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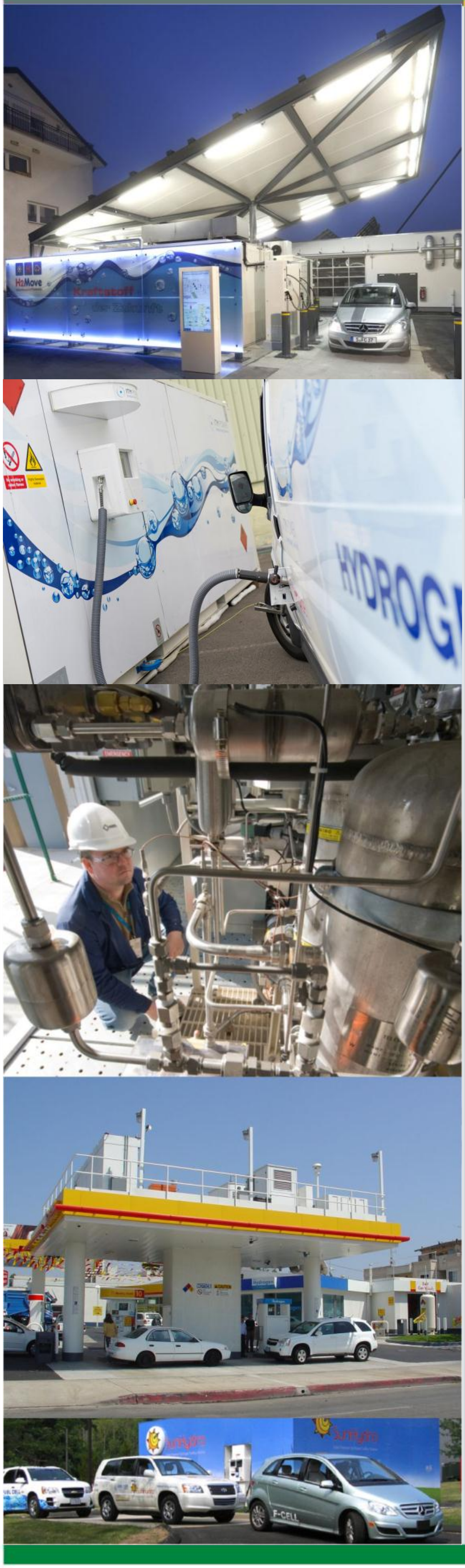

# 2014 Electrolytic Hydrogen Production Workshop Summary Report

July 2014

## About the Cover

(Photos from top to bottom)

*A vehicle refueling at an electrolysis-based fueling station. Photo courtesy of Proton OnSite.*

*A vehicle refuels at an ITM Power mobile refueler. Photo courtesy of ITM Power.*

*Dr. Kevin Harrison inspects a hydrogen-producing electrolyzer system. Photographer: Greg Martin. Photo courtesy of NREL. (NREL 23852-C)*

*Shell's Santa Monica Blvd. hydrogen fueling station in west Los Angeles. Photographer: Keith Wipke. Photo courtesy of NREL. (NREL 17321)*

*Vehicles at an electrolysis-based fueling station. Photo courtesy of Proton OnSite.*

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# 2014 Electrolytic Hydrogen Production Workshop

## Summary Report

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Proceedings from the Electrolytic Hydrogen Production Workshop

National Renewable Energy Laboratory
February 27–28, 2014

July 2014

Sponsored by:

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# NOTICE

# Electrolytic Hydrogen Production Workshop

Workshop held February 27–28, 2014
National Renewable Energy Laboratory, Golden, Colorado

**Sponsored by:**

U.S. Department of Energy (DOE) – Fuel Cell Technologies Office (FCTO)

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# Executive Summary

## Objectives and Approach

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Fuel Cell Technologies Office (FCTO) held the Electrolytic Hydrogen Production Workshop on February 27th-28th, 2014 at The National Renewable Energy Laboratory (NREL) to discuss and share information on the research, development, and demonstration (RD&D) needs for enabling low-cost, effective hydrogen production from all types of water electrolysis systems, both centralized and forecourt.

Experts from industry and national laboratories representing polymer electrolyte membrane, traditional liquid alkaline, solid oxide electrolysis, alkaline exchange membrane, and reversible systems attended the workshop. The two days were organized into breakout sessions that investigated challenges to meeting U.S. Department of Energy (DOE) targets for commercial and pre-commercial systems, additional market opportunities, and manufacturing/scale-up issues. Workshop presentations are at: http://energy.gov/eere/fuelcells/workshop-and-meeting-proceedings.

## Technical Challenges and RD&D Needs

Electrolysis systems can provide a relatively simple, scalable and easily-deployed source of hydrogen for smaller retail and commercial uses near the point of consumption. Water electrolyzers employ many technologies with different levels of commercial readiness and attributes that make them suited for particular applications. The dominant technologies in commercial installations are alkaline and PEM, with the others in pre-commercial development in laboratories.

### *Commercial*

The challenges identified during the Commercial Technologies breakout session had an emphasis on both stack and system concerns; the top RD&D needs were all considered to be near term. These were: improved stack performance, scale up to megawatt size, grid integration, high pressure operation, and a variety of market issues. All of these needs relate directly to increased participation of electrolysis systems in hydrogen markets. In one of these markets, on-site hydrogen generation at vehicle stations, it was noted by one speaker that at 700-bar (nominal) pressures, pre-compression in PEM stacks can reduce the compression costs by ~40% relative to mechanical compression.

Stack performance needs include improved membranes and catalysts. Megawatt scale up (required for 1,500 kg/day forecourt stations) needs include reducing capital costs by 50% on a per kilowatt basis, manufacturing issues (discussed later), demonstration and low cost testing.

The electricity costs alone for megawatt testing can be cost prohibitive for small companies. The needs with respect to grid integration include valuation of alternate value streams (e.g. ancillary grid services), and scale, cost, and efficiency of power supplies.

### *Pre-Commercial*

In contrast, the RD&D needs identified during the Pre-Commercial Technologies breakout session had an emphasis on materials development at the cell component level. Some pre-commercial technologies such as alkaline exchange membrane (AEM) systems have the potential to put electrolysis on a completely new cost reduction curve; reductions of 50% in membrane thickness (increases efficiency) and 90% in catalyst loading (reduces cost) are feasible. High temperature technologies have the potential to use 20-25% less electrical power per kilogram of hydrogen produced. This is significant as electricity costs are often the largest cost contribution component to hydrogen cost. Additionally, heat is usually a lower cost form of energy on a kWh basis than electricity.

Participants saw improving the durability of cell materials, including obtaining a better understanding of degradation mechanisms, as important. Currently, high temperature and reversible systems have degradation rates on the order of 2-4%/1000 hours. AEM systems have been tested up to 2000 hours, and have identified improved voltage stability as a need. Participants identified improving the performance of catalysts, especially with respect to more efficient electrolysis cell operation, as a significant need. One presenter noted that efficiencies of high temperature systems can reach 75%. Scale up to larger cell and stack sizes was a common theme for the Pre-Commercial Technologies breakout session. Longer-term RD&D needs identified include integrated system durability testing, identification of lower temperature SOEC materials, and demonstration of pressurized electrolysis stack operation.

## Markets & Manufacturing

The Additional Market Opportunities session focused on identifying potential additional revenue opportunities for an operator of an electrolysis plant, in addition to hydrogen production. The Manufacturing and Scale Up session discussed challenges and needs related to the development of megawatt scale electrolysis systems.

### *Additional Market Opportunities*

Participants identified the following high priority markets to investigate: power-to-gas, ancillary grid services, renewable hydrogen for petroleum refining, and fuel for material handling equipment. Participants felt that prior to entering any of these markets, technoeconomic study would be necessary to evaluate the potential business risks and rewards for market entry.

If the analysis points to the viability of a particular market, the participants felt it would be important to start a megawatt-scale development program, including a facility with access to low cost electricity capable of testing resultant systems. Participants felt that systems would initially need to scale to the 1500-2000 kg/day level (~3-4 MW) to be relevant in many markets, with an ultimate goal to scale a 1MW system up to a 40 MW plant. This could enable demonstration projects to validate the ability of electrolysis systems to provide value in the target markets, educate stakeholders, and reduce risk.

### *Manufacturing & Scale Up*

The costs and risks associated with scale up and manufacturing are significant for companies active in the North American electrolysis market. In the 2000-2011 timeframe, one manufacturer scaled its system sizes from 7 kW to 175 kW while reducing cost 70%. However, in order to build markets for electrolysis technologies, the consensus among participants was that the systems must grow to the megawatt scale while reducing manufacturing costs. The investment in this scale of product and manufacturing development could consume a significant percentage of company annual revenues. The challenge is to balance these needs (high capital intensity) with the realities of the markets that exist today (low volume, localized).

Participants identified RD&D needs including: support for megawatt stack development, increased material purity and reduced cost, system validation, limited availability of BOP components, and development of advanced manufacturing processes and analysis techniques which can yield high quality, low cost parts at modest volumes. Additive manufacturing was suggested as a possible direction for this last need.

In order to meet DOE cost targets for electrolytically-produced hydrogen, it is important to pursue four simultaneous approaches: (1) improve efficiency at the stack and system level (by 15-20%) (2) make use of low-cost stranded electricity in available markets, (3) develop scaled up (multi-megawatt) systems which can enable alternate revenue streams and markets such as ancillary support and power-to-gas (4) reduce capital costs by 50%.

# Workshop Objectives and Organization

The workshop started with a basic safety briefing and notice that there would be no discussion of current or future Funding Opportunity Announcements (FOAs) at the meeting.

Following the opening plenary sessions, the balance of the workshop consisted of panel discussions and breakout sessions. Participants and speakers were asked in the panel presentations and breakout sessions to focus their attention on two areas:

1. Technical challenges (internal and external) to achieving DOE's electrolysis production cost goals of \$2.30/kilogram (kg) for forecourt (1,500 kg/day) and \$2.00/kg for centralized (50,000 kg/day) by 2020.
    a. Internal challenges – Issues over which developers of electrolysis systems have some degree of influence.
    b. External challenges – Issues over which developers of electrolysis systems have little or no influence.
2. Suggestions for additional RD&D activities that will help overcome those challenges in the near term (2014–2016) and long term (2017–2020+).

Additionally, the Additional Market Opportunities session identified which markets should be the highest priority for the electrolysis community.

The first day focused on technical challenges, with specific breakout sessions on commercial (PEM and alkaline liquid) and pre-commercial (SOEC, AEM, reversible) technologies. Additional panels and breakout sessions on the second day focused on manufacturing/scale-up issues and additional market opportunities.

Participants identified their top ideas for internal and external challenges to meeting the DOE goal, then shared them one idea at a time, until all ideas were exhausted.

The attendees voted on the importance of the internal challenges using a two-step process to indicate both their top five choices and their one top priority. Moderators instructed participants not to vote on external challenges, because, by definition, external challenges are not subject to control by the RD&D community. In the remainder of the breakout sessions, attendees brainstormed and voted on the RD&D needs to address the top 3–5 internal challenges.

# Introductory Session

**Mr. Keith Wipke**, Laboratory Program Manager for the Fuel Cell and Hydrogen Technologies Program at NREL, gave an overview of NREL's hydrogen and fuel cell activities and the DOE facilities located at NREL for performing this work.

**Dr. Sara Dillich**, DOE FCTO Acting Hydrogen Production and Delivery Program Manager, then presented an overview of the DOE FCTO Hydrogen Production Subprogram. The ultimate DOE goal is to produce, deliver, and dispense hydrogen at <$4 per gallon of gasoline equivalent (gge), untaxed (U.S. Department of Energy, Fuel Cell Technologies Office, 2012). Dr. Dillich discussed methods by which hydrogen is currently produced as well as its primary uses. She related hydrogen production methods and uses to hydrogen production requirements regarding support for fuel cell electric vehicles. The fueling of 1 million fuel cell electric vehicles (FCEV) would require substantially less hydrogen than is produced in the United States today, while roughly seven times the current production levels would be required to support 250 million FCEVs (equivalent to the number of cars on U.S. roads today).

Dr. Dillich covered the hydrogen production pathways that DOE is supporting, including their technology readiness, which ranges from commercially available technologies such as natural gas steam reforming to longer-term renewable pathways such as photobiological production. Hydrogen production via electrolysis falls in between these two ends of the spectrum. She described recent DOE technical accomplishments in electrolysis and the importance of technoeconomic analysis in guiding DOE programmatic decisions. In addition, Dr. Dillich discussed the cost status of near-/mid-term hydrogen production pathways on which slow but steady progress is being made. For electrolysis, the major cost driver is the electricity feedstock cost. Dr. Dillich finished her remarks by reviewing the strategy to meet the workshop objective of identifying RD&D needs to enable the electrolysis of water to meet the DOE cost goals for hydrogen production.

The keynote speaker of the workshop, **Dr. Whitney Colella** of Strategic Analysis, Inc. (SA), presented technoeconomic analysis of PEM electrolysis. SA and NREL recently completed four case studies on hydrogen production from PEM-based water electrolysis using the Hydrogen Analysis (H2A v3) model (James, 2013). She began her presentation with an overview of the H2A discounted cash flow model and the systematic technical approach used to develop the case studies. Four PEM electrolyzer manufacturers provided detailed technical and cost information that was used to generate the four cases. The results of the analysis were vetted by the electrolyzer companies.

The four cases developed (U.S. Department of Energy, Fuel Cell Technologies Office, 2014) were for current (2010) and future[1] (2025) technology at forecourt (1,500 kg/day) and central (50,000 kg/day) production capacities. Resulting costs ranged from ~$4.20/kg to ~$5.10/kg, with greater cost reduction seen from moving from a current case to a future case, as opposed to from a forecourt case to a central case. There was very little difference between forecourt and central costs (2-3 cents/kg). Feedstock costs (electricity) are responsible for between 44% and 82% of the total hydrogen production cost, with the hydrogen cost varying linearly with electricity price. In these scenarios, the electrolyzers are run at near full power. Different dispatch algorithms (night only, load follow) will have different implications beyond the scope of the study.

Sensitivity analysis showed that the hydrogen production costs are highly dependent on electricity cost, electrolyzer efficiency, and electrolyzer capital cost, in that order.

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[1] "Current" cases assume a short-term projection from technology that is commercially available or that has been demonstrated in the lab in terms of technology readiness level. Current cases assume that advances that already have been demonstrated in individual components are simultaneously able to be successfully implemented in a full-scale system. Current cases assume that equipment capital costs are reduced by high-volume manufacturing and the resulting economies of scale. Current technology generally references only advancements that could be incorporated into a commercial product with a high degree of confidence, fairly quickly, and with little risk.

In contrast to Current cases, Future cases project the development of the technology with new materials and capabilities and improved hydrogen production efficiencies, and include longer equipment lifetimes. Generally, capital costs of the systems are further reduced, compared with the Current case. Details of the analysis are discussed in FCTO program record 14004, http://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

# Technical Challenges and RD&D Needs

The Technical Challenges and RD&D Needs panel and breakout sessions consisted of two separate but related topics. One focused on commercial, nearer-term technologies, while the other addressed pre-commercial, longer-term technologies. There was no absolute delineation regarding how technologies were divided into these two categories; however, some general guidelines were provided. Based on these guidelines, the Commercial Technologies breakout session included discussion on traditional approaches such as alkaline and PEM electrolysis, while the Pre-Commercial Technologies breakout session included technologies such as alkaline membrane, high-temperature solid oxide, and reversible electrolysis. In both cases, discussions focused on identifying challenges and issues encountered with these electrolysis technologies and RD&D activities that could result in overcoming these concerns. Given the very broad range of electrolyzer technologies considered, the challenges and RD&D needs identified were varied and extensive.

## Technical Challenges and RD&D Needs Panel Presentations

**Dr. Monjid Hamdan** of Giner, Inc., spoke on the status, key issues, and challenges for high-pressure PEM electrolysis. Pressurization of up to ~12,600 pounds per square inch (psi) (869 bar) (for 10,000 psi [700 bar] refueling of FCEVs) was considered. Following a review of some of the advantages of high-pressure operation (e.g. a ~40% reduction in compression costs relative to purely mechanical compression), he focused primarily on the advancements needed at membrane, stack, and system levels in order to reach commercial viability. Dr. Hamdan noted challenges in mechanical strength, chemical conductivity, efficiency, systems integration and the external challenge of hydrogen codes and standards. Dr. Hamdan highlighted the impact of membrane material properties on the efficiency of compression. Current commercial membranes, which have been adopted from PEM fuel cells, have a high back diffusion of hydrogen when operated at high pressures, so membranes that are thicker than desired are often utilized to compensate. Membrane materials with low permeability coupled with high conductivity and good membrane properties need to be developed. At the system level, challenges include developing system components designed specifically to operate efficiently at high pressures while reducing current costs. The near-term and long-term RD&D needs identified by Dr. Hamdan, including increased hardware capability for high pressure applications, reduced stack cost, improved chemical stability of cell components, and long term testing and validation are applicable to both 5,000 psi (345 bar) and 10,000 psi (700 bar) refueling of FCEVs. Higher-pressure operation requires significant changes to the stack design compared to near-ambient-pressure electrolyzer operation. In order to use high-pressure electrolysis technology for refueling applications, the cell size and the number of cells in a stack will need to be scaled up. Materials with improved properties are needed for this purpose as well as to improve the lifetime of the stacks. Simultaneously, the stack cost needs to be decreased. In particular, the anode support structure, which requires high strength and conductivity, currently dominates the high-pressure electrolyzer stack cost.

The next speaker, **Mr. Geoffrey Budd** of ITM Power, addressed hydrogen production via water electrolysis at forecourt stations that provide approximately 1,500 kg of hydrogen/day. The internal challenges that Mr. Budd identified included reducing footprint, response time of PEM and alkaline technologies, and the power infrastructure required for forecourt systems (1,500 kg/day ~= 3 MW). One potential challenge is the station footprint required to generate and store the amount of hydrogen required at the forecourt scale. Another consideration is the need for electrical infrastructure at the station location to accommodate the electrolyzer.

The near-term RD&D needs discussed by Mr. Budd included: reduction in capital and operating expenditure, improvements in efficiency, packaging, and over-run capacity. He noted that capital cost needs to be reduced by ~50%, along with an efficiency improvement of 15-20%. These goals are often competing, because while capital cost can be reduced by operating at higher current density, this will often come at the expense of efficiency. He stated that most of ITM's needs are focused on continued technology developments, including cost reductions and electrolyzer system efficiency improvements. He stressed that inexpensive electricity is key to lowering production costs. In addition to vehicle refueling applications, he mentioned the use of electrolyzers for energy storage, with one option being to inject generated hydrogen into natural gas pipelines, which operate at 1160 psi (80 bar).

The next speaker in this session was **Dr. Kathy Ayers** of Proton OnSite. She presented on AEM-based electrolysis, which is a longer-term technology. Dr. Ayers noted that reductions of 50% in membrane thickness and 90% in catalyst loading are feasible. Proton OnSite has made significant recent progress on AEM technology but is still at a low maturity level, especially compared to PEM and traditional liquid potassium hydroxide-based alkaline electrolysis.

Dr. Ayers gave a brief summary of cost and efficiency advancements that are still possible with PEM electrolysis and indicated that many of these advances could be relevant to AEM development. She said that AEM electrolysis, in theory, can enable a new, better cost curve; however, this needs to be balanced with possible efficiency losses and lower performance compared to PEM electrolysis. For a given efficiency, AEM electrolysis cells will likely operate at a lower current density. Ultimately, the technology chosen for a given application may depend on the relative importance of operating expenses versus capital expenses.

The challenges presented for AEM electrolysis included: material maturity and stability, transfer of non-PGM catalysis systems from liquid alkaline systems, and water management. Most are related to materials at the cell component level. The durability of the membrane needs to be significantly improved. Significant performance degradation is seen with existing materials at more than 2,000 hours of operation. Water management in these hydroxide-ion-conducting membranes is more difficult than in PEM membranes and could negatively impact performance. The membranes do not transport water as well as PEM membranes. One significant advantage of

AEMs is that platinum group metal (PGM) catalysts should not be needed. However, there have been difficulties in translating performance results from catalyst studies to membrane electrode assembly (MEA)-level tests.

The near-term RD&D needs presented by Dr. Ayers included: the need to build cohesive teams, consistent device testing, and materials improvements. Team efforts featuring members with different areas of expertise will help make progress toward a better fundamental understanding of the complicated system presented by an AEM MEA. Testing standards to allow for valid comparisons among different materials and designs would help advance AEM technology. Dr. Ayers stressed the need for integrators of the AEM component technologies to have an active role.

The next speaker was **Dr. Jim O'Brien** of Idaho National Laboratory. He spoke on high-temperature electrolysis for efficient hydrogen production. His studies have included analyses with directly coupling of a high-temperature electrolyzer with a high-temperature gas-cooled reactor from a nuclear plant that would provide the electric power and high-temperature heat. He provided results from several different hydrogen production cost analyses, including some H2A model studies. The costs ranged from ~$2.50/kg of hydrogen to ~$3.90/kg of hydrogen.
The main challenge presented by Dr. O'Brien is to improve the durability of the SOEC technology. Degradation in electrolysis mode is substantially higher than in solid oxide fuel cell (SOFC) operating mode. Improvements have been made to bring down this degradation from ~50% per 1,000 hours to less than 2%. However, this needs to be decreased by another order of magnitude. Some of the possible sources of the degradation include: chromium migration, corrosion of metallic parts, catalyst morphology change, and electrode delamination.

The near-term RD&D needs provided by Dr. O'Brien included: continued support of research into cell and stack materials and fabrication techniques, small-scale testing, and pilot-scale demonstration.

The final speaker of the first day's panel session was **Mr. Randy Petri** of Versa Power Systems. He spoke on reversible solid oxide electrolysis, with an emphasis on the status of Versa Power's technology in these areas. There have been substantial improvements to SOEC technologies over the last several years (reducing degradation at the stack level to 4%/1000 hours); however, this technology is at a lower maturity level than PEM electrolysis. SOEC is only at the stage of kilowatt-scale stack demonstrations. An advantage resulting from the high operating temperature (700°–850°C) associated with SOEC technology over those technologies that operate at <100°C is that approximately 20%–25% less electrical power is required to split water; however, additional heat is required to maintain the elevated operating temperature. Heat, however, tends to cost less on a kWh basis than electricity.

The challenges presented by Mr. Petri included: technoeconomic assessment of SOEC systems, material durability improvement, and stack scale-up. He would like to see degradation improved over the current status of 0.5%/1000 hours in fuel cell mode and 1%/1000 hours in electrolysis mode. The high operating temperature should allow SOEC systems to use less electricity than low-temperature electrolysis systems for the production of a given quantity of hydrogen. It is not clear, however, how much this parameter influences hydrogen production cost. A technoeconomic analysis would shed some light on this issue. Given the lower maturity level of this technology, there has been insufficient work toward developing overall electrolysis system designs incorporating high-temperature stacks. Mr. Petri said that it is possible to operate SOEC at very high current densities; however, the impact of these high current densities is unknown, and little effort has been made to optimize cells to operate under these conditions. Scale-up of the cells and stacks to sizes relevant for hydrogen production via electrolysis is challenging.

The near-term RD&D needs shared by Mr. Petri were to: advance cell and stack durability and performance through further improvements to the cell and stack materials, scale-up to kilowatt levels while focusing on thermal management within the cells, and exploring the impact of harsher, high-current-density operating conditions.

## Technical Challenges and RD&D Needs Panel Discussion

Discussion following the panel presentations began with a question of the largest opportunity for capital cost reductions outside of the stack. The panelists agreed on power electronics. There was discussion concerning the development of accelerated stress tests (ASTs) for electrolysis. The challenge is in relating the accelerated test to real-world conditions in a meaningful way. It was seen as an area that potentially could have some value, but it could be more difficult to develop relevant ASTs compared to what has been done with PEM fuel cells. Finally, there was discussion on how to compete with steam methane reforming (SMR) for hydrogen production, given the long-term projections of low-cost natural gas availability. Some approaches mentioned include taking advantage of the different economics associated with stranded resources (e.g., idle wind capacity); initially looking at island economies (e.g., Hawaii), where natural gas is more expensive.

## Technical Challenges and RD&D Needs Breakout Discussion

The breakout sessions for day one were in two parallel tracks: one on commercial (near-term) technologies, and one on pre-commercial (longer-term) technologies. The Commercial Technologies breakout session included discussion on traditional approaches such as alkaline and PEM electrolysis. The Pre-Commercial Technologies breakout session included technologies such as alkaline membrane, high-temperature solid oxide, and reversible electrolysis.

# Commercial Technologies (Near Term)

### *Challenges*

The top internal challenges identified by the attendees are shown in Table 1; details of the brainstorming and subsequent voting are presented in Table 14, Appendix D: Voting Results.

**Table 1. Commercial Technologies Internal Challenges**

1. Improved stack performance
2. Increase stack size to at least 1 MW.
3. High-pressure stack/system/components to eliminate at least one stage of mechanical compression at 700-bar.
4. Market issues
5. Grid integration

The Commercial Technologies breakout group was tasked with discussing the internal and external challenges as well as critical RD&D needs associated with commercially available technologies such as PEM and alkaline electrolyzers. The greatest concern of the group in terms of external issues was the cost of electricity. Without reduced electricity costs, electrolysis could end up being a viable hydrogen production pathway only for niche applications. Another external issue discussed was the limited continuity of funding and the need for increased levels of funding in the area of electrolysis particularly in light of heavy German investment in electrolysis research (~$10-million annually) and the threat to maintaining U. S. competitiveness.

Participants discussed an extensive range of internal challenges, from the need to lower catalyst costs, to the manufacturability of balance of plant (BOP), to grid integration. Several of the top internal challenges identified were broadly related to electrolyzer stacks, as reflected in challenges 1, 2, and 3 in Table 1. Participants identified stack performance as one of the most critical issues and named improved catalysts, lower resistance membranes, improved durability, and higher current efficiency as significant sub-issues. Participants highlighted high-pressure stacks (improved design) and high-pressure stack components (e.g., more durable membranes with lower hydrogen crossover) as internal issues. Scale-up (i.e., increasing stack size) was recognized as an internal issue that needs to be addressed in order for electrolysis to be a competitive hydrogen production pathway.

The other top internal challenges identified in Table 1 are market issues (challenge 4) and grid integration (challenge 5). The group determined that market issues such as identifying global markets and integrated functionalities to capture multiple streams and access new revenue streams are major internal issues. Participants identified system-level integration with renewables, power converters optimized for interfacing electrolyzers with the grid, and renewable power sources as grid-integration-related challenges.

### *RD&D Needs*

The group discussed RD&D needs associated with commercial electrolyzer technologies; the needs receiving the most votes were all considered to be near term. These top near-term needs are identified in Table 2. Voting results are presented in Table 15, Appendix D: Voting Results.

Reflecting participants' desire to address the issue of improved stack performance and design, RD&D for improved catalysts and membranes received the most votes from the group. For high-pressure stacks, the group indicated that studies are needed to look at the trade-offs between higher-pressure electrolysis versus conventional compression and the development of better anode support materials. System and stack scale-up will require development of lower-cost hardware and demonstration of cost-effective performance at large scale.

**Table 2. Commercial Technologies Near-Term RD&D Needs (2014–2016)**

1. Improved Stack Performance **(Challenge 1)**
    a. Improved membranes
    b. Improved catalysts
    c. Inexpensive water purification system
2. Megawatt Scale-up **(Challenge 2)**
    a. Low-cost hardware
    b. Demonstrate large-scale viability, megawatt-scale demonstration (MEA, power conversion, etc.)
3. Grid Integration **(Challenge 5)**
    a. Validate multiple value streams (grid support, oxygen market)
4. Operation at high pressure **(Challenge 3)**
    a. Studies of high pressure electrolysis versus compression
5. Market Issues **(Challenge 4)**
    a. Studies determining best markets for electrolysis
    b. Market acceptance of electrolysis

Grid integration will require a multi-megawatt demonstration to validate proposed value streams, such as providing grid ancillary services. Early engagement with the electric/utility companies is important to facilitate stakeholder interest in electrolysis technologies and technology adoption by power plants. Establishing the required outputs of the electrolyzer will be necessary for grid integration. Market issues will need to be addressed by educating the public and key stakeholders with regard to the opportunities associated with electrolysis, identifying regions and scales where electrolyzers can compete with SMR, and finding a value proposition for the co-product oxygen in order to bring the hydrogen cost down. Everett Anderson (Proton OnSite) presented analysis at this workshop showing near equivalence between SMR and electrolysis at productions rates of ~100 $Nm^3$/hr (~8.4 kg/hr) [2] (Anderson, 2014).

The group identified several other RD&D needs that did not receive as many votes but are still areas where RD&D is needed, such as improved flow field designs, improved water purifiers, and development of models for assimilating grid integration with renewable energy supplies.

# Pre-Commercial Technologies (Long Term)

## *Challenges*

### Internal Challenges

Table 3 summarizes the top internal challenges the group identified; details of the brainstorming and subsequent voting are presented in Table 16, Appendix D: Voting Results.

**Table 3. Pre-Commercial Technologies Internal Challenges**

1. Increased understanding of degradation mechanisms, at high current densities and under cycling conditions.
2. Scale-up: Large format cells
3. Material durability, prove endurance to less than 0.5% degradation per 1000 hours
4. Characterization of material interactions for low technology readiness level (TRL) technologies.
5. Improved initial performance, and efficiency, especially at high current density (cell performance)
6. High quality thermal integration for SOEC to heat source with low stack thermal gradients.

Much of the discussion focused on materials and system durability. These issues are reflected in challenge 1 (understanding degradation) in Table 3. The low durability of materials for both alkaline membrane and high-temperature SOEC was seen as a barrier to overall system durability. The underlying challenge to improving materials durability is reflected in challenge 3 in Table 3, understanding degradation mechanisms. Many of the ways in which materials fail are not well understood, which makes improvement difficult. In the cases of both alkaline membrane and high-temperature SOEC technologies, fundamental materials development is a challenge.

Performance of materials, as it relates to system efficiency, is an important factor in system development. Participants discussed the need for higher initial performance, in terms of conductivity, diffusion, and current density. Running at higher current density, though it can lead to better utilization of capital, usually comes at the cost of efficiency and durability. A balance between these competing forces is required of the material set. These competing needs are

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[2] Normal cubic meters per hour. Normal conditions assumed to be: 20°C, 1 atm.

reflected in challenges 3 (material durability), 5 (improved initial performance and efficiency at high current density) in Table 3.

Participants defined scale-up (challenge 2, Table 3) as the next most important challenge. The discussion centered on how to develop and manufacture large format cells and multi-cell stacks with adequate manufacturing tolerances that will lead to viable system performance at the megawatt scale. SOEC developers may find this challenge particularly important because the friability of the ceramic materials with which they work can result in low part yield, though learnings from SOFC development efforts can be directly applied.

Participants discussed the logistics of scale-up development and testing, such as laboratory space, heat and electricity requirements, and the costs of operating a megawatt-scale test unit for even short periods of time. Many of these challenges, while not specific to the science of technology development are very important to the companies pursuing the technology.

### External Challenges

External challenges identified by the group are shown in Table 4. Although votes were not cast on the importance of these issues, recent analysis commissioned by DOE on PEM electrolysis (James, 2013) showed that the cost of electricity is the largest cost driver for electrolytic hydrogen both now and into the future.

Other challenges included the cost of materials, lack of consistent hydrogen policy, identification of key markets, and transportation of hydrogen from centralized plant locations to the point of use.

| Table 4. Pre-Commercial Technologies External Challenges |
|---|
| 1. Cost of electricity<br>2. Material costs (and fluctuations)<br>3. Lack of consistency on hydrogen energy policy<br>4. Market identification<br>5. Hydrogen transport |

## *RD&D Needs*

### Near Term (2014–2016)

The participants identified near-term RD&D needs that clearly reflect the challenges they previously identified. The largest category of needs relates to materials issues, as seen in items 1, 3, and 4 in Table 5. These items reflect the need for more durable; efficient; and in the case of SOEC, lower-temperature materials. The importance of durability applies to both SOEC and AEM technologies. AEM technologies need more active catalyst materials to improve efficiency. SOEC technologies have shown high-efficiency operation; however, the impact on durability of operating at the higher current densities afforded by higher-efficiency operation needs to be better understood. The development and use of accelerated stress tests could aid in developing more durable materials.

Participants identified the need to scale up to large, megawatt sizes, starting with a multi-kilowatt plant demonstration capable of advancing the technology readiness level (TRL) of the technologies. Voting results on near-term RD&D needs are shown in Table 17, Appendix D: Voting Results.

**Table 5. Pre-Commercial Technologies Near-Term RD&D Needs (2014–2016)**

1. Materials durability: Degradation mechanisms, accelerated testing, multidisciplinary studies **(Internal Challenge 3,4)**
2. Scale-up: Large-format cells, multi-kilowatt pilot plant (advance TRL) **(Internal Challenge 2)**
3. Efficiency at high current density, new, more active catalyst materials (AEM) **(Internal Challenge 1,5)**
4. Lower-temperature SOEC materials **(Internal Challenge 3,6)**

### Long Term (2017–2020+)

Participants identified extended durability testing of integrated systems as a long-term RD&D need. This assumes that short-term materials durability needs are met. Participants suggested higher-pressure operation in order to provide more value to the hydrogen product gas. These needs are summarized in Table 6. Voting results on long-term needs are shown in Table 18, Appendix D: Voting Results.

**Table 6. Pre-Commercial Technologies Long-Term RD&D Needs (2017–2020+)**

1. Pressurized testing
    a. Additional demonstration
2. Long-term integrated system testing focused on durability. **(Internal Challenge 3)**

# Technical Challenges and RD&D Needs Final Discussion

The challenges identified during the Commercial Technologies breakout session had an emphasis on the stack level, and the top RD&D needs were all considered to be near term. Operation of electrolyzer stacks at high pressures, manufacturing and materials issues are all key challenges. Given the commercial status of these technologies, participants identified topics outside of stack and system-level development as important. One example is the optimized integration of electrolyzers with the grid and renewable energy sources.

In contrast, the challenges and RD&D needs identified during the Pre-Commercial Technologies breakout session had an emphasis on materials development at the cell component level. Participants saw improving the durability of cell materials, including obtaining a better understanding of degradation mechanisms, as important. They identified improving the performance of materials, especially with respect to more efficient electrolysis cell operation, as a significant need. Scale-up to a larger cell size and larger stacks was a common theme for the Pre-Commercial Technologies breakout session. Longer-term RD&D needs identified include long-term integrated system testing and demonstration of pressurized electrolysis stack operation.

Results of the breakout sessions are mapped against identified barriers in the hydrogen production MYRD&D Plan as seen in Table 7. Among the needs identified, megawatt scale-up fits best with capital cost, which the MYRD&D Plan calls out specifically in order to reduce cost. In addition, larger systems should increase the market reach of electrolysis systems resulting in economies of scale. This need was reflected for both commercial and pre-commercial technologies.

Regarding system efficiency and electricity cost, commercial and pre-commercial technologies need development of cell and stack components with higher efficiency, and lower rates of hydrogen diffusion (PEM only). Operation at higher pressure was discussed for commercial technologies, but there is a lack of information on what the optimal outlet pressure should be from the perspective of a viable hydrogen market for vehicle fuel.

The need to understand and value participation in the electric grid as more than a consumer was discussed for commercial technologies. This need maps to barrier J, Renewable Electricity Generation Integration. This topic was discussed in much greater detail in the Additional Market Opportunities breakout session.

The need to address market issues, specifically the ability to invest in tooling to decrease manufacturing costs, when the market is too small to support such an investment, relates to many issues with electrolysis systems, but for commercial systems, it most closely maps to the manufacturing barrier.

Materials durability, lower temperature materials (SOEC) and demonstration of long term durability on integrated systems were all needs expressed by the participants in the pre-commercial technologies breakout. Addressing these needs will affect progress against the Operations and Maintenance cost barrier.

**Table 7. Classification of RD&D Needs into Program Technical Barriers**

| Barrier | RD&D Need Commercial Technologies | RD&D Need Pre-Commercial Technologies |
|---|---|---|
| **F. Capital Cost** | • Megawatt scale-up, Large-format cell and stack development | |
| **G. System Efficiency and Electricity Cost** | • Improved stack performance<br>• Development of components, stack and system for high pressure operation. | • Efficiency at high current density (AEM)<br>• Development of components, stack and system for high pressure operation. |
| **J. Renewable Electricity Generation Integration** | • Grid Integration | |
| **K. Manufacturing** | • Market issues | |
| **L. Operations and Maintenance** | | • Materials durability<br>• Lower-temperature SOEC materials<br>• Long-term integrated system testing focused on durability |

# Markets and Manufacturing

The Markets and Manufacturing session of the workshop was formatted slightly differently from the first day. The work was organized into two parallel panel and breakout sessions: one on additional market opportunities for electrolysis and the other on manufacturing and scale-up issues.

## Additional Market Opportunities

The Additional Market Opportunities session focused on identifying potential additional revenue opportunities for an operator of an electrolysis plant. The procedure followed by the participants was slightly different from other sessions in the workshop. Participants were first asked to identify what they thought were the most important markets to investigate, then to identify the challenges to market entry and the RD&D needs to overcome those challenges.

The top market opportunities identified (in rank order of the number of votes received) include power to gas, ancillary grid services (frequency/voltage regulation), renewable hydrogen for petroleum refining, and material handling equipment (MHE).

Many of the top challenges and needs identified apply to all four of these markets. Participants generally agreed that prior to entering any new market, it would be necessary to first assess the size and potential of the market from an economic point of view to determine whether it is worth entering. Participants noted that a megawatt-scale development program would be needed following the assessment. Some aspects of this program could include standardization of test conditions, identification of the technical process parameters and requirements that would apply to any electrolysis system in that market, and a roadmapping exercise to determine the technology development pathway to follow in order to enter the market. Other activities needed would include development of large-area cells and cell stacks with uniform flow and current distribution, as well as a concerted effort among electrolysis system manufacturers to standardize components. This standardization would not necessarily have to be at the stack and cell level, because that is where much of the proprietary intellectual property lies, but instead at the BOP and system interface level.

Participants discussed the difficulty of testing at the megawatt scale, noting both the size of the equipment and the cost of operating that equipment. Electricity becomes a burdensome expense for small companies when testing at this scale, especially for durability tests. Many participants mentioned the need for a test facility that could alleviate these problems.

The most-discussed external challenge to megawatt-scale electrolysis was the cost of electricity. Recent DOE-sponsored analysis on PEM electrolysis, as summarized by Dr. Whitney Colella during her keynote presentation, (U.S. Department of Energy, Fuel Cell Technologies Office, 2014) , showed that the price of electricity is the largest single contributor to the cost of hydrogen. One important piece of information in this session came from the panel presentation of Frank Novachek, Director of Corporate Planning for Xcel Energy. Mr. Novachek noted that Xcel studies show that at 30% wind penetration in the electric grid, 15% of the time the turbines are curtailed (turned off and not producing power even if the wind is blowing, due to low demand). At 40% penetration, the curtailed time doubled to roughly 30%. Combining these numbers (penetration and curtailment), there is a potentially large amount of low-cost electricity available for electrolysis systems designed to take advantage of it. Studies of the opportunity for wind-based electrolysis have been completed previously (Barbir, 2005) (Spath, 2004). However, it may be useful to further examine co-located wind-powered electrolysis at locations which are geographically located near natural gas distribution pipeline networks.  Utilizing the existing natural gas distribution network, or pipeline right-of-way, may help deliver low-cost renewably produced hydrogen to urban consumption centers.

## Additional Market Opportunities Panel Presentations

**Dr. Kevin Harrison** of NREL spoke on integrating electrolysis systems with the grid and, specifically, with renewable power sources. The project’s objective is to design, develop, and test advanced experimental and analytical methods to validate electrolyzer stack and system efficiency, including contributions of subsystem losses (e.g., power conversion, drying, and electrochemical compression) of advanced electrolysis systems. Dr. Harrison gave an overview of installed wind capacity in the United States, noting that the 60 gigawatts of installed capacity meet about 4% of U.S. energy needs. This represents an opportunity for electrolysis systems to provide a solution for curtailment (a situation in which the grid operator requires wind turbines to shut down because the power is not needed, even though the wind is blowing).

Dr. Harrison reviewed research completed by NREL’s wind-to-hydrogen project on direct photovoltaic (PV) solar cell to electrolyzer coupling and the potential efficiency benefits of configuration. He then discussed testing that concluded that electrolyzers (both PEM and traditional alkaline) are able to respond quickly enough to provide grid ancillary services such as frequency support.  In his tests, a microgrid returned to normal frequency  after a load disturbance up to three times faster when an electrolyzer was employed to shed load, than when it was not.

Dr. Harrison discussed investigations of the effect of variable wind power profiles on electrolyzer decay rates and research into bipolar operation of an electrolyzer stack. The latter is investigating whether designers could intentionally size the number of cells in an electrolyzer to allow direct connection to the bipolar direct-current (DC) bus of a variable-speed wind turbine, resulting in cost and efficiency improvements.

**Mr. Frank Novachek** of Xcel Energy spoke next on the potential impact of electrolytic hydrogen production on utilities. He discussed both the challenges and opportunities of electrolysis with respect to the electric grid. Utilities, especially integrated gas and electric utilities such as Xcel Energy, see an opportunity to sell more energy with electrolysis because of the higher energy inputs (~50 kilowatt-hours [kWh]/kg of hydrogen with electrolysis versus 4–5 kWh/kg with SMR). Mr. Novachek summarized these opportunities as: increased system load, system regulation services, and increased integration of renewables.

Regarding the opportunity for system ancillary service and frequency regulation, Mr. Novachek noted that while electrolyzers can respond with sufficient speed, the market for regulation services is relatively small and likely would saturate quickly, possibly with competing technologies. He noted that the industry generally considers the required size for providing ancillary support to be larger than 50 MW. Perhaps a better opportunity is in the area of renewables integration, providing dispatchability and relief from curtailment as well as enabling the high penetration of renewables by firming of electricity supply by using hydrogen to store energy that could be used on demand later, regardless of the status of the renewable resource.

Curtailed wind represents a large window of low-cost energy with which to make hydrogen. Future studies should carefully consider the lower capacity utilization of electrolysis systems within this niche market, which can increased the levelized cost of hydrogen.

Mr. Novachek noted that the pricing for ancillary services in organized markets such as the PJM Interconnection and for Midcontinent Independent System Operator (MISO) averages about $9 per MW. The price paid for "mileage[3]" is about $0.5 per megawatt-hour. In some sense, this represents the opportunity cost of not generating and results in a payment to the service provider.

In bilateral markets (e.g., Public Service of Colorado), there is limited transparency on market pricing, and the focus is more on providing power to interruptible loads, which could result in reduced electricity prices. Given that the cost of electricity is one of the largest cost drivers for electrolytic hydrogen, this type of market arrangement could be important.

**Mr. Mitch Ewan** of Hawai'i Natural Energy Institute [HNEI] presented on the place of electrolysis in an island grid. On island grids, such as those on each island of Hawaii, the high penetration of renewables is both a challenge and an opportunity. High electricity prices and abundant renewable resources in wind and solar encourage widespread adoption of the technologies. However, because of the small size of the grids, the intermittency of these technologies can lead to instability. HNEI has modeled the impact of electrolysis plants providing both hydrogen fuel and ancillary support and found that even modest scales of electrolysis could provide very good stability support. HNEI compared the regulation capability of a 250-kilowatt (kW) electrolyzer with that of a 1 MW, 250 kWh battery system and found it to

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[3] Mileage represents the absolute value of the movement in generation (or consumption) output in response to a regulation signal over the course of the regulation hour. Detailed discussion of mileage payments are beyond the scope of this report. For more information, see (PJM Independent System Operator, 2001)

be comparable with respect to grid stability, while maintaining capital utilization of the electrolyzer and operating it within its dynamic capability.

Mr. Ewan categorized challenges in terms of scale (especially for compression systems), cost, and efficiency. Reflecting Mr. Novachek's comments, he noted that it is important to scale electrolysis technology up to the megawatt size (~2000 kg/day or about 4.2 MW). This will require scale-up of compression and power supply technology.

External challenges presented included: the complexity and pace of codes and standards compliance, the industry movement to 700-bar fueling, and the slow pace of resolving legal and indemnity issues along with a general lack of a sense of urgency. These may be broadly categorized as regulatory, legal, and design issues, with the design issue being the choice by automotive original equipment manufacturers (OEMs) to move to 700-bar filling, which complicates issues at the forecourt station.

**Mr. Rob Harvey** of Hydrogenics spoke on the opportunities for electrolysis to supply a power-to-gas market. This scenario may include, but does not necessarily rely on, turning generated hydrogen back into electricity with a fuel cell. Other uses include vehicle fuel, industrial hydrogen, and direct injection into the natural gas grid as an augmentation of renewable British thermal units for heating applications.

Mr. Harvey presented an analysis of hydrogen storage in salt caverns compared to compressed air energy storage and pumped hydro, noting that for the same storage volume, hydrogen could store orders of magnitude more energy, enabling electricity generators to provide power for weeks or months. He then provided analysis supporting the case for the ancillary support market at megawatt scales.

The challenges noted by Mr. Harvey are summarized as: administrative barriers to energy storage market development, megawatt scale stack testing, and the launch of megawatt scale pilot projects. In addition to the challenges of scale and pilot plant testing mentioned by previous speakers, Mr. Harvey noted barriers relating to energy storage and participation in the ancillary support markets. Mr. Harvey focused on the near-term need to build a 1 MW PEM pilot project, scaling up to 40 MW in the future.

**Dr. Cortney Mittelsteadt** of Giner, Inc. spoke on the opportunity for home refueling of FCEVs. The challenges he discussed were broadly categorized, as cell stack components (which must operate at high pressure and resist hydrogen embrittlement), catalysts, and safety. Safety is particularly important, given the proximity of the refueling and generation equipment to residents.

The near-term RD&D needs identified in closely match the challenges. At high pressures, existing membranes are subject to high hydrogen back diffusion losses and extrusion.

Perfluorosulfonic acid (PFSA) membranes at the desired thickness for PEM fuel cells are too thin (i.e., insufficient mechanical strength) for high pressure electrolysis and have permeability rates that are too high for the application. Dr. Mittelsteadt suggested that other types of membranes may be suitable, such as hydrocarbon and alkaline technologies.

Because a home refueler is essentially an appliance, it needs to be less expensive and therefore have lower catalyst loading than industrial machines. Dr. Mittelsteadt mentioned the need for rigorous accelerated testing to identify and eliminate failure modes in such a product. He felt the technology could approach the DOE target of <$4/kg of hydrogen, including compression, storage and dispensing costs, with a cost of $4.64/kg.  Achieving that goal may require the use of low cost off-peak electricity, and equipment utilization of over 40%.

**Dr. Dmitri Bessarabov** of Hydrogen South Africa (HySA) Infrastructure spoke on current initiatives for electrolytic hydrogen production in South Africa. The strategic goals of HySA Infrastructure are to develop low-cost hydrogen generation based on renewable resources, sustain wealth creation from PGM resources, and promote equity and inclusion in the economic benefits of South Africa’s natural resources.

As the dominant world supplier of PGMs, South Africa has a vested interest in electrolytic technology. The South African domestic energy supply comes primarily from coal, but the country has high-quality solar resources that are largely untapped.

Dr. Bessarabov gave an overview of why PEM electrolysis may be attractive to HySA in light of its strategic goals. These include PEM electrolysis’ high PGM content, fast response for integration with renewables, high discharge pressure, and potential for large-scale deployment. Current HySA hydrogen production targets for electrolytic hydrogen are in the range of $0.90–$3.00/kg.

## Additional Market Opportunities Panel Discussion

Following the presentations, the audience asked questions of the panelists. The questions and ensuing conversation focused primarily on scale-up and ancillary services. When asked what the market spaces are for both PEM and alkaline technologies, a participant answered that alkaline will likely be best suited to steady industrial applications that provide hydrogen, and that PEM would have a place in variable renewable integration and ancillary grid support operations. Another countered that PEM can support industrial applications and is becoming preferred where available at the necessary scale.

A participant asked if there is a good understanding of the monetary value of ancillary services. The consensus answer was that it is not well understood. There was general consensus that hydrogen has to be the main product of any electrolysis plant, with ancillary services providing a small fraction of the total revenue.

## Additional Market Opportunities Breakout Discussion

### *Market Opportunities*

The top market opportunities identified by participants are listed in Table 8, in descending order of the number of votes cast. The votes cast are presented in Table 19, Appendix D: Voting Results. It is worth noting that the top priority item, power to gas, received priority votes from six participants, with the next closest receiving only two priority votes. This is an indication of the level of priority for this market among the community.

**Table 8. Highest-Priority Market Opportunities for Electrolysis**

1. Power to gas
2. Ancillary grid services (frequency/voltage regulation)
3. Renewable hydrogen for petroleum refining
4. Material handling equipment (MHE)

Priority 2 (Table 8), ancillary grid services, could include a number of different services such as frequency support (which is a grid-wide service), voltage support (a service at the distribution level, accomplished by providing reactive power support volt-amperes reactive [VARs]) from the power electronics, and peak and demand charge shaving. It should be noted that the last service represents value that system owners might realize by reducing their electric bill, as opposed to a service that is sold to the grid operator and generates revenue, such as the first two.

### *Challenges*

**Table 9. Highest-Priority Market Opportunities for Electrolysis**

| *Market* | *Challenge to Market Entry* |
|---|---|
| Power-To-Gas | 1. Large-scale testing<br>2. MW-scale pilot projects<br>3. Definition of product requirements |
| Ancillary grid services | 1. Lack of infrastructure for large-scale demo<br>2. Lack of data at large scale<br>3. Valuing electricity markets |
| Renewable hydrogen for petroleum refining | 1. Scale of current systems and development cost to get to appropriate scale |
| MHE | 1. Systems analysis—technoeconomic analysis for electrolysis<br>2. Infrastructure costs for forecourt production |

## *RD&D Needs*

### Near Term (2014–2016)

Near-term needs across the four top market opportunities are identified in Table 10. In general, participants felt that prior to entering any of these markets, further study of the size of the market would be necessary in order to evaluate the potential business risks and rewards for entry, as reflected in Table 10, needs 1 and 6.

If the analysis points to the viability of a particular market, the participants felt it would then be important to develop a megawatt-scale development program, with a facility that is capable of testing systems of this size and that has access to cheap electricity to offset testing costs. A megawatt-scale development program is especially important for durability tests. Another core need of such a program is reflected in need 3 of Table 10, definition of electrolyzer requirements across applications. Participants discussed this in the context of developing standardized test methods, and possibly hardware specifications, eventually leading to some standardization of equipment; perhaps not stacks, but BOP.

If systems are successfully tested, the participants then felt that megawatt-scale pilot projects providing ancillary support services and hydrogen would be a necessary step to build stakeholder confidence that the equipment could participate in the markets. These steps are common across all of the proposed markets.

**Table 10. Additional Market Opportunities Near-Term RD&D Needs (2014–2016)**

1. Study the size and value of additional market opportunities currently and in the future
2. Create MW-scale development program including large-scale testing and MW-scale test laboratory with cheap electricity (Power-To-Gas Challenge 1, Ancillary Services
3. Definition of electrolyzer requirements across applications
4. Education (of stakeholders)
5. MW-scale pilots to provide ancillary services (regional grids)
6. Develop electrolyzer roadmap—prove out costs and critical elements
7. MHE—projects do not have funding for on-site hydrogen production

### Long Term (2017–2020+)

Although the group was encouraged to discuss long-term RD&D activities, nearly all of the focus of the breakout session was on the 2014–2016 time frame, because many of the issues identified are very pressing for the companies involved.

### Other Needs

There was some discussion of other needs during the breakout session that did not directly relate to technology development, but nevertheless were important to participants and are reflected here. These needs fall into three broad categories: technoeconomic analysis, test protocols, and efficiency.

Much of the discussion on technoeconomic analysis involved the H2A spreadsheet tool. Several participants felt that its underlying assumptions need to be revisited and made more realistic and relevant to industry. Others asked for a better, more user-friendly user interface.

Regarding pressurized operation of electrolyzers, it remains unclear what pressure is best in terms of minimizing cost across the production and delivery pathways. Participants suggested a trade study to help answer this question and provide guidance to developers on pressure specifications that would add the most value to the market.

Standardizing testing protocols and reporting procedures was discussed as a way for electrolysis system manufacturers to better collaborate with one another, customers, and DOE. Activities in this area could include reporting efficiency at a common current density to allow direct comparisons of different systems, development of accelerated stress tests, and a framework for protecting intellectual property in a public-private partnership.

Several OEMs asked for an effort to improve the efficiency of power supplies across applications. This effort would likely be facilitated by the standardization effort, giving power supply manufacturers the opportunity to engineer products that are more closely aligned with the requirements of electrolysis systems.

### *Power to Gas*

Participants identified research into developing cells and stacks with uniform current distribution across the face of the cell as important for power to gas, which will require scale-up to megawatts scales for market entry. One important external challenge relates to Federal Energy Regulatory Commission (FERC) rules regarding hydrogen content in natural gas pipelines. See Table 20, Appendix D: Voting Results for details.

### *Ancillary Grid Services (Frequency/Voltage Regulation)*

The top RD&D activity identified with respect to the ancillary service market was a megawatt-scale demonstration large enough to provide useful data to grid operators. Participants noted that by the nature of the criticality of the service electric utilities provide, they tend to be hesitant with new technologies, and that such a demonstration could help build confidence. Table 21, Appendix D: Voting Results shows a summary of this voting and discussion.

### *Renewable Hydrogen for Petroleum Refining*

The discussion on electrolytic hydrogen for the petroleum upgrading market centered on the need for analysis of the market to determine at what point the price of natural gas becomes high enough that electrolysis would be cost competitive. Participants again mentioned a megawatt-scale development program as a priority need. This discussion is summarized in Table 22, Appendix D: Voting Results. It was noted that as more electricity generation is provided by natural gas, the price of electricity may never become price competitive with natural gas, because a major (but not the only) cost component of electricity will be the price of its natural gas feedstock.

### ***MHE***

Discussion on MHE was limited. The only RD&D need identified was to include on-site electrolysis as an option for MHE stations. The discussion is summarized in Table 23, Appendix D: Voting Results.

## Manufacturing and Scale-Up Challenges

The costs and risks associated with scale-up and manufacturing are significant for the relatively small companies currently active in the North American electrolysis market. One presenter estimated that a megawatt scale development program could consume more than 50% of gross revenues. Nevertheless, in order to build markets for electrolysis technologies, the consensus among participants was that the systems must grow in capacity to the megawatt scale and manufacturing costs must decrease. The challenge is to balance these needs with the realities of the markets that exist today. Specifically, participants identified challenges, and their corresponding RD&D needs, that fall into the following categories: materials, manufacturing, BOP, and testing.

Materials issues identified include the need to develop lower-cost materials with higher durability, efficiency, and pressure capability that are compatible with high-throughput manufacturing processes such as roll-to-roll lines (in the case of lower-temperature electrolysis). In the high-temperature sector, there was discussion of a DOE-brokered bulk purchase of raw materials, which reportedly had some success under the Solid State Energy Conversion Alliance (SECA) Program.

In manufacturing, the identified challenges center on how best to balance today’s small manufacturing volumes with the need for capital investment in engineering innovations for cost reduction in the manufacturing process. One suggestion was to develop a tooling consortium that could help spread out the risks and costs of non-recurring engineering charges related to high-volume tooling. Some participants felt that there is a need for guidance on system design for manufacture and assembly, suggesting that consulting with high-volume manufacturers of complex systems (e.g., automotive manufacturers) may help. Others felt that the recent advancements in additive manufacturing could be employed to create large, high-quality parts in low volumes.

A perennial challenge with BOP is the lack or limited availability of suitable commercial-off-the-shelf (COTS) parts. BOP suppliers among the participants suggested that the industry could benefit from standardization of specifications and interfaces to the greatest extent possible. This would allow suppliers of BOP to invest their resources in fewer part numbers, resulting in lower costs and better yields and efficiency (specifically in the case of power supplies.)

Finally, participants mentioned testing as an issue, as in other sessions of this workshop. The costs of laboratory space and operation of a megawatt-scale test program can be prohibitive. By way of illustration, an electrolysis plant running at the forecourt production target of 1.5 metric tons per day could consume more than $5,000 of electricity in a single day of operation.[4] Testing

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[4] Assuming 50 kWh/kg of hydrogen and 7 cents per kWh of electricity.

a 50-metric-ton-per-day plant could cost more than $150,000 just in energy charges. This is in addition to any demand charges and the cost of the electrical gear to run at this power level. This makes durability and multi-unit reliability tests prohibitively expensive. As a solution to this problem, electrolysis companies are looking heavily to leverage the infrastructure and expertise in place at DOE national laboratories for stack and system validation, especially accelerated durability tests.

## Manufacturing and Scale-Up Challenges Panel Presentations

**Mr. Everett Anderson** of Proton OnSite spoke about the manufacturing challenges of scaling electrolysis systems up to megawatt scales. These included: cost reduction for stack and system, materials substitution, development of a technology roadmap, capital investment, development of electrolysis-specific manufacturing processes, in-line quality control, and increased yield from suppliers. Key among these is the need to reduce stack and system costs by about 50%. Mr. Anderson believes this is achievable, although it is very capital intensive and could consume more than 50% of company annual revenues, making it a high-risk prospect. However, there is precedent within Proton OnSite; between 2000 and 2011, Proton OnSite scaled its product line from 7 kW to 175 kW while reducing $/kW cost by 70%. Cost reductions will require collaboration with key partners, investment in manufacturing within Proton OnSite and throughout the supply chain to increase yield from suppliers, and implementation of online quality control measures in the manufacturing line. However, he mentioned that the market opportunity could be in the billions of dollars.

Regarding external challenges, Mr. Anderson referenced the lack of consistent, long-term investment in hydrogen in the United States. He mentioned strong competition from Europe for leadership in the electrolysis market due to the research consortia set up and funded in Europe (U.S. companies are excluded).

Mr. Anderson discussed the near-term RD&D needs including better utilization of off-the-shelf components (COTS), investment in tooling, increased production volumes, investment in larger BOP, product design and sourcing for world markets, and optimization of the grid and DC stack interfaces.

**Dr. Krzysztof Lewinski** of 3M spoke about cell components, membranes, and catalysts. The challenges he identified include: catalyst compositions not yet proven in electrolysis service, development of electrolysis catalyst-coated membranes (CCMs), incompatibility of existing GDLs with roll processing, and cost. He described the very-early-stage PEM electrolysis market as an external challenge because it is difficult to realize economies of scale. While catalyst development is well advanced for fuel cells, using those same catalysts effectively for electrolysis has not yet been proven and is not well understood. Manufacturing scale-up of specific electrolysis catalysts has not yet taken place; to this point, the bulk of the work has happened at a laboratory scale. A major challenge to manufacturability is the incompatibility of existing gas diffusion layers (GDLs) with roll-to-roll processes due to their stiff, brittle mechanical properties.

Near-term RD&D needs include the development of electrolysis-specific membranes, GDLs that can be roll processed, and a better understanding of failure mechanisms. Dr. Lewinski felt that there was a medium-term need for fundamental electrolysis catalyst and cell component development. He identified size scale-up and design for manufacturability as long-term needs.

**Mr. Owen Hopkins** of Entegris spoke primarily about his company's capabilities and areas of development for BOP-integrated manifolds, including the use of semi-dissipative materials, impregnation of titanium into graphite, chemical and physical vapor deposition, and the use of silicon carbide and graphene.

**Mr. Seth Paradise** of Power-One spoke about the general requirements for designing power supplies for electrolysis systems. Common characteristics of the application include the need for robust components to handle alternating current (AC) power surges, a wide range of controllability, and parallel design for scalability. These include the controllability requirement that limits the possible efficiency because of the need to design for a wide range of power, current, and voltage set points. Mr. Paradise discussed the need for standardized requirements and test protocols across electrolysis system manufacturers and tight definition of those requirements.

**Mr. Joseph Hartvigsen** of Ceramatec discussed the manufacturing challenges of high-temperature electrolysis systems. He addressed the challenges of developing a 50,000 kg/day plant using 232-square-centimeter ($cm^2$) active area planar cells. Using this technology, a plant would require approximately 8,000 stacks (of 100 cells each) if run at a low current density of 300 $mA/cm^2$. Mr. Hartvigsen suggested that this was not feasible due to wiring and plumbing interconnects and suggested that molten salt $CO_2$ electrolysis cells that Ceramatec is developing with the Weizmann Institute may be more scalable. Such a system could have a similar efficiency to solid oxide electrolysis and could produce syngas (from a $CO_2$ feedstock) or hydrogen (from a water feedstock).

## Manufacturing and Scale-Up Challenges Panel Discussion

Following the presentations, the audience was able to ask questions of the presenters. One participant asked what the heat source was for high-temperature systems. It was answered that the heat would likely come from a small natural gas burner that supplies just enough heat to keep the stack at its thermo-neutral point.

Discussion then turned to the scale-up of power supplies to megawatt scales. It was noted that the capability currently exists to scale up to 30 kW modules, but that the design of the device is fundamentally different when designing at this scale and requires standardization of requirements to facilitate higher-volume manufacture across electrolysis system designs. A participant asked whether it is possible to design high-current, low-voltage devices. This would be a challenge because of thermal management of joule heating, which is proportional to the square of current (Ohm's Law, $P=I^2R$). Attention then turned to efficiency and its upper limit. It was mentioned that a system with four output stages and 95% efficiency could be designed for electrolysis systems.

With respect to membranes, it was noted that early catalyst-coated membrane (CCM) prototypes seem to meet targets.  Testing against durability targets is currently underway and results are not yet known. Durability improvements are limited by the allowable thickness of membranes on a web line of 50–70 microns, however other manufacturing processes such as melt extrusion are compatible with thicker membranes. Anything thicker tends to jam. Discussion of roll processing GDLs followed, with a participant noting that the current titanium-based GDLs are too stiff to allow for roll processing and that the carbon felt or paper GDLs used in fuel cells will not work for low-temperature electrolyzers because the voltages are too high and will result in carbon corrosion.

The question-and-answer period ended with discussion on molten salt electrolyzers for high-temperature applications. Participants felt that this technology may be scalable up to megawatt sizes.

# Manufacturing and Scale-Up Challenges Breakout Discussion

## *Challenges*

The top challenges identified by the attendees are shown in Table 11; details of the voting are in Table 24, Appendix D: Voting Results.

**Table 11. Manufacturing and Scale-Up Challenges**

1. Cost and limited availability of component and process validation
2. Financial support
3. Material purity/development
4. Develop advanced manufacturing processes
5. Design for Manufacture and Assembly (DFMA™) analysis for low volume
6. Low-cost manufacturing development for low-volume market

The top challenge identified in Table 11 reflects discussion during the session on the need to address the limited availability of BOP components and manufacturing process validation before scaling up to megawatt-sized systems.  Challenge 1 reflects the fact that for unlike low-cost, high-volume components, it is not possible to perform multiple manufacturing runs for electrolysis components to tune process parameters, or to provide samples of electrolysis components for durability tests. The high cost of iridium was mentioned as a possible barrier. Material issues extended beyond the electrolysis cell and also included BOP.

Once these issues are addressed, the participants felt a key challenge is the scale-up of both manufacturing capacity and system size when the market is very small. The situation represents a “chicken-or-the-egg” scenario, balancing market demand with manufacturing and system capacity. Participants felt that companies would have to apply advanced manufacturing methods and analysis that are suitable for low-volume production to help address this challenge. This issue is represented in challenges 4-6 of Table 11.

### External Challenges

There is a relative dearth of capital investment available for tooling and the infrastructure needed to scale up manufacturing. The high cost of large systems provides few opportunities for process and component validation.

## *RD&D Needs*

### Near Term (2014–2016)

The near-term RD&D needs identified are shown in Table 12 in rank order of the total number of votes for each category.  These correspond closely with the challenges identified earlier (Table 11), however the voting (Table 25, Appendix D: Voting Results) makes the priority clear.

## Table 12. Manufacturing and Scale-Up Near-Term RD&D Needs (2014–2016)

1. Financial support **(Challenge 2)**
    a. Megawatt stack development
    b. Market transformation activities
2. Material purity and cost **(Challenge 3)**
    a. Catalyst development
    b. Electrode development (high reliability, activity)
3. Cost of validation and limited availability of components **(Challenge 1)**
    a. Stack and BOP scale-up, design and validation
    b. Collaboration support with national laboratories for MW-scale system/stack validation
4. Develop advanced manufacturing process **(Challenge 4)**
    a. Improve and streamline manufacturing processes for materials
    b. Engineer materials suitable for advanced manufacturing processes
5. DFMA™ analysis assistance, additive manufacturing **(Challenge 5)**
    a. Develop design studies for very low volume using additive manufacturing
6. Low-cost manufacturing for low volume **(Challenge 6)**
    a. Low volume MEA fabrication.

The highest priority among the participants was financial support for megawatt stack development and market transformation activities (need 1, Table 12). This is followed closely by materials needs for catalyst and electrode development, reflected in need 2 from Table 12. Participants indicated that there needs to be fundamental work on material purity and cost, as well as development of membrane materials suitable for high-pressure operation.

Need 3 in Table 12 address the issue of the high cost of testing megawatt-scale components and systems—this includes both the space required and the high cost of electricity. Participants suggested that the DOE national laboratory system could provide testing and validation services using its existing infrastructure, much of which is beyond the reach of the small companies developing electrolysis systems.

Advanced manufacturing techniques for high- and low-volume production are reflected in needs 4 through 6 from Table 12. Chief among these is the need to apply advanced manufacturing processes such as physical vapor deposition (PVD)/chemical vapor deposition (CVD), atomic layer deposition (ALD)/physical layer deposition (PLD), or 3D printing to cell components. Several participants mentioned the need for design for manufacture and assembly (DFMA™) assistance from experts in the field, particularly for the transition from low to high volume.

Several manufacturers of electrolysis systems noted the need for lower-cost, higher-efficiency power supplies. The presentation from Power-One, a manufacturer of power supplies, indicated that it would likely be necessary for electrolysis system suppliers to develop some common requirements and tighter operating ranges in order to increase efficiency. Although this need was widely discussed, it did not receive a preponderance of votes in the breakout session.

## Markets and Manufacturing Final Discussion

Results of the markets and manufacturing breakouts are summarized in Table 12, and compared to the relevant barriers in the MYRD&D plan.

Regarding capital cost, the need to scale systems to the megawatt level was discussed and generally agreed upon as important. Larger systems will be able to participate in markets such as power-to-gas and ancillary grid support. An important driver of capital cost is the lack of standard electrolyzer requirements across different applications. This leads to custom designs or non-optimal utilization of COTS items in systems, driving up cost.

Participants felt that there was a need to demonstrate mega-watt scale pilot systems to demonstrate the ability to participate in ancillary markets.

In the manufacturing discussion, there was agreement that advanced manufacturing processes must be deployed to enable low cost production of systems, even at low volume. A variety of thin-film deposition technologies were discussed as was additive manufacturing. DFMA™ may play a role in implementing these technologies and other manufacturing process improvements.

The need to understand the value of different market opportunities and how, or whether, electrolysis technologies can be developed to address these opportunities does not map well into the MYRD&D barriers, but was seen as important by participants in order to mitigate risks and target RD&D investment into the most promising areas, before embarking on mega-watt scale development activities.

**Table 13. Classification of RD&D Needs into Program Technical Barriers**

| Barrier | RD&D Need: Markets | RD&D Need Manufacturing |
|---|---|---|
| **F. Capital Cost** | • Large-scale testing and MW-scale test laboratory w/ cheap electricity<br>• Definition of electrolyzer requirements across applications<br>• Develop electrolyzer roadmap—prove out costs and critical elements | • Megawatt scale-up, Large-format cell and stack development<br>• Large-scale testing and MW-scale test laboratory w/ cheap electricity<br>• Material purity and cost |
| **J. Renewable Electricity Generation Integration** | • MW-scale pilots to provide ancillary services | |
| **K. Manufacturing** | | • Develop advanced manufacturing process<br>• DFMA™ analysis assistance, additive manufacturing<br>• Low-cost manufacturing for low volume |
| **Unclassified** | • Study what the additional market opportunities are worth<br>• Education (of stakeholders)<br>• MHE—projects do not have funding for on-site hydrogen production | |

# Conclusions and Next Steps

Given the importance of electricity usage in meeting DOE's electrolysis targets for hydrogen production, it is critical for the RD&D community to pursue four simultaneous approaches to address cost reduction: (1) improve efficiency, the most important aspect of the systems that contribute to decreased electricity consumption, (2) make use of low-priced stranded electricity and, (3) develop mega-watt scale system which can enable alternative revenue streams and markets which can decrease the hydrogen production cost, (4) capital cost reduction. Increases in efficiency can be made in all electrolysis technologies, with one PEM manufacturer targeting 15-20% improvement and an SOEC manufacturer targeting 75% efficiency. Multiple OEMs discussed the need to reduce capital cost by 50%, and indicated that it is feasible to do so in commercial technologies. Pre-commercial technologies, such as AEM may result in a new cost reduction curve, enabled by the possibility of 90% lower catalyst loading, and thinner membranes.

In light of the attendees' strong preference for investigating the Power-to-Gas market, it may be useful to review current analysis on this topic (Marc Melaina, 2013) to investigate the feasibility of the power-to-gas market based on curtailed wind resources.

Prior to entering any new market, it is advisable to investigate the value of the market, the cost of developing a product to suit it, and the potential return on the investment. Although the workshop participants identified four top markets that could be a fit for electrolysis (power-to-gas, ancillary services, petroleum upgrading, and material handling), there was a general uncertainty regarding how the markets should be valued, including what impact they would have on decreasing the cost of hydrogen production. Formal investigation of potential markets is required before they can be developed for electrolysis.

Irrespective of additional market opportunities, development is needed to increase efficiency. This can take many forms on the stack level, including improved material sets for membranes, catalysts, anode support media, and GDLs. Although the solutions may take different forms, these needs are similar for all electrolysis technologies represented. There are opportunities to improve system efficiency as well, including development of higher-efficiency power supplies and product drying systems.

Improvement in these categories requires close coordination with suppliers, and the electrolysis industry—to the maximum extent possible—should develop standard test and performance reporting protocols and interface specifications. This can enable suppliers to develop engineered solutions specific to electrolyzer operating requirements with minimum investment and a maximum potential market. A logical place to start this effort is in the reporting of system efficiency at a common current density and temperature. Other testing and reporting protocols could follow from that first confidence-building step.

Testing capabilities for megawatt-scale systems are difficult and expensive to build. The kilowatt-hour energy costs of electricity to run durability tests, or even the demand charges, can be prohibitive for small companies. Electrolysis companies, to the maximum extent possible, should leverage existing testing capabilities at facilities in order to ease the financial burden of investing in test infrastructure. These could include early adopter sites, where the value of the product hydrogen made during the testing can offset testing costs, or universities, national laboratories, and other test locations.

Strong needs were identified in manufacturing, including achieving efficient manufacture of the large components needed for megawatt-scale systems, while minimizing the investment in tooling. Several avenues for exploration in this area were identified, including developing a tooling consortium among the electrolysis system manufacturers and exploring opportunities to employ recent advances in additive manufacturing. The market plays a large role in the decisions companies face when considering investment in manufacturing capability. It is difficult to justify large capital outlays if the market will not support the return on investment.

# Appendix A: Abbreviations and Acronyms

| Abbreviation/ Acronym | Definition | Page |
|---|---|---|
| 3D | three-dimensional | 34 |
| AC | alternating current | 30 |
| AEM | alkaline exchange membrane | 5 |
| ALD | atomic layer deposition | 34 |
| AST | accelerated stress test | 45 |
| BOP | balance of plant | iv |
| CCM | catalyst-coated membrane | 31 |
| CNJV | Corporate Allocation Services - Navarro Joint Venture | |
| COTS | commercial off the shelf | 28 |
| CVD | chemical vapor deposition | 34 |
| DC | direct current | 21 |
| DFMA™ | Design for Manufacture and Assembly (DFMA is a registered trademark of Boothroyd Dewhurst, Inc.) | 32 |
| DOE | U.S. Department of Energy | |
| EERE | U.S. DOE Office of Energy Efficiency and Renewable Energy | |
| FCEV | fuel cell electric vehicle | 6 |
| FCTO | Fuel Cell Technologies Office | |
| FERC | Federal Energy Regulatory Commission | 27 |
| GDL | gas diffusion layer | 29 |
| gge | gallon of gasoline equivalent | 6 |
| hr | hour | 10 |
| H2A | Hydrogen Analysis | 6 |
| H35 | 350-bar nominal hydrogen refueling | |
| H70 | 700-bar nominal hydrogen refueling | |
| HNEI | Hawai’i Natural Energy Institute | 22 |
| HySA | Hydrogen South Africa | 23 |
| ISO | Independent System Operator | 22 |
| ITC | Investment Tax Credit | 38 |
| kg | kilogram | iii |
| kW | kilowatt | 22 |

| | | |
|---|---|---|
| kWh | kilowatt-hour | 21 |
| LANL | Los Alamos National Laboratory | 59 |
| MEA | membrane electrode assembly | 9 |
| MHE | material handling equipment | 2 |
| MISO | Midcontinent Independent System Operator | 22 |
| MSRI | Materials and Systems Research Inc. | 59 |
| MW | megawatt | 9 |
| MYRD&D | Multi-Year Research Development and Demonstration Plan | 17 |
| NREL | National Renewable Energy Laboratory | 2 |
| OEM | original equipment manufacturer | 23 |
| PEM | Polymer electrolyte membrane | 3 |
| PFSA | Perfluorosulfonic acid | 23 |
| PGM | platinum group metal | 9 |
| PJM | The Pennsylvania, New Jersey, Maryland ISO | 22 |
| PLD | physical layer deposition | 34 |
| PNNL | Pacific Northwest National Laboratory | 59 |
| psi | pounds per square inch | 8 |
| PV | photovoltaic | 21 |
| PVD | physical vapor deposition | 34 |
| RD&D | research, development, and demonstration | 35 |
| RFS2 | Renewable Fuel Standard | 48 |
| RSF | Research Support Facility, NREL | 42 |
| RTO | Regional Transmission Organization | 51 |
| SA | Strategic Analysis, Inc. | 6 |
| SECA | Solid State Energy Conversion Alliance | 28 |
| SMR | steam methane reforming | 11 |
| SOEC | solid oxide electrolysis cell | 4 |
| SOFC | solid oxide fuel cell | 10 |
| SRNL | Savannah River National Laboratory | 59 |
| TRL | technology readiness level | 14 |
| USGS | United States Geologic Survey | 57 |
| VAR | volt-ampere reactive | 25 |

# Appendix B: References

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# Appendix C: Agenda

| Thursday, February 27, 2014 | | Room |
|---|---|---|
| 8:30 am | Check in and security processing | San Juan A/B |
| 9:00 am | Welcome and Introductions, **Chris Ainscough**, *DOE/NREL* | San Juan A/B |
| 9:20 am | Overview of DOE Production Work, **Sara Dillich**, DOE | San Juan A/B |
| 9:50 am | Techno-economic Analysis of PEM Electrolysis, **Whitney Colella**, *Strategic Analysis Inc.* | San Juan A/B |
| 10:50 am | Break | |
| **Technical Challenges and RD&D Needs – Near and Long Term** | | |
| 11:00 am | Panel Presentations and Discussion:<br>High Pressure PEM Electrolysis, **Monjid Hamdan**, Giner Inc.<br>Electrolysis at Forecourt Stations, **Geoffrey Budd,** ITM Power<br>Alkaline Membrane Electrolysis, **Kathy Ayers,** Proton OnSite<br>High Temperature & Nuclear-Driven Electrolysis, **James O'Brien,** Idaho National Laboratory<br>Reversible Solid Oxide Electrolysis, **Randy Petri,** Versa Power Systems | San Juan A/B |
| 12:30 pm | Lunch | San Juan A-C |
| 1:15 pm | Breakout Discussions | Breakout 1 – Long Term, San Juan C<br>Breakout 2 – Near Term, San Juan A/B |
| 3:15 pm | Break | |
| 3:30 pm | Breakout reporting | San Juan A/B |
| 4:00 pm | Full group discussion | San Juan A/B |
| 5:00 pm | Adjourn | |

## Friday, February 28, 2014

### Markets and Manufacturing

8:00 am Assemble

| 8:10 am RSF X320 Beaver Creek A/B/C | RSF X305 Bear Creek |
|---|---|
| Parallel Panel:<br>**Additional Market Opportunities** | Parallel Panel:<br>**Manufacturing and Scale-up Challenges** |
| Renewables and Grid Integration,<br>**Kevin Harrison**, NREL | MW Scale-up,<br>**Everett Anderson**, Proton OnSite |
| Grid Impacts and Ancillary Markets,<br>**Frank Novachek**, Xcel Energy | Cell Components, Membranes, & Catalysts<br>**Krzysztof Lewinski**, 3M |
| Electrolysis on an Island Grid,<br>**Mitch Ewan**, Hawai'i Natural Energy Institute | Manufacturing Challenges for BOP, and stack components<br>**Owen Hopkins**, Entegris |
| Power to Gas and Energy Storage,<br>**Rob Harvey**(tentative), Hydrogenics | Power Supply Challenges,<br>**Seth Paradise**, Power-One |
| Electrolysis for Home Refueling<br>**Cortney Mittelsteadt,** Giner, Inc. | Manufacturing High Temperature Systems,<br>**Joseph Hartvigsen**, Ceramatec |
| International Applications/Markets,<br>**Dmitri Bessarabov**, HYSA Infrastructure | |

| | | |
|---|---|---|
| 9:40 am | Break | |
| 9:50 am | Breakout Discussions | Breakout 1 – Markets, X320 Beaver Creek A/B/C<br>Breakout 2 – Manufacturing, in RSF X305 Bear Creek |
| 11:50 pm | Lunch | X320 Beaver Creek A/B/C |
| 12:30 pm | Breakout Reporting - together | X320 Beaver Creek A/B/C |
| 1:30 pm | Full Group Discussion | X320 Beaver Creek A/B/C |
| 2:30 pm | Adjourn | |

# Appendix D: Voting Results

## Table 14. Commercial Technologies Internal/External Challenges Brainstorming and Voting

**Improved Stack Performance (10) (5)**

- Improved high-pressure stack hardware designs
- Demonstrated high current density

**Increase Stack Size (13) (3)**

- Validation of stack advancements at relevant scale
- Difficult to develop large-scale stack technology (multi-megawatt). Difficult to test
- Larger size stack
- Make bigger electrolyzers (i.e., 1,500–2,000 kg/day)

**High-Pressure Stack/System/Components (7) (4)**

- High permeability of PEM
- High-conductivity, low-crossover membrane for high pressure
- High cost of power conditioning
- Develop stronger, low-cost membrane materials for high-pressure hydrogen production

**Market Issues (8) (2)**

- Access additional markets/sectors (electricity, heating fuel, transportation)
- Identification of regions where the production can be cheapest due to low electricity rates and/or favorable rate structures
- Developing competitive marketplace for forecourt power supply systems

**Grid Integration (11) (1)**

- Develop set of power system standards for grid tie applications. Optimized power conversion for grid and renewables interface
- System-level (photovoltaic [PV], wind) integration optimization (electrolyzer stacks matched with PV/wind characteristics)

**Durability (8) (1)**

- Improve electrolyzer durability—reduce maintenance costs
- Durability at low loadings uncertain

**Membranes (8) (1)**

- Membranes (failing)
- MEA costs down
- Improved efficiency through better cell performance—(1) better catalysts, (2) lower resistance membrane, (3) lower resistance cell gas diffusion layer (GDL), and (4) flow field (FF)

## Commercial Technologies Internal/External Challenges Brainstorming and Voting

**BOP Improved (7) (1)**

- Design for manufacturing to reduce stack BOP costs
- Reduced component cost
- BOP components—high-pressure designs
- Reduce BOP costs—improve reliability, improve efficiency

**Accelerated Test Protocols (7) (1)**

- Accelerated test protocol for new material/design evaluation

**Power Conditioning (8) (0)**

**Catalyst (3) (0)**

- Catalyst cost reduction

**Uncategorized**

- Carbon credits (external)
- Demand response/spinning reserves (external)
- Access to global market size
- Cost of input electrons
- A minimum linking infrastructure that is funded by government/private partnership machining
- Electrical cost (external)
- Renewable electricity costs down (external)
- Novel systems/process (external)
- Grid control coupling electrolyzers with supply/demand fluctuations in real time
- Fuel cells benefited from large funding—the challenge is how to raise the opportunity profile for electrolysis to raise money
- Limited continuity of research and development funding for extended periods to foster team interaction/cohesiveness (external)
- Power cost (external)
- Take advantage of intermittent sources (cheap electricity) via the use of low-cost hardware

**Votes in (green), priority votes in (blue).**

## Table 15. Commercial Technologies RD&D Needs Brainstorming and Voting

### Improved Stack Performance

**Near Term**

- Develop novel high-conductivity, low-permeability and high durability membranes (6) (3)
- Improved catalysts (3) (2)
- System components: Develop inexpensive water purification system for feed water (3)
- Increase performance of membrane (2)
- More conductive cell bi-polar plates, gas diffusion layer, current collection (2)
- Tests versus end-of-life prediction (1)
- Push temperature limits on polymer electrolyte membrane electrolysis cell similar to polymer electrolyte membrane fuel cell (internal) (1)
- Control of conductivity/permeability ratio in PEMs

**Long Term**

- Alkaline, PEM fundamentals: Catalyst, transport, role of function group (1)
- Investigate use of ultrasonic systems to improve stack performance (1)
- Stack performance—better flow distribution (current, $H_2$, water)
- Efficiency; flexible operation of SOEC, combine with cell material developments

### Increase Stack Size

**Near Term**

- Demonstrate design path to (low-cost) large stack (1) (2)
- Low-cost hardware for stacks (1) (2)
- Increased stack size, grid integration (6)
- MEA scale-up—large area/stack (4)
- Increase stack, standardize power requirement (2)
- Investigate electrolyzer stackable power supply topology for target 3-kilowatt forecourt (2)
- Large, 6-sigma quality MEAs (increase stack size) (1)
- Understanding of scale-up correlations between small and large stack size (performance) (1)

**Long Term**

- Engage power supply original equipment manufacturers to develop next-generation power convertors targeted for stacks (low voltage, high current (3)
- Large stack prototype (1)

## Commercial Technologies RD&D Needs Brainstorming and Voting

### Grid Integration

**Near Term**

- Multi-megawatt pilot plant demonstration site (validate value streams, large stack testing) (5) (2)
- Engage electric power industry to establish required testing and desired outputs to enable easier adoption of electrolyzer systems in ancillary markets (4) (1)
- Communication and controls to interact with independent system operator/regional transmission organization/utility (3)
- Simulation/modeling showing the impact of increasing renewables and grid integration of electrolyzers (2)
- Technology validation demos in real-world applications at real size (1)
- Hybrid utilization of electrolyzer power supply with synergistic devices (1)
- Grid integration, increased stack size

### High-Pressure Stack System Components, Membranes

**Near Term**

- Trade-off between high-pressure electrolysis and compression (4) (1)
- Multi-year, large-scale, high-pressure collaborative and demonstration program (1) (1)
- Better anode support media (6)
- High-pressure stack/system/membrane: Low creep ionomers (2)
- High-performance stack/system membrane: Novel reinforcement strategies (1)
- Improve performance of chiller units: Noise signature, efficiency (1)
- High pressure: Market analysis for high-pressure electrolysis applications
- High-porosity gas diffusion layer (improved stack performance)

**Long Term**

- High pressure: Develop/demonstrate high-pressure (stack and BOP) designs (1)

### Market Issues

**Near Term**

- Market challenge contest: Find a value proposition for oxygen to offset cost (3) (1)
- Market issues: Direct hydrogen grid injection, large demo evaluation (3) (1)
- Determine regions where electrolytic hydrogen can best compete with SMR based on price, carbon dioxide footprint, and market size (7)
- Search for new application (1)

**Long Term**

- Roadmap for multi-megawatt systems (power to gas)

**Votes in (green), priority votes in (blue).**

## Table 16. Pre-Commercial Technologies Internal/External Challenges Brainstorming and Voting

### Internal

- Increased technical understanding of SOEC degradation mechanisms, including at high current densities and under cycling conditions (4) (3)
- Large-format cells and megawatt stacks (7) (2)
- Prove endurance—single cell to stack, to system demo. → affects stack swap out frequency → cost (5) (1)
- Definition of material interactions from low-TRL technologies (4) (1)
- More active materials to increase efficiency (3) (1)
- Increased understanding and demonstration of high-quality thermal integration between the SOEC and the external heat source, including low-temperature gradients in the stack (3) (1)
- Durable materials to increase lifetime (2) (1)
- Direct coupling with concentrated solar power (2) (1)
- For PEM electrolyzers, how durable are PGM supports (carbon) for electrolysis? Need better supports? Need alternative supports? Ceramic supports, non-carbon? Corrosion/platinum loss issues? (1) (1)
- Pressurized operation high-temperature solid-oxide electrolyzer (4)
- Addressing BOP costs and durability—holistically (power electronics, etc.) (4)
- Lower SOEC operation temperature. Develop related materials (3)
- Thermal management, large-scale systems (3)
- Central—scale-up to required capacities (2)
- Operational flexibility—reversible, intermittent (2)
- Stack costs (PGM catalysts) in efficient stacks (2)
- Lower voltage at higher current → lower system cost at higher efficiency (2)
- Prove feasibility of high-current-density stacks (and systems). Once proven → prove endurance…again (2)
- Increased understanding and demonstration of integrated reversible SOECs/SOFCs, with attention to degradation and failure mechanisms under cycling (2)
- PGM recycling (2)
- Increase efficiency of the alternating current (AC)–direct current (DC) or DC–DC to reduce electricity required (2)
- Understanding degradation caused by ionomers and membranes (AEM) (1)
- Reliability testing as multiple design improvements are needed to meet DOE 2025 targets (1)
- SOEC—cell material cost (new material sets) (1)
- More durable AEM membranes are required. What chemistries are promising? Long-term R&D
- Understanding of ion transport and surface interactions in ionomer versus liquid electrolyte to catalyst surfaces (AEM)
- Manufacturing volumes high enough for low-cost standard parts
- SOEC—fabrication cost (mass production)

## Pre-Commercial Technologies Internal/External Challenges Brainstorming and Voting

**External**

- Appropriate market identification (1)
- Holistic energy policy with respect to hydrogen—energy storage, Renewable Fuel Standard (RFS2) program. No silos
- No global (U.S.) vision on priorities/approach (natural gas, bio), no continuation
- Cheap electric power
- Fluctuations in base material costs are limiting investment
- Hydrogen transportation to local level. Tech solutions needed
- Limited R&D funds for industry/national laboratories for transformational technologies

**Votes in (green), priority votes in (blue).**

## Table 17. Pre-Commercial Technologies Near-Term RD&D Needs Brainstorming and Voting (2014–2016)

### Material Durability

- Degradation studies/material sets to remediate prime degradation mechanisms (5) (1)
- Focus on testing/optimizing ASTs for researchers and industry—standardizing (1) (1)
- Multistage, multidisciplinary approaches to address durability challenges for a given technology (4)
- Accelerated high current and water saturation aging tests of state-of-the-art materials (3)
- Improved studies of alkaline membranes. (3)
- Materials durability/high current—chemistry/morphology modification R&D to reduce ΔT effects (2)
- Platinum dispersion on ceramic supports—increased platinum utilization/platinum support enhancements. RD&D resources (1)
- Develop a more durable AEM (1)
- Material durability—develop new material sets of cathode/electrolyte based on understanding of degradation mechanisms
    - Understand failure modes → accelerated tests

### Scale-Up Cell Size

- Scale-up—large plate/cell tests, short stacks with larger cells to understand flow/current distribution and thermal management. (2) (2)
- Systems analysis studies, cost minimizing operating point considering the stack polarization curve as a function of temperature, pressure and the relationship between power density and capital costs (1) (1)
- RD&D scale-up—pilot plant (3)
- Working laboratory sites for megawatt pilot projects (2)
- Long-term tests of "real-life" SOEC components (not button cells) (2)
- Manufacturing analysis included in early development stages (1)
- Cell architecture/fabrication process for large format cells and megawatt stacks

### Efficiency + High Current Density

- Develop more active catalyst materials (3) (2)
- Material for lower-temperature SOEC, higher-temperature AEM or PEM (4) (1)
- New electrode materials/catalysts (4)
- Upgrade power conversion to higher-efficiency performance
- Lower SOEC operating temperature
- Efficiency; flexible operation of SOEC, combine with cell material developments

**Votes in (green), priority votes in (blue).**

**Table 18. Pre-Commercial Technologies Long-Term RD&D Needs Brainstorming and Voting (2017–2020+)**

### Pressurized Operation

- RD&D additional demo of pressurized operation (4) (3)
- Cell/stack/system BOP concepts for pressurized operation (2)
- Pressurized—SOEC testing at 150–300 psi (1)
- Systems analysis studies of various outlet pressure operation, for both PEM and SOEC, over a range of pressures/stages (1)

### System Durability

- System durability: Long-term integrated system testing (3)
- Industry testing and durability—MEAs (3)
- Stack engineering/modeling and redesign to moderate ΔT (1)
- Kilogram/day stack development/test, >250 kg/day system demo

### Production Volume

- Design for manufacture and assembly (DFMA™[5]) cost analysis of different electrolyzer systems, including PEM and SOEC (2)

### BOP

- Crosscutting initiative with innovative power electronics technologies (3)
- Conceptual BOP designs early in technology development (1)

**Votes in (green), priority votes in (blue).**

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[5] DFMA is a registered trademark of Boothroyd Dewhurst, Inc.

| **Table 19. Additional Market Opportunities Identification Brainstorming and Voting** |
|---|
| **Power to Hydrogen/Gas – Power to Hydrogen for $CH_4$ (3) (6)** |
| **Ancillary Services**<br>• Frequency regulation (9)<br>• End-user markets—demand charge, peak shaving (6)<br>• Voltage regulation (5)<br>• Capacity market<br>• Distribution-level voltage regulation<br>• Interconnection agreements (external)<br>• Independent System Operator (ISO)/Regional Transmission Organization (RTO)/Balancing Authority Area (BA) market participation rules (resource size, demand response) (external)<br>• Limited market for ancillary services (external) |
| **Renewable Hydrogen for Refining (RFS2 to Include Hydrogen) (4) (1)**<br>• Biofuels—methane enhancement (1) |
| **MHE in Distribution Centers (7)**<br>• Utility vehicles—MHE/tow motors<br>• MHE refueling |
| **Data Centers; e.g., Google, Facebook (1) (1)** |
| **Commercial Aircraft Standby Power (1) (1)** |
| **Coal/Gas Power Plant Cooling (1)** |
| **Carbon Credit Markets (5)** |
| **Home Refueling (4)** |
| **Ammonia – SMR May Not Dominate Here? (3)** |
| **Municipal Transportation Fleets (3)**<br>• Mini operation—on-site production linked to renewables (2)<br>• Construction sites—earth moving equipment (e.g., Caterpillar) |
| **Stationary Energy Storage (Cell Towers, Businesses, Farms, Shopping) (2)**<br>• Cell tower stand-alone power |
| **Helium Replacement (Aerostats, Lag, etc.) (2)** |
| **Oxygen (2)** |
| **Buses and Heavy-Duty Vehicles (1)** |
| **Weather Ballooning (Small Scale)** |
| **“Flame” Applications (Small Scale)** |
| **Chloralkali Hydrogen → DC grid for the chloralkali plant** |

**Votes in (green), priority votes in (blue).**

**Table 20. Power-to-Gas Market Entry Challenges and RD&D Needs Brainstorming and Voting**

| Internal Challenges to Market Entry | RD&D Activities |
|---|---|
| - Internal large-scale testing (8) (4)<br>- MW-scale pilot projects (3) (1) | - Uniform areal electrical current distribution (most likely hot spots will be main problems) (8) (2)<br>- Stack scale-up to 250 kg/day (near) (3)<br>- Subscale demos of integrated systems to show application feasibility (3) |
| - Definition of product requirements (process pressure, dew point, etc.) and economics (what does cost need to be?) (5) (4) | - Perform trade study on the optimum electrolyzer pressure output level with respect to forecourt compression technologies. (near) (4)<br>- Technoeconomic analysis required to determine the environment to make power to gas valuable (gas price, $H_2$ sale price, equipment costs) (2)<br>- Systems/technoeconomic analysis to define delivery pressure. RD&D done at pressure |
| - Unfamiliarity with the technology on the part of key stakeholders (9) (1) | - MW system demo—multi-year, multi-partner, stakeholder participation required (7)<br>- Deploy and test larger (≥1 MW) systems (3)<br>- Tutorial on power-to-gas economics (1) |
| **External Challenges to Market Entry**<br>- Low natural gas storage prices (1)<br>- $H_2$ storage<br>- FERC policy, lack of open Hythane standards of max percentage $H_2$ in pipes<br>- Lack of consistent incentives | |

**Votes in (green), priority votes in (blue).**

**Table 21. Ancillary Grid Services Market Entry Challenges and RD&D Needs Brainstorming and Voting**

| Internal Challenges to Market Entry | RD&D Activities |
|---|---|
| • Lack of infrastructure for large-scale demo (6) (1)<br>○ Electrolyzer size (≥1 MW for market entry) (3) | • MW-scale pilots for ancillary services at several regional locations (6) (3)<br>• Set up MW-scale test laboratory (site needs MHE, cheap electricity) (4) |
| • Lack of data at large scale (5) (1)<br>○ MW-scale electrolyzers performance data | |
| • Valuing electricity markets (energy, capacity) (1) | • Technoeconomic analysis. Look at current market values and how values change in the future (renewables, storage, etc.) (near) (5) (1) |

**Votes in (green), priority votes in (blue).**

**Table 22. Renewable Hydrogen for Petroleum Refining Market Entry Challenges and RD&D Needs Brainstorming and Voting**

| Internal Challenges to Market Entry | RD&D Activities |
|---|---|
| • Scale of current systems and development cost to get to appropriate scale (6) (1) | • Create a MW-scale electrolyzer stack/system development program (5) (4)<br>• Development plans/roadmaps to larger scale (prove out critical elements and cost first) (5) (2) |
| • Billions of dollars of existing infrastructure in SMR (external). Must beat internal cost for $H_2$ (5) | • Natural gas price tipping point for electrolytic $H_2$ competitiveness. Analysis (3) |
| **Additional RD&D Activity**<br>• Validate H2A model assumptions and make more user friendly (2) | |
| **External Challenges to Market Entry**<br>• Change in renewable fuel standard to include $H_2$ | |

**Votes in (green), priority votes in (blue).**

**Table 23. MHE Market Entry Challenges and RD&D Needs Brainstorming and Voting**

| Internal Challenges to Market Entry | RD&D Activities |
|---|---|
| • Systems analysis—technoeconomic analysis for electrolysis (4) | |
| • Infrastructure costs for forecourt production (3) | • Demonstration of electrolysis fueling solution (funding included in initial fuel cell demo) |
| • Molecule cost for forecourts | |

Votes in (green), priority votes in (blue).

### Table 24. Manufacturing and Scale-Up Internal/External Challenges Brainstorming and Voting

- Limited ability to validate large-active-area stack components (7)
- Cost of manufacturing process validation for MW scale (7)
- MW scale-up—financial support for large scale-up projects (internal) (6)
- Accessible three-dimensional (3D) prototyping for small volumes (internal) (5)
- Design for manufacture and assembly (DFMA™) analysis assistance to electrolyzer companies and their suppliers. Bringing in manufacturing expertise to electrolyzer system and component manufacturers (4)
- Durability of low-loading catalyst (4)
- Thermal management (heat recuperation, high-temperature heat supply to stack) (4)
- Low-cost fabrication process for components at low volume (MEA, bipolar plate, GDL) (3)
- Iridium content and cost (internal) (3)
- Material purity for BOP/stack components (internal) (2)
- Develop an advanced manufacturing process to fabricate electrolyzer (particularly SOEC), such as new thin-film deposition, new substrate, etc., for lowering cost and increasing high yield rates (2)
- Expensive active materials and hardware (2)
- Standardization of MEA and BOP components (2)
- Limited supplier capability to produce large-active-area “soft goods” (2)
- Assistance to electrolyzer companies with developing low-volume manufacturing strategies. Analysis tools for 3D versus traditional manufacturing techniques (2)
- Optimization of configurations for MW-scale pressurized systems: stack size, manifolding, and pressure vessels (2)
- Manufacturing BOP consideration: Cost/maturity of safety systems—hydrogen safety sensor reliability, etc. (2)
- Establish high-volume supply chain to ensure input availability at a reasonable (target) cost level (1)
- Kilowatt-scale advanced design electrolysis power supply (design, prototype) (internal) (1)
- Small-scale market: Need to develop to take advantage of scale (external) (1)
- Processes for high-rate manufacturing of high-pressure, high-voltage-capable GDL materials (1)
- Designs/architecture of cells suited for large-scale, high-volume manufacturing; e.g., DFMA™ (internal) (1)
- Need the participation of large companies to lower the price/unit
- Need durability data (cannot scale up without having durable product) (internal)
- Accelerated durability evaluation methods for components

## Manufacturing and Scale-Up Internal/External Challenges Brainstorming and Voting

- Costs related to hydrogen storage and transport, infrastructure
- Public education of hydrogen safety and handling (external)
- Safety aspect of hydrogen electrolysis (external)
- Greater market and demand will promote competition between the companies and should lead to lower costs
- Many suppliers not willing to invest in a perceived small market to develop relevant technology
- Standardization of stacks/BOP components
- Improved power supply efficiency over current and voltage range (internal)
- Scale up stack with fewer part counts
- Broader recognition and consideration of hydrogen production in clean-tech manufacturing initiatives and energy grid storage
- Need a cost on carbon dioxide to drive this forward (external)
- Demand/volume to support economy-of-scale component production (external)
- Bring other industries with well-established manufacturing abilities into the hydrogen production society, such as the automotive industry
- Scale-up is expensive—hard to justify investment (internal/external)
- Guaranteed, large-volume order of electrolysis systems, with lead time for R&D and manufacturing development time

### Table 25. Manufacturing and Scale-Up RD&D Needs Brainstorming and Voting

**Financial Support** Total Votes: (16) (5)

**Near Term**

- MW stack development support (6) (3)
- Market-building activities (demonstrations, legislation, incentives, implementation, etc.) (4) (1)
- Pre-commercial market support/early adopter subsidized product placements (2) (1)
- Attract other hydrogen end users (such as small refinery plants who like to have on-site production)

**Long Term**

- Market development; for example, U.S. Department of Defense Fuel Cell Demonstration Program model (3)
- DOE-sponsored "standard" design PEM plant: Competitive design teams, consortium of component manufacturers (1)

**Material Purity and Cost** Total Votes: (14) (5)

**Near Term**

- Catalyst understanding, development (near and long terms) (3) (2)
- Identify reliable, inexpensive, highly active electrodes for electrolyzers (2) (2)
- Develop new catalysts to boost performance and efficiency (1) (1)
- Develop low-cost, thin, and more durable membranes for low- and high-pressure operations (5)
- Commodity price versus volume study. Leverage United States Geologic Survey (USGS) Minerals Yearbook data and experts (2)
- Material purity database for compatible materials in entire system (1)

**Cost and Limited Availability of Components and Validation Processes**

**Near Term** Total Votes: (16) (3)

- Stack and BOP scale-up; design, validation, etc. (7) (1)
- Collaboration with national laboratories, validation, and testing of scaled-up stacks (4) (1)
- Development of standard integrated system—forecourt scale (3) (1)
- Bench-scale testing of pressurized, high-temperature/low-temperature electrolyzers (2)
- Improved designs, power supply efficiency over current/voltage range. Power supply cost and efficiency
- Specification for 3 MW PEM plant. Derive component specifications (targets)

## Manufacturing and Scale-Up RD&D Needs Brainstorming and Voting

### Develop Advanced Manufacturing Process Total Votes: (15) (2)

**Near Term**

- Improve and streamline manufacturing process of hardware materials (2) (1)
- Engineer cell/stack materials suitable for advanced manufacturing processes; such as physical vapor deposition (PVD)/chemical vapor deposition (CVD), atomic layer deposition (ALD)/physical layer deposition (PLD), or 3D printing (2) (1)
- Stack design for lower tolerance requirements for components (4)
- Development of advanced thermal spray technology for cell fabrication, multi-layer (2)
- Creation of ASTs and ways to assess durability commensurate with level of manufacturing processes (2)
- Materials and processes amenable to high-speed manufacturing need to be developed (1)
- Provide expert manufacturing assistance to electrolyzer companies and their component suppliers (1)
- Low-cost hardware manufacturing process
- Advanced automation for stack assembly

**Long Term**

- Investment in equipment capable of large-scale manufacturing (1)

### DFMA™ Analysis Assistance, Low-Volume Manufacturing Total Votes: (4) (2)

**Near Term**

- Develop design for DFMA™ studies for very-low-volume production of electrolysis systems and the transition to higher volumes. 3D printing analysis should be included (1) (2)
- Develop simulation tool for quick and efficient evaluation of making electrolyzer components with either 3D printing or more traditional manufacturing methods. Tool users are suppliers (3)

### Low-Cost Manufacturing for Low Volume Total Votes: (8) (0)

**Near Term**

- Low-cost, large-format MEA fabrication process development (4)
- DOE-brokered multiparty, large-volume buys; e.g., SECA 441 heat steel (3)
- 3D print to make components (1)

**Votes in (green), priority votes in (blue).**

# Appendix E: Participant List

| **Participants (Name – Organization)** | |
|---|---|
| Christopher Ainscough – DOE/NREL | Olga Marina – PNNL |
| Everett Anderson – Proton OnSite | Eric Miller – DOE FCTO |
| Katherine Ayers – Proton OnSite | Cortney Mittelsteadt – Giner, Inc. |
| Dmitri Bessarabov – HySA Infrastructure | Trent Molter – Sustainable Innovations |
| Eric Brosha – LANL | Frank Novachek – Xcel Energy |
| Geoffrey Budd – ITM Power | Jim O'Brien – Idaho National Laboratory |
| Joseph Cargnelli – Hydrogenics Corp. | Seth Paradise – Power-One |
| Kim Cierpik – CNJV | David Peterson – DOE FCTO |
| Whitney Colella – SA Inc. | Randy Petri – Versa Power Systems |
| Sara Dillich – DOE FCTO | Bryan Pivovar – NREL |
| Huyen Dinh – NREL | Todd Ramsden – NREL |
| Josh Eichman – EERE Fellow | Katie Randolph – DOE FCTO |
| Mitch Ewan – HNEI | Robert Sievers – Teledyne Energy Systems |
| Wayne Hambek – Entegris | Voja Stamenkovic – ANL |
| Monjid Hamdan – Giner, Inc. | Bill Summers – SRNL |
| Steven Hamrock – 3M | Erika Sutherland – DOE FCTO |
| Kevin Harrison – NREL | Amit Talapatra – Energetics |
| Joseph Hartvigsen – Ceramatec | Greg Tao – MSRI |
| Rob Harvey – Hydrogenics Corp. | Conghua Wang – Treadstone |
| Owen Hopkins – Entegris | Dylan Waugh – Energetics |
| Hui Xu – Giner, Inc. | |

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