either:

1. Be as convenient as a battery-grid system, or
2. Have such a large increase in “performance” (defined by the user) as to make its inconvenience a secondary issue.

In the first case, the availability of hydrogen is the primary obstacle. When hydrogen is available, it is usually accompanied by complex and/or unfamiliar equipment that is daunting for the average user. Until this issue is solved, the early market approach needs to essentially insulate the user from hydrogen. This is done by introducing cartridge-type systems that consumers can buy at their local stores and either recycle (similar to the propane exchange at many stores and preferred by manufacturers) or throw away (preferred by most consumers for its convenience, whether civilian or military). This is one of the reasons that chemical hydrides, and to a lesser extent metal hydrides, are currently the preferred hydrogen storage technology for portable power and consumer electronics.

In the second case, if "obvious" hydrogen storage methods are to be used (i.e., compressed gas, liquid, user-refillable metal hydrides, etc.), the inconvenience must be counterbalanced by significantly improved performance. A fuel cell system cannot just be equivalent to the battery system it is replacing but must improve upon it. In the military example, a three-fold increase in energy density of the entire system over the best battery technology is required to make up for the extra refueling burden, whereas in the consumer electronics realm, a more than ten-fold increase was required in one case, highlighting the extreme sensitivity that consumers have toward any inconvenience in a product.

3.6.6.1 *Portable Power—Military*

For military needs, a hydrogen system must at least exceed the gravimetric and volumetric energy densities of the Li-145 lithium battery. It must meet military standards for ruggedness and be in a conformal shape for possible on-body use. It must also exceed the minimum safety requirement to be welcomed for use by soldiers. The fuel must impose minimal strain on the military's logistical operations or perhaps utilize the existing energy infrastructure of a country or region. Compressed gas does not look favorable because of the risk of explosion. Metal hydrides look promising but must overcome relatively poor gravimetric energy densities. Chemical hydrides are also another area with potential.

There has been some research toward certain metal hydride hydrogen storage in which the decomposition reaction that liberates hydrogen gas requires energy. Alane is one such hydride whose decomposition is endothermic.[33] This type of hydrogen storage may be of particular interest to address the heat rejection issue and various safety issues regarding thermal runaway, but ultimately temperature control will be a problem for any integrated fuel cell system.

As for hydrogen technology in the military for portable power, nothing has been considered by the U.S. Army for demonstration or deployment because no companies have submitted a device for evaluation, even at Technology Readiness Levels (TRL) 4, 5, or 6.[31]

The lithium-ion battery LI-145 from Ultralife (Figure 30) is presented first as a benchmark against which any new technology would need to compete with. This is the "workhorse" battery for the U.S. Army's remote deployments. Its specifications are given in Table 22.

Figure 30. A picture of the LI-145 lithium ion battery from UltraLife, for U.S. military soldier power.

Table 22. Specifications of the LI-145 military personnel battery from UltraLife. The stated specifications for the LI-145 supplied by Bren-Tronics are identical.

Specification	Military Personnel Battery
Manufacturer	UltraLife, Bren-Tronics
Model	LI-145
Rated Output Power	28.6 W
Run Duration Per Fill/Charge	5 hr max, 1 hr @ rated power and 80% DOD
Output Power Type	10.0 to 16.8 VDC (15.2 VDC nominal)
Overall Dimensions - L x W x H	8.25" x 1.66" x 2.9"
Overall Volume	39.7 in3
Overall Dry (no fuel) Weight	2.2 lb (1.02 kg)
Fuel/Battery Type	Lithium Ion
Fuel Tank or Charge Capacity	9.4 A-hr
Stored Energy (kW-hr)	143 W-hr
Energy Storage System Volume	0.65 L
Energy Storage System Volumetric Energy Density	220 W-hr/L
Energy Storage System Weight	1020 g
Energy Storage System Gravimetric Energy Density	140 W-hr/kg
Engine/FC Model	Not Applicable
Power System (Engine/FC) Weight	Not Applicable
Power System (Engine/FC) Volume	Not Applicable
Combined Energy + Power System Volume	39.7 in3
Combined Energy + Power System Volumetric Energy Density	220 W-hr/L
Combined Energy + Power System Weight	2.2 lb (1.02 kg)
Combined Energy + Power System Gravimetric Energy Density	140 W-hr/kg
Refuel/Recharge Time	2.5 - 3 hr from empty at C/2
Fuel Consumption	Not Applicable
Emissions	None
Operating Temperature Range	-32 °C to 55 °C
Noise level	Not Available
Overall Cost	Not Available

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
2. Power system refers to the engine that generates mechanical power, generator to convert mechanical to electrical power, and associated hardware.

The following products are a sampling of the available fuel cell technologies for a military battery charger that a hydrogen system would need to compete with. The exact specification for a viable hydrogen technology depends on the application; the U.S. Army is flexible to a certain degree regarding device specifications and is willing to sacrifice some specifications for large increases in energy density (gravimetric and volumetric). The most important attributes a system must have are that it is proven safe and it is easily produced in large quantities. User requirements are also highly dependent on application.[31] Specifications are shown in Table 23.

Figure 31. Picture of the JENNY 600S direct methanol fuel cell from SFC Energy. Specifics are given in Table 23.

Figure 32. Picture of the M300-CX direct methanol fuel cell, with fuel tank (to right) from Protonex. Specifics are given in Table 23.

Table 23. Summary table of existing fuel cell-powered battery chargers for the U.S. military. All are powered by methanol; at a minimum, a hydrogen-powered fuel cell would have to meet these specifications to compete in the market.

Specification	Military Battery Charger - FC	Military Battery Charger - FC	Military Battery Charger - FC
Manufacturer	SFC Energy	UltraCell	Protonex
Model	JENNY 600S	XX55	M300-CX
Rated Output Power	25 W	50 W	300 W
Run Duration Per Fill/Charge	11.4 hr (60% methanol/40% water) or 16 hr (100% methanol) at rated power	10 hr @ rated power, 21 hr @ 40% load	4.4 hr @ rated power
Output Power Type	10-30 VDC	12-33 VDC	28 VDC nominal
Overall Dimensions - L x W x H	25.2 cm x 18.4 cm x 7.44 cm	27.2 cm x 20.8 cm x 8.1 cm	30 cm x 37 cm x 24 cm
Overall Volume	3.45 L	4580 cm3	26.6 L
Overall Dry (no fuel) Weight	1.6 kg	1.6 kg	16 kg
Fuel/Battery Type	Methanol	Methanol	Methanol
Fuel Tank or Charge Capacity	350 mL	550 mL	2 L
Stored Energy (kW-hr)	400 W-hr (100% methanol), 285 W-hr (60% methanol/40% water)	430 Wh	1200 Wh
Energy Storage System Volume	0.385 L (est.)	1.146 L	2.2 L (est.)
Energy Storage System Volumetric Energy Density	1143 W-hr/L (100% methanol)	375 W-hr/L	545 W-hr/L
Energy Storage System Weight	371 g (regular) 410 g (desert)	620 g	1588 g
Energy Storage System Gravimetric Energy Density	1078 W-hr/kg (100% methanol	694 W-hr/kg	756 W-hr/L
Engine/FC Model	PEM	PEM	SOFC
Power System (Engine/FC) Weight	1.23 kg (est.)	1.6 kg (est.)	16 kg
Power System (Engine/FC) Volume	3.065 L (est.)	4.58 L (est.)	26.6 L
Combined Energy + Power System Volume	3.45 L	5.73 L	28.8 L
Combined Energy + Power System Volumetric Energy Density	116 W-hr/L	75 W-hr/L	41.7 W-hr/L
Combined Energy + Power System Weight	1.971 kg	2.22 kg	17.6 kg
Combined Energy + Power System Gravimetric Energy Density	203 W-hr/kg	193.7 W-hr/kg	68.2 W-hr/kg
Refuel/Recharge Time	< 5 min. (est.)	< 5 min. (est.)	< 5 min. (est.)
Fuel Consumption	< 1 L/kWh @ 25 W	Not Available	450 mL/hr @ 100% load
Emissions	CO_2, water	CO_2, water	CO_2, water
Operating Temperature Range	-32 °C to 35 °C (Reg), 10 °C to 55 °C (Desert)	-20 °C to +50 °C	-20 °C to +50 °C
Noise level	< 37 dB @ 1 m	Not Available	Not Available
Overall Cost	Not Available	Not Available	Not Available

Table notes: 1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware. 2. Power system refers to the engine that generates mechanical power, generator to convert mechanical to electrical power, and associated hardware.

3.6.6.2 *Summary: Portable Power—Consumer*

Competing energy sources pose an immense obstacle in the way of more widespread adoption of small fuel cell technologies. One potential advantage of a fuel cell power source—a longer device operating time—is perhaps unimportant to a typical consumer, who will rarely be away from grid power sources for an extended time period. A viable hydrogen fuel cell and accompanying hydrogen storage must be conscious of the target consumer audience for its products. While there are less explicit requirements for the system's performance, issues like efficiency, weight, size, power rating, and energy content indirectly influence the subset of consumers who would be interested in such a technology. A competitive system that is easy to use, extremely portable, and environmentally friendly could perhaps appeal to a larger group of consumers.

For consumers, several battery rechargers are available on the market today, including grid-rechargeable battery packs and fuel cell units. Two of the larger battery packs are shown below in Figures 33 and 34, and two fuel cell units are shown in Figures 35 and 36. The specifications are presented in Table 24. As mentioned in Section 3.6.3.2, consumers are extremely sensitive to added inconvenience in the products they purchase. For one product, it was stated that a fuel cell-powered device must run at least ten-times longer than an otherwise identical battery-powered device to make up for the added inconvenience of refueling the fuel cell compared to grid recharging. The data in the table below indicate that battery-based systems currently have 2 to 5 times the energy density as fuel cell based systems; it will be a challenge for similarly sized fuel cells systems to catch up, much less achieve 10 times *greater* energy density than the battery systems. However, if the overall amount of energy to be stored is increased (along with the unit's size) then it becomes easier for fuel cell devices to compete because the typical fuel energy storage capacities are inherently greater than that of the battery.

Figure 33. The Energizer XP4001 travel charger, shown recharging a mobile phone and iPod. It has a 4,000 mAh lithium polymer battery. Specifications are given in Table 24.

Figure 34. The New Trent iCruiser IMP1000 (on the left) recharging an iPhone 4. It has an 11,000 mAh lithium polymer battery. Specifications are given in Table 24.

Figure 35. A picture of the PowerTrekk consumer fuel cell battery recharger from myFC. Specifications are given in Table 24.

Figure 36. A picture of the MiniPAK consumer fuel cell battery recharger from Horizon Fuel Cell Technologies. Specifications are given in Table 24.

Table 24. Specifications for consumer rechargers, both battery and fuel cell-based.

Specification	Consumer Battery Charger	Consumer Battery Charger	Consumer Battery Charger - FC	Consumer Battery Charger - FC	Consumer Battery Charger - FC
Manufacturer	New Trent	Energizer	myFC	Horizon Fuel Cell Technologies	Toshiba America Electronic Components
Model	iCruiser IMP1000	XP4001 Travel Charger	PowerTrekk	MiniPAK	Dynario
Rated Output Power	2.5 W	2.5 W	2.5 W	2.5 W	2.5 W
Run Duration Per Fill/Charge	13.2 hr @ rated power and 60% DOD	4.8 hr @ rated power and 60% DOD	3.9 hr @ rated power and 60% DOD battery	4.8 hr @ rated power	4.8 hr @ rated power
Output Power Type	5 VDC	5 VDC	5 VDC	5 VDC	5 VDC
Overall Dimensions - L x W x H	10.2 x 9.5 x 2.9 (cm3)	13 x 8 x 1.4 (cm^3)	6.6 x 12.8 x 4.2 (cm^3)	10.4 x 6.8 x 2.5 (cm^3)	15.0 x 2.10 x 7.45 (cm^3)
Overall Volume	281 cm3	146 cm3	0.355 L	0.177 L	0.235 L
Overall Dry (no fuel) Weight	285 g	150 g	200 g (no battery)	80 g	280 g
Fuel/Battery Type	Lithium polymer battery	Lithium polymer battery	Hybrid: Fuel cell + NaSi powder and Li-ion battery	Fuel cell + metal hydride H2	Hybrid: Direct methanol fuel cell and Li-ion battery
Fuel Tank or Charge Capacity	11,000 mAh	4,000 mAh	2,600 mAh (1,600 mAh in battery, 1,000 mAh in fuel)	2,400 mAh	2,600 mAh (estimate) (660 mAh in battery)
Stored Energy (kW-hr)	55 W-hr	20 W-hr	9.9 W-hr (4 W-hr in fuel, 5.9 W-hr in battery)	12 W-hr	13 W-hr (estimate)

Specification	Consumer Battery Charger	Consumer Battery Charger	Consumer Battery Charger - FC	Consumer Battery Charger - FC	Consumer Battery Charger - FC
Energy Storage System Volume	0.28 L	0.15 L	0.195 L (est.)	0.031 L	0.022 L
Energy Storage System Volumetric Energy Density	196 Wh/L	137 Wh/L	50.8 Wh/L	390 Wh/L	591 Wh/L
Energy Storage System Weight	285 g	150 g	150 g (est.)	75 g	31 g
Energy Storage System Gravimetric Energy Density	193 Wh/kg	133 Wh/kg	66 Wh/kg	160 Wh/kg	419 Wh/kg
Engine/FC Model	Not Applicable	Not Applicable	PEM	PEM	DMFC
Power System (Engine/FC) Weight	Not Applicable	Not Applicable	135 g (est.)	80 g	260 g
Power System (Engine/FC) Volume	Not Applicable	Not Applicable	0.159 L (est.)	0.146 L (est.)	0.213 L
Combined Energy + Power System Volume	281 cm3	146 cm3	0.355 L	0.177 L	0.235 L
Combined Energy + Power System Volumetric Energy Density	196 Wh/L	137 Wh/L	28 Wh/L	68 Wh/L	55 Wh/L
Combined Energy + Power System Weight	285 g	150 g	285 g	155 g	291 g
Combined Energy + Power System Gravimetric Energy Density	193 Wh/kg	133 Wh/kg	34.7 Wh/kg	77 Wh/kg	45 Wh/kg
Refuel/Recharge Time	4-5 hr (user feedback)	4 hr	Cartridge swap	Cartridge swap	< 1 min.
Fuel Consumption	Not Applicable	Not Applicable	Not Available	Not Available	Not Available
Emissions	None	None	Water	Water	Water and CO_2
Operating Temperature Range	-10 °C to 45 °C	n/a	5 °C to 30 °C	0 °C to 40 °C	10 °C to 35 °C
Noise level	No noise	No noise	Not Available	Not Available	Not Available
Overall Cost	$76.95 (as of 9/12/2011)	$49.99 (as of 9/12/2011)	$200 + $2 for each fuel cartridge (forecast)	$99 with 2 cartridges, $9.99 per cartridge. Higher production levels*: $29.99 for unit and $5.99 for cartridge	$325 (reported 10/29/2010, since discontinued)

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
2. Power system refers to the engine that generates mechanical power, generator to convert mechanical to electrical power, and associated hardware.

*The number of units corresponding to "higher production levels" has not been publicly defined by the manufacturer.

3.6.6.3 *Summary: Laptop Computers*

An integrated laptop system must have very sensitive temperature and perhaps humidity control to deal with the fuel cell waste heat. As with portable power, a hydrogen fuel cell option must be able to, as a system, meet or exceed the performance of laptop computer batteries. A storage solution that acts as a heat sink would be extremely beneficial in the overall system design. The device and fuel storage must also be rugged enough for normal operation.

Panasonic's Toughbook series is a prime example of the ruggedized laptop computer that would be of interest to the remote user. Panasonic offers models with different degrees of ruggedness. The fully ruggedized model with the longest battery life model was selected for illustration—the Toughbook 31. A picture is shown in Figure 37 and the specifications are given in Table 25.

Figure 37. The Panasonic Toughbook 31 laptop computer. This laptop is a prime example of a computer that is commonly used by customers who are away from the grid for extended periods of time and would benefit from the longer run-time that a fuel cell could provide.

Table 25. Specifications of the Panasonic Toughbook 31 laptop computer.

Specification	Laptop Computer
Manufacturer	Panasonic
Model	Toughbook 31 (i5 CPU)
Rated Output Power	8 W (idle) to 35 W (heavy use)
Run Duration Per Fill/Charge	12.5 hr at idle, 2.6 hr at heavy use
Output Power Type	10.65 VDC (battery)
Overall Dimensions - L x W x H	11.5" x 11.9" x 2.9"
Overall Volume	397 in3
Overall Dry (no fuel) Weight	7.9 lb
Fuel/Battery Type	Li-ion
Fuel Tank or Charge Capacity	8.55 A-hr
Stored Energy (kW-hr)	91.1 W-hr
Energy Storage System Volume	0.774 L
Energy Storage System Volumetric Energy Density	118 Wh/L
Energy Storage System Weight	475 g
Energy Storage System Gravimetric Energy Density	192 Wh/kg
Engine/FC Model	Not Applicable
Power System (Engine/FC) Weight	Not Applicable
Power System (Engine/FC) Volume	Not Applicable
Combined Energy + Power System Volume	0.774 L
Combined Energy + Power System Volumetric Energy Density	118 Wh/L
Combined Energy + Power System Weight	475 g
Combined Energy + Power System Gravimetric Energy Density	192 Wh/kg
Refuel/Recharge Time	3.5-4 hr
Fuel Consumption	Not Applicable
Emissions	None
Operating Temperature Range	5 °C to 35 °C
Noise level	Not Available
Overall Cost	$4000 for the computer, $160 for the battery (reported 12/12/11)

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware.
2. Power system refers to the engine that generates mechanical power, generator to convert mechanical to electrical power, and associated hardware.

3.6.7 *Summary Table of Technical Needs*

Some of the relevant energy storage needs for these technologies are summarized below. Table 26 summarizes the energy storage requirements for each piece of equipment. It is the result of stakeholder feedback on what they require from their equipment (taken from interviews and correspondence). In several cases, the feedback was unanimous in stating that the requirements for a hydrogen fuel cell-powered version of a piece of equipment match the specifications of the existing equipment, so in those instances the numbers used for the requirements are generated largely from the specifications (shown previously in Table 22 for the military personnel battery, Table 24 for the consumer battery charger, and Table 25 for the laptop computer). In cases where the stakeholder feedback indicated differences between what they would like to see in fuel cell versions and the current equipment, the stakeholders' numbers are used to generate the requirements shown in the table. So, the stakeholder feedback is the driver for developing the requirements and it is utilized it without judgment. The only modifications to this feedback occurred when it was ambiguous or conflicting, and in those instances investigators used their own knowledge to clarify and decide the most appropriate requirement.

Table 26. Energy storage requirements for a hydrogen fuel cell powered version of each man-portable power supply and consumer electronics device.

Application	Military Personnel Battery	Consumer Battery Charger	Specialized Laptop Computer
Requirements			
Rated Output Power	30 W nominal and 85 W for short bursts	2.5 W	8 W (idle) to 35 W (heavy use)
Run Duration Per Fill/Charge	> 15 hr	40 hr to 100 hr @ rated power	8 hr to 24 hr at heavy use
Restrictions			
Energy Storage System Volume[1]	0.65 L	0.28 L	0.774 L
Energy Storage System Weight[1]	1.02 kg	0.285 kg	0.475 kg
Refuel/ Recharge Time	Cartridge swap	Cartridge swap	Cartridge swap
Operating Conditions - Temperature	MIL-STD-810 (-31 °C to 49 °C)	-10 °C to 45 °C	MIL-STD-810 (-31 °C to 49 °C)
Operating Conditions - Weather[2]	Extreme (MIL-STD-810)	Not designed for weather exposure	MIL-STD-810, IP65 enclosure
Noise level[3]	Negligible	Negligible	Negligible
Emissions	Warm air or none	Warm air or none	Warm air or none

Table notes:

1. Energy storage system refers to the full fuel tank and/or batteries with associated hardware. Restrictions on size assume the storage of enough energy to meet the rated output power for the required run duration; if more energy is stored these restrictions may be relaxed.
2. Extreme weather conditions include rain, snow, hail, ice, blowing sand, blowing water, dirt, mud, dust, high elevation, salt air, and humidity extremes.
3. All noise levels when operating at rated load, at a distance of 5 m unless stated otherwise.

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4 Final Report Summary and Conclusions

In addition to the description of our methods, this report described the five categories of equipment and for each category gave a list of selected specific applications. (For reference, a complete list of equipment categories and the selected applications is given in Table 27.) For each application, a description of its end user requirements, market, technical needs, and implications on hydrogen storage were also given. In this section those findings are summarized. The resulting summary table of energy storage requirements for hydrogen fuel cell-powered versions of each piece of non-motive equipment included in this work is given as Table 1 in the Executive Summary at the beginning of this report.

Table 27. Summary list of the equipment categories and selected applications identified in this study.

Equipment Category	Identified Applications
Construction	Lighting, scissor lifts, air compressors
Aviation ground support	Ground power unit
Telecom	Backup power
Portable power	Small (< 10 kW) generators, large (> 10 kW) generators
Man-portable power and consumer electronics	Military power supplies, consumer power supplies, laptop computers

In construction equipment, portable lighting, scissor lifts, and air compressors were identified for their high potential. The market for all of these is estimated to be in the 100,000's per year. Current lighting and air compressor units are typically diesel powered, while scissor lifts are battery powered, with specifications given in Table 5. For the end user, hydrogen fuel cells are attractive in these applications because of their low emissions and quiet operation. In addition, because many of the lighting and compressor units are towed on trailers, they are amenable to the larger volumes that hydrogen fuel cell systems would occupy compared to diesel generators. Customers of construction equipment are cost-sensitive but are willing to look past the initial cost, taking into account the total cost of a piece of equipment over the duration of a project.

For aviation ground support equipment (GSE), ground power units (GPU) were identified as a primary application and boom lifts as secondary. Portable heater carts were also initially identified but upon further analysis of their power needs they were discarded. Although GPUs are essential airport equipment, their U.S. market is limited and estimated to be in the hundreds or low thousands per year. Boom lifts used air airports are similarly limited in market size, but their application to the construction industry may make them more attractive from a market standpoint, although the size of their overall market is unknown at this time. Specifications for the GPUs are given in Table 8, and that for the boom lifts in Section 3.3.4. For the end user, fuel cells are attractive replacements primarily because they are zero-emission. Current GPUs can tolerate the potentially increased size and weight that a hydrogen fuel system would require compared to its existing diesel power plant. However, the airlines and the service companies that use these pieces of equipment are very capital-cost sensitive and would probably consider a replacement piece of equipment that is similar in cost, or at most, can show a cost-benefit in less than five years.

Portable power was looked at as a separate category, but the need for portable power also arose in discussions about construction equipment and airport GSE. The portable power market is substantial: nearly 1 million units sold per year in North America. Of these, about 80% are less than 10 kW. Existing portable power generators have several limitations that could be improved by fuel cell technology. Small generators have short lifetimes, on the order of 2500 hours and cost $400 to $600/kW. They also require significant preventive maintenance that results in high operating costs (as high as $1400/yr). For some applications these generators are too loud, and, while quieter models are available, they are more expensive and still not quiet enough.

In addition to having noise and maintenance issues like the small gasoline units, large portable generator units are difficult to operate at low load, where they continue to consume 30 to 40% of full load fuel, resulting in poor fuel efficiency. This low load operation results in incomplete combustion or wet stacking, which fouls the exhaust system and requires additional maintenance. Emissions from the diesel units can also be a problem both for the environment and people nearby. The projected costs of a hydrogen fuel cell system at high volume seem to be competitive with the smaller units. There is also likely to be some acceptance of the increase in size and weight that a hydrogen fuel cell would require in many applications, but those marketed for handling by a single person may be excluded. A summary of the specifications of low-power generators is given in Table 14 and of high-power generators in Table 15.

Telecom backup power is a category that was previously identified by DOE as a target application for fuel cells, and fuel cells are currently being deployed in this area: The U.S. currently has 3.7 megawatts of fuel cells deployed at about 1300 sites. Perhaps because of this experience, the feedback received from end users in this market was more focused on the benefits and drawbacks of hydrogen fuel cells compared to diesel or gasoline generators. One of the benefits listed was that the fuel cell systems are potentially easier to site indoors because of their low noise and zero emissions, although it was noted that regulations surrounding hydrogen storage sometimes preclude this. Another benefit to fuel cell systems is their ability to load follow, whereas fossil-fuel generators may idle for long periods of time, leading to low efficiency and exhaust fouling (wet-stacking). However, one concern for telecom backup power providers was that transporting and supplying hydrogen to remote environments can sometimes be more difficult than supplying diesel or gasoline, which can be carried by hand in a fuel can. A summary of the technical specifications of telecom backup power is shown in Table 20.

Finally, three applications were identified in the man-portable power and consumer electronics market: power supplies for the military, power supplies for the consumer, and laptop computers. In the military market, current fuel cell solutions focus on battery chargers but since the U.S. military's ultimate goal is a battery replacement, that application is selected here. For consumers, the hydrogen fuel cell product that is most likely to be accepted by the end user in the near term is a battery charger. In either application, the end users conveyed that the advantage of a hydrogen fuel cell is that it can replace grid power when not available, or replace fossil-fuel generators with a zero-emissions, quieter solution. The laptop computer market was identified as being the only feasible place for a fuel cell to be integrated into a product in the near term. The benefit is seen as a longer run time, but competition with the current battery is difficult—a summary of the laptop's technical specifications is given in Table 25.

In terms of markets, the military market is limited, with the U.S. Army indicating that all of their recharging needs could be met by a few thousand units. The consumer market is a new area and the market projections that exist are highly protected by the companies who are currently competing in this area, but it is believed to be in the millions. In spite of this market potential, end users and manufacturers feel that hydrogen fuel cell devices have some substantial challenges. First, they must compete (both on a size and cost basis) with other charging solutions such as the grid or, if absent, battery-based rechargers. Second, the feedback received was unanimous in expressing concern with requiring end users to obtain hydrogen to refuel the device, basically saying that they do not believe enough consumers would believe this effort would be worth the benefit to justify development of such a product. Lastly, it is largely believed that a hydrogen fuel cell integrated into existing devices, including laptops, may never be able to compete with battery storage.

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Appendix A: Supplementary Tables—System Data and Patent Filings

Table A-1 contains data for Figures 28 and 29**Error! Reference source not found.**. Volumes marked * indicate systems where the fuel cartridge volume is accounted for in the device dimensions. The total volume for the XX25 using the 550 mL fuel tank, marked †, is approximated. The energy content for the three solar panel systems, marked §, are daily averages taken from the manufacturer's website. Total volumes for all other systems are the sum of the volumes of the device and of the fuel. Fuel dimensions with only two entries have the diameter of the cylinder as the first value. Energy content data is not available for Toshiba's Dynario system (discontinued).

A sampling of recent patent filings by major brand names is shown in Table A-2.

Table A-1. Full specification data for the systems shown in Figures 28 and 29.

Company	Product	Dimensions (cm)			Mass (g)	Fuel Tank Dimensions (cm)			Fuel Mass (g)	Total Mass (kg)	Total Volume (L)	Power (W)	Energy Content (Wh)	Gravimetric Energy Density (Wh/kg)	Volumetric Energy Density (Wh/L)
myFC	PowerTrekk	6.6	12.8	4.2	240		5.2	1.9	30	0.27	0.355*	5	4	14.8	11.3
SFC Energy	JENNY 600S (Regular)	25.2	18.4	7.44	1600	16.5	6	6	371	1.971	3.45*	25	400	202.9	115.9
	JENNY 600S (Desert)	25.2	18.4	7.44	1600	16.5	6	6	410	2.01	3.45*	25	285	141.8	82.6
	JENNY ND Terra (Regular)	49.9	39.3	24	10500	23.1	15.3	11.5	2200	10.5	47.1*	25	2770	263.8	58.9
	JENNY ND Terra (Desert)	49.9	39.3	24	10500	23.1	15.3	11.5	2300	10.5	47.1*	25	1666	158.7	35.4
UltraCell	XX25	23	15	4.3	1140	22.5	4.63	4.88	345	1.49	1.48*	25	180	121.2	121.3
		23	15	4.3	1140	23.5	7.5	6.5	620	1.76	1.55†	25	430	244.3	277.4
	XX55 w/o battery	27.2	20.8	8.1	1600	23.5	7.5	6.5	620	2.22	4.58*	50	430	193.7	93.8
		27.2	20.8	8.1	1600	26.25	17.5	3.75	1400	3.00	6.3	50	1000	333.3	158.6
		27.2	20.8	8.1	1600	30.63	14.38	14.38	3600	5.2	10.9	50	2700	519.2	247.3
		27.2	20.8	8.1	1600	45	23.75	25	16800	18.4	31.3	50	13900	755.4	444.1
Trulite	KH4	34.8	21.59	41.15	10433		7.62	25.91	680	11.11	32.1	150	375	33.7	11.7
Horizon	MiniPAK	10.4	6.8	2.5	80		2.2	8.1	90	0.17	0.177*	2	12	70.6	67.9
Toshiba	Dynario	15	2.1	7.45	280	6.2	2.91	12.2	92	0.372	0.235*	2	–	–	–
FTL Solar	PowerFold 20	20.3	36.8	0.762	480	0	0	0	0	0.48	0.569	19.52	$75^{\S}$	156.3	131.8
	PowerFold 40	20.3	36.8	1.27	963	0	0	0	0	0.963	0.949	19.05	$150^{\S}$	155.8	158.1
	PowerFold 300	35.6	116.8	10.2	12240	0	0	0	0	12.24	42.4	300	$1125^{\S}$	91.9	26.5
Protonex	M300-CX	30	37	24	16000	24.89	21.84	4.83	1588	17.59	26.6*	300	1200	68.2	45.0
UltraLife	UBBL06 Type LI-145	20.96	7.37	4.22	1021	0	0	0	0	1.021	0.652	–	143	140.1	219.4
Bren-Tronics	REPPS system with Solar Panel	30.48	30.48	12.7	2770	133.3	76.2	0.635	1410	4.18	11.8	62	240	57.4	20.3
AMI	300W Propane FC APU	40	20.32	35.56	14515		20.32	10.16	456.3	14.97	32.2	300	1200	80.2	37.3

Table A-2. A sample of recent fuel cell-related U.S. patents that are assigned to consumer electronics companies.

Assignee	Invention	Inventors	U.S. Application Number	Date of Patent
Apple Inc.	Current Collector Plates of Bulk-Solidifying Amorphous Alloys	Trevor Wende, *Boston, MA*	10/548,979	Jan. 4, 2011
Canon Kabushiki Kaisha	Fuel Cell Apparatus Having Fuel Cell Stack and Controller, and Method of Manufacturing Same	Satoshi Mogi, *Yamato, JP* Masaaki Shibata, *Tokyo, JP*	11/300,349	Oct. 19, 2010
	Fuel Cell	Akiyoshi Yokoi, *Yokohama, JP*	12/293,446	Nov. 5, 2009
	Electric Power Supply System of Fuel Cell	Masaaki Kanashiki, *Yokohama, JP*	11/846,754	Apr. 3, 2008
	Fuel Cells Cartridge and Electric apparatus Having Built-In Fuel Cell	Shoji Ihara, *Yokohama, JP*	10/998,640	Jun. 29, 2010
Casio Computer Co.	Chemical Reactor and Fuel Cell System	Tadao Yamamoto, *Tokyo, JP* Masaharu Shioya, *Akiruno, JP*	12/001,325	Jul. 27, 2010
	Fuel Cell System, Fuel Cell System Drive Method and Fuel Container for Power Generation	Yasunari Kabasawa, *Hannou, JP*	12/503,233	Nov. 5, 2009
Motorola, Inc.	Fuel Cell Using Variable Porosity Gas Diffusion Material	Sivakumar Muthuswamy, *Tower Lakes, IL* Steven D. Pratt, Fort Lauderdale, FL Ronald J. Kelley, *Plantation, FL* Gene Kim, Alpharetta, GA	10/687,943	Nov. 7, 2006
Nikon Corporation	Power Supply Apparatus Using Fuel Cell	Seishi Ohmori, *Tokyo, JP*	12/289,842	May 21, 2009
Panasonic Corporation	Liquid Fuel Container, Fuel Cell System, and Portable Information Terminal Device	Makoto Iyoda, *Sakai, JP* Hiroto Inoue, *Hirakata, JP* Suguru Nakao, *Itami, JP* Yukihiro Iwata, *Ibaraki, JP* Yasuo Yokota, *Hirakata, JP* Toshiaki Takasu, *Osaka, JP*	10/567,603	Feb. 22, 2011
	Fuel Cell Separator and Fuel Cell Including Same	Shinsuke Takeguchi, *Osaka, JP* Takashi Nakagawa, *Osaka, JP* Yoichiro Tsuji, *Osaka, JP*	12/767,507	Sep. 9, 2010
	Electrode for Fuel Cells and Method for Manufacturing the Same, and Fuel Cell Using the Same	Junichi Kondo, *Hyogo, JP*	12/771,468	Nov. 4, 2010
	Dynamically Controllable Direct Oxidation Fuel Cell Systems & Methods Therefor	Takashi Akiyama, *Osaka, JP* Chao-Yang Wang, State College, PA	12/837,985	Jan. 13, 2011
	Fuel Cell Stack	Yakashi Akiyama, *Suita, JP* Kohji Yuasa, *Hirakata, JP*	11/099,627	Jun. 29, 2010

Assignee	Invention	Inventors	U.S. Application Number	Date of Patent
		Hideyuki Ueda, *Ibaraki, JP* Shinsuke Fukuda, *Moriguchi, JP*		
Research in Motion Ltd.	Location of a Fuel Cell on a Mobile Device	Chris Wormald, Waterloo, Canada Raymond Reddy, Toronto, Canada Lyall Kenneth, Waterloo, Canada	12/394,641	Sep. 2, 2010
	Attachment for a Fuel Tank of a Fuel Cell Powered System and Electronic Portable Device Equipped Therewith	Dave Rich, Waterloo, Canada Chee-Ming Jimmy Wu, *Waterloo, Canada*	12/394,679	Sep. 2, 2010
Samsung Electronics Co., Ltd.	Organic/Inorganic Complex Proton Conductor, Electrode for Fuel Cell Using the Same, Electrolyte Membrane for Fuel Cell Using the Same, and Fuel Cell Including the Same	Myung--jin Lee, *Seoul, KR* Tae-young Kim, *Seoul, KR* Pil-won Heo, *Yongin-si, KR*	12/902,487	Jun. 16, 2011
Samsung SDI Co., Ltd.	Electrolyte for Fuel Cell and Fuel Cell Employing the Same	Atsuo Sonai, *Yokohama, JP* Toshihiko Matsuda, Chudoji Minami-machi, JP	11/188,780	Jan. 19, 2010
	Catalyst for a Water Gas Shift for a Fuel Cell System, a Method of Preparing the Same, and a Fuel Cell System Including the Same	Leonid Gorobinskiy, *Yongin-si, KR*	11/655,406	Apr. 7, 2009
	Air Breathing Direct Methanol Fuel Cell Pack	Kyoung Hwan Choi, *Kyungki-do, KR* Hyuk Chang, Kyungki-do, KR	10/259,291	Feb. 2, 2010
	Mesoporous Carbon, Manufacturing Method Thereof, and Fuel Cell Using the Mesoporous Carbon	Sang Hoon Joo, *Yongin-si, KR* Chan-ho Pak, *Seoul, KR*	11/445,235	Aug. 17, 2010
Sony Corporation	Fuel Cell Unit, Fuel Cell Stack, and Electronic Device	Kengo Makita, *Kanagawa, JP* Shinichi Uesaka, *Kanagawa, JP*	12/933,272	Feb. 24, 2011
	Fuel Cell and Fuel Cell System, and Electronic Device	Kiyoshi Kumagae, *Kanagawa, JP*	12/727,919	Sep. 30, 2010
	Fuel Cell and Method of Manufacturing Fuel Cell	Masahiro Kinoshita, *Aichi, JP*	12/997,741	Apr. 28, 2011
	Power Generation Unit and Fuel Cell	Kazuhiko Otsuka, *Saitama, JP*	11/048,796	Jun. 16, 2009
	Fuel Cell Apparatus and Method for Controlling Fuel	Masahiko Tahara, *Kanagawa, JP*	10/478,393	Jul. 14, 2009

Appendix B: Example of Kano Analysis

The description of the Kano methodology in Section 2.3 considered a cell phone; it asked how do people feel about the ON button. The functional or positive Kano question could be, “How would you feel if the cell phone had an “ON button?” The dysfunctional question is, “How would you feel if the cell phone did not have an ON button?.” More than likely, people would EXPECT the cell phone to have the ON button. They would not just like it, they expect it! They would answer 4 to the first functional question. In addition, they would intensely dislike a phone without an ON button, giving a 1 for the second dysfunctional question, so the answers can be designated (4, 1). That answer would identify the ON button feature as a Dissatisfier that indicates that the feature is essential. The Dissatisfier identifies required features.

Continuing with the cell phone example, one might want to learn about how people feel about cell phone maintenance. The functional (more positive) question can be asked, “How would you feel if the cell phone was rarely sent back to the company for maintenance?” The companion dysfunctional (or more negative) question would be, “How would you feel if the cell was sent back a lot to the manufacturer?” A likely response would be a 5 (I like it) to the functional question, and a 1 (dislike it) for the dysfunctional question. This (5, 1) score identifies the feature of maintenance as a Satisfier. The Satisfiers identify directions of growing customer satisfaction, which means that the less frequency you return the cell phone to the store, the better. The more people who answer that way, the clearer the result becomes. A (1, 5) response to this set of Kano questions would indicate an irrational answer, and suggests a “Questionable” Kano response result (perhaps the question was misunderstood).

As a final example, one can ask if a brand new feature would be of interest to cell phone users. Suppose a new technology is developed—the “Find Me” technology—that allows cell phones to “know” when they are lost and then alert their owners. How would people feel about that? Currently people live with the inconvenience of misplaced cell phones without too much bother, but would people like to have that capability? The pair of Kano questions would be posed, “How would you feel if your cell phone had a feature that allowed you to find it when it was lost?” (the functional question), and conversely, “How you feel if the cell phone could not tell you this?” (the dysfunctional question). The result would probably be a (5, 3). Currently phones cannot do this, so if a new cell phone does not have this capability, it is not that big a deal to a customer (the 3). But if the capability was present, the customer would really like it (the 5). The (5, 3) score identifies the new “Find Me” technology as a Delighter. The delighter identifies new areas of customer satisfaction to which the customer has no previous experience.

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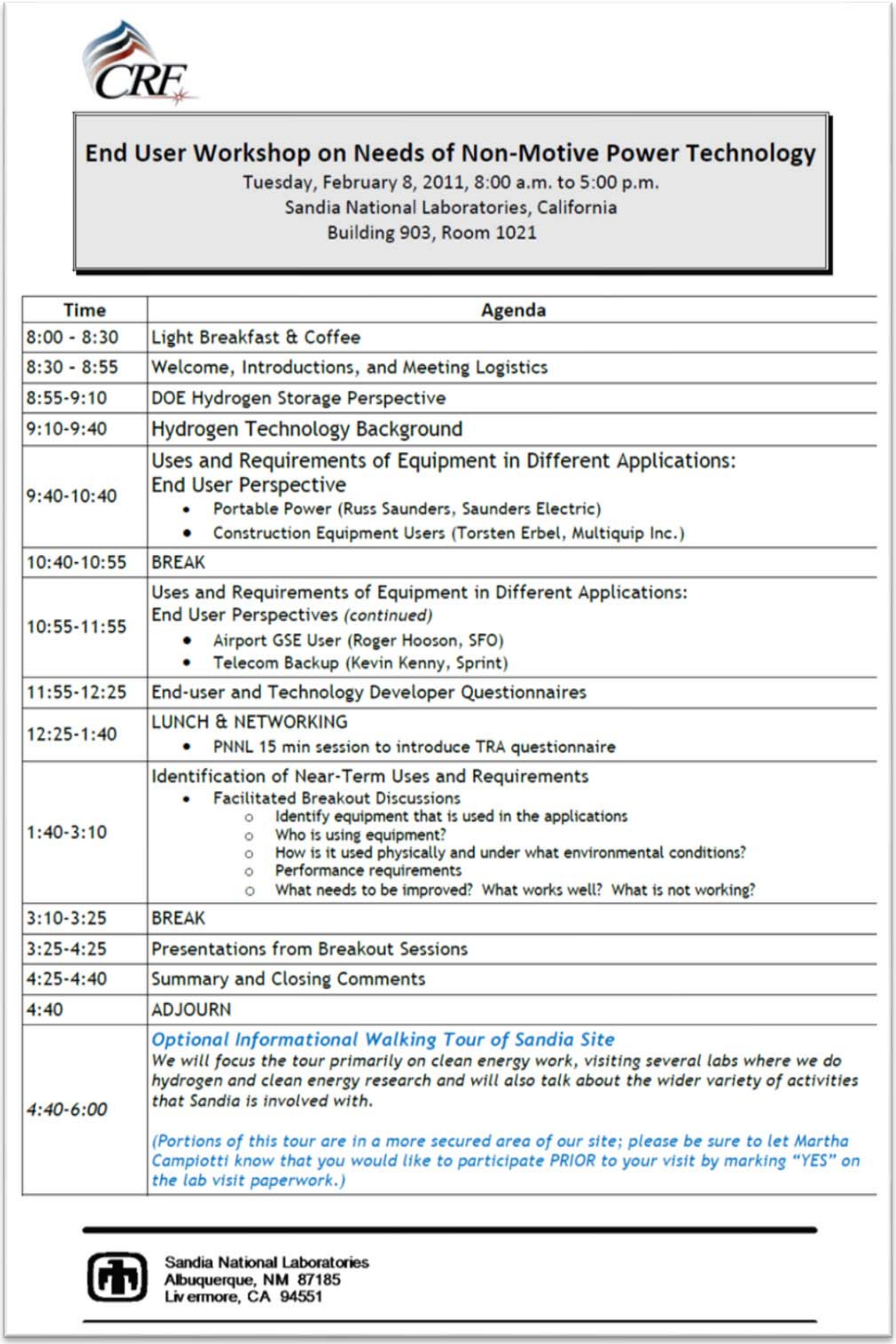
Appendix C: Presentation Materials, Surveys, and Contacts

Agenda: End User Workshop on Needs for Non-Motive Power Technology



CRF

End User Workshop on Needs of Non-Motive Power Technology
Tuesday, February 8, 2011, 8:00 a.m. to 5:00 p.m.
Sandia National Laboratories, California
Building 903, Room 1021

Time	Agenda
8:00 - 8:30	Light Breakfast & Coffee
8:30 - 8:55	Welcome, Introductions, and Meeting Logistics
8:55-9:10	DOE Hydrogen Storage Perspective
9:10-9:40	Hydrogen Technology Background
9:40-10:40	Uses and Requirements of Equipment in Different Applications: End User Perspective • Portable Power (Russ Saunders, Saunders Electric) • Construction Equipment Users (Torsten Erbel, Multiquip Inc.)
10:40-10:55	BREAK
10:55-11:55	Uses and Requirements of Equipment in Different Applications: End User Perspectives *(continued)* • Airport GSE User (Roger Hooson, SFO) • Telecom Backup (Kevin Kenny, Sprint)
11:55-12:25	End-user and Technology Developer Questionnaires
12:25-1:40	LUNCH & NETWORKING • PNNL 15 min session to introduce TRA questionnaire
1:40-3:10	Identification of Near-Term Uses and Requirements • Facilitated Breakout Discussions ○ Identify equipment that is used in the applications ○ Who is using equipment? ○ How is it used physically and under what environmental conditions? ○ Performance requirements ○ What needs to be improved? What works well? What is not working?
3:10-3:25	BREAK
3:25-4:25	Presentations from Breakout Sessions
4:25-4:40	Summary and Closing Comments
4:40	ADJOURN
4:40-6:00	***Optional Informational Walking Tour of Sandia Site*** *We will focus the tour primarily on clean energy work, visiting several labs where we do hydrogen and clean energy research and will also talk about the wider variety of activities that Sandia is involved with.* *(Portions of this tour are in a more secured area of our site; please be sure to let Martha Campiotti know that you would like to participate PRIOR to your visit by marking "YES" on the lab visit paperwork.)*

Sandia National Laboratories
Albuquerque, NM 87185
Livermore, CA 94551

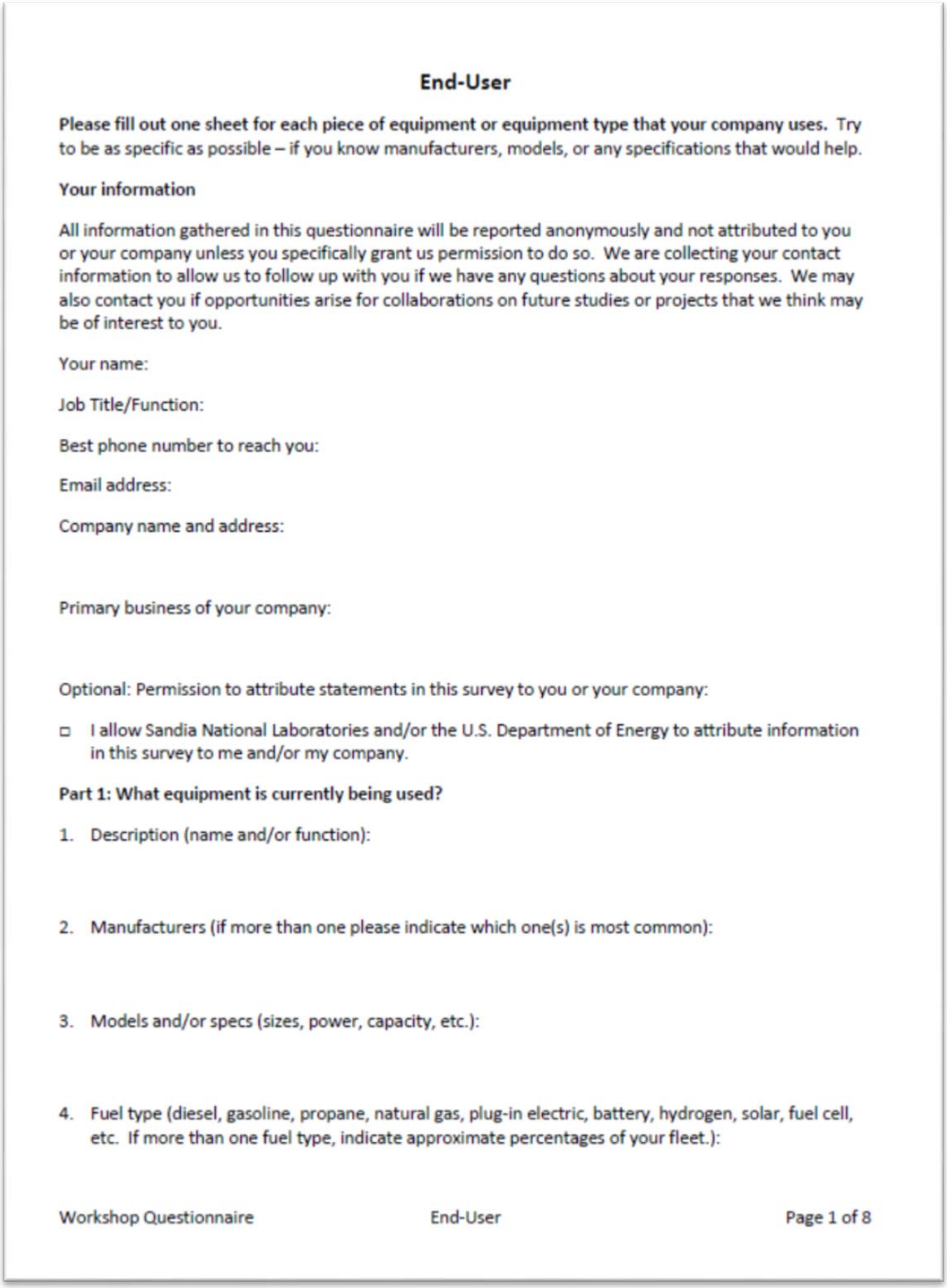
End User Workshop Participant List

End User Workshop on Needs of Non-Motive Power Technology

Tuesday, February 8, 2011, 8:00 a.m. to 5:00 p.m.
Sandia National Laboratories, California
Final Attendees

Last	First	Affiliation	Email	User Type
Aceves	Salvador	LLNL	aceves6@llnl.gov	Technical expert
Akers	Niki	Innoventor	nakers@innoventor.net	End-user
Barber	Carly	Illumnication Dynamics	carly@illuminationdynamics.com	End-user
Bartlett	Mark	US Air Force - Travis AFB	mark.bartlett.1@us.af.mil	End-user
Bauserman	Mark	Paramount Pictures	Mark_Bauserman@Paramount.com	End-user
Boyd	Bob	Consultant	Boyd.rw@gmail.com	H2 Infrastructure
Breit	Joe	Boeing	joe.breit@boeing.com	System integrator
Campiotti	Martha	SNL	mmcampi@sandia.gov	Other
Cargnelli	Joseph	Hydrogenics	jcargnelli@hydrogenics.com	FC mfg
Chao	Benjamin	Ovonic Hydrogen Systems	bchao@ovonic.com	Storage mfg
Cobbler	Robert	CA Dept. of Transportation	robert_cobbler@dot.ca.gov	End-user
Cookson	Bob	Illumnication Dynamics	bob@illuminationdynamics.com	End-user
Couper	Dave	Viking Steel	d.couper@vikingsteel.net	End-user
Dorotinsky	Ralph	Kinetics Mechanical	rdorotinsky@kms-inc.com	End-user
Dowell	Daniel	US Air Force - Travis AFB	daniel.dowell@us.af.mil	End-user
Erbel	Torsten	Multiquip Inc.	terbel@multiquip.com	System integrator
Fliess	Derek	San Francisco International Airport	derek.fliess@flysfo.com	End-user
Flores	Thomas	Verizon Wireless	Thomas.Flores@VerizonWireless.com	End-user
Hanley	Rick	CT Dept. of Transportation	richard.hanley@ct.gov	End-user
Hooson	Roger	San Francisco International Airport	roger.hooson@flysfo.com	End-user
Hydrogenics	Sookhoo	Ryan	rsookhoo@hydrogenics.com	FC mfg
Johnson	Terry	SNL	ajohnson@sandia.gov	Technical expert
Kenny	Kevin	Sprint	Kevin.P.Kenny@sprint.com	End-user
Klebanoff	Lennie	SNL	lekleba@sandia.gov	Technical expert
Makinson	John	Lincoln Composites Inc.	jmakinson@lincolncomposites.com	Storage mfg
McWhorter	Christopher	DOE	Christopher.McWhorter@EE.Doe.Gov	Other
Moreno	Marcina	SNL	mamore@sandia.gov	Other
Natesan	Nitin	Linde North America LLC	nitin.natesan@linde.com	H2 Infrastructure
Ordaz	Grace	DOE	Grace.Ordaz@ee.doe.gov	Other
Oros	Mickey	Altergy Systems	mickey.oros@altergy.com	FC mfg
Polson	Cranston	Hawaii Hydrogen Carriers, LLC	cranstonhhc@gmail.com	Technical expert
Pratt	Joe	SNL	jwpratt@sandia.gov	Technical expert
Prey	Steve	Caltrans	steve_prey@dot.ca.gov	End-user
Proton Energ	Schiller	Mark	MSchiller@protonenergy.com	H2 Infrastructure
Read	Carole	DOE	carole.read@ee.doe.gov	Other
Ronnebro	Ewa	PNNL	ewa.ronnebro@pnl.gov	Collaborator
Salter	John	Southwest Airlines	John.Salter@wnco.com	End-user
Saunders	Russ	Saunders Electric Inc.	russell@saunderselectric.com	End-user
Saunders	Candace	Saunders Electric Inc.	candace@saunderselectric.com	End-user
Simpson	Lin	NREL	Lin.Simpson@nrel.gov	Technical expert
Smith	Carl	Sandia Site Services	cesmit@sandia.gov	End-user
Stetson	Ned	DOE	ned.stetson@ee.doe.gov	Other
Tam	Ricky	SNL	rtam@sandia.gov	Other
Woolley	Randy	Caltrans	randy_woolley@dot.ca.gov	End-user
Zelinsky	Michael	Ovonic Hydrogen Systems	mzelinsky@ovonic.com	Storage mfg

End User Survey



End-User

Please fill out one sheet for each piece of equipment or equipment type that your company uses. Try to be as specific as possible – if you know manufacturers, models, or any specifications that would help.

Your information

All information gathered in this questionnaire will be reported anonymously and not attributed to you or your company unless you specifically grant us permission to do so. We are collecting your contact information to allow us to follow up with you if we have any questions about your responses. We may also contact you if opportunities arise for collaborations on future studies or projects that we think may be of interest to you.

Your name:

Job Title/Function:

Best phone number to reach you:

Email address:

Company name and address:

Primary business of your company:

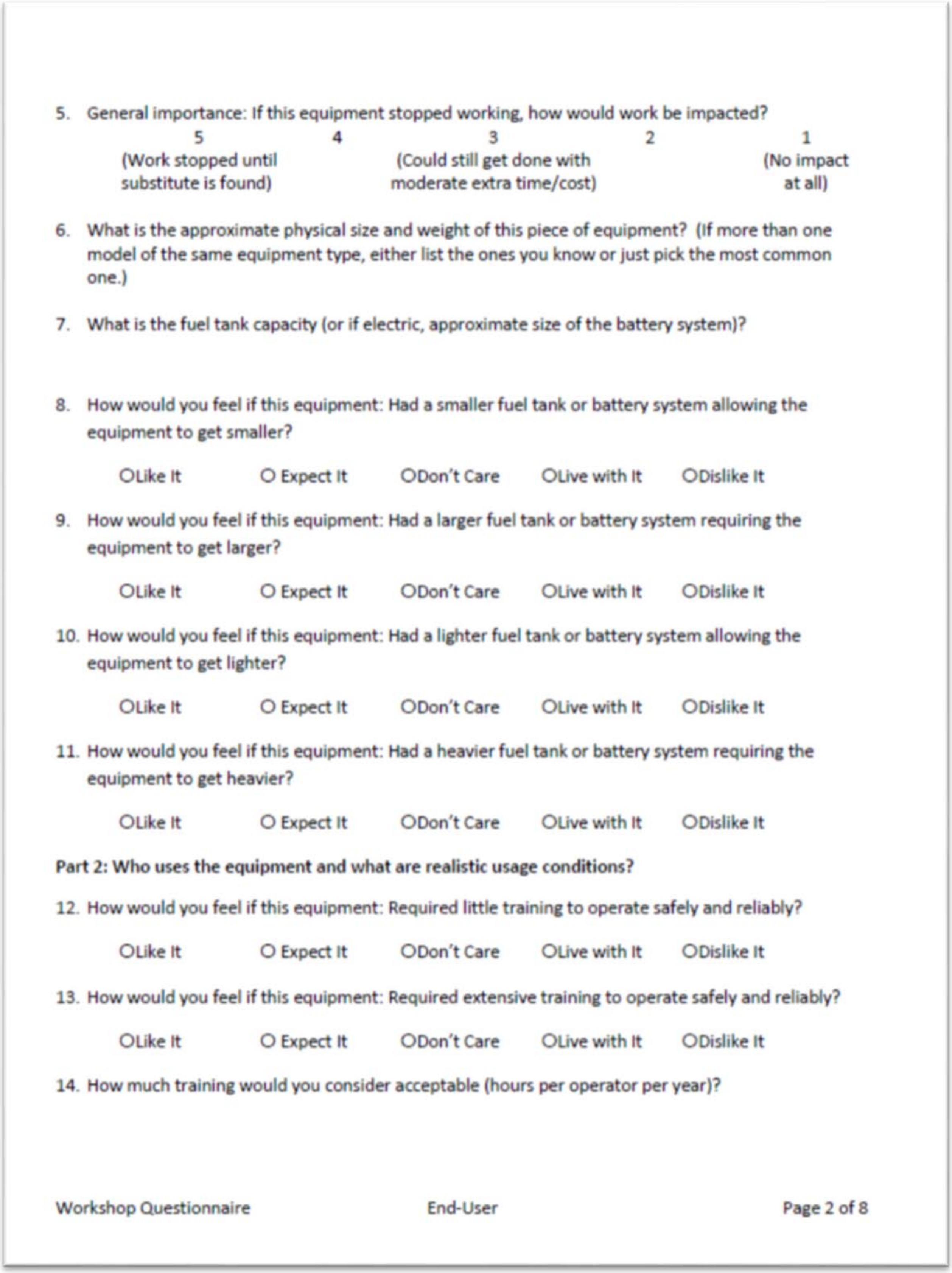
Optional: Permission to attribute statements in this survey to you or your company:

☐ I allow Sandia National Laboratories and/or the U.S. Department of Energy to attribute information in this survey to me and/or my company.

Part 1: What equipment is currently being used?

1. Description (name and/or function):
2. Manufacturers (if more than one please indicate which one(s) is most common):
3. Models and/or specs (sizes, power, capacity, etc.):
4. Fuel type (diesel, gasoline, propane, natural gas, plug-in electric, battery, hydrogen, solar, fuel cell, etc. If more than one fuel type, indicate approximate percentages of your fleet.):

Workshop Questionnaire End-User Page 1 of 8



5. General importance: If this equipment stopped working, how would work be impacted?

5	4	3	2	1
(Work stopped until substitute is found)		(Could still get done with moderate extra time/cost)		(No impact at all)

6. What is the approximate physical size and weight of this piece of equipment? (If more than one model of the same equipment type, either list the ones you know or just pick the most common one.)

7. What is the fuel tank capacity (or if electric, approximate size of the battery system)?

8. How would you feel if this equipment: Had a smaller fuel tank or battery system allowing the equipment to get smaller?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

9. How would you feel if this equipment: Had a larger fuel tank or battery system requiring the equipment to get larger?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

10. How would you feel if this equipment: Had a lighter fuel tank or battery system allowing the equipment to get lighter?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

11. How would you feel if this equipment: Had a heavier fuel tank or battery system requiring the equipment to get heavier?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

Part 2: Who uses the equipment and what are realistic usage conditions?

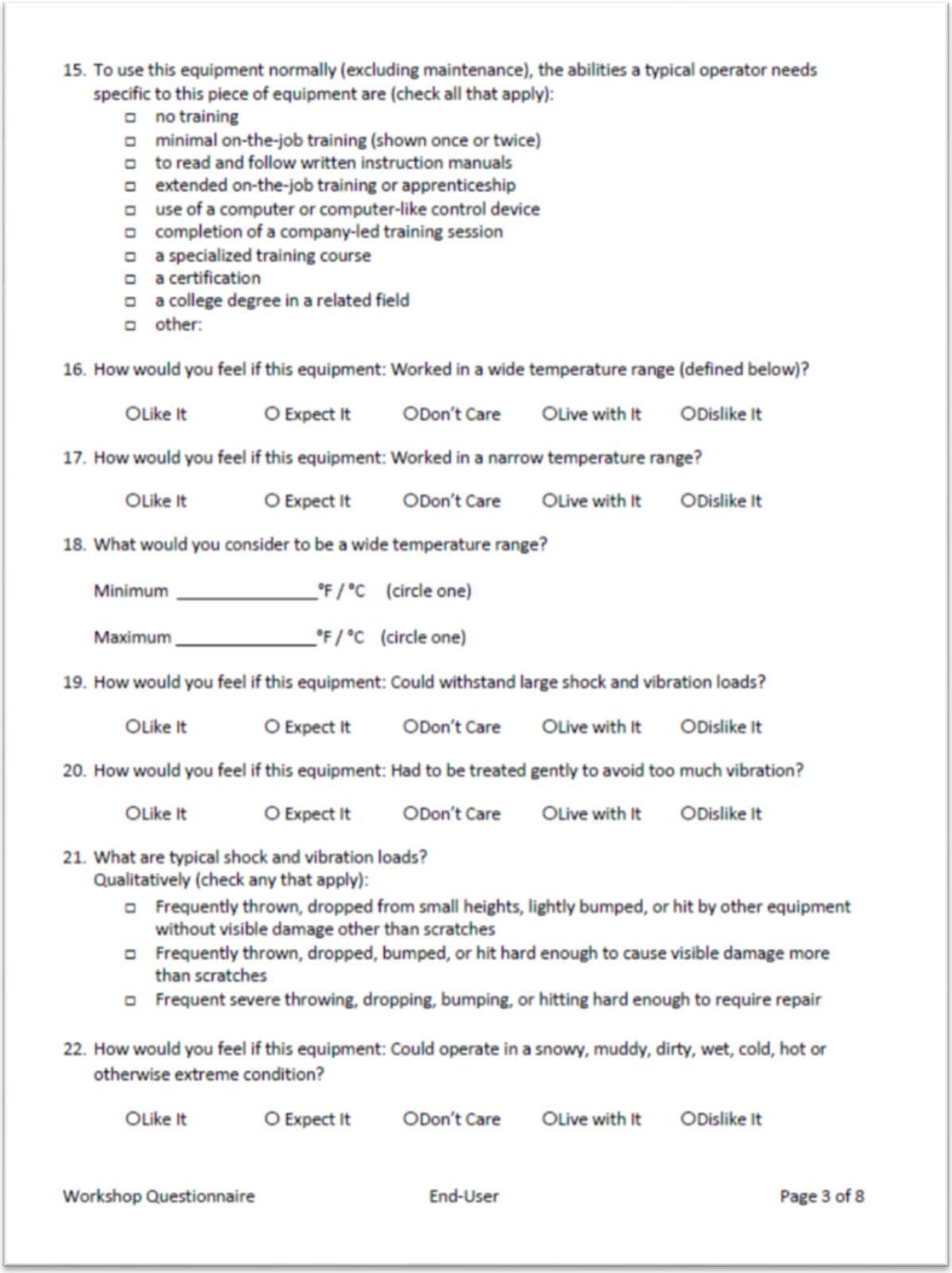
12. How would you feel if this equipment: Required little training to operate safely and reliably?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

13. How would you feel if this equipment: Required extensive training to operate safely and reliably?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

14. How much training would you consider acceptable (hours per operator per year)?



15. To use this equipment normally (excluding maintenance), the abilities a typical operator needs specific to this piece of equipment are (check all that apply):
    - ☐ no training
    - ☐ minimal on-the-job training (shown once or twice)
    - ☐ to read and follow written instruction manuals
    - ☐ extended on-the-job training or apprenticeship
    - ☐ use of a computer or computer-like control device
    - ☐ completion of a company-led training session
    - ☐ a specialized training course
    - ☐ a certification
    - ☐ a college degree in a related field
    - ☐ other:

16. How would you feel if this equipment: Worked in a wide temperature range (defined below)?

    ○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

17. How would you feel if this equipment: Worked in a narrow temperature range?

    ○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

18. What would you consider to be a wide temperature range?

    Minimum _______________°F / °C (circle one)

    Maximum _______________°F / °C (circle one)

19. How would you feel if this equipment: Could withstand large shock and vibration loads?

    ○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

20. How would you feel if this equipment: Had to be treated gently to avoid too much vibration?

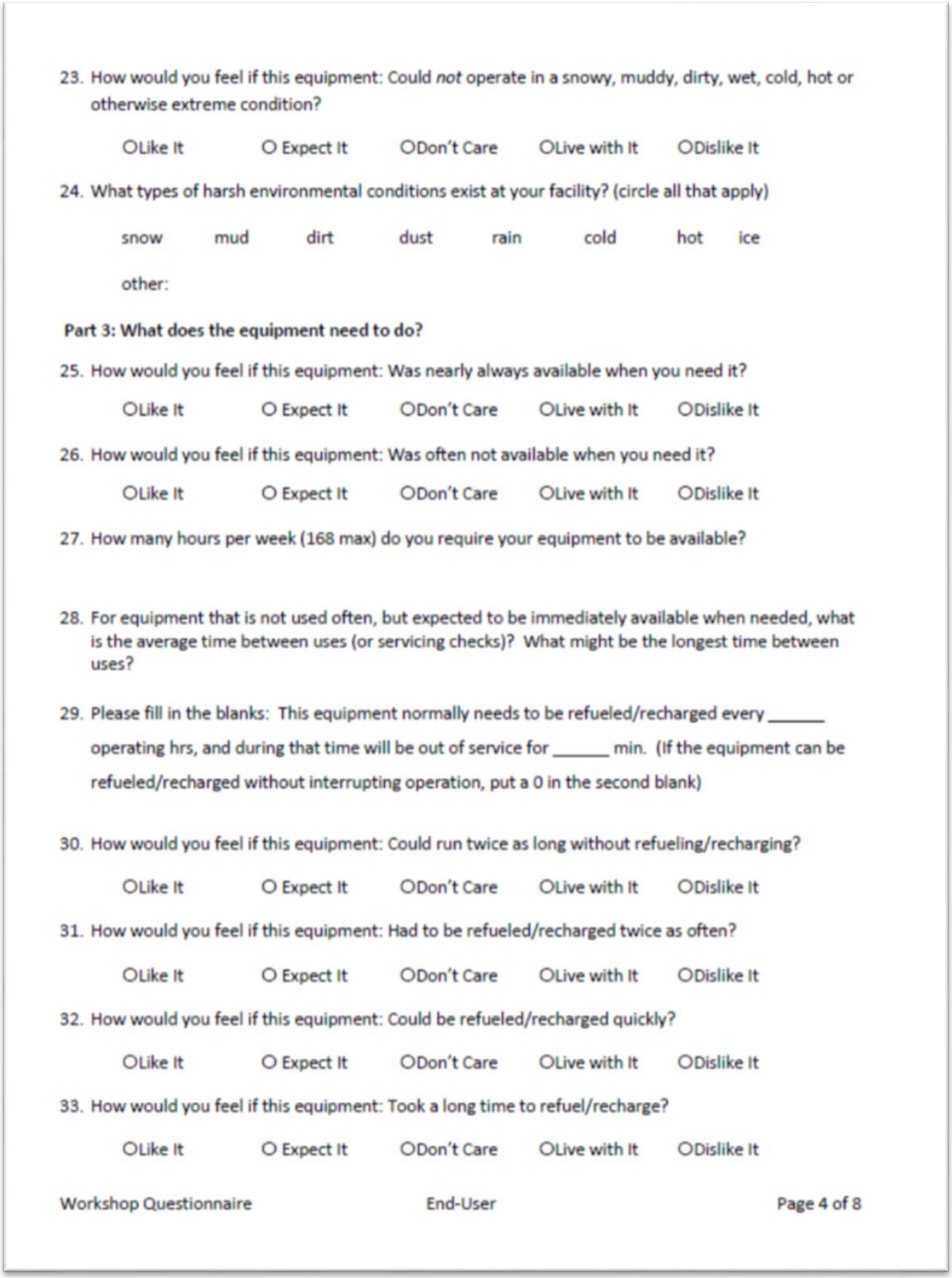
    ○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

21. What are typical shock and vibration loads?
    Qualitatively (check any that apply):
    - ☐ Frequently thrown, dropped from small heights, lightly bumped, or hit by other equipment without visible damage other than scratches
    - ☐ Frequently thrown, dropped, bumped, or hit hard enough to cause visible damage more than scratches
    - ☐ Frequent severe throwing, dropping, bumping, or hitting hard enough to require repair

22. How would you feel if this equipment: Could operate in a snowy, muddy, dirty, wet, cold, hot or otherwise extreme condition?

    ○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

Workshop Questionnaire End-User Page 3 of 8



23. How would you feel if this equipment: Could *not* operate in a snowy, muddy, dirty, wet, cold, hot or otherwise extreme condition?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

24. What types of harsh environmental conditions exist at your facility? (circle all that apply)

snow mud dirt dust rain cold hot ice

other:

Part 3: What does the equipment need to do?

25. How would you feel if this equipment: Was nearly always available when you need it?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

26. How would you feel if this equipment: Was often not available when you need it?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

27. How many hours per week (168 max) do you require your equipment to be available?

28. For equipment that is not used often, but expected to be immediately available when needed, what is the average time between uses (or servicing checks)? What might be the longest time between uses?

29. Please fill in the blanks: This equipment normally needs to be refueled/recharged every ______ operating hrs, and during that time will be out of service for ______ min. (If the equipment can be refueled/recharged without interrupting operation, put a 0 in the second blank)

30. How would you feel if this equipment: Could run twice as long without refueling/recharging?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

31. How would you feel if this equipment: Had to be refueled/recharged twice as often?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

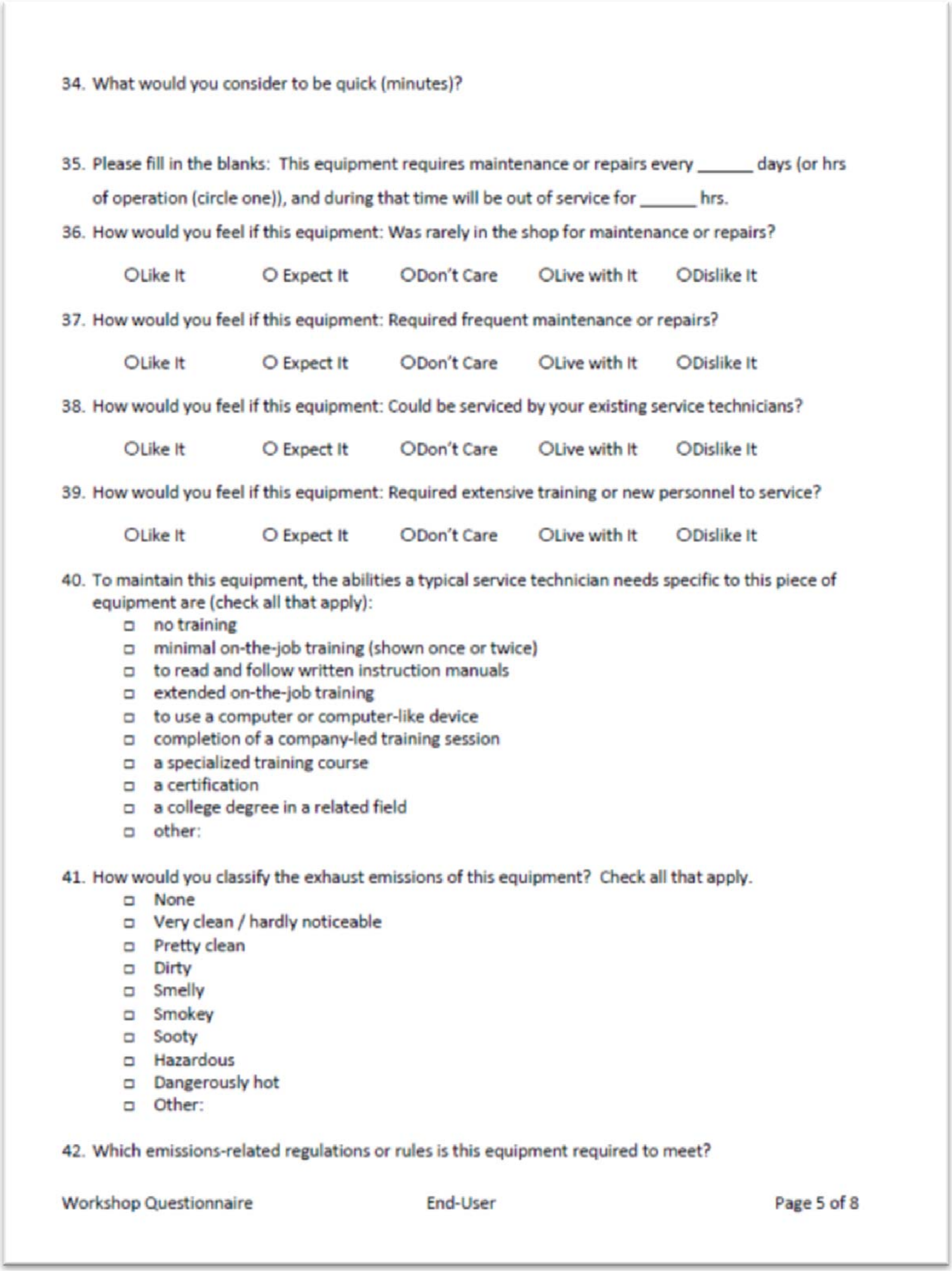
32. How would you feel if this equipment: Could be refueled/recharged quickly?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

33. How would you feel if this equipment: Took a long time to refuel/recharge?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

Workshop Questionnaire End-User Page 4 of 8



34. What would you consider to be quick (minutes)?

35. Please fill in the blanks: This equipment requires maintenance or repairs every ______ days (or hrs of operation (circle one)), and during that time will be out of service for ______ hrs.

36. How would you feel if this equipment: Was rarely in the shop for maintenance or repairs?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

37. How would you feel if this equipment: Required frequent maintenance or repairs?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

38. How would you feel if this equipment: Could be serviced by your existing service technicians?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

39. How would you feel if this equipment: Required extensive training or new personnel to service?

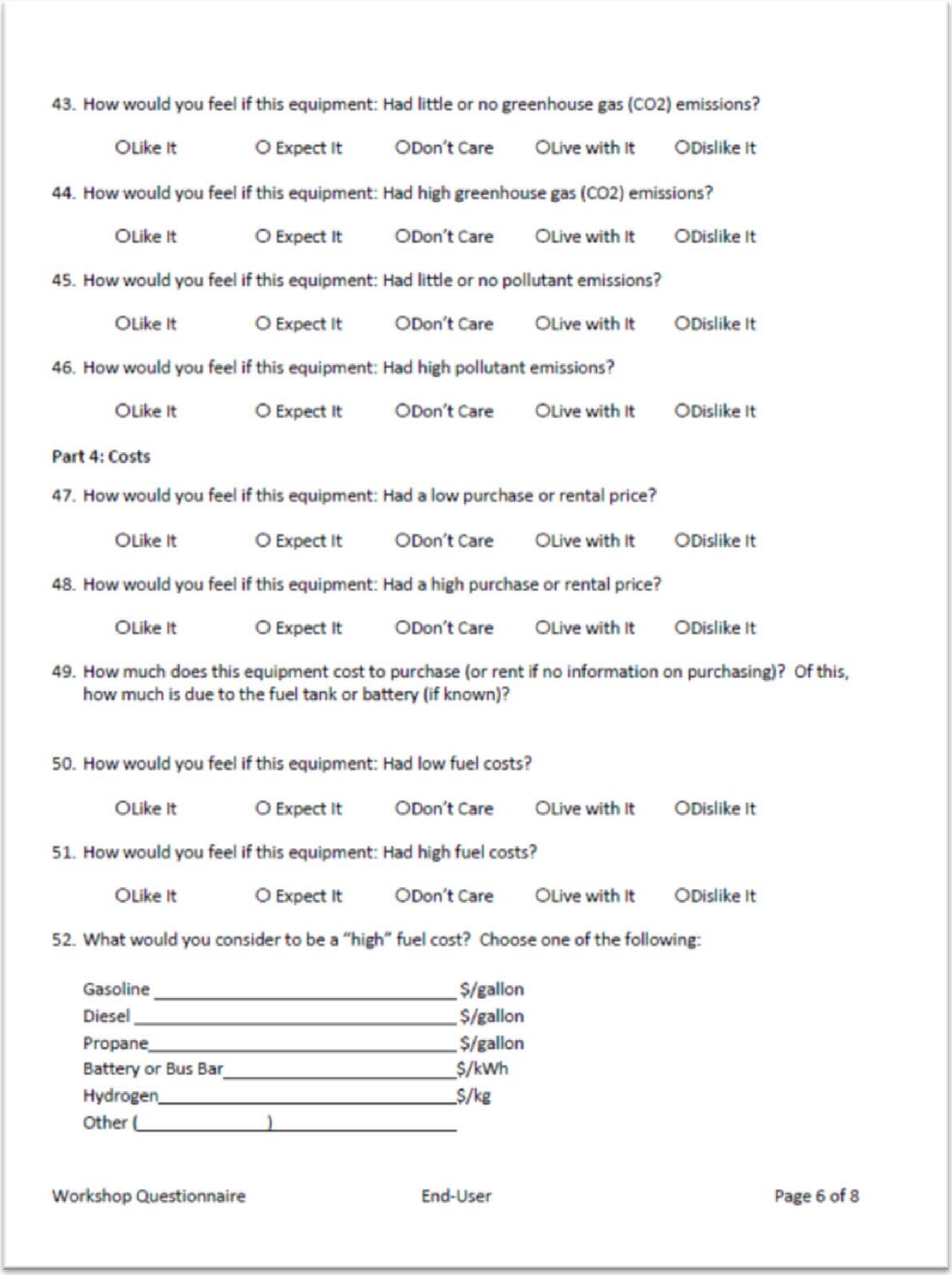
○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

40. To maintain this equipment, the abilities a typical service technician needs specific to this piece of equipment are (check all that apply):
    - ☐ no training
    - ☐ minimal on-the-job training (shown once or twice)
    - ☐ to read and follow written instruction manuals
    - ☐ extended on-the-job training
    - ☐ to use a computer or computer-like device
    - ☐ completion of a company-led training session
    - ☐ a specialized training course
    - ☐ a certification
    - ☐ a college degree in a related field
    - ☐ other:

41. How would you classify the exhaust emissions of this equipment? Check all that apply.
    - ☐ None
    - ☐ Very clean / hardly noticeable
    - ☐ Pretty clean
    - ☐ Dirty
    - ☐ Smelly
    - ☐ Smokey
    - ☐ Sooty
    - ☐ Hazardous
    - ☐ Dangerously hot
    - ☐ Other:

42. Which emissions-related regulations or rules is this equipment required to meet?

Workshop Questionnaire End-User Page 5 of 8



43. How would you feel if this equipment: Had little or no greenhouse gas (CO2) emissions?

○ Like It ○ Expect It ○ Don't Care ○ Live with It ○ Dislike It

44. How would you feel if this equipment: Had high greenhouse gas (CO2) emissions?

○ Like It ○ Expect It ○ Don't Care ○ Live with It ○ Dislike It

45. How would you feel if this equipment: Had little or no pollutant emissions?

○ Like It ○ Expect It ○ Don't Care ○ Live with It ○ Dislike It

46. How would you feel if this equipment: Had high pollutant emissions?

○ Like It ○ Expect It ○ Don't Care ○ Live with It ○ Dislike It

Part 4: Costs

47. How would you feel if this equipment: Had a low purchase or rental price?

○ Like It ○ Expect It ○ Don't Care ○ Live with It ○ Dislike It

48. How would you feel if this equipment: Had a high purchase or rental price?

○ Like It ○ Expect It ○ Don't Care ○ Live with It ○ Dislike It

49. How much does this equipment cost to purchase (or rent if no information on purchasing)? Of this, how much is due to the fuel tank or battery (if known)?

50. How would you feel if this equipment: Had low fuel costs?

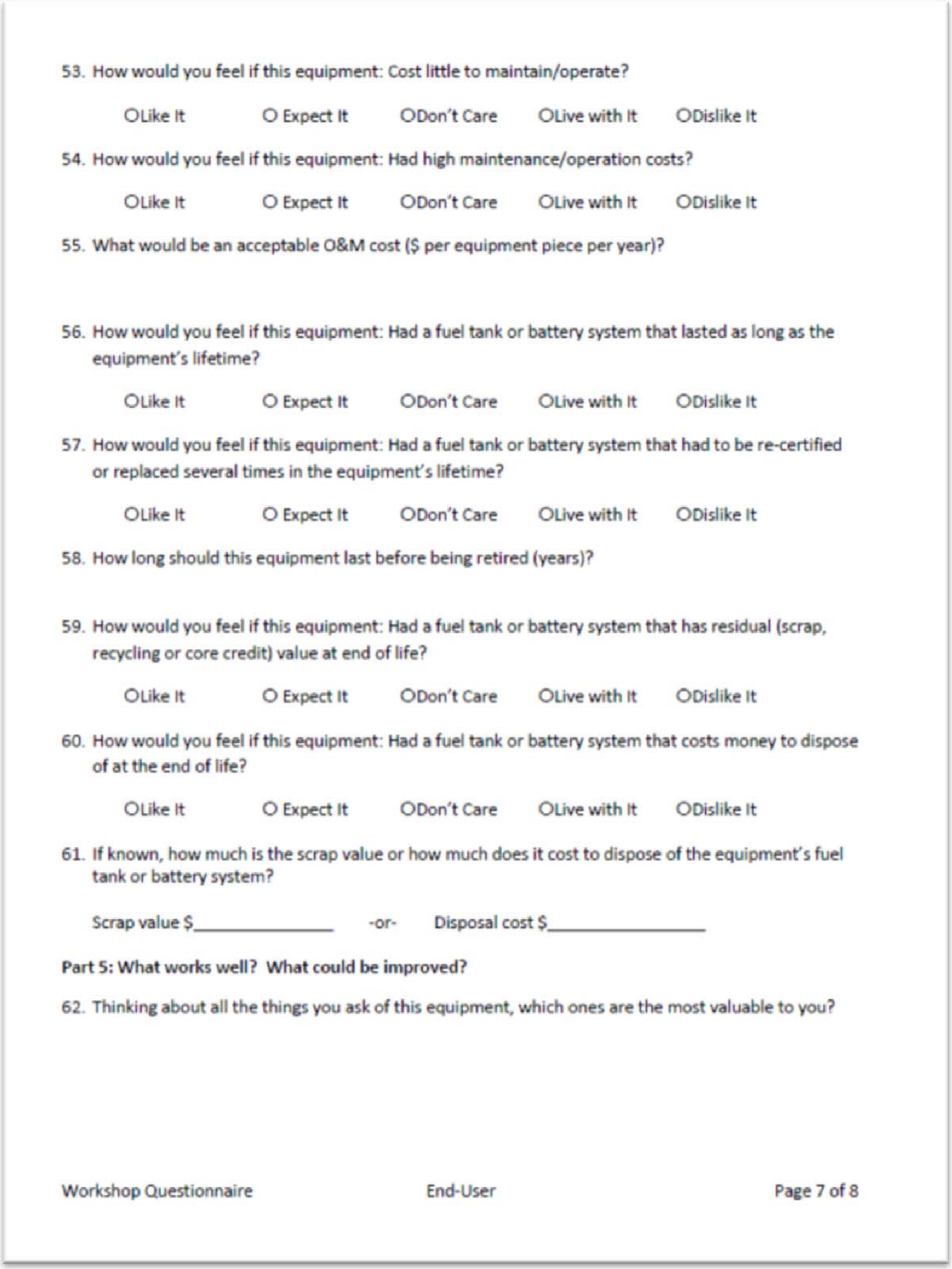
○ Like It ○ Expect It ○ Don't Care ○ Live with It ○ Dislike It

51. How would you feel if this equipment: Had high fuel costs?

○ Like It ○ Expect It ○ Don't Care ○ Live with It ○ Dislike It

52. What would you consider to be a "high" fuel cost? Choose one of the following:

Gasoline ______________________ $/gallon
Diesel ______________________ $/gallon
Propane______________________ $/gallon
Battery or Bus Bar__________________ $/kWh
Hydrogen______________________ $/kg
Other (__________)______________



53. How would you feel if this equipment: Cost little to maintain/operate?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

54. How would you feel if this equipment: Had high maintenance/operation costs?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

55. What would be an acceptable O&M cost ($ per equipment piece per year)?

56. How would you feel if this equipment: Had a fuel tank or battery system that lasted as long as the equipment's lifetime?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

57. How would you feel if this equipment: Had a fuel tank or battery system that had to be re-certified or replaced several times in the equipment's lifetime?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

58. How long should this equipment last before being retired (years)?

59. How would you feel if this equipment: Had a fuel tank or battery system that has residual (scrap, recycling or core credit) value at end of life?

○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

60. How would you feel if this equipment: Had a fuel tank or battery system that costs money to dispose of at the end of life?

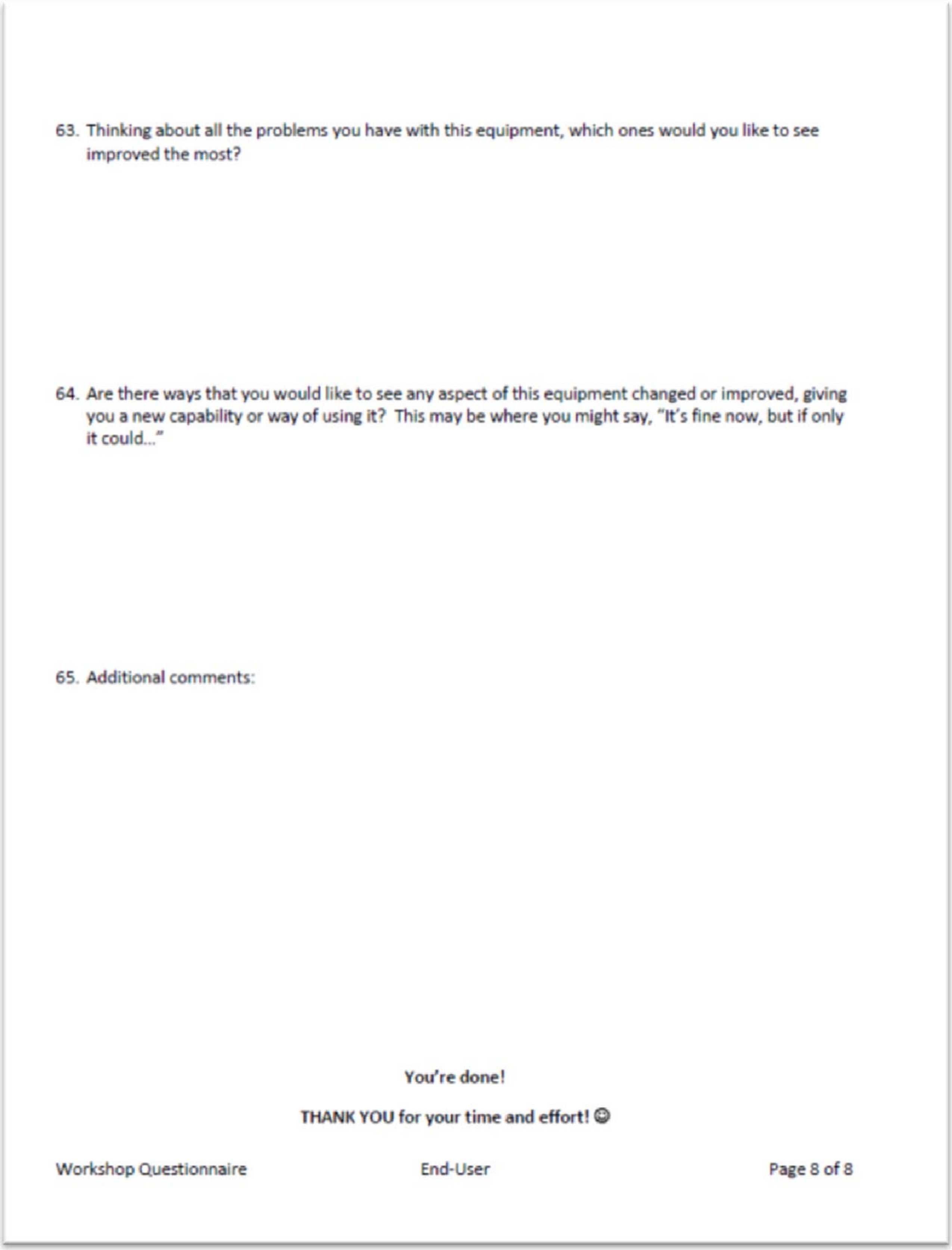
○Like It ○ Expect It ○Don't Care ○Live with It ○Dislike It

61. If known, how much is the scrap value or how much does it cost to dispose of the equipment's fuel tank or battery system?

Scrap value $_______________ -or- Disposal cost $________________

Part 5: What works well? What could be improved?

62. Thinking about all the things you ask of this equipment, which ones are the most valuable to you?



63. Thinking about all the problems you have with this equipment, which ones would you like to see improved the most?

64. Are there ways that you would like to see any aspect of this equipment changed or improved, giving you a new capability or way of using it? This may be where you might say, "It's fine now, but if only it could..."

65. Additional comments:

You're done!

THANK YOU for your time and effort! ☺

Workshop Questionnaire | End-User | Page 8 of 8

Fuel Cell Technologies Program, DOE Hydrogen & Fuel Cell Overview Presentation, Feb. 8, 2011

Fuel Cell Technologies Program

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE Hydrogen & Fuel Cell Overview

February 8, 2011

Dr. Scott McWhorter

Hydrogen Storage Technology
Development Manager
U.S. Department of Energy

Organization

EERE

Strategic Programs

Communications & Outreach

Energy Efficiency

- Buildings
- Industrial
- Vehicles
- Weatherization & Intergovernmental
- Federal Energy Management

Renewable Energy

- Solar
- Biomass
- Wind & Hydropower
- Geothermal
- Hydrogen & Fuel Cells

Business Administration

Field Operations

EERE Goals

Goals

- Reduce energy-related greenhouse gas emissions by 17% by 2020 and 83% by 2050, from a 2005 baseline
- Reduce our daily petroleum consumption in 2020 by 3.5 million barrels, from a 19-million barrel baseline
- Drive new business opportunities and jobs in manufacturing, installation, operations

Methods

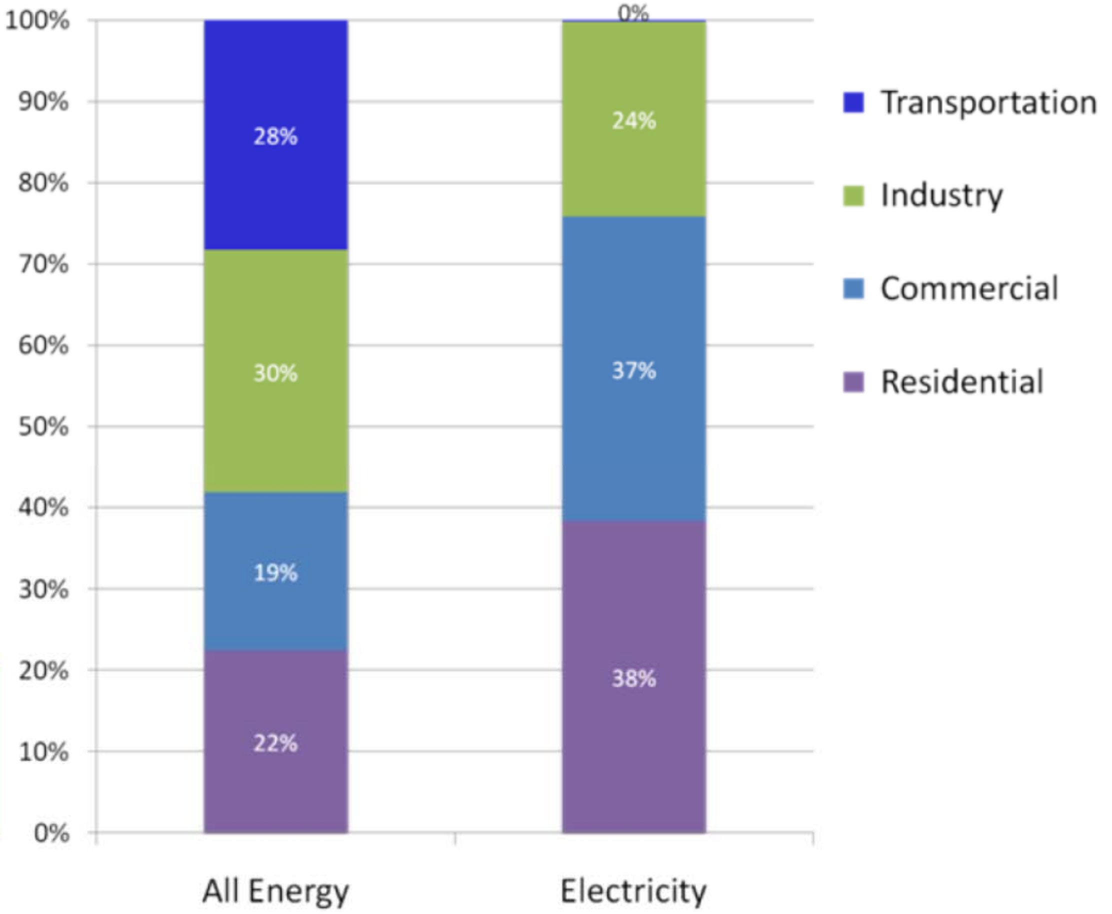
- Research, development, demonstration, deployment activities aimed at making EERE technologies competitive with alternatives without subsidies
- Understanding the financial, institutional, regulatory, and other factors that affect development and adoption of new technologies in construction, utilities, and other areas and using this knowledge to encourage rapid adoption of EERE technologies
- Working with the Congress to strengthen incentives for clean energy technology

Energy Efficiency

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Transportation and industry account for almost ~ 60% of the US energy supply
- Commercial and residential account for 75% of the US electrical usage

Renewable H_2 and Fuel Cells can make a difference!



Source: EIA, *Annual Energy Outlook 2010*, Reference Case

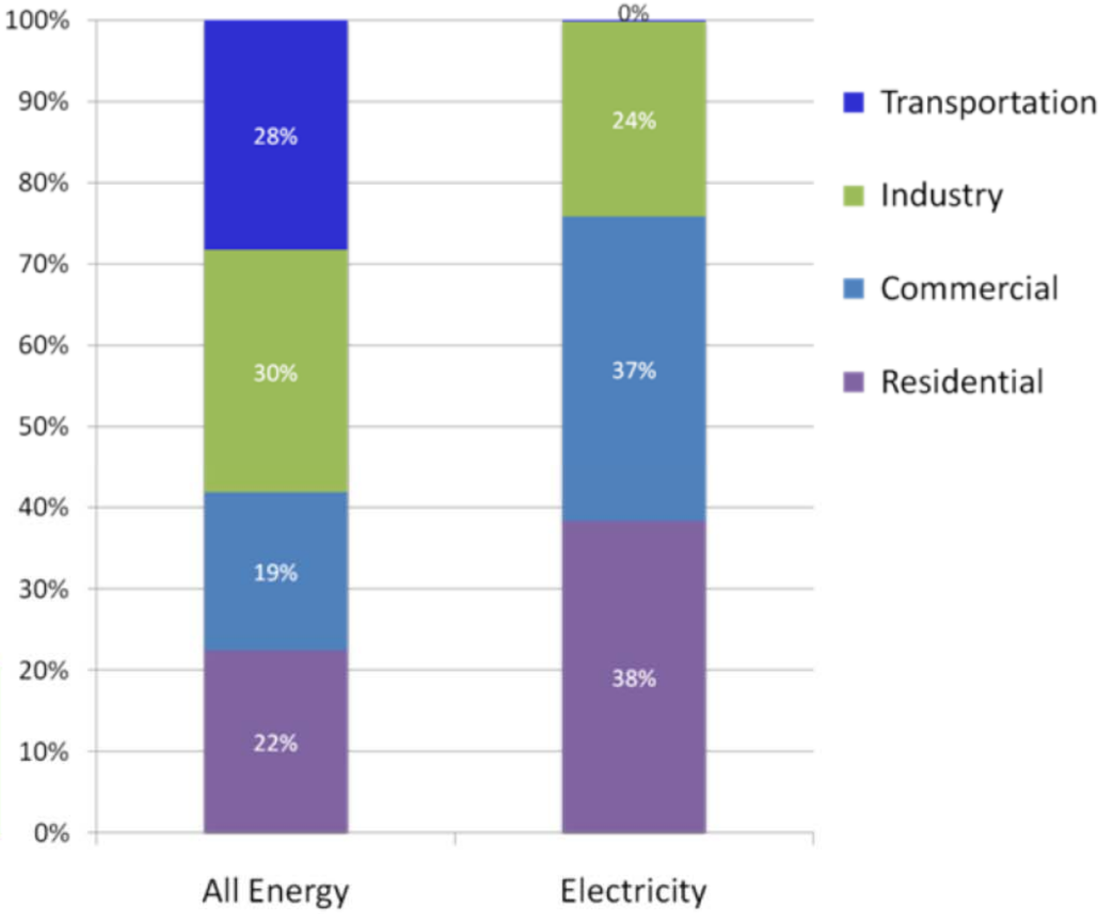
Energy Efficiency

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Transportation and industry account for almost ~ 60% of the US energy supply

- Commercial and residential account for 75% of the US electrical usage

Renewable H_2 and Fuel Cells can make a difference!



Source: EIA, *Annual Energy Outlook 2010*, Reference Case

Program Mission

The mission of the Hydrogen and Fuel Cells Program is to enable the widespread commercialization of a portfolio of hydrogen and fuel cell technologies through basic and applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges.

Key Goals : Develop hydrogen and fuel cell technologies for:

1. Early markets such as stationary power (prime and back up), lift trucks, and portable power
2. Mid-term markets such as residential combined-heat-and-power systems, auxiliary power units, fleets and buses
3. Long-term markets including mainstream transportation applications with a focus on light duty vehicles, in the 2015 to 2020 timeframe.

Source: US DOE 10/2010- draft Program Plan
Includes basic science through the Office of Science and applied RD&D through EERE, FE, NE

Fuel Cells - *Where are we today?*

Fuel Cells for Stationary Power, Auxiliary Power, and Specialty Vehicles

The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and forklifts.

***~75,000** fuel cells have been shipped worldwide.*

***~24,000** fuel cells shipped in 2009 (> 40% increase over 2008).*

Fuel cells can be a cost-competitive option for critical-load facilities, backup power, and forklifts.

Production & Delivery of Hydrogen

In the U.S., there are currently:

***~9 million metric tons** of H_2 produced annually*

***> 1200 miles** of H_2 pipelines*

Source: US DOE 09/2010

Fuel Cells for Transportation

In the U.S., there are currently:

- *> 200 fuel cell vehicles*
- *~ 20 active fuel cell buses*
- *~ 60 fueling stations*

Sept. 2009: Auto manufacturers from around the world signed a letter of understanding supporting fuel cell vehicles in anticipation of widespread commercialization, beginning in 2015.

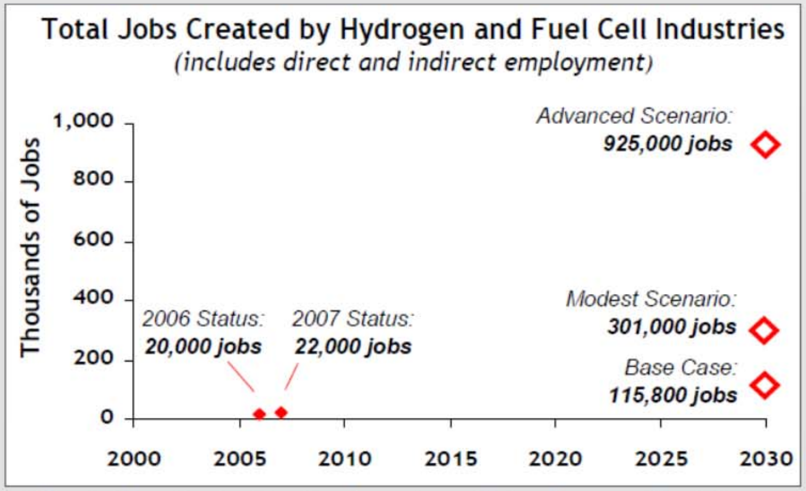
Fuel Cells - *The Economic Potential*

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

The fuel cell and hydrogen industries could generate substantial revenues and job growth.

Renewable Energy Industry Study*

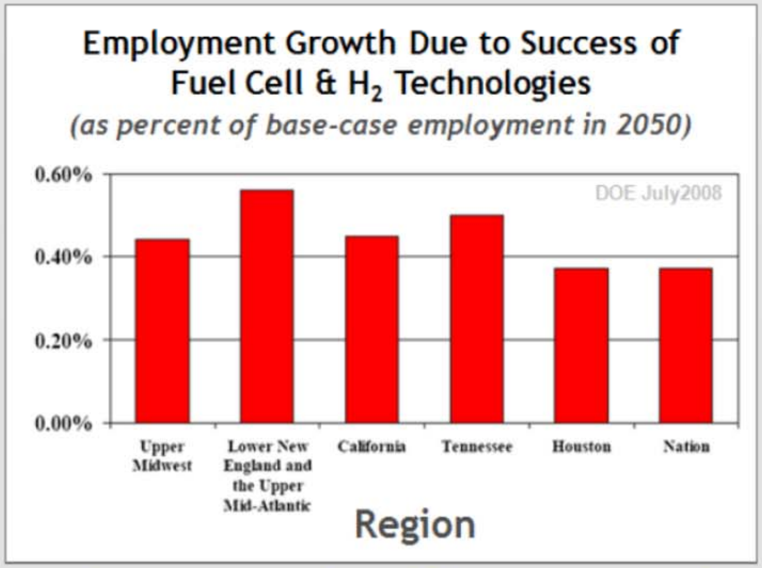
- **Fuel cells are the third-fastest growing renewable energy industry** (after biomass & solar).
- Potential U.S. employment from fuel cell and hydrogen industries of **up to 925,000 jobs** (by 2030).
- Potential gross revenues up to **$81 Billion/year** (by 2030).


Total Jobs Created by Hydrogen and Fuel Cell Industries
(includes direct and indirect employment)

***Study Conducted by the American Solar Energy Society**
www.ases.org/images/stories/ASES/pdfs/CO_Jobs_Final_Report_December2008.pdf

DOE Employment Study

- Projects net increase of **360,000 – 675,000** jobs.
- Job gains would be distributed across up to 41 industries.
- Workforce skills would be mainly in the vehicle manufacturing and service sectors.


Employment Growth Due to Success of Fuel Cell & H_2 Technologies
(as percent of base-case employment in 2050)

www.hydrogen.energy.gov/pdfs/epact1820_employment_study.pdf

Source: US DOE 09/2010

Examples of DOE Funded Fuel Cell Deployments

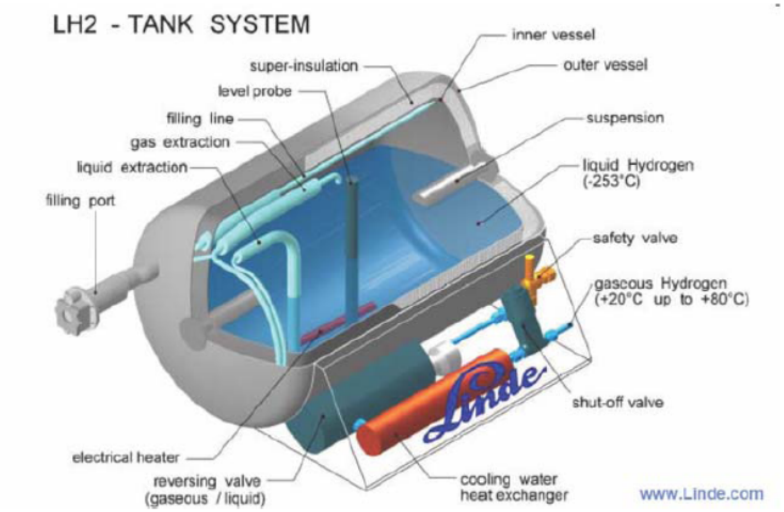
U.S. Fuel Cell Deployments Using DOE Market Transformation and Recovery Act Funding

Primarily forklifts and back-up power units

Source: US DOE 10/2010

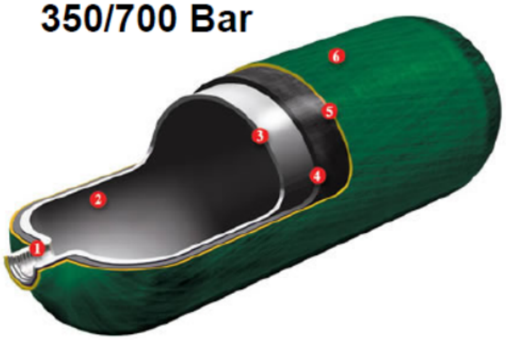
Traditional Storage Technologies

- **Liquid H_2 Tanks**
  - Double-walled vessels
  - Multi-Layer Vacuum Super Insulation (MLVSI)
  - 5-6 wt.% is feasible
- **However**
  - Liquefaction: ~ 30% energy penalty
  - Dormancy (*storage duration prior to boil-off venting*) is an issue



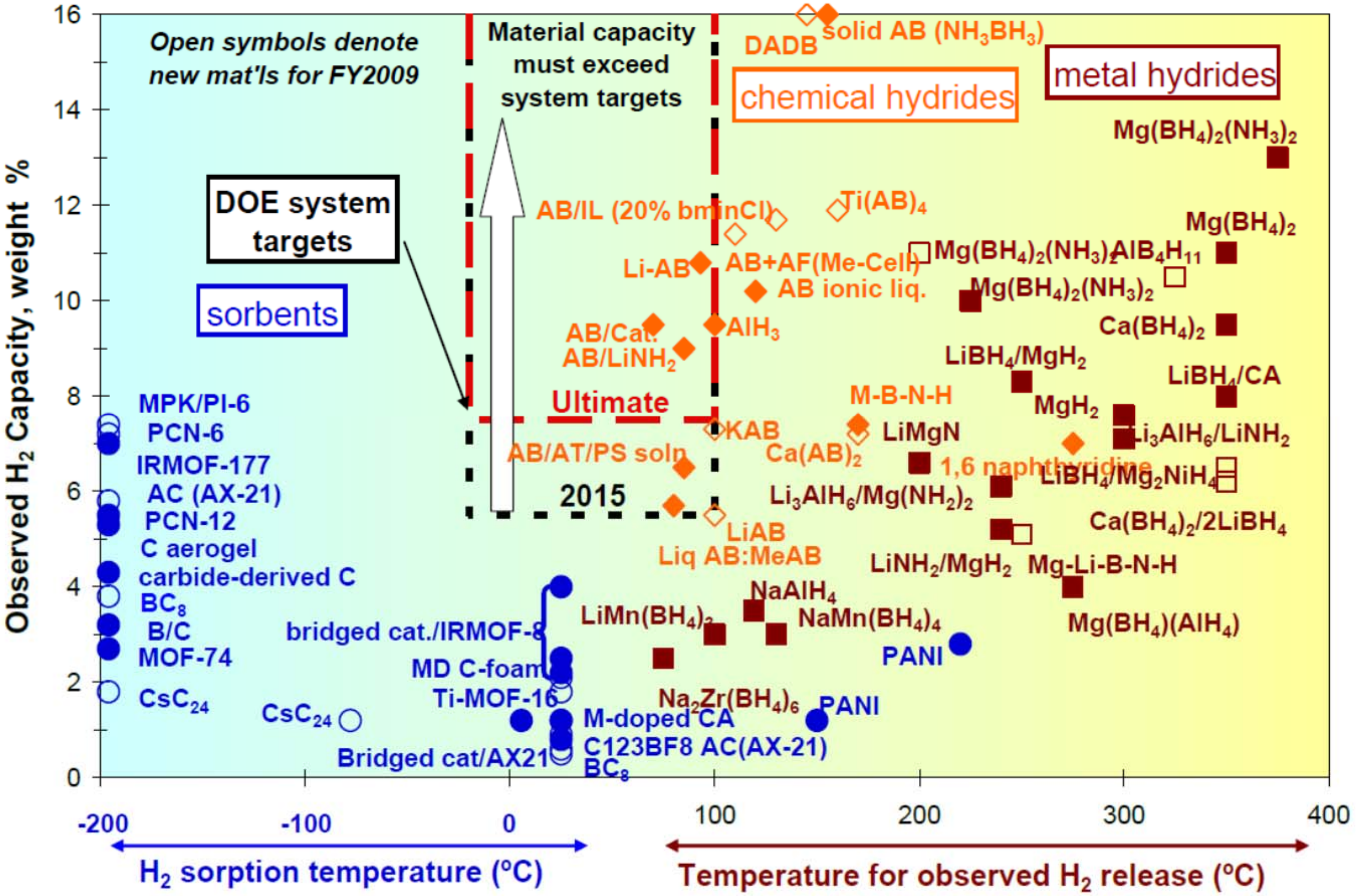
- **Compressed Gas Tanks**
  - High pressure usually delivered at 150 to 200 bar
  - Metal walls must contain all stress
  - gravimetric and volumetric densities usually <2%

Type IV Tank
350/700 Bar



1. Taper / parallel threads
2. Smooth, inert internal finish
3. Aluminum liner
4. High-performance carbon fiber overwrap in epoxy resin matrix
5. Protective glass-fiber overwrap in epoxy resin matrix
6. Durable epoxy gel-coat finish

Wide Variety of Advanced Materials



Examples of Commercial Hydrogen Storage Materials

Jadoo Power Tigershark

SiGNa H300

Trulite, Inc. Hydrocell

ECD, Inc. – Portable Metal Hydride Canisters

Key Reports Recently Published

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FUEL CELLS 2000
www.fuelcells.org
September 2010
The Business Case for Fuel Cells:
Why Top Companies are Purchasing Fuel Cells Today

2009 FUEL CELL TECHNOLOGIES
MARKET REPORT

NREL National Renewable Energy Laboratory
Molten Carbonate and
Phosphoric Acid
Stationary Fuel Cells:
Overview and Gap Analysis
Robert Remick
National Renewable Energy Laboratory
Douglas Wheeler
DJW Technology, LLC
Technical Report

The Business Case for Fuel Cells: Why Top Companies are Purchasing Fuel Cells Today

By FuelCells2000, http://www.fuelcells.org

Profile of 38 companies who have ordered, installed, or deployed fuel cell forklifts, stationary fuel cells or fuel cell units.

See report: http://www.fuelcells.org/BusinessCaseforFuelCells.pdf

2009 Fuel Cell Technologies Market Report

By Breakthrough Technologies Institute, http://www.btionline.org/

This report describes data compiled in 2010 on trends in the fuel cell industry for 2009 with some comparison to previous years. (July 2010).

See report: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/48219.pdf

Molten Carbonate and Phosphoric Acid Stationary Fuel Cells: Overview and Gap Analysis

By NREL and DJW Technology, LLC

This report describes the technical and cost gap analysis performed to identify pathways for reducing the costs of molten carbonate fuel cell (MCFC) and phosphoric acid fuel cell (PAFC) stationary fuel cell power plants.

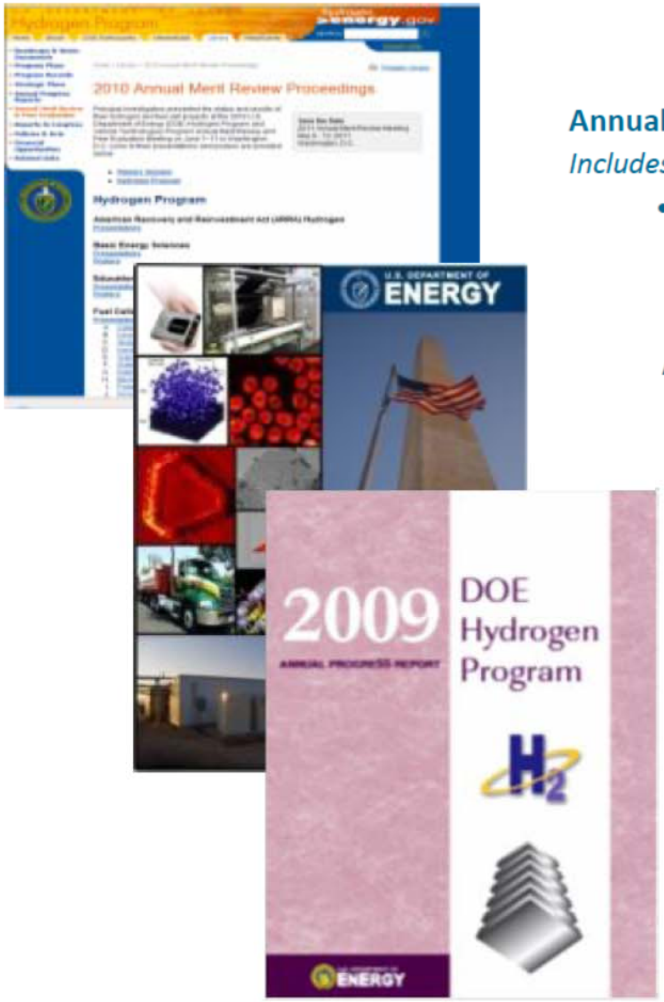
See report: http://www.nrel.gov/docs/fy10osti/49072.pdf

Fuel Cell Today 2009 Market Analysis

The report describes sales of fuel cells in US and worldwide.
October 2010

Source: US DOE 10/2010

Key Program Documents



Annual Merit Review & Peer Evaluation Proceedings

Includes downloadable versions of all presentations at the Annual Merit Review

- **Latest edition released June 2010**

www.hydrogen.energy.gov/annual_review10_proceedings.html

Annual Merit Review & Peer Evaluation Report

Summarizes the comments of the Peer Review Panel at the Annual Merit Review and Peer Evaluation Meeting

- **Released January 2011**

http://www.hydrogen.energy.gov/annual_review10_report.html

Annual Progress Report

Summarizes activities and accomplishments within the Program over the preceding year, with reports on individual projects

- **To be released 2011**

www.hydrogen.energy.gov/annual_progress.html

Next Annual Review: May 9 – 13, 2011

Washington, D.C.

http://annualmeritreview.energy.gov/

Source: US DOE 09/2010

Thank you

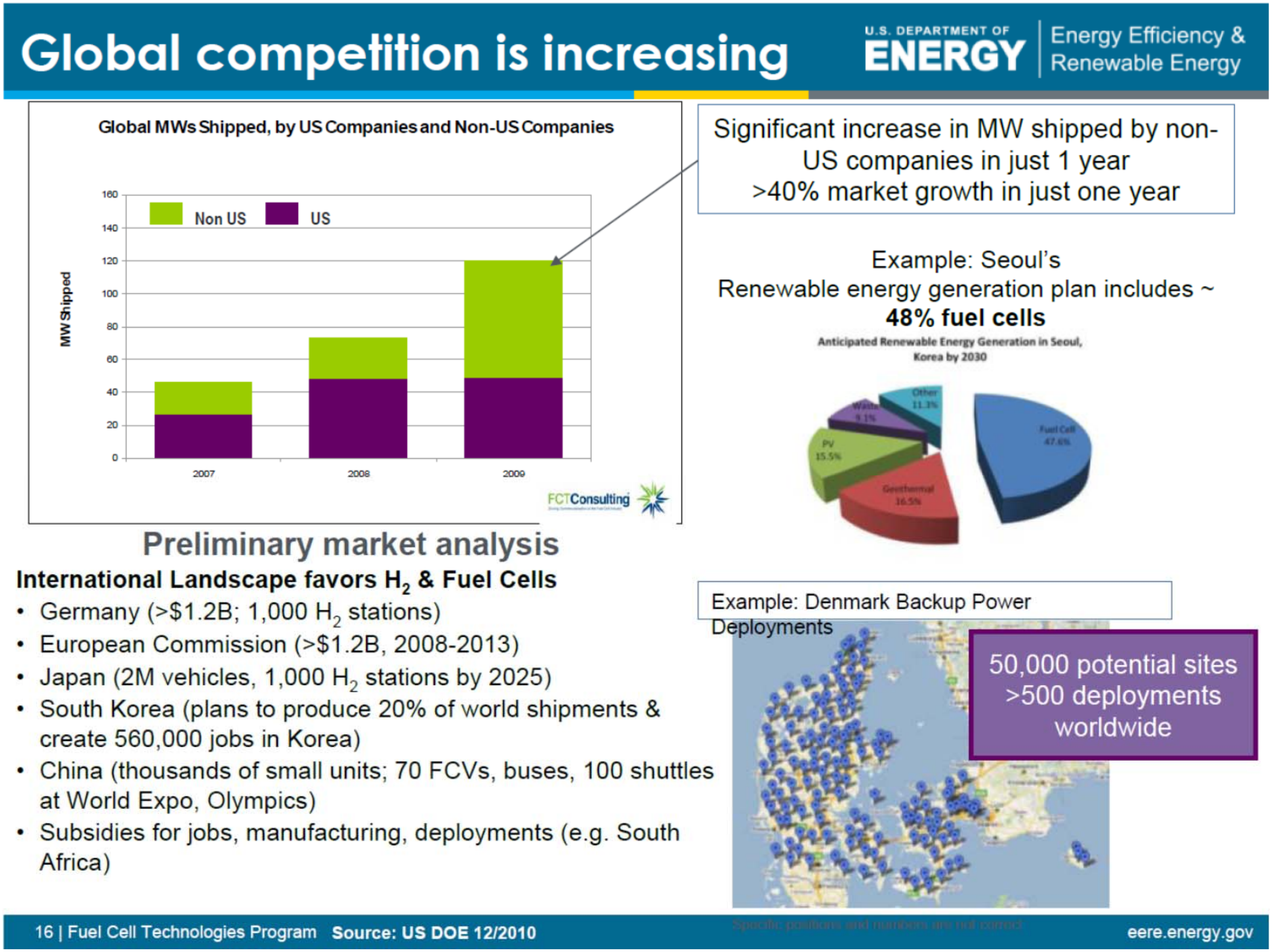
For more information, please contact

christopher.mcwhorter@ee.doe.gov

or

carole.read@ee.doe.gov

hydrogenandfuelcells.energy.gov



Global competition is increasing

Significant increase in MW shipped by non-US companies in just 1 year
>40% market growth in just one year

Preliminary market analysis

International Landscape favors H_2 & Fuel Cells

- Germany (>$1.2B; 1,000 H_2 stations)
- European Commission (>$1.2B, 2008-2013)
- Japan (2M vehicles, 1,000 H_2 stations by 2025)
- South Korea (plans to produce 20% of world shipments & create 560,000 jobs in Korea)
- China (thousands of small units; 70 FCVs, buses, 100 shuttles at World Expo, Olympics)
- Subsidies for jobs, manufacturing, deployments (e.g. South Africa)

Example: Seoul's
Renewable energy generation plan includes ~
48% fuel cells

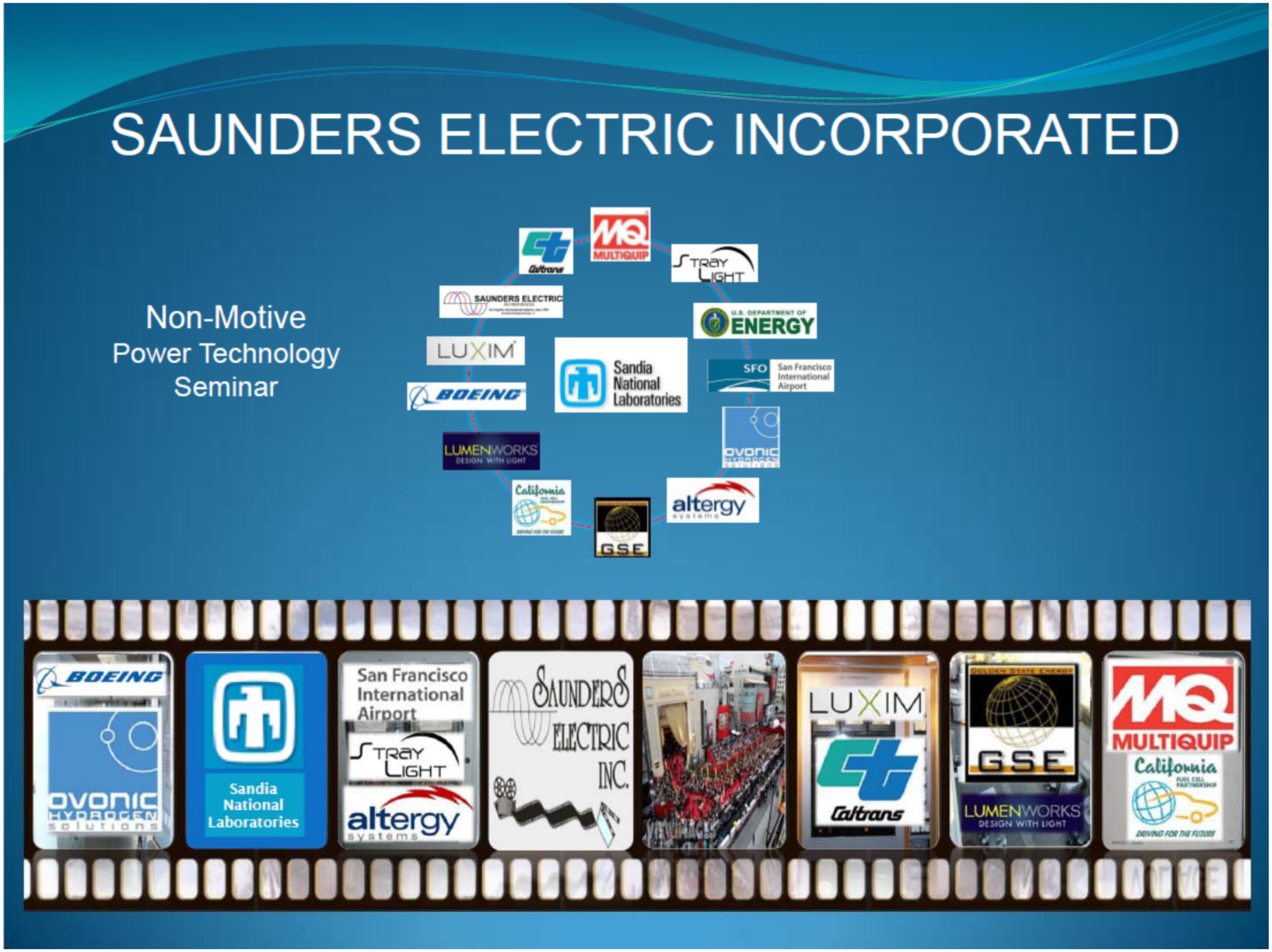
Example: Denmark Backup Power Deployments

50,000 potential sites
>500 deployments worldwide

Specific positions and numbers are not correct

16 | Fuel Cell Technologies Program **Source: US DOE 12/2010** eere.energy.gov

Saunders Electric, Non-Motive Power Technology Seminar Presentation



SAUNDERS ELECTRIC INCORPORATED

Non-Motive
Power Technology
Seminar

SAUNDERS ELECTRIC INCORPORATED

First Live Broadcast of The Academy Awards held on March 19, 1953

The first live Television production was broadcast
from both the Pantages Theatre
in Los Angeles
and the
NBC International Theatre
in New York

The most recent broadcast
of the 82nd Academy Awards
was held at the Kodak Theatre
February 2010

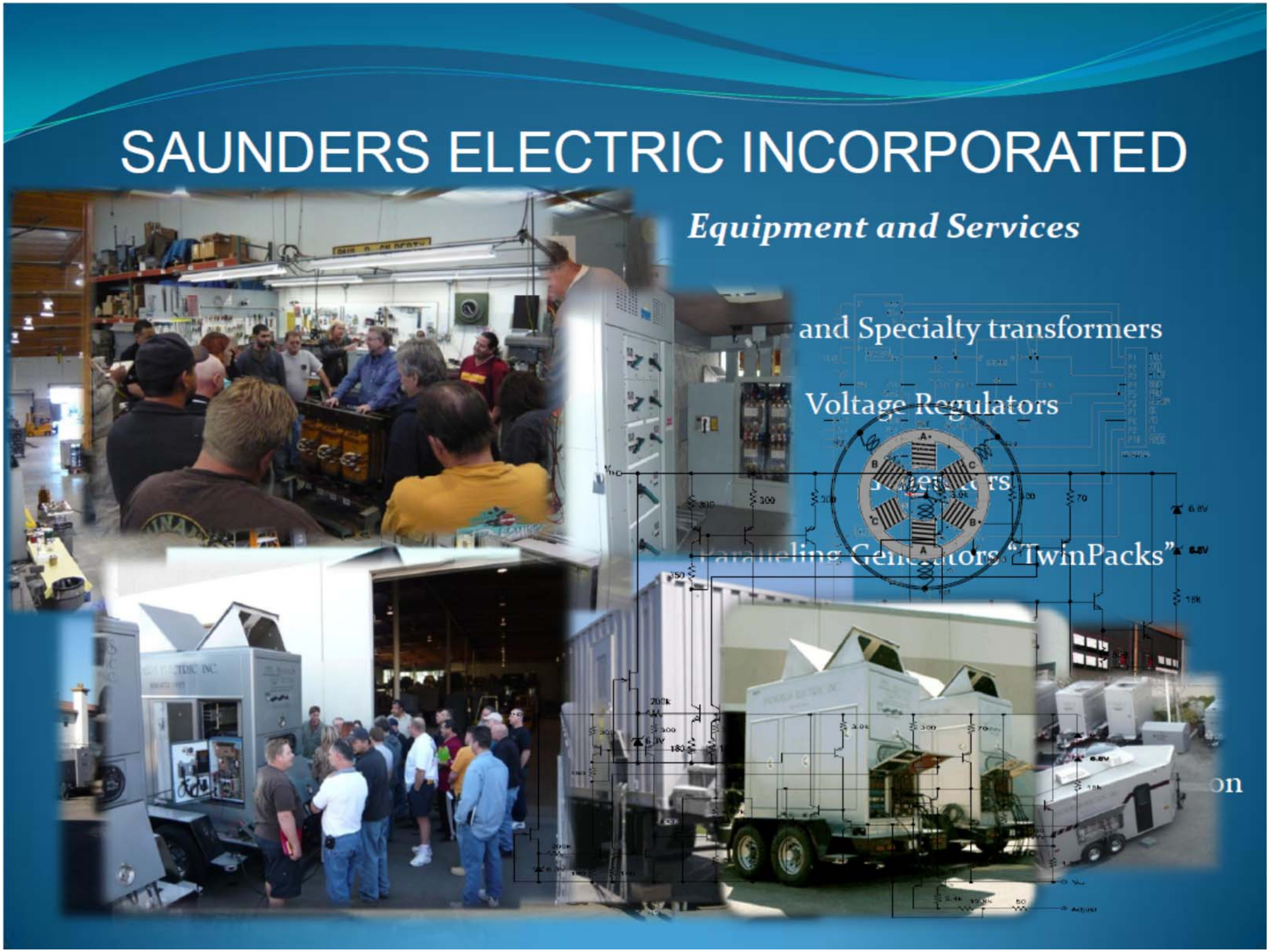
82nd Academy Awards

SAUNDERS ELECTRIC INCORPORATED

- Academy Awards
- Golden Globes
- Disneyland 50th Celebration
- Country Music Awards
- Grammy Awards (NY & LA)
- Daytime Emmys
- Primetime Emmy Awards
- Comic Relief
- Jerry Lewis MDA Telethon
- Miss America Pageant
- Academy of Country Music Awards
- The View (on locations)
- Good Morning America
- Disney California Adventure Grand Opening
- 1984 & 1996 Olympics Broadcast
- Tournament of Roses Parade
- Los Angeles Open Golf Tournament
- Dancing with the Stars (1-8)
- Survivor Finales
- Biggest Loser 1-7 & Finales
- Presidential Debates
- NFL Experience
- American Music Awards
- Super bowl Half-times
- Big Brother 1-12
- America's Best Dance Crew (1-3)

SAUNDERS ELECTRIC INCORPORATED

- ABC Productions
- AMPAS & ATAS
- NBC Productions
- CBS Productions
- Fox Television
- Dick Clark Productions
- KABC
- Cossette Productions
- Disney Broadcast Services
- Disney Entertainment Services
- KTLA Television
- KMEX
- Univision
- Jimmy Kimmel Live
- BET Productions
- Fox Sports West
- AEG Ehrlich Productions
- Seligman Productions
- CBS Production Lighting
- Our House Productions
- Mark Barnett Productions
- Marathon Productions
- E! Entertainment Television
- TV Guide Network
- Access Hollywood
- Hollywood Foreign Press
- Beverly Hilton Hotel
- LA Opera
- George Schlatter Productions
- Jeff Margolis Productions
- Don Cornelius Productions



SAUNDERS ELECTRIC INCORPORATED

Equipment and Services

and Specialty transformers

Voltage Regulators

rs

araleling Gen tors “TwinPacks”

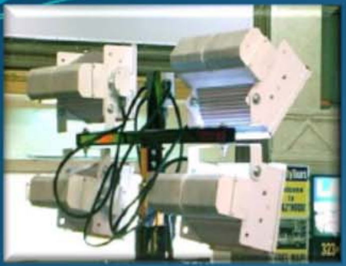
on

Current Systems Deployment

2010 Academy Awards

Altergy's Freedom Fuel Cell at the Oscars

We had been looking for a dependable clean power system to use at the Academy Awards® and in the entire motion picture industry for years. We needed a power system that was portable, efficient, and quiet that could literally be placed at the point of use without emitting the noxious fumes and noise of standard power generators such as diesel driven units .



Current Systems Deployment

SCREEN ACTORS GUILD AWARDS

Awarded the Environmental Media Association (EMA)'s Green Seal, recognizing a production's outstanding efforts to implement sustainable initiatives and promote environmental awareness

2011 Golden Globes

Unlike the diesel generators now in use, the new fuel cell lighting system is a California Air Resources Board (C.A.R.B.) certified "zero-emission" power generator.

2011 Golden Globes

Future Development and Uses

Office/Production trailers

Current industry deployment
of office, bathrooms, production suites
and construction trailers is
approximately
8,500 in southern California

These units traditionally use
2.0KW – 5.0 KW
gasoline driven ac generators

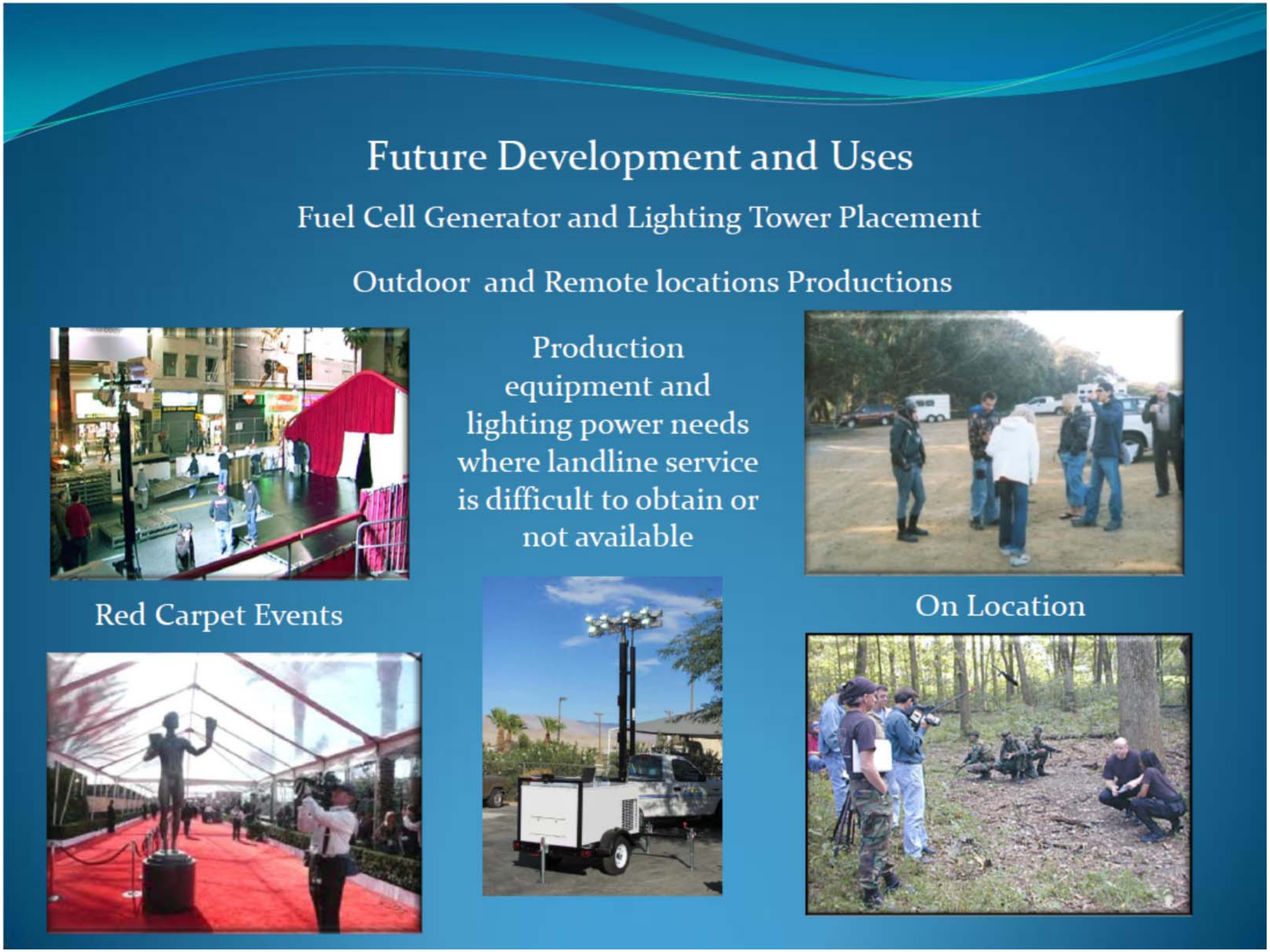
Future Development and Uses

Small Portable Gen-sets

Hydrogen PEM Fuel Cells
will need to be able to compete
with run time, portability, and
paralleling capabilities

Honda EU3000
DC generator
w/120VAC inverter
Run time full load = 7.5 hrs

Honda 5500
AC generator
120/240VAC
Run time full load = 6.5 hrs



Future Development and Uses

Fuel Cell Generator and Lighting Tower Placement

Outdoor and Remote locations Productions

Production equipment and lighting power needs where landline service is difficult to obtain or not available

Red Carpet Events

On Location

Immediate Concerns and Needs

Two Main Concerns

#1 -Fuel tank Capacity vs. footprint

The current 5.0KW Fuel cell generator footprint and full load run time = 24 -36 hours depending upon amount of fuel on board (pressure and quantity of tanks)

A diesel driven unit with the same footprint and run time is capable of producing 60 KW of power

Immediate Concerns and Needs

Two Main Concerns

#2 –Fuel availability and refueling

Limited fueling stations and options –e.g., no portable fueling trucks to transport to remote and secure locations

Future Development and Uses

Possible solutions

Design/Build high pressure Hydrogen tanks with high pressure regulator valves (5000lbs. psi to 80lbs. psi)

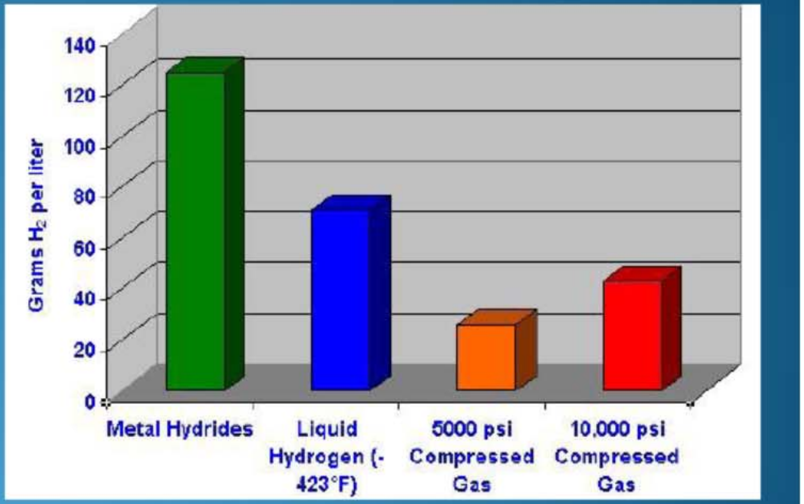
This design concept will allow the end user to "swap-out" spent tanks without exposing them to the high pressure side of the system

Future Development and Research

Develop alternate/higher density
Hydrogen fuels such as:

- Metal hydride
  the big advantage of metal hydride is that there is no high-pressure gas or liquid

- Liquid Hydrogen
  needs to be cooled to 20.28 K (−423.17 °F/−252.87°C)while still pressurized.
  once liquefied it can be maintained as a liquid in pressurized and thermally insulated containers



- Carbon Nanoscrolls

  Greek scientists have found a way to make so- called “carbon nanoscrolls” which store more **hydrogen** than any other material.

Questions/Comments

Multiquip Presentation

A diverse manufacturer and supplier of reliable, quality industrial products

Presented by: Torsten A Erbel, Vice President Product Management, Engineering and Customer Support

About Multiquip Inc.

- Multiquip is one of the largest, most diversified manufacturers and suppliers of reliable, quality industrial products
- Founded in 1973
- 300+ employees
- Wholly owned subsidiary of NY-based ITOCHU International Inc. and parent company, Tokyo-based ITOCHU Corporation, a $34B fortune 500 company
- Worldwide reach distributing products in more than 70 countries through thousands of authorized distribution partners
- Headquarters located in Carson, CA
- Multiquip locations include:
  - Boise, ID; Lewisville, TX; Rancho Dominguez, CA; Honey Brook, PA; Danville, KY; Montreal, Quebec, Canada; Puebla, Mexico; Manchester, United Kingdom; Shanghai, China

About Multiquip Continued

- Distribution partners in Asia, United Kingdom, Latin America and Europe
- Our product portfolio includes:
  - Light to medium construction equipment
  - Power generators
  - Lighting
- Our target markets include:
  - Construction
  - Industrial
  - Telecommunications
  - Government
  - Military/aerospace
  - Entertainment
  - Oil and gas exploration

Multiquip Business Lines

Power

Lighting

Construction

Parts

Power Business Line

- Multiquip has a full line of innovative diesel, gasoline and natural gas powered generators ranging from 2.3 kW to 2,000 kW
- Unsurpassed reliability, efficiency and ultra-quiet performance
- Superior technology
- Durable and environmentally compliant generators
- Markets we serve:
  - Construction
  - Industrial
  - Entertainment
  - Government
  - Military
  - Telecommunications
  - Oil and gas exploration

Power Solutions

- **Portable generators**
  - Gasoline powered
  - Diesel powered
  - Studio
- **Stationary generators**
  - Diesel powered
  - Natural gas powered
- **Containerized generators**
  - 500 kW to 2,000 kW
- **Custom generators**
- **Stationary and portable welders**
  - 135 amps – 500 amps

MULTIQUIP

Power Product Customers

STEWART & STEVENSON
aggreko
ASSOCIATED Power INC.
MoDOT
CATERPILLAR®

LTR
LIGHT TOWER RENTALS
NOV NATIONAL OILWELL VARCO
Carrier
A United Technologies Company

TRANE®
WESTERN SHELTER SYSTEMS
AlaskaStructures®

Sprint
at&t
U.S. Cellular
T · · Mobile · · ·

FEMA
Texas Department of Transportation
GRAINGER.
FOR THE ONES WHO GET IT DONE
GraybaR
works to your advantage.

Power Product Customers Continued

Illinois Department of Transportation
Division of Traffic Safety

AMTRAK

H·E·B

Hertz

WENZLAU
ENGINEERING

VIKING
DRILLING

Red·D·Arc
Welderentals

Volvo Rents
Construction Equipment

Northeast
Utilities System

SUNBELT
RENTALS

NEFF
RENTAL

BASE-X

Oregon
Department of
Transportation

US Army Corps
of Engineers

United
Rentals

RSC
Equipment Rental

Multiquip Business Lines

Power

Lighting

Construction

Parts

Lighting Business Line & Solutions

- Portable lighting solutions for industrial or entertainment applications
- Lighting solutions include:
  - **Lighting towers**
    - Night Hawk
    - MLT series
  - **Balloon lighting systems**
    - GloBug series
  - **EarthSmart® Environmentally Sensitive Products**
    - H_2LT Hydrogen power Light tower

Lighting Product Customers

FEMA

Texas Department of Transportation

Oregon Department of Transportation

Illinois Department of Transportation
Division of Traffic Safety

MoDOT

Multiquip Business Lines

Power

Lighting

Construction

Parts

Construction Business Line

- Multiquip has highly reliable light to medium construction equipment including:
  - Rammers, rollers, plate compactors, and other compaction equipment
  - Concrete and masonry pumping, cutting, placing and finishing equipment
  - Dewatering pumps
  - Blades, bits and cutting equipment
    - We distribute Mikasa, Denyo, Rammax, Collomix and EZ Grout
    - We manufacture and distribute MQ Whiteman, Stow, Sanders, Mayco and Essick

Construction Solutions

- **Compaction Equipment**
  - Rammers
  - Plate compactors
  - Rollers
- **Dewatering Equipment**
  - Electric submersible pumps
  - Centrifugal pumps
  - Trash pumps
  - Diaphragm pumps
- **Mixers**
  - Concrete mixers
  - Mortar mixers
  - Handheld mixers
  - Stationary mixers
- **Grout Delivery Systems**
- **Specialty Fencing Products**

Concrete and Masonry Equipment

- Concrete vibrators
- Screeds
- Power trowels
- Saws
- Rebar equipment
- Power buggies
- Core drill machines
- Floor preparation equipment
- Diamond tools/blades
- Concrete/masonry pumps

MQ MULTIQUIP

Construction Product Customers

GRAINGER
FOR THE ONES WHO GET IT DONE

GraybaR
works to your advantage.

United Rentals

Hertz

BAKER
CONCRETE CONSTRUCTION
expect more

VIKING
DRILLING

NR

CATERPILLAR®

SUNBELT
RENTALS

RSC
Equipment Rental

NEFF
RENTAL

Volvo Rents
Construction Equipment

Tool Rental

True Value
Help Is Just Around The Corner.

CNH

ACE
The helpful place.

HD SUPPLY

Do it Best

evergreen
VENTURE PARTNERS

Concrete Coring Company

safetygrooving&grinding

Sphere 1

Multiquip Business Lines

Power

Lighting

Construction

Parts

Parts Business Line

- SmartEquip
  - Parts procurement program
  - Multiquip partner
    - Integral part of SmartEquip's development due to customer demand for parts
    - We were first to use this service
  - Allows new and existing customers access to:
    - Parts lists
    - Exploded parts diagrams
    - Direct parts ordering
  - Preferred model for part replacement for our customers
  - Significant parts inventory to support our customers
    - Centralized shipping
    - Fast fulfillment rate – 98% of orders are filled in 48 hours

Sales Support and Customer Service

- Authorized service centers worldwide
- Technical support
- Field service managers
- Online product warranty process
- Online access to manuals and support documents
- Customer service and product training
  - In the field
  - Classroom style
- National sales team in place

MULTIQUIP

Summary

- Established and proven company, well positioned for steady, long-term growth
- Provider of high quality and reliable industrial products
- Exceptional customer service
  - Worldwide sales and service support
- Worldwide reach distributing products in more than 70 countries through thousands of authorized distribution partners
- Committed to investing in superior technology and products
- Experienced sales, service and management teams
- Long-term customer relationships

H_2LT Hydrogen Light Tower

Time Line

- Fall 2008 initial contacts
- Spring 2009 First assembly of team at Sandia for feasibility study
- May 2009 initial work started on Alpha unit
- Aug 2009 ASHTO wants to see it
- Oct 2009 ASHTO presentation
- Jan 2010 Paramount Studio presentation
- Febr 2010 Red Carpet lighting at Oscars
- March 2010 NAB
- May 2010 NASA is showing interest
- Nov 2010 Beta unit constructed
- Dec 2010 PowerGen Orlando Public showing
- Jan 2011 World of Concrete

H_2LT Hydrogen Light Tower

19 1/2 x 8

H_2LT Hydrogen Light Tower

H$_2$LT Hydrogen Light Tower

H_2LT Hydrogen Light Tower

H_2LT Hydrogen Light Tower

H_2LT Hydrogen Light Tower

H_2LT Hydrogen Light Tower

H_2LT Hydrogen Light Tower

Challenges that remain:

- Customer option definition
- Fuel availability
- Supply & demand manufacturing
- Consumer Education
- Myths about Hydrogen and Safety
- Initial investment into manufacturing and inventory
- On board fuel storage & run time
- Overall pricing
- Inconsistancy of Energy Credits in all States
- Responding to the initial demand and interest into this product

H_2LT Hydrogen Light Tower

San Francisco International Airport Hydrogen Opportunities and Challenges Presentation

SFO

San Francisco International Airport

HYDROGEN OPPORTUNITIES
AND CHALLENGES

San Francisco International Airport

SFO

San Francisco International Airport

SFO

San Francisco International Airport

Major SFO Off-Road Vehicle Operators

- The Airport Commission
- Six Major Airlines: UA, CO, AA, DL, US, WN
- Skywest, a Regional Airline
- Three Major Ground Handlers:
  - Menzies, Swissport, Servisair
- Signature, a Business Aviation Handler

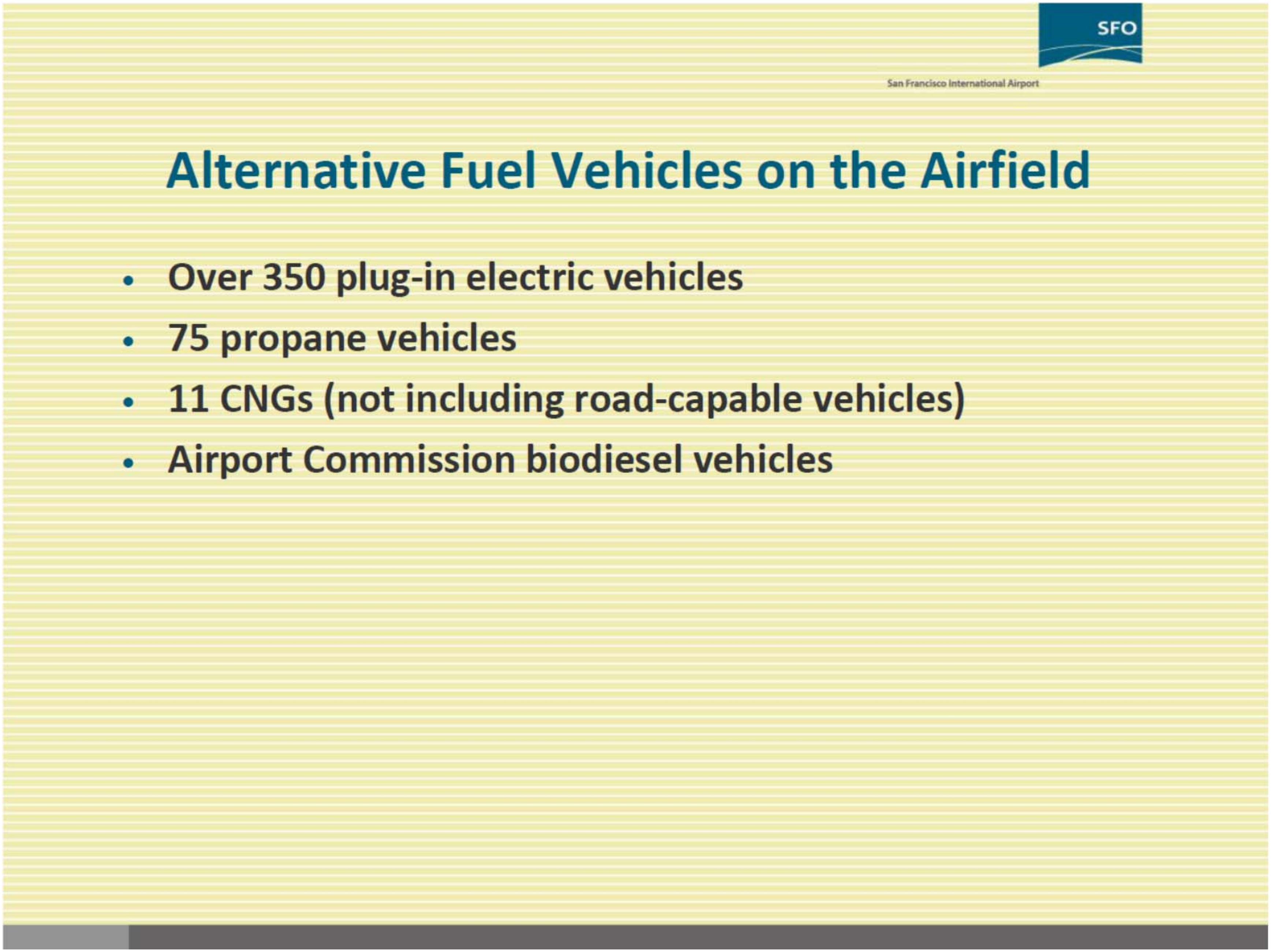
SFO

San Francisco International Airport

Number and Types of Vehicles

Over 1,200 off-road vehicles, mainly airfield

- **Airport Commission specialized vehicles**
- **Over 400 baggage tractors**
- **Almost 200 belt loaders**
- **Over 100 aircraft pushback tractors**
- **90 maintenance/cabin lifts**
- **80 ground power units**
- **50 container loaders**
- **30 lavatory trucks**
- **Over 150 forklifts**
- **100 carts and other units**



SFO

San Francisco International Airport

Alternative Fuel Vehicles on the Airfield

- Over 350 plug-in electric vehicles
- 75 propane vehicles
- 11 CNGs (not including road-capable vehicles)
- Airport Commission biodiesel vehicles

San Francisco International Airport

Airport Operating Environment

- Major bottom-line emphasis
- Absolute requirement for reliability
- Legacy diesel vehicles can be repowered
- Electric GSE may be cost-effective, however
  - chargers must be available, batteries replaced
- Clean vehicle grant funds are limited
- CARB off-road diesel regulations were delayed
- CARB LSI rule discourages propane
- However, the Airport Commission must use low-emission vehicles whenever feasible

San Francisco International Airport

Pending SFO Hydrogen Infrastructure

- SFO is building a $5M-plus hydrogen fueling complex using CARB, CEC, BAAQMD, San Mateo C/CAG, private sector and Airport funds
- The facility will be located landside near the 101 freeway, but close to airfield gates
- Anticipated opening 1Q 2012
- Major automakers, a transit provider, and courtesy shuttle operators will recharge fuel cell and hybrid vehicles at the site
- Specialized off-road vehicles could use hydrogen from the facility

SFO

San Francisco International Airport

Can Hydrogen Power a Variety of Airfield Vehicles at SFO?

- Several Airport Commission vehicles are candidates including mobile lighting units
- We anticipate clear benefits, but have no ability to fund incremental costs
- A tougher bar applies to tenant vehicles
- Our tenants are looking for cost savings and regulatory relief
- Vehicles must be easy to manage
- Fuel must be easy to obtain
- Green credentials are valuable to a few tenants


thansa.com
D-ABVL


687E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JLG


swissport


85


N223SW


065


AS5

Questions/Contact

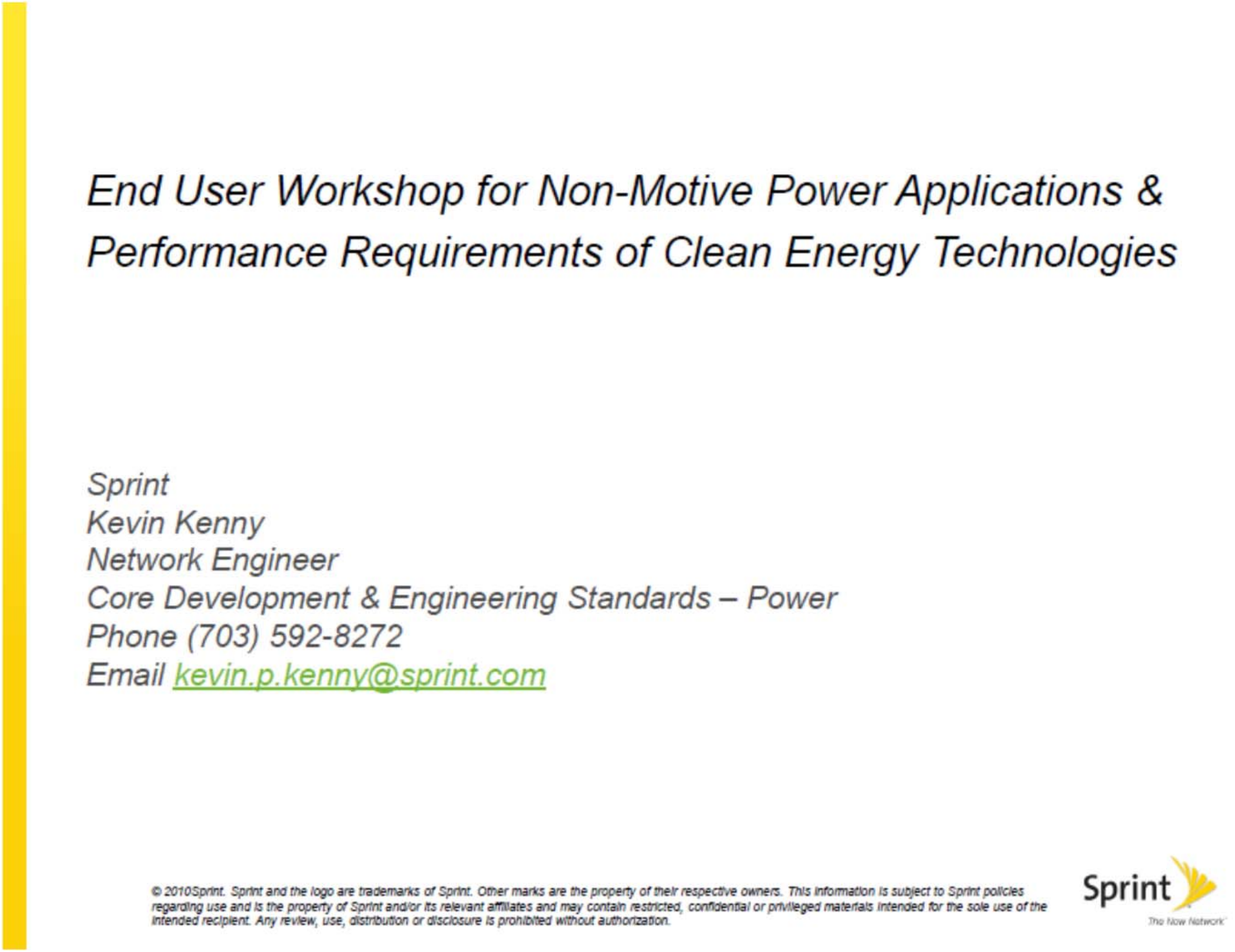
Roger Hooson, Senior Planner,

Landside Operations

roger.hooson@flysfo.com

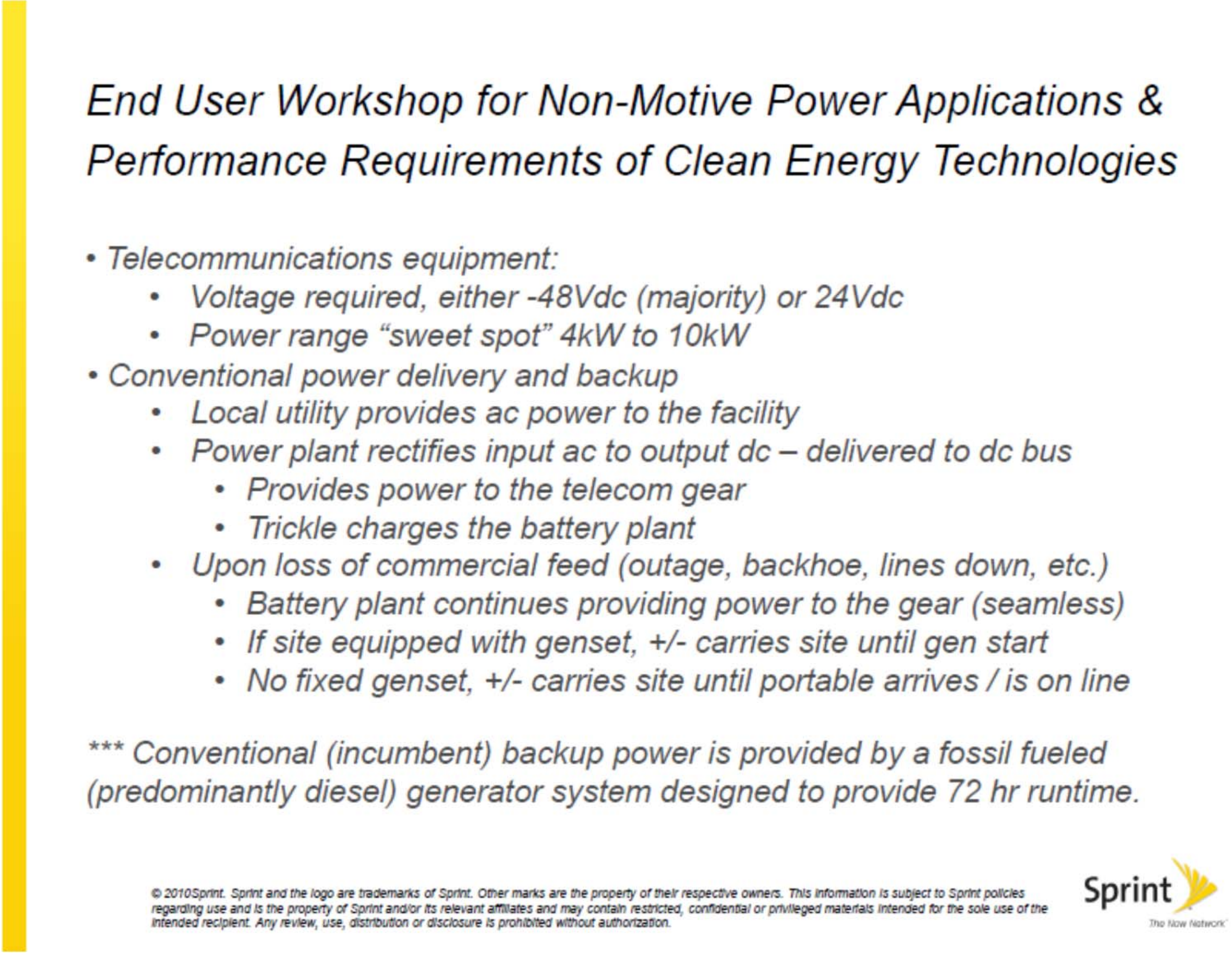
650-821-6511

End User Workshop for Non-Motive Power Applications & Performance Requirements of Clean Energy Technologies: Sprint Presentation



End User Workshop for Non-Motive Power Applications & Performance Requirements of Clean Energy Technologies

Sprint
Kevin Kenny
Network Engineer
Core Development & Engineering Standards – Power
Phone (703) 592-8272
Email kevin.p.kenny@sprint.com



End User Workshop for Non-Motive Power Applications & Performance Requirements of Clean Energy Technologies

- *Telecommunications equipment:*
  - *Voltage required, either -48Vdc (majority) or 24Vdc*
  - *Power range "sweet spot" 4kW to 10kW*
- *Conventional power delivery and backup*
  - *Local utility provides ac power to the facility*
  - *Power plant rectifies input ac to output dc – delivered to dc bus*
    - *Provides power to the telecom gear*
    - *Trickle charges the battery plant*
  - *Upon loss of commercial feed (outage, backhoe, lines down, etc.)*
    - *Battery plant continues providing power to the gear (seamless)*
    - *If site equipped with genset, +/- carries site until gen start*
    - *No fixed genset, +/- carries site until portable arrives / is on line*

**** Conventional (incumbent) backup power is provided by a fossil fueled (predominantly diesel) generator system designed to provide 72 hr runtime.*

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- *Alternative backup power solutions deployed*
  - *In 2005, began deployment of PEM Fuel Cells (Hurricane Alley)*
  - *3kW, 5kW, and 6kW systems deployed (~250 total units)*
  - *Low pressure Hydrogen storage – six (6) "K" bottles*
    - *16 – 20 hour runtime, depending upon load*
    - *Cumbersome refueling – bottle swap out required*
    - *Logistics challenge in the event of large scale outage*
    - *Hydrogen fuel providers faced "new" business model*

"There's gotta be a better way!"

- *Medium Pressure, On-Site Refillable, Hydrogen Storage Solution:*
  - *Awarded DOE grant - deploy 260 new HFCs / retrofit 70 in-service units*
  - *Medium pressure Hydrogen storage – 16 bottles*
    - *72 hour + runtime, depending upon load*
    - *Fueling infrastructure is small but growing (Market Transformation)*
    - *Fill in place with standardized connector*
    - *Topping off available / encouraged (reduces truck roll costs)*

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The good, …

- *Department of Energy offers wealth of support & guidance*
- *HFC vendors are in there fighting with us to be successful*
- *Fuel vendor making investments to support "Critical Infrastructure" needs*
- *A&E / installation contractors getting up to speed poised to deliver results*
- *Unit costs forecasted to decline over time*
- *MLA partners beginning to understand / support HFC in their facilities*

the bad, …

- *More siting / permitting workshops necessary in strategic markets*
- *Universal (standardized?) performance monitoring / alarm reporting system*
- *Overall deployment cost not at parity with diesel genset (OPS yardstick)*
- *In these economic times, backup power is not center stage (want vs. need)*

and the ugly!

- *No deployment FOAs on the radar screen*
- *Educate, educate, educate (DTMWA story, PSAs)*
- *No one size fits all*
- *Is stored gas the way to go (nanotechnology, reformer based, fuel type)*
- *Fuel Cells in CHP applications – what, where, how?*

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