NATIONAL RENEWABLE ENERGY LABORATORY

Hydrogen Energy Storage:
Grid and Transportation Services

February 2015

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Proceedings of an Expert Workshop Convened by the U.S. Department of Energy and Industry Canada, Hosted by the National Renewable Energy Laboratory and the California Air Resources Board
Sacramento, California, May 14 –15, 2014

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List of Acronyms

CaFCP	California Fuel Cell Partnership
CARB	California Air Resources Board
CEC	California Energy Commission
CED	U.S.–Canada Clean Energy Dialogue
CPUC	California Public Utilities Commission
DOE	U.S. Department of Energy
EARTO	European Association of Research and Technology Organisations
EPA	U.S. Environmental Protection Agency
FCEV	fuel cell electric vehicle
FERC	Federal Energy Regulatory Commission
GO	(California) Governor's Office
HES	hydrogen energy storage
IPHE	International Partnership for Hydrogen and Fuel Cells in the Economy
MHE	material handling equipment
NREL	National Renewable Energy Laboratory
PEM	polymer electrolyte membrane
PUC	Public Utility Commission
R&D	research and development
SCAQMD	South Coast Air Quality Management District

Abstract

Hydrogen energy storage (HES) systems provide multiple opportunities to increase the resiliency and improve the economics of energy supply systems underlying the electric grid, gas pipeline systems, and transportation fuels. This is especially the case when considering particular social goals and market drivers, such as reducing carbon emissions, increasing reliability of supply, and reducing consumption of conventional petroleum fuels. The topic of HES was addressed by approximately 65 attendees at an expert stakeholder workshop convened by the U.S. Department of Energy and Industry Canada on May 14–15, 2014, in Sacramento, California. The workshop focused on potential applications and policy support options for electric grid and transportation services. A total of 17 plenary presentations addressed different aspects of HES systems, policy issues, and market potential, and a number of high-priority items were identified through a facilitated breakout group process. The items identified fall into three general categories: (1) criteria for evaluation and barriers to deployment, (2) next steps for HES applications, and (3) policy issues related to deployment and economics.

An important concept emphasized by participants is that competitive HES systems cannot rely upon the simple service of storing grid electricity for later conversion back to grid electricity. Instead, it is likely that competitive HES systems will receive multiple revenue streams by providing more than one energy service or industrial feedstock. Providing multiple services and feedstocks distinguishes HES systems from other types of energy storage, such as batteries or compressed air energy storage systems. HES systems have unique flexibility that can assist energy planners, facility owners, and grid operators with system reliability and the integration of renewable energy into multiple energy end-uses within the power, heating, and transportation infrastructure. Workshop participants identified 12 distinct next steps to be pursued by a variety of stakeholders to support near and mid-term HES deployment activities and policy or regulatory reforms. These items focus on multi-megawatt-scale demonstration projects and the development of successful business cases.

Executive Summary

Hydrogen energy storage (HES) systems present an opportunity to increase the flexibility and resiliency of sustainable energy supply systems while potentially reducing overall energy costs on account of system integration and better utilization of renewables. HES systems involve a broader range of energy services than just storing grid electricity for later reconversion to grid electricity. They also provide ancillary grid services; fuel for fuel cell electric vehicles (FCEVs) or material handling equipment (MHE), such as forklifts or airport tugs; backup power supply; and feedstock supply to refineries, ammonia production facilities, or for other industrial processes. Additionally, the opportunity exists for the natural gas industry and regulators to enable hydrogen blending that could increase renewable energy supply via the extensive natural gas infrastructure. As contraints on the electric grid increase (from renewable portfolio standards [RPS], carbon regulations, and demands for greater reliability and flexibility), storage sytems in general will prove more valuable, and HES sytems can play a unique role in both near- and long-term markets. This report compiles feedback collected during a 1.5-day workshop attended by experts in the field, which was held on May 14–15, 2014, in Sacramento, California, and hosted by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) and the California Air Resources Board (CARB). The workshop focused on policy and regulatory issues related to HES systems. Report sections include an introduction to HES pathways, market demand, and the "smart gas" concept; an overview of the workshop structure; and summary results from panel presentations and breakout groups.

HES systems are unique when compared with other types of energy storage. One unique feature is the large scale at which energy can be stored, on the order of 1 GWh to 1 TWh. Batteries typically range from 10 kWh to 10 MWh, and compressed air storage and pumped hydro range from 10 MWh to 10 GWh. A pathway of recent interest is the direct injection of hydrogen into natural gas pipelines, often referred to as power-to-gas or power-to-hydrogen. The hydrogen product can also be converted to methane before injection, which avoids various hydrogen blending issues. Other uses of hydrogen generated from HES systems are for FCEVs, and near-term markets, such as fuel cell forklifts and backup power systems. The present report focuses on the production of hydrogen by electrolysis, which is the origin of multiple hydrogen pathways serving both the electric grid and the transportation sectors, and, in some cases, industry end uses. "Smart gas" as a concept encompasses these various hydrogen pathways, as well as the complex interface of electrolysis units with demand response and other grid services.

The May workshop was developed and convened by the U.S. Department of Energy (DOE) and Industry Canada as part of the growing U.S.–Canada Clean Energy Dialogue (CED) launched in 2009. The goal of the workshop was to identify challenges, benefits, and opportunities for commercial HES applications to support grid services, variable electrical generation, and hydrogen vehicles. The scope of the workshop spanned four key areas: (1) lessons learned and demonstration status, (2) market opportunities and business models, (3) technology research and development (R&D) and near-term market potential, and (4) policy and regulatory challenges and opportunities. Workshop participants benefited from 17 expert panel presentations and discussions ensuing from panels addressing each area. Given these reviews and updates, participants joined one of four facilitated breakout sessions to respond to and discuss the key questions about criteria and barriers to successful demonstrations, policy issues, and next steps. Each key question is indicated in Table ES-1.

Participants were given an opportunity to raise high-priority items in response to each question. Items were then discussed and clarified through group facilitation, and participants voted on the most important high-priority items. All items and voting results were collected for these proceedings. (See Appendix A for the complete list.)

Table ES-1. Key Questions Posed During the Breakout

Morning Breakout Session: Demonstration Criteria and Opportunities

- **CRITERIA:** What criteria should be used to identify promising near-term (next one to three years) demonstration projects with high potential for learning and early-commercial success?
- **POLICIES:** What existing or proposed policies/regulations can (or could) enable opportunities for successful near-term demonstrations of hydrogen energy storage?
- **NEXT STEPS:** What actions, analyses, or demonstrations are needed to best inform industry and government decision makers to build support for a broader rollout of hydrogen as an energy storage medium?

Afternoon Breakout Session: Transportation, Renewables, and Other Synergies

- **BARRIERS:** What technical and policy barriers are hindering integration across multiple energy sectors using hydrogen energy storage (i.e., heating fuel, transportation fuel, electric grid)?
- **POLICIES:** What existing or proposed policies/regulations can (or could) enable cross-sector synergies that strengthen the (near- or long-term) business case for hydrogen energy storage?
- **NEXT STEPS:** What actions, analyses, or demonstrations are needed to inform key stakeholders about the potential for cross-sector synergies using hydrogen storage?

The highest priority items within each category include the following:

- **Criteria and barriers**—Technical and economic viability; multiple end uses; unified supportive policy; partnerships and coordination
- **Next steps**—Demonstrations and pilot projects; analyze business cases; develop or revise policies and regulations; develop and implement plan and targets
- **Policy**—Equal treatment with resource credits and other markets; tax credits, incentives, and rebates; develop and streamline codes and standards; more inclusive and complete definitions; develop and standardize regulations; develop targeted policies; other financial mechanisms.

The number of items and votes received for each of these categories is summarized in Table ES-2. Responses are shown color coded by breakout group number. Each group represents roughly the same number of participants. Attendees were assigned to breakout groups to increase the diversity of viewpoints and types of expertise in each group. The common emphasis on items within particular categories and the relatively equal balance of responses in the highest priority categories suggests that the parallel breakout groups identified priority areas with a high degree of agreement. Categories with fewer total votes or total items tended to be dominated by one or more of the four breakout groups, suggesting a lower level of agreement across all workshop participants.

The final summary and discussion section of the report includes a list of next-step items derived from the categories indicated in Table ES-2 and overall feedback received by participants. The summary and discussion section proposes roles for various stakeholders, including lead roles, supporting roles, and advisory roles, as indicated in Table ES-3.

Table ES-2. Summary of High-Priority Items Identified During Workshop Breakout Sessions

This mapping of action items to stakeholders was not addressed explicitly during the workshop. Instead, a preliminary version was proposed as a synthesis of workshop feedback, and then reviewed by participants and peers and revised in response to recommendations. The intent of this list is to make high-priority items from the workshop more tangible. For example, it is likely that industry stakeholders would play a lead role in next steps associated with deployment activities; whereas analysis stakeholders (universities, national laboratories, industry consortia, nongovernmental organizations, regulatory analysts, etc.) would play a lead role in analyzing business case topics. Other stakeholder types, as described in the notes on Table ES-3, could play a supportive or advisory role in next-steps items; whereas, by definition, road map development would ideally involve support and active engagement across all relevant stakeholders. Entities like the California Energy Commission (CEC) and CARB are California-specific; however, there are corollaries for many of these groups that can be extended to other states or the federal level. One example is CARB, which regulates air quality and has similar duties to the U.S. Environmental Protection Agency, which operates at the U.S. federal level. Another example is Ontario's Ministry of the Environment and Climate Change, which works to protect and improve air quality in Ontario; on the Canadian federal level, Environment Canada is tasked with protecting the environment.

In conclusion, it is likely that HES systems will be deployed within a complex interface of multiple market forces and regulatory or policy influences, which will provide benefits to the electrical grid, transportation applications, and, in some cases, industry applications. Near-term applications may be at the megawatt scale or larger and can benefit from multiple revenue streams, including grid services and emerging markets, such as fuel cell forklifts or backup power systems, that provide demand in the near term, whereas FCEVs may provide greater demand in the medium to long term. Large-scale HES systems have the potential to influence transmission planning and the economics of renewables integration. Results from this workshop provide insights to help guide deployment activities, and policy and regulatory reforms needed to remove market barriers and increase the sustainability and resiliency of multiple integrated energy systems.

Table ES-3. Summary of Action Items and Stakeholder Involvement

Proposed Next Step	Stakeholder (L = Lead role; S = Supporting role; A = Advising role)								
	Industry	Utilities	DOE	FERC	PUCs	CEC	CARB	Analysts	Other
Demonstrate large-scale (multi-megawatt) HES systems, multi-fuel (natural gas, anaerobic digester gas, landfill gas), and multi-use (FCEVs, electric vehicles, grid, vehicle-to-grid, station-to-grid) systems with utility involvement and renewables integration	L	S	S	A	S	S	A	A	
Develop projects that show successful business cases, such as large-scale, multi-use projects that are coordinated among state, federal, and other stakeholders	L	S	A	S	S	S	A	S	
Fund multiple large-scale demonstrations	S	S	L		A	L			
Demonstrate autonomous, remote power applications for a user, site, or community	L	S	S			S			S[2]
Identify site(s) for hydrogen energy storage with multiple uses, particularly those on federal land	S	A	S	A				A	L[1]
Focus on hydrogen fuel cell buses, vehicle fleets, or other demand centers, such as seaports or airports	S		A			S	S		L[3]
Perform analysis to establish a business case by monetizing co-optimized value streams, system performance, and financial viability	S	A	S		S	S	A	L	
Develop models for siting, sizing, and evaluating the financial feasibility of HES systems compared with competing systems	S	A	S		S	S	A	L	
Articulate environmental performance of HES systems. Look at carbon reductions per vehicle mile driven, per kWh of electricity, and on an end-use utility basis.	S	A	S			S	S	L	
Introduce regulatory framework to facilitate the provision of grid support services from HES and change regulatory and/or incentive definitions of energy storage to be more than simply "electricity in, electricity out," with inclusion of power-to-gas as an eligible storage option	A	A	A	S	L	S	A	S	
Develop a roadmap for integrating renewable and fossil energy sources with hydrogen	S	S	L	A	S	S	S	S	A[4]
Enable fair and inclusive market treatment for HES. Allow HES systems to participate in multiple markets and recognize hydrogen from HES as an eligible fuel for renewable fuel standard and low-carbon fuel standard.	A	A	S		S	A	L	S	L[5]

NOTE: Other categories:
(1) Multiple federal agencies could be lead participants, such as the U.S. Department of Transportation, Bureau of Land Management, or Department of Defense.
(2) Community or end-user leadership required.
(3) Transit agency, fleet, or seaport/airport leadership required.
(4) A broad range of stakeholders may be required, including industry representatives (such as the Electric Power Research Institute, Gas Technology Institute, or others), environmental nongovernmental organizations, the Environmental Protection Agency, etc.
(5) Regulatory agencies such as the Environmental Protection Agency.

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01 Introduction & Background

Hydrogen energy storage (HES) systems present an opportunity to increase the flexibility and resiliency of sustainable energy supply systems while potentially reducing overall energy costs on account of system integration and better utilization of renewables. Drivers for more sustainable energy supply include climate change, energy security, and health impacts from poor air quality.

Recent discussions about HES systems involve a broad range of energy services in addition to storing grid electricity as hydrogen for later conversion back to grid electricity. The use of HES systems for grid support can be more accurately conceptualized as enabling the appropriate allocation of electrical resources to high-end markets while improving overall system sustainability and resiliency and lowering supply costs. Electrolysis units can provide ancillary grid services; renewable hydrogen can be stored and delivered as a natural gas blend component; and hydrogen can be used in multiple transportation and industrial end-use markets. When hydrogen is provided to zero-emission fuel cell electric vehicles (FCEVs), the resulting revenue is higher than that from supplying grid electricity because of the higher market price per unit of energy for transportation fuels.

Providing both grid and transportation energy services can result in a more robust business case for HES systems. Current markets include feedstock supply to petroleum refineries, advanced biorefineries, ammonia production facilities, or other industrial processes, and emerging near-term markets including material handling equipment (MHE), such as forklifts or airport tugs, backup power supply for telecommunications, or remote power systems and range-extenders for battery electric vehicles. As constraints on the electric grid increase, including more ambitious renewable portfolio standards or carbon regulations and demands for greater reliability and flexibility, storage systems in general will tend to prove more valuable (Denholm et al. 2013). The degree to which HES systems can compete in electrical storage markets will depend on a broad range of factors, many originating from market demands outside the electrical sector.

This report presents proceedings from an expert workshop focused on both near- and long-term HES applications and the criteria, barriers, policies, and next steps toward making those systems competitive and economically viable. Approximately 65 participants met in Sacramento, California, for 1.5 days for a series of expert panel presentations and facilitated breakout sessions. The scope of the workshop was relatively broad, and addressed multiple supply pathways and end-use markets. The questions posed to attendees during breakout sessions tended to emphasize policy and deployment issues. More technical aspects of electrolytic hydrogen production, storage, and delivery have been addressed elsewhere (Ainscough et al. 2014a, Ainscough et al. 2014b, Carmo et al. 2013). Results of the workshop include various highlights from panel presentations and priority items identified during breakout group sessions.

> Hydrogen energy storage is more than "electricity in, electricity out."
>
> – Workshop Participant

HES systems have been the topic of numerous studies and analyses. These systems typically involve the production of hydrogen from electricity by electrolysis, in which electrical energy is used to split water molecules into hydrogen and oxygen gas.[1] Most electrolysis units involve alkaline or polymer electrolyte membrane (PEM) conversion processes (Barbir 2005, Zeng and Zhang 2010). As early as 1999, Ogden provided an overview of hydrogen infrastructure components, which included storage systems (1999), and Yang reviewed general similarities and differences between hydrogen and electricity as energy carriers (2008). Many studies of future hydrogen scenarios have been developed (Greene et al. 2008, National Research Council 2008), and this complementarity between hydrogen and electricity has been the focus of high-renewable scenarios developed by Barton and Gammon for the United Kingdom (2010), and more recently by Jacobson et al. for California (2014). Several

[1] For an introduction to electrolysis and other hydrogen production processes, see the DOE website on Hydrogen Production: http://energy.gov/eere/fuelcells/hydrogen-production. In addition, see a May 2013 report from Fuel Cell Today focused on electrolysis systems: http://www.fuelcelltoday.com/media/1871508/water_electrolysis___renewable_energy_systems.pdf

studies have compared hydrogen storage systems with other storage systems on the basis of cost, performance, and other attributes relevant to market viability and policy development (Schoenung and Hassenzahl 2003, Steward et al. 2009, Parfomak 2012, Oberhofer 2012).

In addition to numerous analytical studies, multiple grid-connected and remote demonstration projects have been executed during the past decade with approximately 80 hydrogen fueling stations currently based on electrolysis, 35 of which are located in North America (Fuel Cell Today 2013). Recently, interest has focused on power-to-gas applications, with several projects, especially in Germany, converting electrolytic hydrogen to synthetic methane (CH_4) by methanation. Methanation involves combining electrolytic hydrogen with carbon dioxide (CO_2) by a thermocatalytic or biologic process. The concept of power-to-gas (a phrase derived from the German "Strom zu Gas") is to produce "green gas" with hydrogen from renewables and carbon dioxide from bioenergy or other sources, which allows for a significant increase in the overall utilization of renewable energy assets (Sterner 2010). Power-to-gas and biogas projects in Austria, the Netherlands, Denmark, Sweden, Germany, and elsewhere were reviewed by Iskov and Rasmussen (2013). Gahleitner reviewed 41 international power-to-gas projects and concluded with recommendations to improve overall system performance, develop codes and standards, and determine optimum system configurations (2013). Grond, Schulze, and Holstein reviewed technologies for power-to-gas systems and concluded that these systems can provide community energy storage, time shifting/load leveling, and transmission and distribution management services (2013).

One approach to power-to-gas is to inject hydrogen directly into natural gas pipelines rather than to undertake the additional step of methanation. This pathway was researched thoroughly in the European Union's NaturalHy project (Florisson 2009) and discussed by Melaina et al. (2013) in the context of the U.S. natural gas pipeline systems. In general, few changes to existing natural gas transmission or distribution pipeline networks are required if the hydrogen blend level is very low. Although industry codes and standards have become more stringent and society's tolerance for risk has decreased, for nearly a century leading up to 1950, hydrogen was a major constituent of town gas used for heating and lighting in homes, commercial buildings, and industry (Castaneda 1999, Tarr 2004, Melaina 2012). Dodds and Hawkes reviewed issues related to hydrogen blending potential in the U.K. natural gas system and advised that early blend levels be limited to 2% to 3% hydrogen by volume (2014). Standards in Germany suggest up to 5%, with potential to increase to 6% to 20% (Winkler-Goldstein and Rastetter 2013). As is evidenced by these studies, there is continued interest in pipeline material research for enabling power-to-gas. Power-to-gas projects today have a bias toward methanation, partly because of the lack of standards and pipeline-specific analysis required to approve direct injection of hydrogen. However, if suitable gas quality standards exist to facilitate direct hydrogen blending, it will likely lower the development cost for these systems. Furthermore, methanation processes are not expected to achieve 100% conversion of the input hydrogen feedstock, so the development of gas quality standards for lower levels of direct hydrogen blending is also expected to facilitate the growth of the methanation technologies.

In addition to injection into the natural gas system, underground geologic formations can be used to store large amounts of natural gas or hydrogen. This concept has several successful demonstrations and continues to attract interest in North America and Europe (HyUnder, 2014). Salt caverns, which are currently used to store natural gas seasonally, are perhaps the best example of very large-scale hydrogen storage (Lord et al. 2011). For example, Ozarslan recently evaluated a particular large-scale solar hydrogen storage system that used salt caverns (2012).

HES units can not only increase the utilization of renewable energy resources but also have the potential to provide services to the grid. These services can be on the transmission or distribution level and enable access to additional revenue streams for HES systems. Several studies have been performed to assess the ability and value for electrolyzers, acting as demand response devices, to provide grid services (Hydrogenics 2011, Eichman et al. 2014, Judson-McQueeney et al. 2013). In this respect, electrolytic hydrogen can play a role within the larger architecture of a smart grid and/or "smart gas" system by providing increased flexibility and resiliency. As is the case with other energy storage options, there are challenges to characterizing the value of these grid services to equipment owners, utilities, and electricity market operators.

To better understand these and other related issues, the sections below continue to introduce the topic of HES by reviewing various hydrogen conversion systems and delivery pathways (Section 1.1), discussing emerging demand from FCEVs, ancillary services, and emerging markets (Section 1.2), and conceptualizing "smart gas" within integrated energy systems (Section 1.3).

1.1 Hydrogen Storage System Processes and Pathways

Workshop participants emphasized the importance of regarding HES systems as being more than "electricity in, electricity out" systems. A more complete conceptualization of HES systems involves multiple processes, pathways, and end-user markets that do not come into play for batteries, compressed air storage, or pumped hydro. The core process is electrolysis, the conversion of electrical energy into hydrogen energy by splitting water into its constituent parts, hydrogen and oxygen. Conceptually, the electrolysis process can be thought of as establishing a new intertie with the electricity network to allow wholesale energy deliveries to other energy networks. In effect, this becomes a new electricity export option that can simultaneously support high-value electricity grid and ancillary services. The resulting hydrogen may be consumed in one of three ways:

1. **Directly as a fuel**—Hydrogen can be used in near-term markets, such as for MHE or backup power systems (e.g., telecom towers), or in emerging markets, such as FCEVs. Hydrogen can be converted to electricity through a fuel cell or combustion engine (e.g., turbine or internal combustion engine). The oxygen byproduct of electrolysis can be used to improve conversion efficiency, such as in high-efficiency hydrogen-oxygen turbines.

2. **As a feedstock**—Conventional feedstock uses include hydrogen in refineries, for hydrocracking or sulfur removal, and in ammonia production. An important energy storage pathway discussed at the workshop is the biological or chemical combination of hydrogen and carbon dioxide to produce synthetic natural gas ($2H_2 + CO_2 \rightarrow CH_4 + O_2$), which can then be injected into natural gas pipelines. When the hydrogen is produced from renewable sources, the resulting synthetic gas is referred to as a renewable gas. Hydrogen is also an important feedstock for some advanced biofuel production processes.

3. **Blended with natural gas**—At relatively low concentrations, such as 2% to 10%, hydrogen may be injected into some natural gas pipeline systems with only minor modifications to supply infrastructure or end-use devices. Acceptable concentrations and required modifications are very pipeline and utility dependent. It has also been proposed to inject hydrogen in higher concentrations, such as 25% or more, with extraction of the hydrogen downstream (Florisson 2009).

These three general uses are indicated with reference to natural gas and electrical supply pathways in Figure 1. The figure generally flows from energy production on the left to end-use markets on the right. Across the top of the figure is the conventional electrical grid (solid black lines with grey shadows) with natural gas plants producing electricity, which is delivered via transmission lines to substations and then to end users through the distribution grid. Across the bottom of the figure is the conventional natural gas pipeline grid (double-lined pathways with red shadows), with natural gas production in the bottom left and gas transmission pipelines and large-scale storage (i.e., caverns) upstream of the pressure letdown stations, where the gas pressure is reduced before entering the distribution pipeline system. Interspersed between these two conventional grid systems are various hydrogen production and conversion processes and pathways (shown with blue shadows) that are proposed as a means of adding value to overall grid sustainability and resiliency. These include examples of each of the three general uses listed above, including blending hydrogen into natural gas pipelines (which results in the pathways shown with purple shadows). The figure does not include all possible processes and pathways, but it does serve as an introduction to the scope of HES systems discussed during the workshop. Additionally, a single system may be able to pursue multiple processes and pathways. More detailed descriptions of specific processess and pathways within Figure 1 are provided in Sidebar 1.

Not included in this figure are specific hydrogen storage components, such as caverns for central production or compressed gas for distributed systems. Some additional pathways are also not included for the sake of simplicity. For example, integrating anaerobic digestion biogas systems can provide a carbon dioxide source with methanation upgrading the biogas product (Jurgensen et al. 2014).

SIDEBAR 1. Value-Added Hydrogen Processes and Pathways

Each HES pathway or process shown in Figure 1 is indicated with a yellow circle and described below

A **Electrolysis for grid support**—This pathway involves electrolysis units providing ancillary services to grid operators by supplying regulation (Frequency Control) and ramping services. This is similar to the use of demand response devices for services; however, it should be noted that the electrolysis units are purpose built for wholesale energy services unlike traditional demand response devices. In addition, the resulting hydrogen can be delivered to multiple markets or uses, including methanation or delivery to FCEVs (see below).

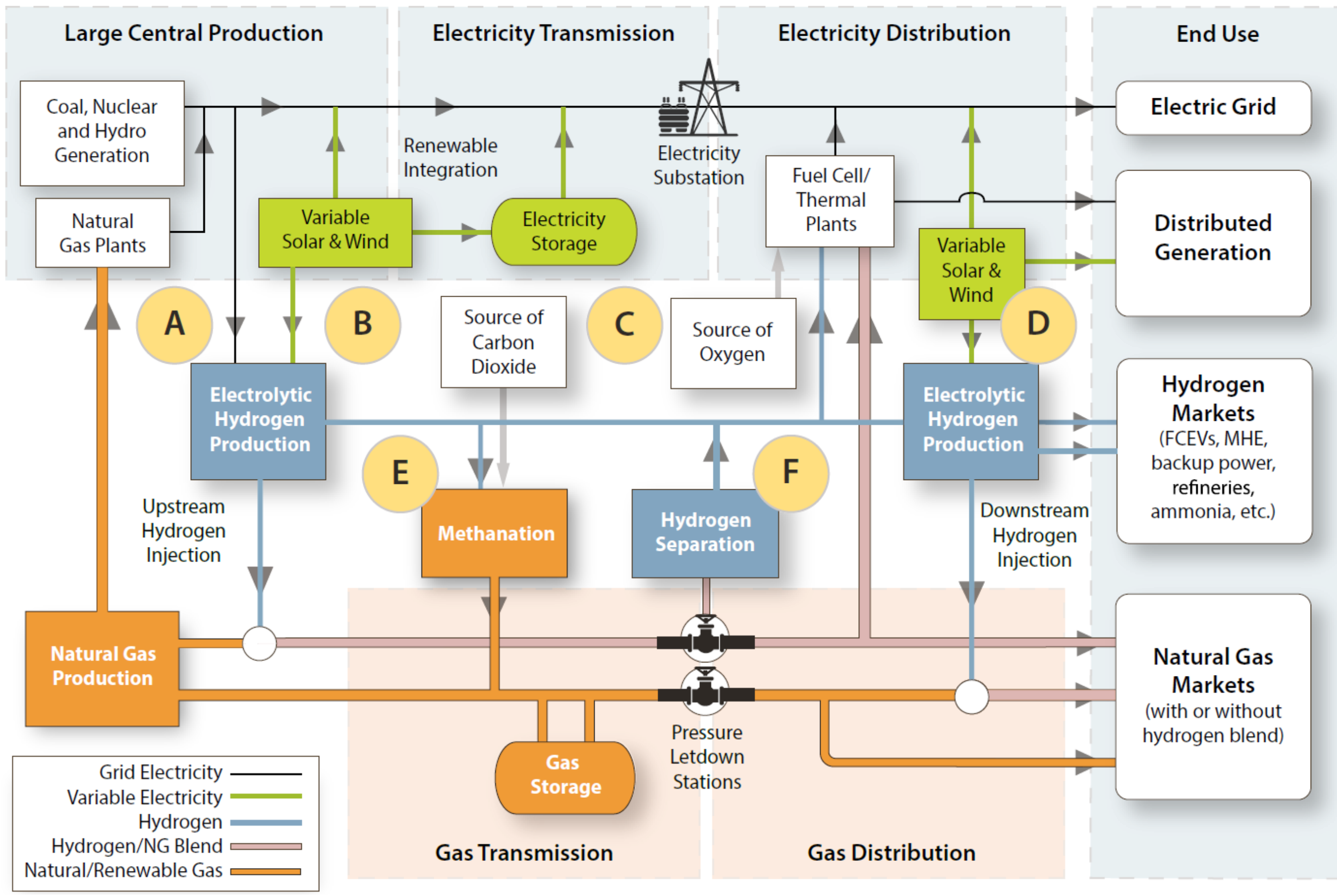
B **Integration of large-scale, central renewables**—Variable wind and solar energy production is indicated as being either directly delivered to the grid as electricity or first stored in a generic "electricity storage" process and then delivered to the transmission grid as electricity. These green or variable electricity pathways are indicated as solid lines with green shadows. An alternative to this "electricity in, electricity out" storage pathway is indicated by the "B" circle: electricity is converted to hydrogen via electrolysis and is either injected into a natural gas transmission pipeline or delivered by other means (e.g., pipeline, liquid truck, gaseous truck), indicated as double-line pathways with blue shadows. Benefits of this proposed pathway are increased utilization of renewable production faclities, greater flexibility of supply, potential transmission deferral, and access to additional end-use markets for renewable power producers.

C **Re-conversion to grid electricity**—The conversion of hydrogen back to grid electricity was downplayed during workshop discussions. Although this may prove viable for remote locations that require longer-term storage or premium backup or seasonal storage, in the near term it is challenging economically for grid-connected systems because of significant efficiency losses. Where reconversion to grid electricity is viable, it may be achieved by using either stationary fuel cells or thermal conversion units, such as turbines. The oxygen byproduct of electrolysis can be used to improve either combustion or fuel cell re-conversion efficiency. It is worth noting that as renewable electricity supplies increase, the potential for renewable supplies competing with other renewable supplies becomes a reality. Short-term electricity storage options may be inadequate to resolve this supply-demand balancing requirement. For regional power networks that have large seasonal demand variations, the long-term storage potential for hydrogen may result in hydrogen conversion back to grid electricity being attractive on a marginal cost basis in regional markets where natural gas networks, gas storage, and gas turbine power plants already exist.

D **Distributed production from variable sources**—In contrast to large-scale, centrally produced hydrogen production (Pathway B), this involves production close to the point of end use. Electricity that is not used on-site can be sent to either the distribution grid or to electrolysis units. If sent to electrolysis units, the resulting hydrogen can be used either on-site or injected into natural gas distribution pipelines. Additionally, using distributed electrolyzers as responsive loads can enable greater flexibility for grid support and end-user energy management, such as distribution deferral, outage mitigation, and demand charge reductions.

E **Methanation for renewable gas synthesis**—Electrolytic hydrogen can be converted to synthetic methane through the thermocatalytic process of methanation, which converts carbon dioxide (CO_2) and hydrogen (H_2) to methane (CH_4). When hydrogen is produced from renewable sources, the resulting gas product is renewable gas. A source of carbon dioxide (or carbon monoxide [CO], or carbon) is required as an input feedstock.

Figure 1. Processes and pathways for HES systems. *Illustration by the National Renewable Energy Laboratory*



1.2 Demand: FCEVs, Grid Services, and Emerging Niche Markets

Although the long-term market potential of FCEVs may justify significant investments in hydrogen storage systems and future hydrogen infrastructure systems that rely upon renewable energy sources, emerging markets for ancillary services, MHE, and backup power systems can support storage system projects in the near term. Each of these markets is reviewed briefly below in sections 1.2.1, 1.2.2, and 1.2.3. The implication of relying upon multiple revenue streams and being closely coupled to the electrical grid is that future HES systems will be one component within a larger smart grid or smart gas system, as discussed in Section 1.3.

1.2.1 Fuel Cell Vehicle Demand

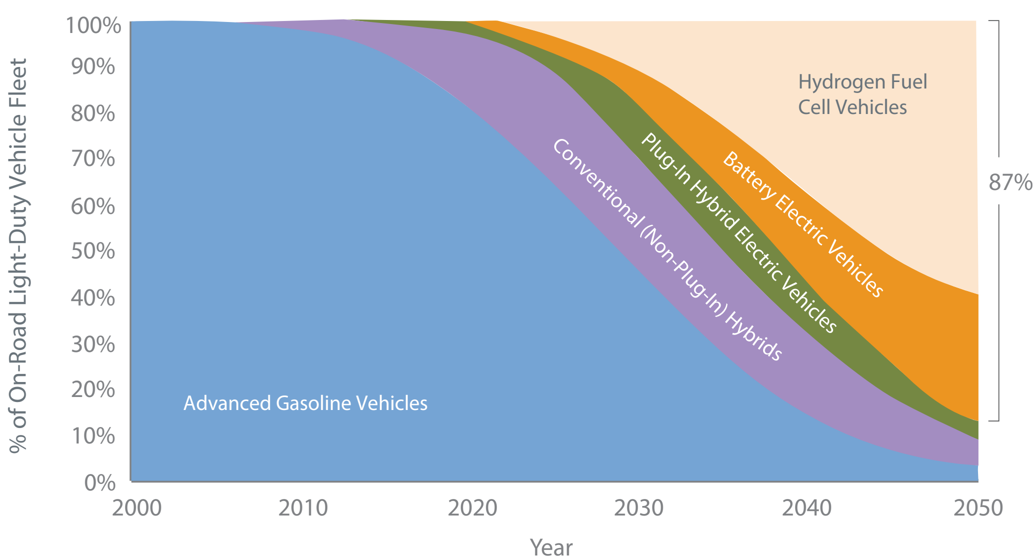
A high-profile market for hydrogen is as a transportation fuel for FCEVs. FCEVs have been in development for many years, and several automakers have completed light-duty vehicle demonstrations with hundreds of vehicles. At present, relatively small volumes of light-duty vehicles are starting to be introduced by Hyundai, with Toyota and Honda announcing plans for model releases in 2015 and other major automakers to follow in the 2016–2017 time frame ("Fuel Cells" 2014). In the United States, California has been identified as an early market, with state policies supporting the installation of hydrogen refueling stations through the California Energy Commission's (CEC's) Alternative and Renewable Fuel and Vehicle Technology Program, the California Fuel Cell Partnership's (CaFCP's) development and updating of a detailed roadmap, and the zero-emission vehicle mandate, which offers significant credits for FCEVs because of their expected all-electric range of 300 or more miles (CEC 2014, CaFCP 2014, CARB 2013). Relatively large-scale market adoption scenarios and projections have been examined, discussed, and evaluated by the U.S. Department of Energy (DOE) (Greene et al. 2008), the National Academy of Sciences (National Research Council 2008, National Research Council 2013), and the International Energy Agency (2010). As an example at the state level, the market adoption trend from the California Resources Board (CARB), shown in Figure 2, suggests the degree to which hydrogen FCEVs can contribute to the long-term transformation of the light-duty vehicle fleet in a more sustainable low-carbon and zero-emission future in California. The 2013 National Research Council report offered additional support for this long-term market potential by projecting future FCEV costs to drop below those of hybrid electric vehicles (National Research Council 2013). A recent automaker survey conducted by CARB suggested that more than 18,000 FCEVs will be in operation in California by 2020 (CARB 2014).

1.2.2 Grid Services

Providing grid services offers an additional revenue stream for hydrogen energy storage systems that are able to participate in the grid services market. Several important properties establishing the ability to provide services are listed in Table 1. A number of studies have been released that explore the ability for hydrogen technologies to provide particular services within this list. One important requirement is response time, the ability of hydrogen equipment to respond sufficiently quickly. Both the National Renewable Energy Laboratory (NREL) and Hydrogenics have run experiments with electrolyzers to assess their potential to provide grid services (Hydrogenics 2011, Eichman et al. 2014). Results show that electrolyzers can respond sufficiently fast to participate in electricity and ancillary service markets, including contingency reserves, load-following, and regulation.

Several other studies have considered opportunities for integrating HES and demand response into the electric grid (ChemCoast et al. 2013, Kroposki et al. 2006). These opportunities include the integration of intermittent renewables; participation in energy, ancillary service, and other grid markets; and integration with mobile or industrial processes. Additional studies have, to varying degrees, quantified the value of participation in energy markets (Saur and Ramsden 2011, Steward et al. 2009) and/or ancillary service markets (Bertuccioli 2014, Judson-McQueeney et al. 2013). The technical capability to integrate variable renewables by modulating the electricity consumption of an electrolyzer has been addressed by two demonstration projects, one at NREL and the other at the University of North Dakota (Rebenitsch et al. 2009, Harrison et al. 2009). In both projects, the renewable hydrogen produced on-site is pressurized and used as a transportation fuel.

Figure 2. Percentage[2] of on-road light-duty vehicles in California according to one future scenario under examination by CARB.
Image from the presentation by Analisa Bevan at the HES Workshop



[2] The percentage of new vehicle sales by year would need to be more aggressive than the percentages shown in the figure to attain these on-road penetration rates.

Table 1. Simple Descriptions of Grid Services

Important Properties for Providing Grid Services	Simple Descriptions
Response time	How quickly can it begin responding?
Ramp rate	How fast can it change response?
Energy capacity (duration)	For how long can it respond?
Power capacity	How much response can it provide?
Minimum turndown	What is its lowest operating point?
Start-up time	How long does it take to start up?
Shutdown time	How long does it take to shut down?

In addition to being able to participate in electricity markets, the markets must have sufficient depth to accommodate additional storage and HES must be competitive with the conventional methods for providing grid services. The value of these services changes hourly based on market conditions and seasonally or yearly based on available system capacity and need for these services. However, there are methods to predict the price and the required quantity that can be used to assess the value of these services in the future with higher renewable penetration or different market conditions (Hummon et al. 2013). Use of these tools will allow for greater risk mitigation when developing business cases for HES systems.

These studies were all written within the last eight years, which shows that hydrogen providing grid services is in the early stages of development and will be better understood with continued research and demonstration. However, data collected from the demonstration projects show that hydrogen systems are capable of rapid response and variable demand, which strongly suggests that there is potential for these systems to increase their value by providing grid services (Eichman et al. 2014). Continuing analysis of the integration of renewables into the electricity grid will provide additional insight into the general role of energy storage, as well as the degree to which HES systems can continue to benefit from a business case based upon the provision of grid services.

1.2.3 Emerging Markets

Although FCEV markets may expand significantly in the future, and grid services may bolster the business case for HES projects in the near term, significant demand for additional hydrogen production and delivery infrastructure is building today with emerging markets such as MHE, fuel cell forklifts (Figure 3), and backup power systems for sectors such as telecommunications. Fuel cell MHE offer advantages compared with their battery-powered electric counterparts because of continuous operation at full power and fast refuel times, both of which reduce labor costs and increase unit productivity. This is especially the case in large multi-shift warehouses in the United States and Canada. By 2012, more than 4,000 MHE units were operating in 40 different locations in 19 states; whereas only hundreds of units were in operation four years earlier. Growth in the fuel cell market for remote and backup power also continues to expand, with approximately 400 Ballard Power Systems units shipped in 2012 for telecom applications, as well as new applications, such as gas pipeline facilities and road monitoring equipment (Breakthrough Technologies Institute 2013). Growth in these new markets typically requires new distributed hydrogen generation and delivery infrastructure. As these and other non-light-duty vehicle markets continue to grow in the near term, demand for distributed electrolytic hydrogen production will increase.

1.3 Smart Gas

Energy storage is often discussed as an important component of a future electricity grid with a greater percentage of variable generation from renewable sources such as wind and solar. However, the benefits of energy storage will be provided in the context of a grid that is smarter and more flexible than today's grid. This expected evolution is one of the reasons why the benefits of future energy storage systems are difficult to value, which results in uncertainty and risk for investors and regulators (Ma et al. 2011). Similar difficulties exist in determining the value of HES systems for both the electrical grid and, in the case of power-to-gas, the natural gas pipeline network. It is likely that the future market conditions for grid-supporting HES applications will depend on a variety of evolving factors that emerge as the natural gas industry moves toward a smart gas network with both parallels to and differences from electricity's smart grid evolution. "Smart gas" systems will include a broad range of improvements compared with today's natural gas system, including increased flexibility; acceptance of nonconventional gases, such as biomethane, coal-bed methane, and hydrogen; increased efficiency of utilization, because of dual-fuel appliances, gas-fired cooling, cogeneration, and combined heat and power; and more active control systems to manage safety, monitoring, and integrity management (EG4 2011). HES sytems will be only one component within this larger coevolution of smart grid and smart gas systems.

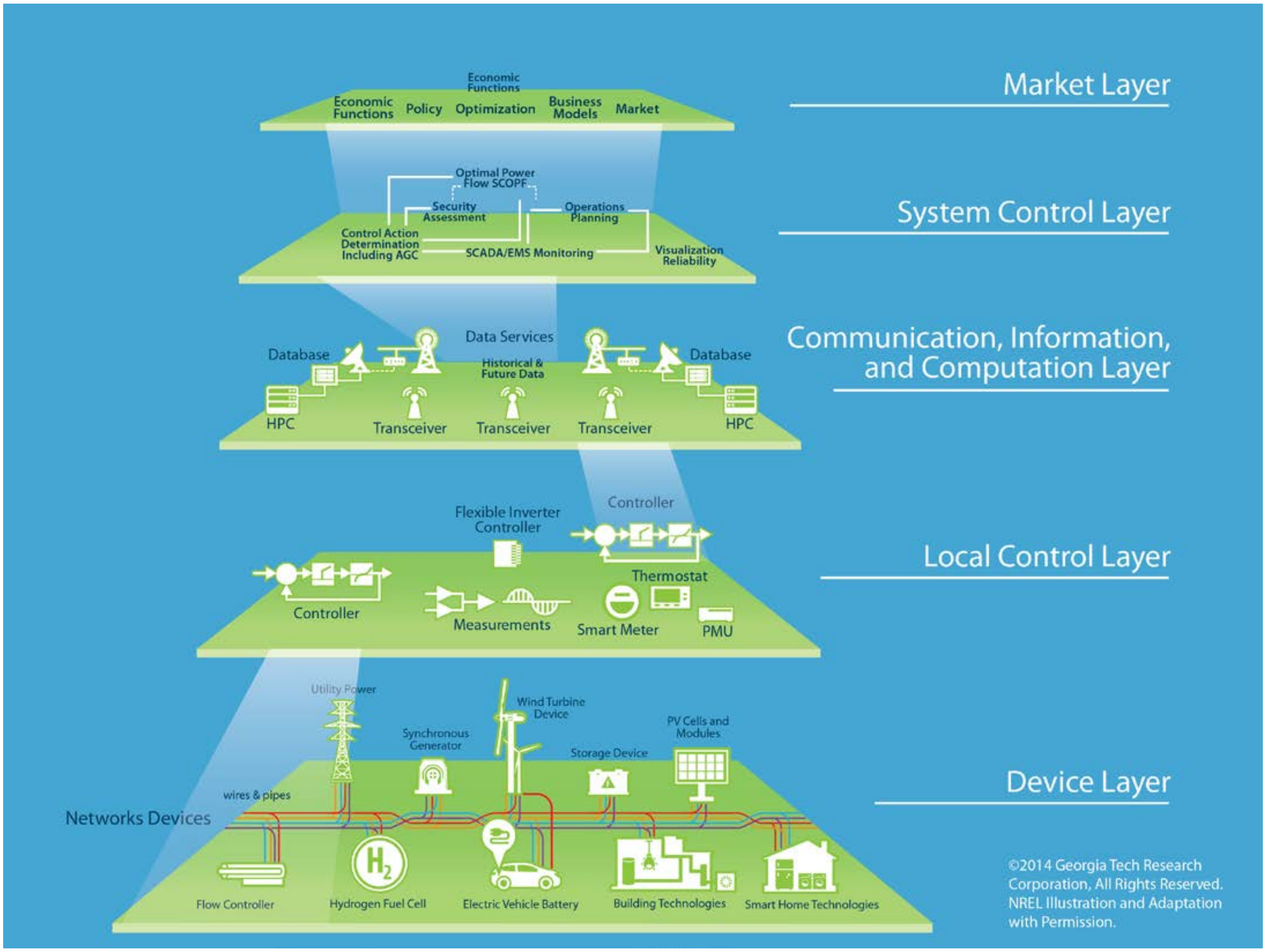
Future markets for HES systems, which offer both electrical grid support services and hydrogen or green gas injection into natural gas pipelines, will be subject to a variety of potentially transformative drivers, including decarbonization, increased reliability and security, and more elaborate degrees of systems integration. HES systems offer policymakers an opportunity to diversify how consumers participate in green energy purchases by offering a level of consumer choice that has historically been absent. Where green energy premiums are paid to suppliers of renewable power, HES systems can enable suppliers to receive green premiums for renewable gas.

Several recent studies make contributions to understanding future potential transformations of more integrated electricity grid and pipeline grid systems (Dodds and McDowall 2013, Schlag et al. 2014, Grond et al. 2013). Figure 4 shows an architectural overview of the conceptual layers relevant to a more integrated energy system. The lowest layer in the figure, the device layer, consists of the physical devices and networks producing, delivering, storing, and consuming energy. Wires and pipes provide the infrastructure connections among devices serving buildings, vehicles, and industrial facilities. These individual devices are managed in a stand-alone manner through a local control layer, which consists of sensors, flow controllers, inverters, and smart meters by electromechanical, electronic, or software-based control modules. A third layer contains the communications, information, and computation platforms that enable control applications within a fourth system control layer. This fourth layer is responsible for ensuring the security and reliability of a network of interconnected devices. Finally, the fifth market layer addresses the economic, regulatory, financial, and policy aspects of the integrated energy system (Lynn 2014). HES systems must be integrated on each layer to ensure effective operation and the ability to participate in multiple sectors.

Figure 3. A hydrogen fuel cell forklift in airport service.
Photo courtesy of Hydrogenics, NREL 15987

It is anticipated that HES systems can contribute to the evolution of a more integrated and sustainable energy system, but a wide range of factors must be better understood both to build a business case and inform regulatory or policy support mechanisms to accelerate market adoption. In addition to analyzing the revenue and cost of HES systems it is also important to consider ownership models that will enable successful deployment, taking into account who will own the assets and the associated operational and financial risks. The results of this workshop can contribute to this improved understanding.

Figure 4. Architecture for energy systems integration



02 Workshop Structure

2.1 Workshop Background

DOE's Fuel Cell Technologies Office has conducted or participated in a series of workshops to better understand key issues related to the development of hydrogen and fuel cell technologies. Proceedings from these workshops are available online (Energy Efficiency and Renewable Energy 2014) and include reports and presentations from two workshops that are closely related to the present workshop:

- **Electrolytic Hydrogen Production Workshop**—DOE, February 27–28, 2014, Golden, Colorado
- **Hydrogen Transmission and Distribution Workshop**—DOE, February 25–26, 2014, Golden, Colorado
- **Hydrogen: A Competitive Energy Storage Medium for Large-Scale Integration of Renewable Electricity**—International Partnership for Hydrogen and Fuel Cells in the Economy, (IPHE), November 15–16, 2012, Seville, Spain
- **2012 Flow Cell Workshop**—DOE, March 7–8, 2012, Washington, D.C.
- **Reversible Fuel Cells Workshop**—DOE and NREL, April 19, 2011, Crystal City, Virginia
- **Hydrogen Infrastructure Market Readiness Workshop**—DOE and NREL, February 16–17, 2011, Washington, D.C.

The 2011 workshop on market readiness examined opportunities and barriers for near-term deployment of hydrogen refueling stations, which included ways to leverage infrastructure being developed for emerging markets, such as MHE and backup power systems (Melaina et al. 2012). The reversible fuel cell workshop in 2011 looked at the capability and technical challenges facing reversible fuel cell technologies. These technologies have the potential to lower the total cost of electric storage using hydrogen technologies (Remick and Wheeler 2011). The IPHE workshop in 2012 focused on the integration of renewables (2012); whereas the 2012 DOE workshop focused on technical progress in flow cell technologies (Weber 2012). Flow cells are able to operate reversibly, and due to the similarity between flow cells and fuel cells much of the lessons learned from the fuel cell and electrolyzer community can be used to improve flow cells and vice versa. The two U.S. DOE workshops in early 2014 focused on transmission and distribution infrastructure and electrolysis technology issues (Ainscough et al. 2014a, Ainscough et al. 2014b). The present workshop builds on results from these previous workshops by focusing on policy and regulatory issues that are related to both grid support and transportation applications.

In addition to these DOE Fuel Cell Technologies Office activities, Bhatnagar et al. (2013) conducted a series of interviews in key regions to better understand the role of energy storage to support the electricity grid. This project identified the high cost of storage systems as the primary barrier to deployment, along with several other barriers associated with outdated regulations, market and revenue compensation issues, and utility and developer business model issues.

2.2 Workshop Goal and Scope

The goal of the HES workshop was to identify challenges, benefits, and opportunities for commercial HES applications to support grid services, variable electricity generation, and hydrogen vehicles. Meeting this goal required discussion across a broad range of topics to address services from hydrogen storage systems in both the near and long term. The scope of the workshop was defined along four key topics:

- Lessons learned and demonstration status
- Market opportunities and business models
- Technology R&D and near-term market potential
- Policy and regulatory challenges and opportunities.

Panel presentations, discussions, and breakout group questions were organized around these topic areas to provide structure and focus.

2.3 Panels, Breakouts, and Participants

The workshop began with opening comments from the following representatives: Kevin Lynn (DOE), Tim Karlsson (Industry Canada), Analisa Bevan (CARB), and Fernando Pina and Jim McKinney (CEC). Four subsequent panels included 17 presentations that addressed the topics and key panel questions indicated in Table 2. Presentation highlights are reviewed in Section 3.1, and slide presentations are available on the workshop website (Energy Efficiency and Renewable Energy 2014).

Approximately 65 participants representing a diverse set of stakeholder types and expertise attended the panels and breakout sessions. Figure 5 shows the breakdown of participants by organization type and indicates significant participation by federal and state government agencies, as well as industries, utilities, academics, and industry consortia. Several participants also served as breakout group facilitators, scribes, technical advisors during breakout group discussions, and breakout session reporters.

Table 2. Panel Topics, Key Questions, and Presenter Organizations

Panel 1. Lessons Learned and Demonstration Status

Key Questions

- What have we learned from past workshops and studies on hydrogen and other energy storage systems?
- What is the current status of ongoing and proposed projects?
- What lessons can be passed on from existing demonstration projects to inform future projects, including unintended consequences?

Presentations

- Monterey Gardiner, DOE Fuel Cell Technologies Office
- Dave Teichroeb, Enbridge, Inc., Alternative & Emerging Technology, Business Development
- Hanno Butsch, National Organisation Hydrogen and Fuel Cell Technology
- Mitch Ewan, Hawaii Natural Energy Institute

Panel 2. Market Opportunities and Business Models

Key Questions

- What are the future market opportunities for hydrogen storage?
- What business model approaches capture the value and unique benefits of using hydrogen as an energy storage medium?
- How can hydrogen storage effectively interface with and improve the performance of regional electricity grids?

Presentations

- Josh Eichman, NREL
- Patrick Balducci, Pacific Northwest National Laboratory
- Anna Lord, Sandia National Laboratories
- Brian Weeks, Gas Technology Institute
- Valri Lightner, DOE, Loan Programs Office

Panel 3. Technology R&D and Near-Term Market Potential

Key Questions

- Under what conditions and where will electrolytic-based HES projects succeed in North America?
- What are the competitive advantages of electrolytic hydrogen storage compared to other technologies?
- Have the R&D priorities necessary to ensure market success changed from the Challenges-5X and R&D-10X needs captured at the last electrolyzer workshop in February at the National Renewable Energy Laboratory?
- What are the most important drivers that should influence R&D priorities (operations and maintenance, capital cost, efficiency, near versus long-term market opportunities, regulations)?

Presentations

- Robert Rose, ITM Power
- Hector Maza, Giner, Inc.
- Steve Szymanski, Proton OnSite
- Rob Harvey, Hydrogenics

Panel 4. Policy and Regulatory Challenges and Opportunities

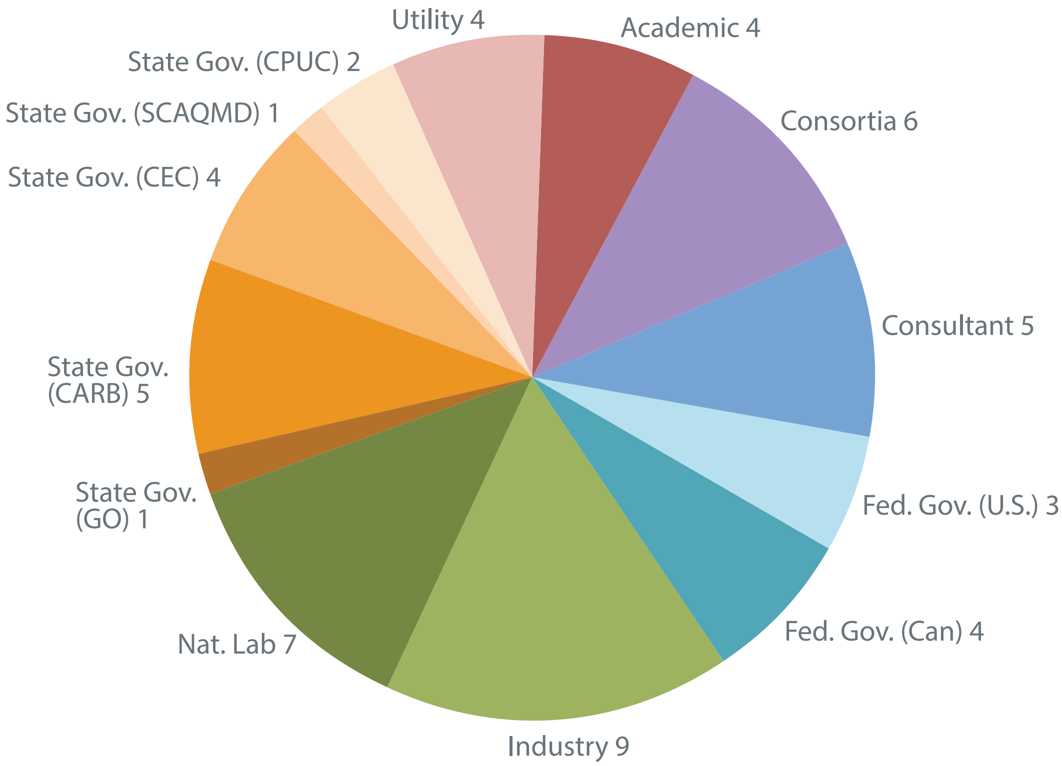
Key Questions

- What policy/regulatory objectives drive energy storage systems (e.g., environmental goals, permitting issues, aging infrastructure) and how does hydrogen use fit in this environment?
- What is the role of the policy/regulatory decisions compared to current market drivers in the business case for hydrogen use?
- How might future policies/regulations on energy storage and management change the business environment and how could hydrogen fit into this future?

Presentations

- Melicia Charles, California Public Utilities Commission
- Jeff Reed, Sempra Utilities
- Gerhard Achtelik, CARB
- Kourosh Malek, National Research Council

Figure 5. Workshop participants by stakeholder type



Abbreviations:
CPUC: California Public Utilities Commission
SCAQMD: South Coast Air Quality Management District
CEC: California Energy Commission
CARB: California Air Resources Board
GO: (California) Governor's Office

2.4 Breakout Group Questions

The second day of the workshop included two roughly 1.5-hour breakout discussion sessions, with all participants assigned to one of four groups. The mix of participants in each group was determined according to stakeholder type and areas of expertise to increase the diversity of viewpoints and backgrounds for each discussion. Each group was presented with the key discussion questions indicated in Table 3. Session facilitators, with assistance from technical advisors, guided the discussions that ensued from each key question. Participants were asked to write down their top priority responses on note cards and then introduce their response item as it was collected on storyboards. After each participant had responded, the groups discussed the content, significance, interrelationships, and categorization of all items proposed for each question. Clarifying questions were posed in response to items that were unclear or difficult to categorize. Facilitators worked with participants to agree upon clustering items when two or more had very similar content.

At the end of each breakout session, participants were asked to vote by allocating five dots to the highest priority items proposed in response to each question. Participants were allowed to vote for their own items, and they could place one or more dots on any individual item or cluster of similar items. When tallying votes, clusters of proposed items (i.e., note cards) were treated as one item. Results of this facilitated discussion and prioritization process are discussed in the next section, and a complete list of proposed items, categories, and votes is presented in Appendix A.

Table 3. Key Discussion Questions from the Breakout Sessions

Morning Breakout Session: Demonstration Criteria and Opportunities
CRITERIA:
What criteria should be used to identify promising near-term (next 1 to 3 years) demonstration projects with high potential for learning and early-commercial success?
POLICIES:
What existing or proposed policies/regulations can (or could) enable opportunities for successful near-term demonstrations of HES?
NEXT STEPS:
What actions, analyses, or demonstrations are needed to best inform industry and government decision makers to build support for a broader rollout of hydrogen as an energy storage medium?

Afternoon Breakout Session: Transportation, Renewables, and Other Synergies
BARRIERS:
What technical and policy barriers are hindering integration across multiple energy sectors using HES (i.e., heating fuel, transportation fuel, electric grid)?
POLICIES:
What existing or proposed policies/regulations can (or could) enable cross-sector synergies that strengthen the (near- or long-term) business case for HES?
NEXT STEPS:
What actions, analyses, or demonstrations are needed to inform key stakeholders of the potential for cross-sector synergies using hydrogen storage?

03 Workshop Results

3.1 Summary of Presentations

The sections below briefly review topics covered during the opening remarks and panel presentations. More details can be found in the presentation slides on the workshop website (Energy Efficiency and Renewable Energy 2014). These presentations provided background and updates on issues related to the key questions addressed in the breakout sessions.

3.1.1 Opening Remarks

The workshop began with a series of opening remarks from the U.S. and Canadian governments, as well as two California state agencies, CARB and CEC. Four discussion panels, summarized below, followed the opening remarks. Opening remarks highlighted many challenges faced by the energy industry, including air quality, climate change, renewable integration, grid modernization, and sustainable transportation. Various strategies and policies to address these challenges were reviewed. Kevin Lynn reviewed various aspects of DOE's Grid Integration Program, and Tim Karlsson discussed Industry Canada's support for energy storage and related activities in Canada. Analisa Bevan of CARB reviewed the suite of policies and programs being implemented in California, and Fernando Pina and Jim McKinney reviewed CEC's support for energy storage technologies and recent awards for hydrogen stations through the Alternative and Renewable Fuel and Vehicle Technology Programs. The opening remarks and subsequent discussions suggested that as the challenges associated with energy storage become clearer, the role for hydrogen technologies should become better defined.

3.1.2 Panel 1: Lessons Learned and Demonstration Status

The first panel discussed two main topics: (1) lessons learned from previous analyses and workshops and (2) the status of current and future demonstration projects.

The panel included lessons learned and demonstrations from North America, Hawaii, and Europe. Three past workshops were discussed. The workshop on electrolytic hydrogen production hosted at the National Renewable Energy Laboratory in February 2014 was highlighted as a valuable workshop that focused on the technological challenges and R&D needs specifically for electrolyzers and also included discussions on the use of hydrogen to provide grid and transportation services. It was noted that the results of this workshop were considered when the content and goals for the HES workshop were developed. The International Partnership for Hydrogen and Fuel Cells in the Economy held a hydrogen storage workshop in November 2012 (2012), which was discussed along with the workshop on flow cells for energy storage hosted by Lawrence Berkeley National Laboratory in 2012 (Weber 2012).

In addition to workshops, the panel provided a description of how hydrogen technologies can potentially be used in multiple applications. Multi-use and multi-sector systems were discussed, along with closer partnerships with industry, and these topics were later identified in the breakout sessions as some of the most important criteria for enabling successful demonstrations. Several examples of demonstration projects were presented. Many of these projects explore the use of hydrogen storage to enhance renewable integration. Lessons learned from both stationary and transportation-based hydrogen projects were discussed.

3.1.3 Panel 2: Market Opportunities and Business Models

Panel 2 focused on new opportunities for hydrogen technologies, technology readiness, and requirements to participate in new markets. Opportunities, challenges, and next steps were discussed for assessing the feasibility of hydrogen pipeline injection and separation, large-scale underground storage of hydrogen, integration with the electric grid, and clean energy project financing and loan assistance.

Work has been done on the injection of hydrogen into gas pipelines and for underground storage, and there are successful examples in North America and Europe; however, continued work needs to be done to assess the overall potential, economic feasibility, and limitations. Similarly for electric grid integration, work has been done to assess the value of different grid services for conventional storage and demand response devices; less has been done for HES systems. However, tools are available to quantify the value of services such as distribution upgrades and deferrals, outage mitigation, arbitrage, ancillary services, capacity, and capital costs. In addition to analyzing the revenue from services provided by HES systems it is valuable to consider ownership models (e.g., private, utility, retailers) that will enable successful deployment. Several of the panelists noted the importance of understanding both the technical and economic viability of hydrogen projects, which were identified during the breakout sessions as an important criteria and next steps for demonstrations.

SIDEBAR 2. Estimated Revenue from Ancillary Services

Figure 6 shows a breakdown of future costs associated with hydrogen that is produced via central electrolysis, with a baseload reference case slightly above $4 per kg of hydrogen produced. When energy services revenue from HES is taken into account, total costs are reduced (offset) by 9.8%; including all ancillary services, this results in a 24.1% reduction, equal to approximately $1 per kg. Production costs from central steam methane reforming (SMR) and biomass gasification are shown for reference. For additional details, see Eichman 2014.

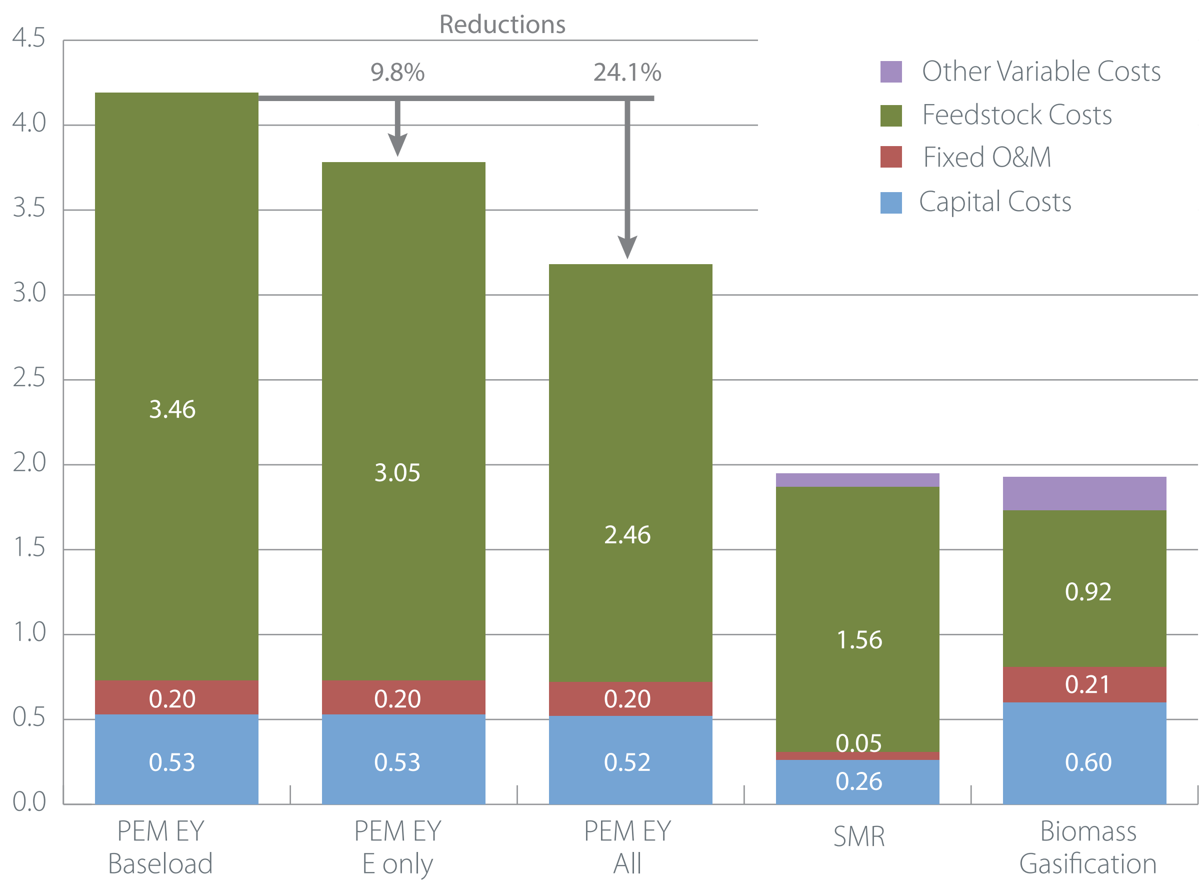


Figure 6. Hydrogen production cost results with revenue from ancillary services (Source: Eichman 2014)

KEY:
EY: Electrolysis
E only: Energy Only
All: All Ancillary Servies
SMR: Steam Methane Reforming

Presentations were given on two key components of HES system supply chains: large-scale seasonal storage in salt caverns and flexible, high-pressure truck trailer delivery to retail stations. As discussed earlier, the potential for large-scale storage is a unique feature of HES systems, though the most promising geologic formations, salt deposits, are prevalent only in certain regions of North America (see Sidebar 3). Flexible, high-pressure truck delivery can improve options for supplying hydrogen to multiple end users. Last, financing opportunities for renewable and energy efficiency projects were discussed, and the DOE Loan Programs Office was presented as an example of a program in place to accelerate innovative technologies into robust clean energy markets. The importance of financial mechanisms to enable HES technologies was reiterated during the breakout sessions.

3.1.4 Panel 3: Technology R&D and Near-Term Market Potential

The third panel provided insight into market opportunities and challenges from the perspective of electrolyzer manufacturers. Although each company may have different target markets, many topics resonated with all companies. The need for cost reductions to enable greater penetration of hydrogen production was universal. Cost reduction can be realized through a variety of ways, including material processing and substitution, scaling up unit size to the megawatt range, and production at volume.

Expanding current markets and opening new markets was discussed in great detail during the panel. There is also interest in pursuing multiple markets, including combinations of renewable integration, electric grid services, power-to-gas, industrial supply, vehicle fuel, and renewable or low-carbon credits, which are a central focus of the results from the breakout sessions, as well. HES systems are currently able to participate in some but not all of these markets.

3.1.5 Panel 4: Policy and Regulatory Challenges and Opportunities

Policy and regulatory challenges were addressed to some degree in each of the first three panels. However, the final panel provided more focused information on these topics. Hydrogen has a role to play in the electric, gas, transportation, and industrial sectors. The switch to hydrogen and electricity for transportation represents an important step to improve air quality and reduce greenhouse gas emissions over the long term.

With the way that policy, regulation, codes, and standards are currently written, there are challenges to realizing the full value of hydrogen technologies. Regarding participating in energy storage markets, hydrogen energy storage and power-to-gas do not follow the traditional behavior of energy storage devices (i.e., electricity in at device, electricity out from device). Although challenges exist for the injection of hydrogen into the gas pipeline system, there is precedent for enabling new technologies on the gas grid. As an example, enabling the injection of biogas from landfills was made possible in California, but it did take several years. Also, there is a challenge to combining funding for multipurpose facilities that integrate multiple sectors. Similarly, there was discussion about financial mechanisms to encourage energy storage devices in an agnostic way. All of these topics were identified during the breakout sessions as important policies and next steps for enabling successful HES projects.

SIDEBAR 3. Geographic Prevalence of Salt Deposits

Figure 7 depicts the geographic prevalence of four types of potential geological storage formations. Salt deposits, a candidate for hydrogen storage, are highlighted. These deposits are prevalent along the Gulf Coast, across the Texas panhandle and into western Kansas, across the Montana–North Dakota border, and across the northern edge of the Rust Belt region, which includes the Chicago and Detroit metropolitan areas (Lord 2009).

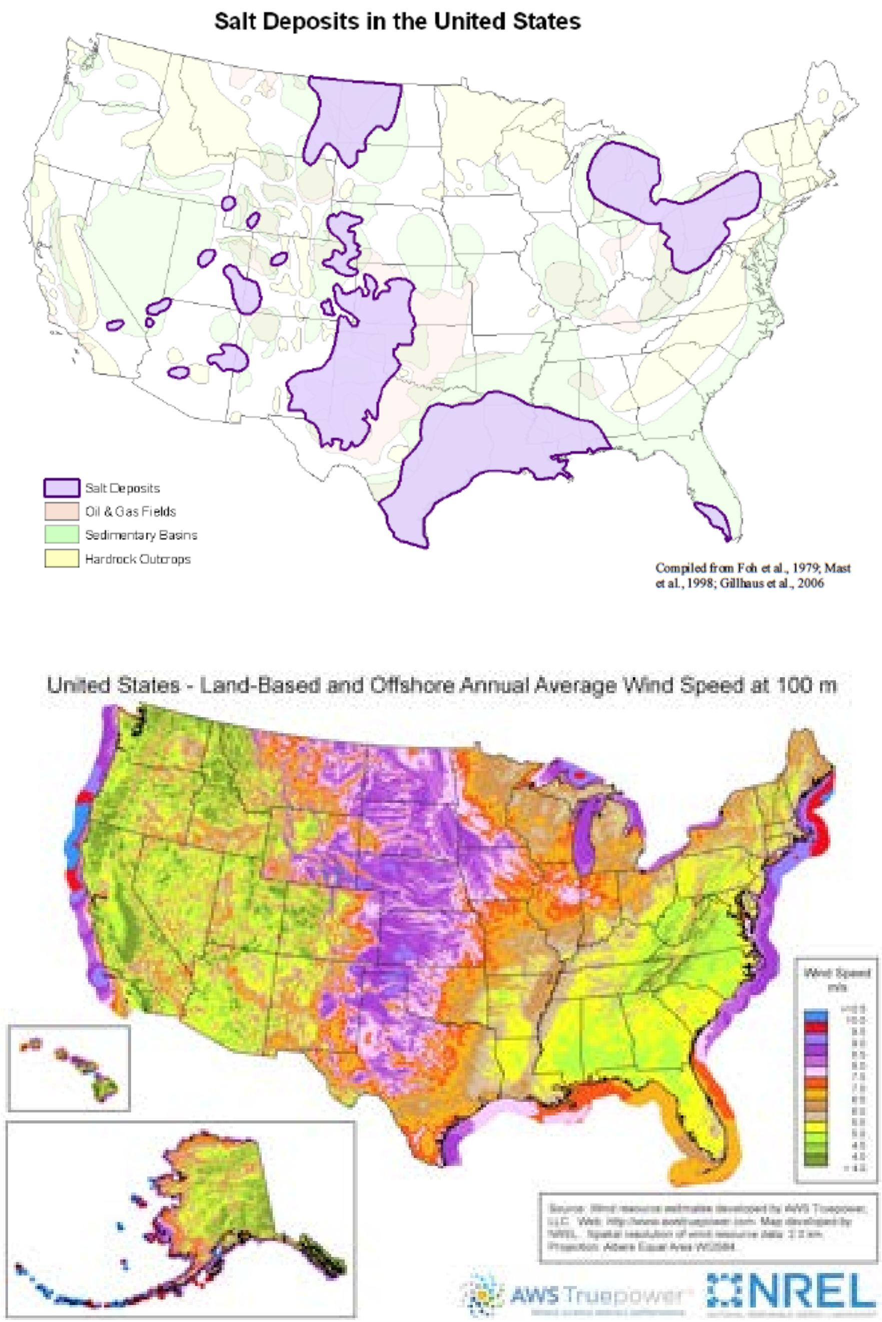


Figure 7. TOP: Geographic location of major U.S. salt deposits (Source: Lord 2009).
BOTTOM: U.S. wind resource estimates at 100 m

3.2 Summary of Breakout Group Results

The feedback collected from the breakout group discussions has been organized around the three key topics of criteria and barriers, policies, and next steps (see Table 3). Each of the four breakout groups addressed the same discussion questions following the facilitated process described above in Section 3.1. Breakout groups collected similar ideas on notes, voted on high-priority items for responses to each guiding question, and reported results back to the larger group. This section reviews items and themes determined as high priority or of high importance through the voting process of the breakout group.

Figure 8. David Teichroeb of Enbridge reporting results of the breakout group at the plenary session. *Photo by Adam Langton, CPUC*

Within each breakout group discussion, responses to key questions were often organized into themes or topics, some of which followed nomenclature from the key questions and some of which followed the general flow of the breakout group's discussions. For example, the items shown in Figure 9 were collected under a "Government/Regulation 2" and "Credit Market 1" heading. Additional comments, observations, and questions were raised during the plenary sessions when breakout group reporters reviewed key results from each session.

The resulting lists of items from each breakout group and results of the voting process were collected into a series of topical categories that organize the breadth of feedback received into a consistent and comprehensible structure. The complete collection is presented as Appendix A, and topical categories that received the greatest number of both proposed items and votes are summarized in Table 4. The categories are grouped under the key question headings of criteria and barriers, policies, and next steps, and are listed in order of greatest number of votes received. The bar charts indicate the total number of votes and items within each category, broken out by color-coded group number. This breakout reveals the degree to which different groups focused on particular topics and the degree to which topics were discussed and deemed as high priority across multiple groups. For example, votes within the topic of technical and economic viability were relatively evenly distributed across all four groups, participants in Group 3 tended to emphasize partnerships and coordination more than the other groups did, and Group 4 placed a relatively large number of votes on items within the demonstration and pilot project category. This visualization also reveals that topic areas that received fewer overall votes tended to become dominated by votes or items proposed by one or two groups, which suggested a lower level of common support across all workshop attendees. Alternatively, strong support across all groups for the topics with many votes and many items suggests a higher degree of agreement.

Figure 9. Examples of breakout session voting results

In aggregate, the items included within the categories shown in Table 4 account for 76% of all breakout group votes and 75% of all items proposed across all breakout group sessions. Additional categories and items are included in Appendix A. The sections below detail particular items within each category that received the largest number of votes and identify trends and themes across the different topics and types of breakout group responses.

3.2.1 High-Priority Criteria and Barriers

The majority of high-priority items discussed with relation to success criteria and barriers for successful demonstrations fell into two categories: (1) technical and economic viability and (2) the ability to provide hydrogen for multiple end uses. Important success criteria for technical and economic viability include the following:

- Assessments of general technological readiness, such as the technology readiness level evaluation approach
- Identification of promising niche applications
- Demonstration of continuing technical advancement
- Maintain high utilization rates
- Ensure long-term host sites plan for economic viability after government funding ends.

Important barriers to technical and economic viability include:

- Insufficient comparative and cross-sector data from successful demonstrations
- Supply-chain limitations and resulting high costs because of low volumes
- Identification of requirements for purity, scale, and compression.

The flexible supply of hydrogen to multiple end users was the second high-priority category of success criteria and barriers for demonstrations. Projects will benefit from a demonstration of this flexibility, an economic assessment of the resulting value streams, and analysis of the long-term viability of market demand for the services provided by HES systems with flexible supply. When performing an economic assessment it is essential to consider how HES compares to competing technologies. Additionally, considerations for how the value is affected by temporal, geographic, and long-term policy factors will likely be an integral part of an economic assessment. Near-term projects will also benefit from an improved ability to manage changes in supply and demand over time, especially with regard to future FCEV fuel demand and renewable electricity supply. An important barrier within the multiple end uses category is the constraint of applying incentives and grants to single end uses or services. If HES systems can provide benefits to multiple end uses or sectors, the ability to appropriately stack incentives for these multiple end uses would improve the economic viability of demonstrations.

Another important barrier or challenge is the increased uncertainty for the business case that results from the volatility of market conditions when multiple markets are being served. For example, this barrier may emerge when providing services to both utility end users and transportation fuel end users. This item received less attention than the success criteria of supplying hydrogen to multiple end markets, and is therefore considered a sub-issue under that more dominant theme.

The relative importance of these two demonstration criteria and barrier categories is indicated visually in Figure 10, in which the vertical axis indicates the number of items proposed in the breakout groups within each category and the horizontal axis indicates the total number of votes received by items within each category. For example, the technical and economic viability category includes 45 distinct items, which in aggregate received a total of 63 votes across all four breakout groups. In comparison, the multiple end use category included 23 items receiving a total of 51 votes.

As indicated in Figure 10, two additional categories received a relatively large number of total votes: (1) unified supportive policy and (2) partnerships/coordination. Key success criteria for unified supportive policy include clarifying or identifying the energy policy issues being addressed by HES systems, aligning projects with future policy alternatives or initiatives (such as the use of surplus renewable energy within the gas and transport sectors), and taking advantage of subsidies, tax incentives, and utility policies offered by local and state governments. Key barriers for this category include the lack of a unified policy framework, which crosses multiple sectors, equal treatment or "technology agnostic" incentives and regulations, and a more realistic or performance-oriented basis for some financial incentives and credits.

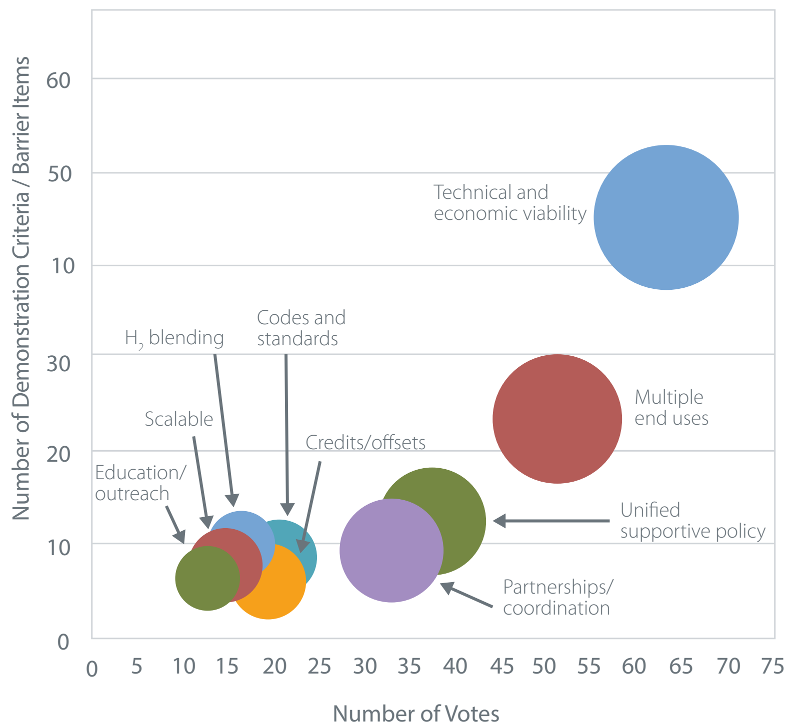
Success criteria within the partnerships/coordination category include the ability to partner with industry and increase participation with regulators and the investment community. Identifying (or generating, via policy) motivated host entities is an additional success criteria. The major barrier identified for this category is the silo-like nature of government departments, jurisdictions, definitions, policies, and plans.

Table 4. Breakout Session Results by Topical Category and Group with Number of Votes and Items

In addition to these four major categories, five other categories, shown at the bottom left of Figure 10, received a smaller number of proposed items and total votes: (1) codes and standards, (2) credits/offsets, (3) hydrogen blending, (4) scalability, and (5) education/outreach. Particular items within these categories that received a large number of votes include keeping codes and standards up to date with the pace of technical implementation, establishing the transferability of credits or offsets among systems or sectors (such as cap-and-trade, the low-carbon fuel standard, renewable energy credits, etc.), and a comprehensive technical assessment of hydrogen injection into natural gas pipelines with a focus on end-use implications.

The categories used for breakout group results are somewhat subjective and are relied upon here only to simplify and focus breakout highlights and priorities. Groupings based upon a different set of categories might change the relative emphasis of priorities shown in Figure 10, but probably not to a significant degree. A full list of feedback items provided during breakout group discussions, along with the number of votes received for each item, is included in Appendix A.

Figure 10. Number of criteria and barrier items and votes



3.2.2 High-Priority Policies

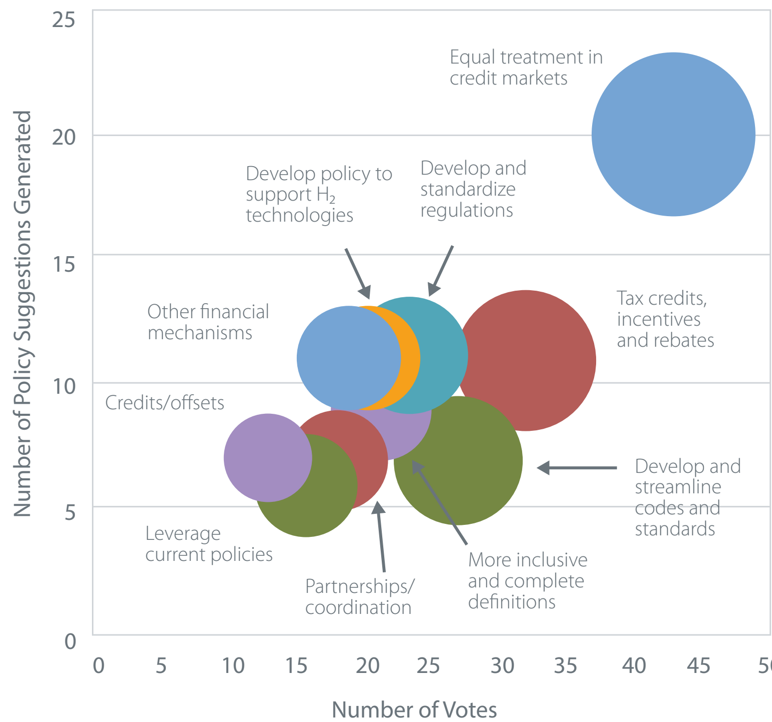
Of all the policy topics discussed during the breakout discussion, those falling into the category of equal treatment in credit markets were both the most numerous and received the greatest number of total votes. This category included various proposals to ensure either revenue or compensation by enabling the participation of HES systems in renewable or low-carbon credit markets. The three highest priority items within this category are the following:

- Recognize hydrogen as an eligible fuel within the renewable fuel standard. For example, establish an equivalency level for renewable hydrogen as an alternative compliance option for the refining industry's fuel blending mandates for bio-diesel and ethanol.
- Allow credit multipliers for very low-carbon fuels under the low-carbon fuel standard so that low-carbon fuels can receive a fraction of a credit.
- Develop carbon content regulations for energy services and products that favor low-carbon pathways for electricity, transportation, and heating fuels.

Nine additional policy categories were identified and are indicated in Figure 11 in terms of total items proposed and total votes received. Within these various categories, which span a wide range of policy options and support mechanisms, the items that received the greatest number of votes were the following:

- Implement "technology agnostic" carbon reduction incentives, with a fixed escalation of carbon values across sectors. (This item was proposed as a long-term influence.)
- Consider hydrogen as a fuel or energy carrier to be treated the same as natural gas or biogas.
- Include hydrogen energy storage systems in peak load shifting.
- Develop natural gas quality standards for hydrogen blends.
- Allow a partial exception to codes and standards while state-level interconnection standards are being developed.
- Establish feed-in tariffs for hydrogen energy storage.
- Establish energy (kWh) goals for energy storage mandates, rather than only capacity (kW) goals.

Figure 11. Number of policy items and votes



Additional policy items proposed during the breakout sessions are listed in Appendix A, along with the number of votes received from participants.

3.2.3 High-Priority Next Steps

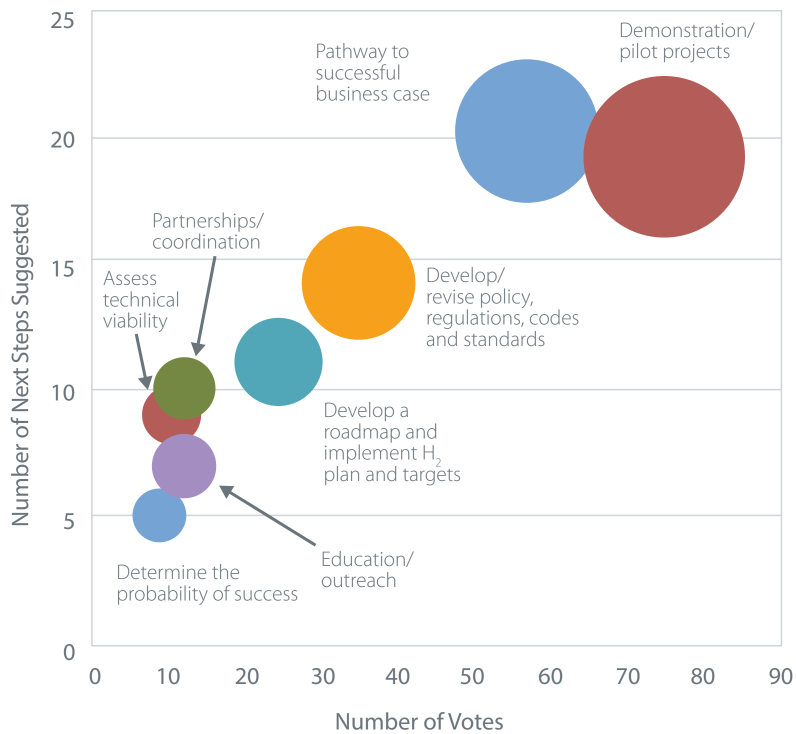
As indicated by the two large bubbles shown in the top right of Figure 12, a large fraction of high-priority items suggested in response to the next-step breakout questions fall into the categories of demonstration/pilot projects and pathway to a successful business case. Several other categories are indicated in the figure, but these two categories accounted for more than 50% of the total votes received for next steps. The following items received the greatest number of votes in the category of demonstration/pilot projects:

- Demonstrate large-scale (multi-megawatt) HES systems, multi-fuel (natural gas, anaerobic digester gas, landfill gas), and multi-use (FCEVs, electric vehicles, grid, vehicle-to-grid, station-to-grid) systems with utility involvement and renewables integration.
- Develop demonstration projects that show successful business cases, such as large-scale, multi-use projects that are coordinated among state, federal, and other stakeholders. (This item is closely connected to the pathway category below, but it suggests a demonstration approach rather than analysis.)
- Identify site(s) on federal land for hydrogen energy storage with multiple uses.
- Fund multiple large-scale demonstrations.
- Demonstrate autonomous, remote power applications for a user, site, or community.
- Focus on hydrogen fuel cell buses, vehicle fleets, or other high-demand centers, such as seaports or airports.

High-priority next steps within the pathway to a successful business case category include the following:

- Perform analysis to establish business cases by monetizing co-optimized value streams, system performance, and financial viability.
- Develop models for siting, sizing, and evaluating the financial feasibility of HES systems.
- Articulate carbon reductions per vehicle mile driven, per kWh of electricity, and on an end-use utility basis.

Figure 12. Number of next-step items and votes



The other two categories that received a large number of next-step suggestions and votes involve developing or revising policies, regulations, or codes and standards, and developing a roadmap and implementing HES plans and targets. Within these two categories, the next-step suggestions that received the largest number of votes include the following:

- Change regulatory and/or incentive definitions of energy storage to be more inclusive than simply "electricity in, electricity out," with inclusion of power-to-gas as an eligible storage option.
- Develop a roadmap for integrating renewable and fossil energy sources with hydrogen.
- Develop a common, standardized currency to allow for the trade of disparate revenue streams.

A complete list of next-step suggestions from the breakout sessions is included in Appendix A.

04 Summary and Discussion of Next Steps

A workshop attended by expert stakeholders was convened on May 14–15, 2014, in Sacramento, California, to collect feedback on HES technologies and systems, including criteria for successful projects, barriers to deployment, policy issues, and next steps. Participants to the workshop discussions and breakout sessions benefited from 17 presentations by experts, which covered a broad range of issues related to HES technology, market, policy, and regulatory issues (Figure 13). During the panel discussions, a wide variety of topics were reviewed and suggestions were made to improve our understanding of market conditions and policy needs, and to facilitate implementation of HES demonstrations. Not all of the topics from the panel sessions are reflected in the feedback collected during the breakout sessions, and some of the topics that were discussed during the panel discussions were not identified as high-priority items during the breakout sessions; however, there was significant agreement from all four breakout groups about several high-priority items in the categories of criteria and barriers, policy, and next steps.

The majority of high-priority criteria for HES demonstration projects fell into the category of technical and economic viability, with a focus on demonstrating technological advances, and assessing market readiness with respect to other energy storage or energy supply systems. Identifying applications for promising niche markets, achieving high utilization rates, and ensuring long-term economic viability beyond government support were also high-priority criteria. These criteria highlight the importance of deploying successful near-term projects, validating technical performance, and achieving near-commercial status in terms of economic performance. Important barriers in this category include a lack of performance data to allow for comparative assessments, potential supply-chain limitations as volumes increase, and the identification of requirements for purity, scale, and compression. Additional criteria include the importance of serving multiple end users to improve system economics and to take advantage of flexible supply options. Along these lines, it was emphasized that policy incentives are too siloed by sector or application and should be applied cumulatively to systems that serve more than one end-use market.

Figure 13. Professor Joan Ogden of the University of California, Davis and Dr. Monterey Gardiner of the U.S. Department of Energy during a networking break. *Photo by Adam Langton, CPUC*

The largest category for policy priorities was enabling or allowing equal treatment in credit and other markets. These include the federal renewable fuel standard, the low-carbon fuel standard, and carbon credits under cap-and-trade or other mechanisms. Items addressing tax credits, incentives, and rebates were also a high priority, as were efforts to develop streamlined codes and standards. These include revisions to the gas quality standards, renewable gas standards, and state interconnection standards. Additional policy issues identified as high priority include the standardization of hydrogen as an energy carrier and HES systems as providing peak shaving, and the potential supportive role of carbon price signals and feed-in tariffs.[3]

A follow-up meeting was held with many of the workshop participants in Washington, D.C., on June 16 in conjunction with the DOE Annual Merit Review and Peer Evaluation Meeting. Workshop results were reviewed during this meeting and attendees offered support for the following general framework for pursuing next steps:

1. Define real use cases. Take historic events as examples and apply them to more generic scenarios.

[3] Some workshop participants questioned the potential effectiveness of feed-in tariffs for supporting HES systems.

2. Conduct technology analysis of scenarios. Analyze barriers associated with each scenario.

3. Build business case. Determine what is feasible and competitive in the real world today and which landscape changes will emerge as the grid transforms.

4. Communicate results effectively. Present findings to acquire funding from financial institutions or other sources.

5. Develop flexible policy. Align policies to develop appropriate incentives.

6. Implement incentives. Implement appropriate incentives for HES systems.

7. Expand deployment of viable demonstration projects.

This framework suggests a means of leveraging results from near-term demonstration projects, through analysis and business case development, to attract investment and influence the development of effective policies and incentives to open new markets for HES applications. Although this feedback was collected by a smaller group outside of the formal HES workshop in Sacramento, it provides context for the more detailed feedback and the recommendations received during the workshop for high-priority next steps. Another important recommendation from this follow-up meeting, which was also emphasized during the workshop, is for North American stakeholder groups to maintain awareness of, and connections with, other groups pursuing HES projects internationally, such as the German Hydrogen and Fuel Cell Association (Deutscher Wasserstoff- und Brennstoffzellen-Verband, DWV), the German Energy Agency's Strategieplattform, the International Energy Agency's Hydrogen Implementing Agreement (IEA HIA), the HyUnder program, and the GridGas project in the United Kingdom.[4] Other activities to consider include the workshop hosted by the European Association of Research and Technology Organisations (EARTO), the European Standards Organisations, and the Joint Research Centre of the European Commission related to power-to-hydrogen, blending, and grid integration (Joint Research Centre Petten 2014).

Four high-priority categories of items were raised in response to breakout session questions about next steps, including demonstrations and pilot projects, business case analysis, the development of revised policies and regulations, and the development of plans and targets for commercialization. A list of specific items receiving a large number of votes is included in Table 5. These were discussed in Section 3.2.3, and Table 5 is an attempt to link these action items to the stakeholders likely to be engaged in future HES deployment activities. This mapping of action items to stakeholders was not addressed explicitly during the workshop, but it was reviewed by peers and revised in response to recommendations. The intent of this list is to make high-priority items from the workshop more tangible. For example, it is likely that industry stakeholders would play a lead role in next steps associated with deployment activities; whereas analysis stakeholders (universities, national laboratories, industry consortia, nongovernmental organizations, regulatory analysts, etc.) would play a lead role in analyzing business case topics. Other stakeholder types, as described in the notes on Table 5, could play a supportive or advisory role in next-steps items; whereas, by definition, road map development would ideally involve support and active engagement across all relevant stakeholders. Entities like the CEC and CARB are California-specific; however, there are corollaries for many of these groups that can be extended to other states or the federal level. One example is CARB, which regulates air quality and has similar duties to the U.S. EPA, which operates at the U.S. federal level. Another example is Ontario's Ministry of the Environment and Climate Change, which works to protect and improve air quality in Ontario; on the Canadian federal level, Environment Canada is tasked with protecting the environment.

In conclusion, it is likely that HES systems will be deployed within a complex interface of multiple market forces and regulatory or policy influences, which will provide benefits to the electrical grid, transportation applications, and, in some cases, industry applications. Near-term applications may be at the megawatt scale or larger and can benefit from multiple revenue streams, including grid services and emerging markets, such as fuel cell forklifts or backup power systems, that provide demand in the near term, whereas FCEVs may provide greater demand in the medium to long term. Large-scale HES systems have the potential to influence transmission planning and the economics of renewables

[4] More information can be found on the respective websites for DWV (www.dwv-info.de), Strategieplattform (www.powertogas.info), IEA HIA (ieahia.org), HyUnder (www.hyunder.eu/), and GridGas (www.gridgas.co.uk).

integration. Results from this workshop provide insights to help guide deployment activities, and policy and regulatory reforms needed to remove market barriers and increase the sustainability and resiliency of multiple integrated energy systems.

Table 5. Summary of Action Items and Stakeholder Involvement

Proposed Next Step	Stakeholder (L = Lead role; S = Supporting role; A = Advising role)								
	Industry	Utilities	DOE	FERC	PUCs	CEC	CARB	Analysts	Other
Demonstrate large-scale (multi-megawatt) HES systems, multi-fuel (natural gas, anaerobic digester gas, landfill gas), and multi-use (FCEVs, electric vehicles, grid, vehicle-to-grid, station-to-grid) systems with utility involvement and renewables integration	L	S	S	A	S	S	A	A	
Develop projects that show successful business cases, such as large-scale, multi-use projects that are coordinated among state, federal, and other stakeholders	L	S	A	S	S	S	A	S	
Fund multiple large-scale demonstrations	S	S	L		A	L			
Demonstrate autonomous, remote power applications for a user, site, or community	L	S	S			S			S[2]
Identify site(s) for hydrogen energy storage with multiple uses, particularly those on federal land	S	A	S	A				A	L[1]
Focus on hydrogen fuel cell buses, vehicle fleets, or other demand centers, such as seaports or airports	S		A			S	S		L[3]
Perform analysis to establish a business case by monetizing co-optimized value streams, system performance, and financial viability	S	A	S		S	S	A	L	
Develop models for siting, sizing, and evaluating the financial feasibility of HES systems compared with competing systems	S	A	S		S	S	A	L	
Articulate environmental performance of HES systems. Look at carbon reductions per vehicle mile driven, per kWh of electricity, and on an end-use utility basis.	S	A	S			S	S	L	
Introduce regulatory framework to facilitate the provision of grid support services from HES and change regulatory and/or incentive definitions of energy storage to be more than simply "electricity in, electricity out," with inclusion of power-to-gas as an eligible storage option	A	A	A	S	L	S	A	S	
Develop a roadmap for integrating renewable and fossil energy sources with hydrogen	S	S	L	A	S	S	S	S	A[4]
Enable fair and inclusive market treatment for HES. Allow HES systems to participate in multiple markets and recognize hydrogen from HES as an eligible fuel for renewable fuel standard and low-carbon fuel standard.	A	A	S		S	A	L	S	L[5]

NOTE: Other categories:
(1) Multiple federal agencies could be lead participants, such as the U.S. Department of Transportation, Bureau of Land Management, or Department of Defense.
(2) Community or end-user leadership required.
(3) Transit agency, fleet, or seaport/airport leadership required.
(4) A broad range of stakeholders may be required, including industry representatives (such as the Electric Power Research Institute, Gas Technology Institute, or others), environmental nongovernmental organizations, the U.S. EPA, etc.
(5) Regulatory agencies such as the U.S. EPA.

05 References

Ainscough, C.; Peterson, D.; Randolph, K. (2014). 2014 *Electrolytic Hydrogen Production Workshop Summary Report*. Accessed September 30, 2014: http://energy.gov/eere/fuelcells/downloads/electrolytic-hydrogen-production-workshop.

Ainscough, C.; Randolph, K.; Sutherland, E. (2014). *2014 Hydrogen Transmission and Distribution Workshop Summary Report*. Accessed September 30, 2014: http://energy.gov/eere/fuelcells/downloads/hydrogen-transmission-and-distribution-workshop.

Barbir, F. (2005). "PEM Electrolysis for Production of Hydrogen from Renewable Energy Sources." *Solar Energy* (78:5); pp. 661–669. doi:10.1016/j.solener.2004.09.003.

Barton, J.; Gammon, R. (2010). "The Production of Hydrogen Fuel From Renewable Sources and Its Role in Grid Operations." *Journal of Power Sources* (195:24); pp. 8222–8235.

Bertuccioli, L.; Chan, A.; Hart, D.; Lehner, F.; Madden, B.; Standen, E. (2014). *Development of Water Electrolysis in the European Union: Final Report*. Work performed by E4tech Sàrl (Lausanne, Switzerland) and Element Energy Ltd. (Cambridge, United Kingdom) for the Fuel Cells and Hydrogen Joint Undertaking. Accessed August 4, 2014: http://www.fch-ju.eu/sites/default/files/study%20electrolyser_0-Logos_0_0.pdf.

Bhatnagar, D.; Currier, A.; Hernandez, J.; Ma, O.; Kirby, B. (2013). *Market and Policy Barriers to Energy Storage Development: A Study for the Energy Storage Systems Program*. SAND2013-7606. Work performed by Sandia National Laboratories, Albuquerque, NM.

Breakthrough Technologies Institute, Inc. (2013). *2012 Fuel Cell Technologies Market Report*. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office. Accessed November, 12, 2014: http://energy.gov/eere/fuelcells/downloads/2012-fuel-cell-technologies-market-report.

CaFCP. (2014). *A California Fuel Cell Roadmap, California Fuel Cell Partnership.* Accessed July 23, 2014: http://cafcp.org/carsandbuses/caroadmap.

CARB. (2013). *Staff Report: Initial Statement of Reasons for Rulemaking—2013 Minor Modifications to the Zero Emission Vehicle Regulation.* Sacramento, CA: California Air Resources Board. Accessed August 4, 2014: http://www.arb.ca.gov/regact/2013/zev2013/zev2013isor.pdf.

CARB. (2014). *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development.* Sacramento, CA. Accessed August 4, 2014: http://www.arb.ca.gov/msprog/zevprog/ab8/ab8_report_final_june2014.pdf.

Carmo, M.; Fritz, D.L.; Mergel, J.; Stolten, D. (2013). "A Comprehensive Review on PEM Water Electrolysis." *International Journal of Hydrogen Energy* (38:12); pp. 4901–4934. doi:10.1016/j.ijhydene.2013.01.151.

Castaneda, C.J. (1999). *Invisible Fuel: Manufactured and Natural Gas in America 1800–2000*. New York: Twayne Publishers.

CEC. (2014). "California Energy Commission Advances Construction of Hydrogen Refueling and Electric Vehicle Charging Stations." Press release. July 22, 2014. Accessed August 4, 2014: http://www.energy.ca.gov/releases/2014_releases/2014-07-22_hydrogen_Refueling_EV_Charging_Stations_nr.html.

ChemCoast e.V.; Ludwig Bölkow Systemtechnik; Becker Büttner Held (2013). *Roadmap for the Realisation of a Wind Hydrogen Economy in the Lower Elbe Region.* http://www.lbst.de/download/2013/ChemCoast_Executive%20Summary_Windwasserstoff-Produktion_final_engl.pdf.

Denholm, P.; Jorgenson, J.; Hummon, M.; Palchak, D.; Kirby, B.; Ma, O.; O'Malley, M. (2013). *The Impact of Wind and Solar on the Value of Energy Storage.* NREL/TP-6A20-60568. Golden, CO: National Renewable Energy Laboratory. Accessed August 4, 2014: http://www.nrel.gov/docs/fy14osti/60568.pdf.

Dodds, P.E.; Hawkes, A.; eds. (2014). *The Role of Hydrogen and Fuel Cells in Providing Affordable, Secure Low-Carbon Heat.* London, UK: H2FC SUPERGEN.

Dodds, P.E.; McDowall, W. (2013). " The future of the UK gas network." *Energy Policy* (60:C); pp. 305–316. doi:10.1016/j.enpol.2013.05.030.

EG4. (2011). *EU Commission Task Force for Smart Grids Expert Group 4: Smart Grid aspects related to Gas* (No. EG4/SEC0060/DOC) (pp. 1–27). European Commission.

Energy Efficiency and Renewable Energy. (2014). Workshop and Meeting Proceedings. Accessed August 8, 2014: http://energy.gov/eere/fuelcells/workshop-and-meeting-proceedings.

Eichman, J. (2014). "Analysis of fuel cell/electrolyzer cost of energy storage for California electrical grid", presented at the 2014 U.S. DOE Hydrogen and Fuel Cells Program Annual Merit Review, Washington, D.C., June 17, 2014.

Eichman, J.; Harrison, K.; Peters, M. (2014). *Novel Electrolyzer Applications: Providing More Than Just Hydrogen.* NREL/TP-5400-61758. Golden, CO: National Renewable Energy Laboratory.

Fuel Cell Today: The Leading Authority on Fuel Cells. (2013). "Water Electrolysis & Renewable Energy Systems." May 22. Accessed August 4, 2014: http://www.fuelcelltoday.com/analysis/surveys/2013/water-electrolysis-renewable-energy-systems.

Florisson, O. (2009). "NATURALHY: An Overview." Presented at the NATURALHY Final Public Presentation, November 19, Nederlandse Gasunie at Groningen, the Netherlands.

"Fuel Cells." (2014). Green Car Congress: Energy, Technologies, Issues, and Policies for Sustainable Mobility. Accessed August 4, 2014: http://www.greencarcongress.com/fuel_cells/index.html.

Gahleitner, G. (2013). "Hydrogen from Renewable Electricity: An International Review of Power-to-Gas Pilot Plants for Stationary Applications." *International Journal of Hydrogen Energy* (38:5); pp. 2039–2061.

Greene, D.L.; Leiby, P.N.; James, B.D.; Perez, J.; Melendez, M.; Milbrandt, A.; Unnasch, S.; Hooks, M. (2008). *Analysis of the Transition to Hydrogen Fuel Cell Vehicles & the Potential Hydrogen Energy Infrastructure Requirements.* McQueen, S., ed. ORNL/TM-2008/30. Oak Ridge, TN: Oak Ridge National Laboratory. Accessed August 4, 2014: http://cta.ornl.gov/cta/Publications/Reports/ORNL_TM_2008_30.pdf.

Grond, L.; Schulze, P.; Holstein, J. (2013). *Systems Analyses Power to Gas: Final Report—Deliverable 1: Technology Review.* GCS 13.R.23579. Groningen, the Netherlands: DNV KEMA Energy & Sustainability (now DNV GL). Accessed August 4, 2014: http://www.dnv.com/binaries/dnv%20kema%20%282013%29%20-%20systems%20analyses%20power%20to%20gas%20-%20technology%20review_tcm4-567461.pdf.

Harrison, K.W.; Martin, G.D.; Ramsden, T.G.; Kramer, W.E.; Novachek, F.J. (2009). *The Wind-to-Hydrogen Project: Operational Experience, Performance Testing, and Systems Integration.* NREL/TP-550-44082. Golden, CO: National Renewable Energy Laboratory. Accessed August 4, 2014: http://www.nrel.gov/hydrogen/pdfs/44082.pdf.

Hummon, M.; Denholm, P.; Jorgenson, J.; Palchak, D.; Kirby, B.; Ma, O. (2013). *Fundamental Drivers of the Cost and Price of Operating Reserves.* NREL/TP-6A20-58491. Golden, CO: National Renewable Energy Laboratory and U.S. Department of Energy. Accessed November 6, 2014: http://www.nrel.gov/docs/fy13osti/58491.pdf.

Hydrogenics. (2011). "Hydrogenics Successfully Completes Utility-Scale Grid Stabilization Trial with Ontario's Independent Electricity System Operator." Press release. June 16, 2011. Accessed August 4, 2014: http://www.hydrogenics.com/about-the-company/news-updates/2011/06/16/hydrogenics-successfully-completes-utility-scale-grid-stabilization-trial-with-ontario's-independent-electricity-system-operator.

HyUnder (2014). "Assessment of the Potential, the Actors and Relevant Business Cases for Large Scale and Long Term Storage of Renewable Electricity by Hydrogen Underground Storage in Europe." Accessed September 30, 2014: http://www.hyunder.eu/deliverables-and-publications.html.

International Energy Agency. (2010). *Energy Technology Perspectives 2010: Scenarios and Strategies to 2050.* Paris, France. Accessed August 4, 2014: http://www.iea.org/publications/freepublications/publication/etp2010.pdf.

International Partnership for Hydrogen and Fuel Cells in the Economy. (2012). "Hydrogen: A Competitive Energy Storage Medium for Large-Scale Integration of Renewable Electricity." International Partnership for Hydrogen and Fuel Cells in the Economy Proceedings; Nov. 15–16, 2012, Seville, Spain. Accessed August 4, 2014: http://www.iphe.net/events/workshops/workshop_2012-11.html.

Iskov, H.; Rasmussen, N.B. (2013). *Global Screening of Projects and Technologies for Power-to-Gas and Bio-SNG: A Reference Report. Hørsholm, Denmark: Danish Gas Technology Centre.* Accessed August 4, 2014: https://www.energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Forskning/global_screening_08112013_final.pdf.

Jacobson, M.Z.; Delucchi M.A.; Ingraffea, A.R.; Howarth, R.W.; Bazouin, G.; Bridgeland, B.; Burkart, K.; Chang, M.; Chowdhury, N.; Cook, R.; Escher, G.; Galka, M.; Han, L.; Heavey, C.; Hernandez, A.; Jacobson, D.F.; Jacobson D.S.; Miranda, B.; Novotny, G.; Pellat, M.; Quach, P.; Romano, A.; Stewart, D.; Vogel, L.; Wang, S.; Wang, H.; Willman, L.; Yeskoo, T. (2014). "A Roadmap for Repowering California for All Purposes with Wind, Water, and Sunlight." *Energy* (73); pp. 875–889.

Joint Research Centre Petten. (2014). "Putting Science into Standards: Power-to-Hydrogen and HCNG." Workshop hosted by EARTO, the European Standards Organisations and the European Commission's Joint Research Centre. JRC Petten, The Netherlands. October 21-22, 2014. https://ec.europa.eu/jrc/en/event/workshop/workshop-putting-science-standards-power-hydrogen-and-hcng/presentations-keynotes-conclusions.

Judson-McQueeney, J.; Leyden, T.; Walker, C. (2013). "Clean Energy Group: Resilient Power Project Webinar—Energy Storage: New Markets and Business Models." Accessed August 4, 2014: http://www.cesa.org/assets/Uploads/RPP-Webinar-Presentations-Energy-Storage-New-Markets-and-Business-Models.pdf.

Jürgensen, L.; Ehimen, E.A.; Born, J.; Holm-Nielsen, J.B. (2014). "Utilization of Surplus Electricity from Wind Power for Dynamic Biogas Upgrading: Northern Germany Case Study." *Biomass and Bioenergy* (66); pp. 126–132.

Kroposki, B.; Levene, J.; Harrison, K.; Sen, P.K.; Novachek, F. (2006). *Electrolysis: Information and Opportunities for Electric Power Utilities.* NREL/TP-581-40605. Golden, CO: National Renewable Energy Laboratory. Accessed August 4, 2014: http://www.nrel.gov/docs/fy06osti/40605.pdf.

Lord, A.S. (2009). *Overview of Geologic Storage of Natural Gas with an Emphasis on Assessing the Feasibility of Storing Hydrogen.* SAND2009-5878. Albuquerque, NM: Sandia National Laboratories. Accessed December 2, 2014: http://prod.sandia.gov/techlib/access-control.cgi/2009/095878.pdf.

Lord, A.S.; Kobos, P.H.; Klise, G.T.; Borns, D.J. (2011). *A Life Cycle Cost Analysis Framework for Geologic Storage of Hydrogen: A User's Tool.* SAND20116221. Albuquerque, NM: Sandia National Laboratories. Accessed August 4, 2014: http://prod.sandia.gov/techlib/access-control.cgi/2011/116221.pdf.

Lynn, K. (2014). "EERE Grid Integration Multi-year Program Plan." Presented at the International Energy Systems Integration Workshop. Feb. 18–19, 2014, Arlington, Virginia. Accessed November 3, 2014: http://iiesi.org/assets/pdfs/iiesi_lynn.pdf.

Ma, O.; O'Malley, M.; Cheung, K.; Larocelle, P.; Scheer, R. (2011). *Analytic Challenges to Valuing Energy Storage: Workshop Report*. Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of Electricity Delivery and Energy Reliability. Accessed August 4, 2014: https://www1.eere.energy.gov/analysis/pdfs/analytic_challenges_to_valuing_energy_storage_workshop_report.pdf.

Melaina, M. (2012). "Market Transformation Lessons for Hydrogen from the Early History of the Manufactured Gas Industry." Grasman, S.E., ed. *Hydrogen Energy and Vehicle Systems.* CRC Press.

Melaina, M.W.; Steward, D.; Penev, M.; McQueen, S.; Jaffe, S.; Talon, C. (2012). *Hydrogen Infrastructure Market Readiness: Opportunities and Potential for Near-term Cost Reductions.* NREL/BK-5600-55961. Golden, CO: National Renewable Energy Laboratory. Accessed August 4, 2014: http://www.nrel.gov/docs/fy12osti/55961.pdf.

Melaina, M.W.; Antonia, O.; Penev, M. (2013). *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues.* NREL/TP-5600-51995. Golden, CO: National Renewable Energy Laboratory. Accessed November 6, 2014: http://www.nrel.gov/docs/fy13osti/51995.pdf.

National Research Council. (2008). *Transitions to Alternative Transportation Technologies: A Focus on Hydrogen.* National Research Council of the National Academies, Committee on Assessment of Resource Needs for Fuel Cell and Hydrogen Technologies. Washington, DC: The National Academies Press.

National Research Council. (2013). *Transitions to Alternative Vehicles and Fuels.* Committee on Transitions to Alternative Vehicles and Fuels; Board on Energy and Environmental Systems; Division on Engineering and Physical Sciences; National Research Council. Washington, DC: The National Academies Press.

Oberhofer, A. (2012). *Energy Storage Technologies & Their Role in Renewable Integration.* San Diego, CA: Global Energy Network Institute. Accessed August 4, 2014: http://www.geni.org/globalenergy/research/energy-storage-technologies/Energy-Storage-Technologies.pdf.

Ogden, J.M. (1999). "Prospects for Building a Hydrogen Energy Infrastructure." *Annual Review of Energy and the Environment* (24); pp. 227–279.

Ozarslan, A. (2012). "Large-Scale Hydrogen Energy Storage in Salt Caverns." *International Journal of Hydrogen Energy* (37:19); pp. 14265–14277.

Parfomak, P.W. (2012). *Energy Storage for Power Grids and Electric Transportation: A Technology Assessment*. Tech. Rep. R42455. Washington, DC: Congressional Research Service. Accessed August 4, 2014: http://fas.org/sgp/crs/misc/R42455.pdf.

Rebenitsch, R.; Bush, R.; Boushee, A.; Woeste, J.; Stevens, B.G.; Peters, R.R.; Williams, K.D.; Bennett, K. (2009). *Wind-to-Hydrogen Energy Pilot Project*. 2009-EERC-06-11. Washington, DC: U.S. Department of Energy. Accessed August 4, 2014: http://www.osti.gov/bridge/product.biblio.jsp?osti_id=951588.

Remick, R.J.; Wheeler, D. (2011). *Reversible Fuel CellsWorkshop Summary Report*. DOE, National Renewable Energy Laboratory and DJW Technology. Accessed September 30, 2014: http://energy.gov/eere/fuelcells/downloads/reversible-fuel-cells-workshop-summary-report.

Saur, G.; Ramsden, T. (2011). *Wind Electrolysis: Hydrogen Cost Optimization.* NREL/TP-5600-50408. Golden, CO: National Renewable Energy Laboratory. Accessed August 4, 2014: http://www.nrel.gov/hydrogen/pdfs/50408.pdf.

Schlag, N.; Olson, A.; Kwok, G.; Ming, Z.; Bolze, M.; Hemingway, K. (2014). *Natural Gas Infrastructure Adequacy in the Western Interconnection: An Electric System Perspective.* San Francisco, CA: Energy and Environmental Economics, and DNV GL. Accessed November 6, 2014: https://www.ethree.com/documents/E3_WIEB_Report_3-17-2014.pdf.

Schoenung, S.M.; Hassenzahl, W.V. (2003). *Long- vs. Short-Term Energy Storage Technologies Analysis: A Life-Cycle Cost Study—A Study for the DOE Energy Storage Systems Program.* SAND2003-2783. Albuquerque, NM: Sandia National Laboratories.

Sterner, M. (2010). "100% Renewable Energy Supply for Cities and Nations." Presented at the Sustainable Energy Week, March 22–26, 2010. Accessed August 4, 2014: http://www.klimabuendnis.org/fileadmin/inhalte/dokumente/EUSEW2010_1.IWES_M.Sterner.pdf.

Steward, D.; Saur, G.; Penev, M.; Ramsden, T. (2009). *Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Electrical Energy Storage.* NREL/TP-560-46719. Golden, CO: National Renewable Energy Laboratory. Accessed August 4, 2014: http://www.nrel.gov/docs/fy10osti/46719.pdf.

Tarr, J.A. (2004). "History of Manufactured Gas." Encyclopedia of Energy. Vol. 3, Elsevier, Inc.; pp. 733–743.

Weber, A.Z. (2012). *Flow Cells for Energy Storage: Workshop Summary Report*. Berkeley, CA: Lawrence Berkeley National Laboratory; pp. 1–39. Accessed August 4, 2014: http://energy.gov/eere/fuelcells/downloads/flow-cells-energy-storage-workshop-summary-report.

Winkler-Goldstein, R.; Rastetter, A. (2013). "Power to Gas: The Final Breakthrough for the Hydrogen Economy?" *Green* (3:1); pp. 69–78. DOI: 10.1515/green-2013-0001.

Yang, C. (2008). "Hydrogen and Electricity: Parallels, Interactions, and Convergence." *International Journal of Hydrogen Energy* (33:8); pp. 1977–1994.

Zeng, K.; Zhang, D. (2010). "Recent progress in alkaline water electrolysis for hydrogen production and applications." *Progress in Energy and Combustion Science* (36:3); pp. 307–326.

A Appendix A: Details of the Breakout Session Feedback

Breakout Session Topic: Criteria and Barriers
Breakout Session Questions
DEMONSTRATION CRITERIA AND OPPORTUNITIES: What criteria should be used to identify promising near-term (next 1 to 3 years) demonstration projects with high potential for learning and early commercial success?
TRANSPORTATION, RENEWABLES, AND OTHER SYNERGIES: What technical and policy barriers are hindering integration across multiple energy sectors using hydrogen energy storage (i.e., heating fuel, transportation fuel, electric grid)?

Criteria/Barriers		Votes
Technical and economic viability	Technology readiness	7
	Insufficient demonstrations and data for comparison	6
	System requirements	5
	Existing niche opportunities	5
	Supply chain	4
	Demonstrate technical advancement	4
	Equipment utilization	4
	Cost, performance, and reliability	4
	Demonstrated business case	3
	Compare to competition	3
	Post-funding support viability	3
	Implement technology readiness level evaluation	3
	Safety and reliability	2
	Value streams for storage	2
	Carbon content	2
	Near-term market potential	2
	R&D support for electrolyzers	1
	Transparent and replicable	1
	Manufacturability	1
	"Anchor" customer	1
	Determine meaningful impacts	0
	Valuable for existing process?	0
	Underground storage	0
	Revenue opportunities (e.g., curtailment)	0
	Ideal locations	0
	Electricity market depth and viability	0
	Core technology viability	0
	Stations versus vehicles (chicken-and-egg problem)	0
	Proprietary issues	0
	Technology risk	0

Criteria/Barriers		Votes
Multiple end uses	Incentives and grants do not stack with multiple uses	11
	Multiple markets	7
	End-use flexibility	7
	Renewable integration	5
	Value streams	5
	Market volatility and security	4
	Managing supply and demand	4
	Manage infrastructure with vehicle rollout	3
	Grid support	2
	Vehicle charging	1
	Hydrogen delivery pathways	1
	Commercial and industrial uses for hydrogen	1
	Improves competitiveness	0
	Provide reliable service for multiple markets	0
	Need sink/demand for hydrogen	0
	Multiple co-localized services	0
	Serve national interest	0
	Micro "hydrogen economy"	0

Criteria/Barriers		Votes
Unified supportive policy	Technology agnostic policy, regulations, and standards	9
	Cross-sector policy framework	7
	Financial incentives with realistic credits	6
	What energy policy issue are we solving?	5
	Supportive policies	4
	Alignment with future policy	3
	Gap assessment	2
	Low-carbon intensity requirements for heating fuel	1
	Mismatched maturity in regulations, codes, and standards	0
	Cross-functional policy presence	0

Criteria/Barriers		Votes
Partnerships/ coordination	Silo-like government departments, policies, and plans	12
	Regulatory community	4
	Financial participation	4
	Partner with industry	4
	Eligibility of hydrogen for energy storage	3
	Address silo-like technology definitions to enable multiple uses	3
	Regulatory pressure to motivate acceptance	3

	Criteria/Barriers	Votes
Codes and standards	Keep up with technology implementation	11
	Need blending standard	3
	Ability to meet performance standards	3
	Need testing protocol	2
	Lack of protocols for co-benefits	1
	Comply with current standards	0
	Overconservative design requirements in standards	0
	Need working group for hydrogen storage	0

	Criteria/Barriers	Votes
Credits/offsets	Transferability and standardization	8
	Equal treatment for renewable hydrogen	8
	Credit pathway requirements	2
	Renewable portfolio standards versus renewable fuel standards	1
	Renewable heating fuel standard	0

	Criteria/Barriers	Votes
Hydrogen blending	Technical assessment	6
	Injection policies and standards	3
	R&D	3
	Inform codes and standards	2
	Performance of blended fuel	2
	Gas quality standards	0
	Business case	0
	Pipeline accessibility	0

	Criteria/Barriers	Votes
Scalable	Rapid scale-up	6
	Large-scale power-to-gas	3
	Small-scale	2
	Cost-effective	2
	Large-scale	2
	Clean and durable	0

	Criteria/Barriers	Votes
Education/ outreach	Experience	4
	Public visibility	4
	Keep hydrogen in smart grid dialog	2
	Site tours	1
	Media campaign	1

Breakout Session Topic: Policies

Breakout Session Questions

DEMONSTRATION CRITERIA AND OPPORTUNITIES: What existing or proposed policies/regulations can (or could) enable opportunities for successful near-term demonstrations of hydrogen energy storage?

TRANSPORTATION, RENEWABLES, AND OTHER SYNERGIES: What existing or proposed policies/regulations can (or could) enable cross-sector synergies that strengthen the (near- or long-term) business case for hydrogen energy storage?

Policies		Votes
Enable hydrogen participation and equal treatment in low-carbon, renewable and electricity markets	Hydrogen in renewable fuel standards	11
	Low-carbon fuel standard credit multiplier for very low-carbon fuels	8
	Hydrogen in low-carbon fuel standards	7
	Hydrogen as renewable pathway	4
	Carbon content regulations	4
	Wholesale market participation	3
	Widespread renewable fuel standards	2
	Hydrogen alternative fuel	2
	Policies include hydrogen for energy storage	1
	Hydrogen in renewable portfolio standards	1
	Allow electrolyzer to provide positive and negative balancing	0
	Market incentives	0
	Leverage existing policies	0

Policies		Votes
Tax credits, incentives, and rebates	Agnostic CO_2 reduction incentives	9
	Tax credits for equipment depreciation	5
	Energy storage tax credits	5
	Tax credits and fast depreciation	4
	Levelize incentive value between liquid and gaseous hydrogen	2
	Tax credit for HES	2
	Uniform incentives	2
	Tax credits, incentives, and rebates	1
	First mover credits	1
	Production tax credit for renewables used to produce hydrogen	1
	Incentives, low interest rate, tax credits, and feed-in-tariff	0

Policies		Votes
Develop and streamline codes and standards	Gas quality standards	7
	State-level interconnection standards	6
	Renewable gas standard	5
	Combine transportation and storage	3
	Interdepartmental coordination	3
	Regulations, codes, and standards	2
	Review Department of Transportation and hazardous materials regulations	1

Policies		Votes
More inclusive and complete definitions	Hydrogen as energy carrier	8
	Hydrogen included in peak shifting	7
	Renewable definitions	2
	Include HES in load-shifting definition	2
	Storage requirements	2
	CEC solicitation need not contain size versus power versus energy	1
	Hydrogen valued as energy carrier	1
	Ancillary service markets	0

Policies		Votes
Develop and standardize regulations for hydrogen	Carbon tax and global cap-and-trade	8
	Gas interoperability standards	5
	Hydrogen injection consensus	5
	Characterization and testing for hydrogen with natural gas	2
	Standardize evaluation metrics across technology policy areas	2
	Establish renewable portfolio standards across all sectors	1
	Hydrogen injection regulations	0
	Standardize renewable and fuel regulations	0
	Increase carbon regulations	0
	Hydrogen blending regulations	0
	Hydrogen blending standards	0

Policies		Votes
Develop policy to support hydrogen technologies	Near-term market targets	5
	Policies enabling injection, grid services, low-carbon fuel standards, renewable fuel standards	5
	Quantify resiliency needs	3
	Distributed and net zero production	2
	Use hydrogen policy to support other sectors	2
	Vehicle-to-grid interconnection policies	1
	100% renewable vehicles	1
	Policy to credit renewable hydrogen injection into heavy oil	1
	Infrastructure support	0
	Renewable ammonia requirement	0

Policies		Votes
Other financial mechanisms	Feed-in tariff	8
	Market transformation investment	3
	Transparency	2
	Cross-sector energy tariff	2
	Increase governmental storage budget	1
	Loan guarantee	1
	Pay for performance tariff	1
	Lower feedstock costs	1
	Infrastructure funding	0

Policies		Votes
Partnerships/ coordination	Federal agencies host hydrogen storage sites	5
	Isolate regions that need reliability, security, etc.	5
	Collaboration between jurisdictions	4
	Investment coordination	2
	Incentivize public-private partnerships	2
	Critical/military base power federal mandate	0

Policies		Votes
Leverage current policies	Energy goals should accompany energy mandate (not only 1,325 MW of storage)	6
	HES in hydrogen U.S. mandate	4
	Wheeling of curtailed electricity like biogas	4
	CPUC energy storage mandate (AB2514)	2
	Create hydrogen demand with zero-emission vehicle fleet mandate	0
	Enable cross-sector synergies	0

Policies		Votes
Credits/ offsets	Marketable credits for hydrogen	6
	Coordinate credit programs	5
	Put fuels in the carbon cap in California	1
	Carbon credit per kg regardless of liquid or gaseous	1
	Transmission infrastructure	0
	Capacity credits	0
	Carbon credit offsets	0

Breakout Session Topic: Next Steps

Breakout Session Questions

DEMONSTRATION CRITERIA AND OPPORTUNITIES: What actions, analyses, or demonstrations are needed to best inform industry and government decision makers to build support for a broader rollout of hydrogen as an energy storage medium?

TRANSPORTATION, RENEWABLES, AND OTHER SYNERGIES: What actions, analyses, or demonstrations are needed to inform key stakeholders of the potential for cross-sector synergies using hydrogen storage?

Next Steps		Votes
Demonstrations/ pilot projects	Demonstrate large-scale systems with multiple value streams	14
	Show successful business case	13
	Multi-fuels, multi-use, large-scale demonstrations	12
	Federal land site for HES with multiple uses	9
	Fund multiple large-scale demonstrations	4
	Focus on fleets and high-demand centers	4
	Autonomous remote power demonstration	4
	Capture imagination of the nation and world	3
	Multiple cross-sector demonstrations	3
	Flexibility of hydrogen storage to meet a variety of needs	2
	Increase government hydrogen vehicle fleets	2
	Demonstrate vehicle-to-grid, biomass gasification, biomethanation, vehicle fueling, and HES	2
	Evaluate financial feasibility of project	1
	End-to-end demonstration with utility	1
	Led by stakeholder and solves their needs	1
	Incentivize stakeholders to scale up	0

Next Steps		Votes
Analyze the business case for hydrogen energy storage	Establish business case for multiple markets	12
	Hydrogen impact on gasoline/natural gas	9
	Techno-economic, siting, and sizing analysis	9
	Predict favorable technologies, actions, and policies	8
	Determine viable and robust hydrogen markets given policy uncertainty	5
	Carbon reduction comparison	4
	Techno-economic and siting/location analysis	3
	Form defensible business case for hydrogen storage	2
	Integrate multiple sectors into modeling efforts	2
	Quantify financial benefit to ensure monetization	1
	Standardized, comparative metrics	1
	Applicable to multiple areas/states/provinces	1
	Quantify hydrogen demand by sector and location	0
	Review and validate Hydrogen Analysis (H2A) model	0

	Next Steps	Votes
Develop or revise policy, regulations, codes and standards	Make hydrogen eligible for storage, including power-to-gas	17
	Standardize comparison and the ability to trade revenue streams	5
	Carbon intensity transparency for large emitters, government agencies, etc.	4
	Advance hydrogen pipeline codes and standards	4
	Establish regulatory framework for power-to-gas	2
	Form regulations, codes and standards working group to identify barriers and inform codes	1
	Hydrogen participation in renewable portfolio standards	1
	Simplify carbon tax	1
	Address tax issues	0
	Demonstrate hydrogen can achieve regulatory recovery	0
	Add energy storage to DOE budget	0
	Policy scale-up potential	0

	Next Steps	Votes
Develop roadmap and implement hydrogen plan and targets	Roadmap for integrating renewables and fossil fuels with hydrogen	6
	Develop plan for national energy future	6
	Develop roadmap to avoid premature regulations, codes, and standards	4
	Develop and implement research, development, and deployment plan for hydrogen injection	3
	Critically review hydrogen program technical goals	2
	Develop R&D plan for hydrogen storage capacity scale-up	1
	Establish renewable gas target	1
	Explore net zero/micro-grid business models	1
	Show value of hydrogen across multiple sectors	0

	Next Steps	Votes
Education/ outreach	Develop the public case	4
	Public education on use of hydrogen	3
	Safety demonstration for public	2
	Encourage office of electricity to acknowledge hydrogen as a viable energy storage option	1
	Educate policy makers regarding synergy between energy and fuels	1
	Mobile fuel cell for public events	1

	Next Steps	Votes
Partnerships/ coordination	Increase collaboration between customers, utilities, system operators, gas companies, vehicle manufacturers, etc.	10
	Government use of energy storage technologies	1
	Develop stakeholder group around HES	1
	Coordinated zero-emission vehicle plan and FCEV rollout	0
	Hydrogen Delivery Technical Team need to discuss HES	0

Next Steps		Votes
Assess technical viability	Market synergy potential	5
	Assess technical performance	3
	Identify shortcomings in technology process	1
	Technology scale-up potential	1
	Enable electrolyzers to participate in electricity markets	0
	Revenue from waste streams	0

Next Steps		Votes
Determine the probability of success	Must be reproducible	3
	Probability of success, impact, benefit	3
	Must show success at the project and commercial levels	3
	Comparison to other energy storage systems	0
	Show pathway for commercial success	0

B Appendix B: Workshop Agenda

The following four pages include content of the workshop agenda as distributed to participants.

A Workshop Convened by
the U.S. Department of Energy and Industry Canada
Hosted by the National Renewable Laboratory and the California Air Resources Board
Sheraton Grand Hotel, Sacramento, California, May14 –15, 2014

Workshop Goal	Identify challenges, benefits, and opportunities for commercial hydrogen energy storage applications to support grid services, variable electricity generation, and hydrogen vehicles.
Workshop Scope	A broad range of services from hydrogen storage systems in the near and long term.
Workshop Focus	The four key topics shown as discussion panels in the agenda below.

Agenda Overview

Wednesday, May 14: Lessons Learned, Demonstrations, and Market Opportunities	
1:00 – 2:00 PM	Opening Remarks
2:00 – 3:00 PM	Discussion Panel: Lessons Learned and Demonstration Status
3:00 – 3:20 PM	Break
3:20 – 4:45 PM	Discussion Panel: Market Opportunities and Business Models
4:45 – 5:00 PM	Review Breakout Group Topics and Process
Thursday, May 15: Technology R&D, Future Potential, and Policy	
8:30 – 9:55 AM	Breakout Session A: Lessons and Demos, Markets and Business Models
9:55 – 10:15 AM	Break
10:15 – 11:00 AM	Breakout Group Reports and Discussion
11:00 AM – 12:00 PM	Discussion Panel: Technology R&D and Near-Term Market Potential
12:00 – 1:15 PM	Lunch (on your own/coordinated phone orders if confirmed by 10 a.m.)
1:15 – 2:15 PM	Discussion Panel: Policy and Regulatory Challenges and Opportunities
2:15 – 3:40 PM	Breakout Session B: Policy and Regulatory Role for R&D and Opportunities
3:40 – 4:00 PM	Break
4:00 – 4:45 PM	Breakout Group Reports and Plenary Discussion
4:45 – 5:00 PM	Closing Remarks

Wednesday, May 14: Lessons Learned, Demonstrations, and Market Opportunities

1:00 – 2:00 PM Opening Remarks

Introduction: Monterey Gardiner, U.S. Department of Energy

- Kevin Lynn, Director, Energy Systems Integration, U.S. Department of Energy
- Tim Karlsson, Director, Emerging Technologies, Industry Canada
- Analisa Bevan, Chief, Sustainable Transportation Technology Branch, ECARS Division, California Air Resources Board
- Fernando Pina, Manager, Energy Systems Research, California Energy Commission

2:00 – 3:00 PM Discussion Panel: Lessons Learned and Demonstration Status

Moderator: Monterey Gardiner, U.S. Department of Energy
Key Panel Questions:

  - What have we learned from past workshops and studies on hydrogen and other energy storage systems?
  - What is the current status of ongoing and proposed projects?
  - What lessons can be passed on from existing demonstration projects to inform future projects, including unintended consequences?

- **Monterey Gardiner**, U.S. Department of Energy's Fuel Cell Technologies Office
- **Dave Teichroeb**, Enbridge, Inc., Alternative & Emerging Technology, Business Development
- **Hanno Butsch**, National Organisation Hydrogen and Fuel Cell Technology
- **Mitch Ewan**, Hawaii Natural Energy Institute

3:00 – 3:20 PM Break

3:20 – 4:45 PM Discussion Panel: Market Opportunities and Business Models

Moderator: Timothy Lipman, UC Berkeley, Transportation Sustainability Research Center
Key Panel Questions:

  - What are the future market opportunities for hydrogen storage?
  - What business model approaches capture the value and unique benefits of using hydrogen as an energy storage medium?
  - How can hydrogen storage effectively interface with and improve the performance of regional electricity grids?

- **Josh Eichman**, National Renewable Energy Laboratory
- **Patrick Balducci**, Pacific Northwest National Laboratory
- **Anna Lord**, Sandia National Laboratories
- **Brian Weeks**, Gas Technology Institute
- **Valri Lightner**, Loan Programs Office, U.S. Department of Energy

4:45 – 5:00 PM Review Breakout Group Topics and Process (Marc Melaina, National Renewable Energy Laboratory)

5:15 PM Reception, Sheraton Grand Lobby
Cash bar, with food compliments of the Breakthrough Technologies Institute

Thursday, May 15: Technology R&D, Future Potential, and Policy

8:30 – 9:55 AM Breakout Session A: Lessons and Demos, Markets and Business Models

See Breakout Session Topic and Rooms Assignment Handout

9:55 – 10:15 AM Break

10:15 – 11:00 AM Breakout Group Reports and Discussion

11:00 AM – 12:00 PM Discussion Panel: Technology R&D and Near-Term Market Potential

Moderator: Frank Novachek, Xcel Energy
Key Panel Questions:

- Under what conditions and where will electrolytic-based hydrogen energy storage projects succeed in North America?
- What are the competitive advantages of electrolytic hydrogen storage compared to other technologies?
- Have the R&D priorities necessary to ensure market success changed from the Challenges-5X and R&D-10X needs captured at the last electrolyzer workshop in February at the National Renewable Energy Laboratory?
- What are the most important drivers that should influence R&D priorities (operations and maintenance, capital cost, efficiency, near- versus long-term market opportunities, regulations)?

- **Robert Rose**, ITM Power
- **Hector Maza**, Giner
- **Steve Szymanski**, Proton OnSite
- **Rob Harvey**, Hydrogenics

12:00 – 1:15 PM Lunch (on your own)

1:15 – 2:15 PM Discussion Panel: Policy and Regulatory Challenges and Opportunities

Moderator: Tim Karlsson, Director, Emerging Technologies, Industry Canada
Key Panel Questions:

- What policy/regulatory objectives drive energy storage systems (e.g., environmental goals, permitting issues, aging infrastructure) and how does hydrogen use fit in this environment?
- What is the role of the policy/regulatory decisions compared to current market drivers in the business case for hydrogen use?
- How might future policies/regulations on energy storage and management change the business environment and how could hydrogen fit into this future?

- **Melicia Charles**, California Public Utilities Commission
- **Jeff Reed**, Sempra Utilities
- **Gerhard Achtelik**, California Air Resources Board
- **Kourosh Malek**, National Research Council Canada

2:15 – 3:40 PM Breakout Session B: Policy and Regulatory Role for R&D and Opportunities

See Breakout Session Topic and Rooms Assignment Handout

3:40 – 4:00 PM Break

4:00 – 4:45 PM Breakout Group Reports and Plenary Discussion

4:45 – 5:00 PM Closing Remarks

Breakout Sessions				
Breakout Session Numbers and Rooms	**#1 Compango**	**#2 Beavis**	**#3 Bondi**	**#4 Clark**

AM Breakout TOPIC: Demonstration Criteria and Opportunities

1. **CRITERIA:** What criteria should be used to identify promising near-term (next 1 to 3 years) demonstration projects with high potential for learning and early commercial success?

   a. What criteria will distinguish competitive hydrogen energy storage projects in the long term (next 5 to 15 years)?

2. **POLICIES:** What existing or proposed policies/regulations can (or could) enable opportunities for successful near-term demonstrations of hydrogen energy storage?

   a. How can the unique benefit of hydrogen storage systems be appropriately valued?

3. **NEXT STEPS:** What actions, analyses, or demonstrations are needed to best inform industry and government decision makers to build support for a broader rollout of hydrogen as an energy storage medium?

   a. Is your suggestion applicable in the near term (next 1 to 3 years) or the long term (next 5 to 15 years)?

PM Breakout TOPIC: Transportation, Renewables, and Other Synergies

1. **BARRIERS:** What technical and policy barriers are hindering integration across multiple energy sectors using hydrogen energy storage (i.e., heating fuel, transportation fuel, electric grid)?

2. **POLICIES:** What existing or proposed policies/regulations can (or could) enable cross-sector synergies that strengthen the (near- or long-term) business case for hydrogen energy storage?

3. **NEXT STEPS:** What actions, analyses, or demonstrations are needed to inform key stakeholders of the potential for cross-sector synergies using hydrogen storage?

C Appendix C: Speaker and Moderator Short Bios

Gerhard H. Achtelik Jr., Manager, California Air Resources Board, Zero Emission Vehicle Infrastructure Section

Gerhard H. Achtelik is manager of the Zero Emission Vehicle Infrastructure Section at the California Air Resources Board (CARB). He supports the deployment of California publicly cofunded hydrogen fueling stations, the development of hydrogen metering evaluation, and the development of regulations relating to emissions from hydrogen production. He has been with CARB since 1986, and his work has included ambient air monitoring, multi-media technology certification, and zero-emission bus regulatory development. Achtelik holds a bachelor's degree in atmospheric science from the University of Washington.

Patrick Balducci, Senior Economist, Pacific Northwest National Laboratory

Patrick Balducci is a senior economist at the Pacific Northwest National Laboratory, where he has been employed since 2001. Balducci has developed program- and project-specific economic and financial analyses for a number of public agencies and research institutions around the country, including the U.S. Department of Energy, Bonneville Power Administration, Internal Revenue Service, National Oceanic and Atmospheric Administration, and the National Academy of Sciences. His areas of expertise include benefit-cost and return on investment analysis, environmental valuation and impact analysis, economic modeling, and financial analysis. Balducci holds a bachelor's degree in economics from Lewis and Clark College, where he graduated with honors, and a master's degree in applied environmental economics from the University of London, Imperial College London. He serves as an adjunct professor of business at Marylhurst University, where he was honored with the 2013 Excellence in Academic Service & Teaching Award. He also serves on the board of directors of the Pacific Northwest Regional Economics Conference.

Hanno Butsch, National Organisation Hydrogen and Fuel Cell Technology

Dr. Hanno Butsch studied environmental planning with a focus on technological issues at the UmweltCampus Birkenfeld (Trier University, Germany). He earned his Ph.D. in material science in liaising with Freudenberg Fuel Cell Component Technologies KG from the Technical University of Darmstadt, Germany, in 2012. Butsch began his professional career at Freudenberg-Nok General Partnership, where he managed the fuel cell laboratory in Plymouth, Michigan. In June 2012, he joined the National Organisation Hydrogen and Fuel Cell Technology and is responsible for international cooperation, including the development of intergovernmental and industrial exchange.

Melicia Charles, California Public Utilities Commission

Melicia Charles is an energy advisor for Commissioner Carla Peterman. Charles previously supervised the California Public Utilities Commission's (CPUC's) customer generation programs, which oversee the California Solar Initiative, Self-Generation Incentive Program, and net energy metering policies. Charles began her tenure at the CPUC in 2006, and she has developed policies and programs related to solar and other distributed generation, energy storage, and energy efficiency. Charles also served as chief of staff to Commissioner Timothy Alan Simon. Prior to working at the CPUC, Charles was a Ford Scholar for a joint project between Harvard University and Boston University, where she conducted research on Boston's Haitian communities. After completing that project, Charles worked as a management consultant focusing on program evaluation and strategic planning. Charles has an MBA from the University of San Francisco and a bachelor's degree from the University of California at Berkeley.

Josh Eichman, National Renewable Energy Laboratory

Josh Eichman began working with the National Renewable Energy Laboratory's Hydrogen Systems Analysis Team in January 2013 as an Energy Efficiency and Renewable Energy postdoctoral fellow. His research focuses on the integration of hydrogen technologies with the electrical grid and growing interactions between the transportation and electric sectors. Eichman completed his Ph.D. and master's degree in mechanical and aerospace engineering from the University of California at Irvine, with a focus on renewable integration and fuel cell commercialization barriers, and his bachelor's degree in mechanical engineering from Clemson University.

Mitch Ewan, Hawaii Natural Energy Institute

Mitch Ewan is a graduate of the Royal Military College of Canada, where he earned a degree in applied science. After a successful naval career that included commanding submarines and a destroyer, Ewan entered private industry, where he has served in a variety of senior executive positions, including senior management of publicly traded companies. His career in hydrogen and fuel cells spans more than 20 years. He led the team that designed and built the "Green Car," the world's first polymer electrolyte membrane (PEM) fuel-cell powered automobile. This car was featured on the Discovery Channel's "Beyond 2000" program and makes a cameo appearance in the Steven Seagal movie *On Deadly Ground*. The Green Car's fuel cell was developed by Ewan's team, and it was the world's most powerful PEM fuel cell at the time. Ewan is the former vice chairman of the U.S. National Hydrogen Association and has served on the business advisory board of the Florida Solar Energy Center. He was awarded a patent for an electrochemical load management system for transportation systems that has been referenced in Ford and Daimler-Benz patents. Ewan is currently on the staff of the Hawaii Natural Energy Institute, where he is helping to develop their hydrogen and fuel cell programs, including management of the Hawaii Hydrogen Power Park.

Monterey R. Gardiner, U.S. Department of Energy Fuel Cell Technologies Office

Monterey R. Gardiner serves as a technology manager in the U.S. Department of Energy (DOE) Fuel Cell Technologies Office, under the Office of Sustainable Transportation. He is responsible for international relationships, explores the economics of using hydrogen for energy storage, and serves as a liaison to the DOE Grid Tech Team, which is focused on grid modernization and lowering the barriers for renewable energy integration. For more than a decade he has worked through academia, industry, and government positions to place hydrogen vehicles on the road. He graduated in 2004 with a Ph.D. in transportation technology and policy from the University of California at Davis Institute of Transportation Studies; his dissertation was on designing, building, and testing a prototype cryogenic hydrogen storage system using activated carbon and comparing the system to current technologies for hydrogen-fueled vehicles. He has worked successively as a safety engineer for the California Fuel Cell Partnership and as a fuel cell engineer for Hyundai America, in Sacramento, managing the DOE fuel cell demonstration fleet. In 2007, he moved to Washington, D.C., to work as a technology development manager for DOE, where he managed more than 40 projects with an annual budget of more than $20 million. In 2010, he was selected for a two-year Mike Mansfield fellowship, with one year of language training in Washington, D.C., and one year in Japan, where he worked at the Ministry of Economy Trade and Industry and the New Energy and Industrial Technology Development Organization for five months in Tokyo, returning to DOE in September 2012.

Rob Harvey, Hydrogenics

Rob Harvey is the director of energy storage at Hydrogenics. In this role, he works closely with utilities, regulators, and associations to identify market opportunities and refine the business case for power-to-gas. As a former principal with PHB Hagler Bailly and energy consultant with Oliver Wyman, Harvey worked with several leading North American electric utilities, as well as start-up biogas and waste-to-energy ventures in the areas of strategic analysis and business planning.

Harvey graduated from the University of Waterloo with a degree in systems design engineering and has an MBA from Regent University in Virginia. Harvey serves on the board of directors for Energy Storage Ontario.

Tim Karlsson, Industry Canada

Tim Karlsson is director of Emerging Technologies at Industry Canada. Currently, the directorate focuses on nanotechnology, industrial biotechnology, additive manufacturing, and hydrogen and fuel cells. Previously, Karlsson was the director of the Environmental and Clean Energy Industries Directorate. He has worked on a number of policy issues related to energy and the environment, including working on domestic and international climate change policy. For a number of years, he was a member of Canada's delegation to the United Nations Framework Convention on Climate Change. Karlsson is the Canadian delegate to the International Partnership for Hydrogen and Fuel Cells in the Economy, a forum for governments to share information and policy experiences with the goal of integrating hydrogen into their energy and transportation systems. Prior to coming to government, Karlsson worked in the mining industry in Canada and Australia. He has a bachelor's degree and a master's degree in economics from the University of British Columbia.

Valri Lightner, Assistant Director, U.S. Department of Energy Loan Programs Office, Technical and Project Management Division

Valri Lightner has 30 years of experience managing technology development for the federal government. She has been with the U.S. Department of Energy (DOE) for 20 years. For the last three years, she has worked in the Loan Programs Office providing technical management for a $30 billion portfolio, including advanced technology vehicle manufacturing, transmission, fossil, nuclear, efficiency, and renewable energy projects. Previously, Lightner worked in the DOE's Office of Energy Efficiency and Renewable Energy, where she led public-private partnerships in biomass program deployment, including biorefinery and infrastructure activities; fuel cell technology development for transportation applications; and pulp and paper energy efficiency development. Lightner has a bachelor's degree in chemical engineering from Villanova University.

Timothy Lipman, University of California at Berkeley, Transportation Sustainability Research Center

Dr. Timothy Lipman is an energy and environmental technology, economics, and policy researcher with the University of California at Berkeley. He serves as codirector of the Transportation Sustainability Research Center, based at the Institute of Transportation Studies, and is also a lecturer in the Department of Civil and Environmental Engineering. Lipman's research focuses on electric vehicles, fuel cell technology, combined heat and power systems, renewable energy, and electricity and hydrogen infrastructure. He completed a Ph.D. in environmental policy analysis with the Graduate Group in Ecology at the University of California at Davis (UC Davis) (1999), holds a master's degree from UC Davis in transportation technology and policy (1998), and a bachelor's degree from Stanford University (1990). He is chair of the Alternative Transportation Fuels and Technologies Committee of the Transportation Research Board of the National Academy of Sciences, a member of the Hydrogen and Fuel Cell Technical Advisory Committee for the U.S. Department of Energy, and serves on the editorial board of the *International Journal of Sustainable Engineering*.

Anna S. Lord, Sandia National Laboratories

Anna S. Lord has been a member of the technical staff at Sandia National Laboratories in Albuquerque, New Mexico, since August 2000. She initially worked as an experimental geochemist from 2000 to 2004, conducting experiments related to the continued performance of the Waste Isolation Pilot Plant. Since 2004, Lord has worked as a geologist in the Geotechnology and Engineering department, which is the geotechnical advisor to the nation's Strategic Petroleum Reserve. Lord received her bachelor's degree in geology from Virginia Tech and her master's degree in geology from the University of New Mexico. Currently, Lord's work entails geologic characterization, modeling, and subsidence analysis related to underground storage applications.

Kourosh Malek, National Research Council

Dr. Kourosh Malek is a program technical lead for the Energy Storage Program at the National Research Council in Vancouver, Canada. He is currently leading activities around techno-economic assessment and market evaluation for energy storage technologies, including managing a major project to monitor and assess more than seven publicly funded grid-storage demonstration projects across Canada. He recently served as program manager for a major, multi-party collaborative effort to develop next generation bus fuel cells in partnership with Ballard Power Systems and several academic partners. With an extensive technical background in hydrogen fuel cells and batteries, his current research is focused on developing technology management concepts to perform risk and market opportunity assessments for the early adoption and scalability of emerging clean energy technologies. He holds an MBA, specialized in the management of technology, from Simon Fraser University, in Vancouver, Canada, and a Ph.D. and a master's degree in chemical engineering and physical chemistry jointly from Sharif University of Technology and Delft University of Technology, the Netherlands.

Hector A. Maza, Director of Business Development, Giner, Inc.

During the past 24 years, Hector A. Maza has led international engineering consulting firms in the energy efficiency field, serving as vice president of business development for companies such as PointVerde and General Synfuels International. He has a successful track record in international engineering and technical sales management in mobile devices, tactile technologies, and power connectors for large multinationals, such as Balda GmbH, Tribotek, Inc., Tyco International, Elo Touch Solutions, Raychem Corporation, and Mobil, working seamlessly in four different languages while being based in Europe and the Americas. Maza holds an MBA from Hartford University Business School in Paris, France, a graduate degree in international finance from the University of California at Berkeley, and a bachelor's degree in chemical engineering from Universidad Iberoamericana, in Mexico City. Currently, he serves as director of business development and technical sales for Giner, Inc., negotiating business arrangements, licenses, and sales on behalf of executive management and commercializing hydrogen generators from laboratory to megawatt-scale sizes, in both military and industrial markets.

Marc W. Melaina, National Renewable Energy Laboratory

Dr. Marc W. Melaina is a senior engineer at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). His research addresses early-market transitions for alternative fuels, with a focus on scenario development, market barriers, and hydrogen infrastructure. Before joining NREL in 2007, Melaina was the research track director at the Institute of Transportation Studies at the University of California at Davis. Melaina received his Ph.D. from the School of Natural Resources and Environment and a master's degree in civil engineering from the University of Michigan. He has a bachelor's degree in physics from the University of Utah.

Frank Novachek, Xcel Energy

Frank Novachek is the director of corporate planning for Xcel Energy and has more than 35 years of diverse experience with the company. The first third of his career was spent working at the only commercial advanced high-temperature gas-cooled nuclear reactor in the United States; the balance has had a more corporate focus. He has served in a variety of roles, from chief internal auditor, to director of product development, to integration manager for the two mergers that ultimately created Xcel Energy, to his current role, where he is involved in the development and implementation of the company's new strategy and planning function. During the past several years, he has also had great interest in the assessment and development of strategies around distributed energy resources and hydrogen from the perspective of a combined gas and electric utility. He is vice chair of the U.S. Department of Energy's Hydrogen and Fuel Cell Technical Advisory Committee and chairs the Electric Power Research Institute Energy Storage and Distributed Generation Program Advisory Committee. Frank holds a bachelor's degree in physics from Colorado State University and an MBA from the University of Colorado.

Jeffrey Reed, Southern California Gas Company

Dr. Jeffrey Reed is the director of business strategy and advanced technology for Southern California Gas Company. In that capacity, he leads the development of policies and initiatives aimed at supporting the development and deployment of sustainable energy solutions. In his current and prior roles, Reed has led the natural gas research, development, and deployment, energy efficiency technology transfer, venture investment, and low-emission vehicle programs, and he is responsible for the company's long-range technology forecasting and strategic planning. Reed is currently a board member at CalSTART and the California Hydrogen Business Council. Prior to joining the Sempra utilities, Reed was a senior strategy consultant with Booz Allen Hamilton and Accenture, and he was an officer with ABB Power Generation in Switzerland. Reed holds a doctorate in engineering from the University of California at Berkeley and a master's degree in management from Stanford University.

Robert Rose, Breakthrough Technologies Institute

Robert Rose is executive director of the Breakthrough Technologies Institute, Inc. (BTI), an independent nonprofit advocate for technologies that carry environmental benefits to society. BTI's fuel cell education program was launched in 1993 and is internationally recognized. In a career spanning more than 35 years in Washington, D.C., Rose has served in senior communications and policy positions in the U.S. government and as an adviser to state and regional governments, nonprofit organizations, and the private sector. In 1998, Rose founded the U.S. Fuel Cell Council, the trade association of the fuel cell industry, and was executive director for 10 years. He received a special recognition award from the U.S. Department of Energy in 2013.

Steve Szymanski, Proton OnSite

Steve Szymanski is director of government business at Proton OnSite and has more than 26 years of technical and business development experience in the fields of process chemicals and electrochemical systems. In this role, he is responsible for developing strategic relationships and advancing business and research opportunities with government agencies and government primes in the areas of hydrogen and electrochemical system solutions. Szymanski has held several positions at Proton with increasing levels of responsibility. His previous experience includes several years as an engineer in the electrochemical technology group at the Hamilton Standard Division of United Technologies. In this position, he supported the development of polymer electrolyte membrane (PEM) electrolyzer and fuel cell technology for both space and undersea applications. Subsequent to his tenure at Hamilton, Szymanski pursued a career path in technical sales, working in the process chemical division at Buckman Laboratories, in Memphis, Tennessee. After nine years developing sales territories throughout New England, and advancing into sales management, Szymanski joined Proton to contribute to the technical and business success of its PEM electrolyzer technology. He has a bachelor's degree in chemical engineering from Cornell University and a master's degree of science in operations management from Rensselaer Polytechnic Institute.

David Teichroeb, Enbridge, Inc., Alternative & Emerging Technology, Business Development

David Teichroeb has more than 20 years of experience in the natural gas and power generation sectors. He is responsible for evaluating and developing new business investments involving emergent technologies. This includes distributed generation, fuel cells, energy recovery to power, hydrogen, electricity energy storage, and other renewable technologies. Before joining Enbridge in 1993, Teichroeb worked in the diesel power generation industry. He provided engineering and technical services to a varied customer base that included Canada Steam Ship Lines, the Canadian Coast Guard, and John Deere. Teichroeb graduated from Niagara College with a degree in mechanical engineering technology, and he is a graduate of the Institute of Gas Technology, in Chicago, Illinois, as a chartered industrial gas consultant. He serves on the board of directors for the Canadian Hydrogen and Fuel Cell Association.

Brian Weeks, Gas Technology Institute

Brian Weeks is regional manager for Gas Technology Institute (GTI) in its Houston location. He has 25 years of experience in the energy industry, beginning as a pipeline design and construction engineer for Tennessee Gas Pipeline, then joining the natural gas division of Chevron, where he worked on a variety of projects and emerging technology initiatives focused on both natural gas and hydrogen. He joined GTI in 2005 to lead GTI's Houston office as well as manage demonstration projects of advanced energy technologies developed by GTI and its partnering organizations. He is active in the Houston energy community and serves in leadership positions in local energy industry organizations. He has a degree in engineering from Vanderbilt University and an MBA from the University of Mississippi. He is a registered professional engineer in the State of Texas.

D Appendix D: List of Registered Attendees

First Name	Last Name	Affiliation
Gerhard	Achtelik	California Air Resources Board
Patrick	Balducci	Pacific Northwest National Laboratory
Eric	Barker	Industry Canada
Analisa	Bevan	California Air Resources Board
Avtar	Bining	California Energy Commission
Nico	Bouwkamp	California Fuel Cell Partnership
Hanno	Butsch	NOW GmbH
Melicia	Charles	California Public Utilities Commission
Daniel	Dedrick	Sandia National Laboratories
Catherine	Dunwoody	California Fuel Cell Partnership
Tyson	Eckerle	California State Government, GoBiz
Thomas	Edmunds	Lawrence Livermore National Laboratory
Josh	Eichman	National Renewable Energy Laboratory
Mitch	Ewan	Hawaii Natural Energy Institute
Jonathan	Foster	California Air Resources Board
Monterey	Gardiner	U.S. Department of Energy
Leslie	Goodbody	California Air Resources Board
Rob	Harvey	Hydrogenics
Patrick	Hirl	Burns & McDonnell
Tim	Karlsson	Industry Canada
Jay	Keller	Zero Carbon Energy Solutions
Ronald	Kent	Southern California Gas Company
Mark	Koostra	California Energy Commission
Pramod	Kulkarni	Customized Energy Solutions
Adam	Langton	California Public Utilities Commission
Valri	Lightner	U.S. Department of Energy
Tim	Lipman	Transportation Sustainability Research Center, University of California, Berkeley
Anna	Lord	Sandia National Laboratories
Kevin	Lynn	U.S. Department of Energy
Kourosh	Malek	National Research Council Canada
Hector	Maza	Giner Inc.
Jim	McKinney	California Energy Commission
Marc	Melaina	National Renewable Energy Laboratory
Frank	Novachek	Xcel Energy
Joan	Ogden	Institute of Transportation Studies, University of California, Davis
Mike	Oliver	Atlantic Hydrogen Inc.

First Name	Last Name	Affiliation
Pinakin	Patel	FuelCell Energy Inc.
Robert	Perry	World Business Academy
Nathan	Phillips	California State Senate
Fernando	Pina	California Energy Commission
Glen	Rambach	Third Orbit Power Systems, Inc.
Jeffrey	Reed	Southern California Gas Company
Pierre	Rivard	TUGLIQ Energy Co.
Bob	Rose	Breakthrough Technologies Institute
Jimmy (Jacques-Mathieu)	Royer	NRCan
Susan	Schoenung	Longitude 122 West, Inc.
Jeff	Serfass	California Hydrogen Business Council
Mark	Siroky	California Air Resources Board
Stephen	Szymanski	Proton OnSite
Dave	Teichroeb	Enbridge
Mike	Tosca	Center for Transportation and the Environment
Floyd	Vergara	California Air Resources Board
Emanuel	Wagner	Technology Transition Corporation
Larry	Watkins	South Coast Air Quality Management District
Brian	Weeks	Gas Technology Institute
Max	Wei	Lawrence Berkeley National Laboratory

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Grid and Transportation Services

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National Renewable Energy Laboratory

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