2017 H2@SCALE WORKSHOP REPORT

May 23-24, 2017

University of Houston

Houston, TX

Transformational technologies that reduce the cost of hydrogen distribution, diversify the feedstock available for economic hydrogen production, enhance the flexibility of the power grid through large-scale energy storage, generate jobs, and provide global technology leadership for export of next-generation energy solutions.

Hosted By:
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Fuel Cell Technologies Office

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Executive Summary

The U.S. Department of Energy's H2@Scale initiative will enable innovations to generate hydrogen as an energy carrier, coupling nuclear power, fossil fuels, the electricity grid, and renewables to enhance the economics of both baseload plants and intermittent renewable energy, improve resiliency, and avoid curtailment. [1] Current and emerging hydrogen production technologies utilize diverse energy feedstock, including natural gas, water, electricity, high-temperature heat, and sunlight. The flexibility and performance capabilities of these technologies create potential for their dynamic integration with power generators and the electricity grid. Such integrations would enable hydrogen production technologies to support the grid, such that hydrogen production mitigates power curtailment and enhances grid stability. The resulting growth in hydrogen production would be anchored by emerging domestic industries, such as fuel cell vehicles, along with existing large-scale hydrogen consumers, such as petroleum refineries and ammonia producers.

H2@Scale characterizes the ability of diverse methods of hydrogen production, deployment, and use to collectively achieve national energy system goals. Research efforts within this initiative include scalable concepts for dispatchable hydrogen production, delivery and storage, including hydrogen carriers, liquefaction, materials development, and integration of hydrogen production with diverse power generators.

In May of 2017, DOE, the National Renewable Energy Laboratory (NREL), and the University of Houston hosted a workshop to:

- Gather stakeholder feedback on early-stage research and development (R&D) needs to advance H2@Scale, as outlined in the draft H2@Scale Roadmap shared with participants.
- Identify opportunities to align H2@Scale R&D needs with industry priorities and national lab capabilities.
- Identify regional and near-term opportunities to use domestic hydrogen production to support resiliency of power generation and alignment of industry with global imperatives.

Approximately 80 attendees from across industry, government, and the national laboratories participated in this workshop. Key concepts discussed during the workshop included:

- The upcoming launch of an H2@Scale consortium of national laboratories that facilitates collaborative R&D with industry. The consortium will leverage best practices from the DOE's Energy Materials Network. Key pillars of the consortium will include:
  - Techno-economic Analysis and Modeling
  - Materials Compatibility
  - Grid Simulation and Electrolyzer Integration

[1] For more information, please see: https://energy.gov/eere/fuelcells/h2-scale

- Hydrogen Risk Assessment and Planning R&D

- Preliminary techno-economic analysis indicates that the U.S. has sufficient domestic energy resources to meet aggressive growth in hydrogen demand over the next several decades.

- Lessons learned from the successful integration of renewables with the electricity grid in Texas. Measures implemented by the Electric Reliability Council of Texas to manage intermittency included:
  - Implementation of performance requirements for renewable generators (e.g. ability to remain online during faults and provide certain grid services).
  - Expansion of planning for the availability required of power reserves.

- Uses of fuel cells in heavy duty vehicles such as drayage trucks at ports, including a demonstration planned at Port Houston to reduce pollution emissions.

- Next-generation nuclear reactors have potential for integration with emerging, early-stage high-temperature hydrogen production processes, such as thermochemical cycles. Such integration can take advantage of reactor heat when the reactors are not needed on the grid, thereby mitigating curtailment of baseload power.

- Hydrogen is critical to refining of crude oil into high-value products (e.g. diesel and jet fuel), as well as to removal of impurities from fuel (e.g. sulfur and nitrogen). Hydrogen also has potential value as a combustion fuel to support refineries' emissions reduction goals.

- The availability of hydrogen that is produced as a by-product of industrial processes (such as petrochemical cracking) is expected to grow to 8,000 tonnes H_2/day by 2020, largely due to the growing abundance of low-cost natural gas.

- Integration of multi-megawatt scale electrolyzers with the electricity transmission grid will require fundamental research to lower the costs of electrolyzer components, development of advanced power electronics for grid integration, and development of manufacturing technologies.

- Analysis and coordination are required for large-scale deployment of hydrogen that is produced from grid electricity. Such deployments will require evaluation of economic cases for electrolyzers that supply grid services, development of codes, standards, and technologies that minimize the costs and increase the reliability of hydrogen infrastructure, and alignment across policies that incentivize hydrogen use.

Breakout sessions were also held during the workshop to solicit feedback on methods to collaborate with national laboratories, and areas of interest for collaborative R&D. Discussions from these sessions are summarized in the respective chapters of this report.

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Plenary Session

Overview of Hydrogen and Fuel Cells Technology Status

Dr. Sunita Satyapal, **U.S. Department of Energy Fuel Cell Technologies Office**

Dr. Satyapal opened the workshop by describing strides that the hydrogen and fuel cell industry has taken over the past several decades as a result of strong alignment and collaboration between research conducted by government and commercialization efforts in industry. Key achievements have included:

- Commercial sale or lease of over 1,600 fuel cell electric vehicles (FCEVs) since 2014. Note that as of September, 2017, nearly 3,000 FCEVs have been sold or leased in the U.S.
- Opening of 27 retail hydrogen fueling stations as of April 2017.
- Exponential annual growth in global shipments of fuel cells for portable, transportation, and stationary power applications (e.g. forklifts and backup power units), resulting in over 60,000 fuel cells shipped worldwide in 2015.
- The world's first demonstration of fuel cells in a class 8 heavy-duty truck (2017), fuel cell parcel delivery van prototypes (2017), an Army vehicle (2017), and a fleet of airport cargo trucks (2015).
- World's first deployments of hydrogen fuel cells in a passenger train (2017) and in auxiliary power for a maritime port (2015), and over 17 million passengers in hydrogen fuel cell transit buses in California.

Members of industry are now taking an increasing leadership role in enabling hydrogen-based technologies within the global energy system, as evidenced by the 2017 launch of the Hydrogen Council, a partnership of 13 companies committed to investing over $10.7 billion in hydrogen technologies in the next five years, and to making recommendations to key stakeholders to achieve growth in hydrogen.

Dr. Satyapal summarized the H2@Scale concept and concluded by discussing a national lab consortium approach to enabling R&D necessary for H2@Scale. An H2@Scale consortium would assemble national lab capabilities within the areas of:

1) Technoeconomic analysis and modeling,
2) Materials compatibility,
3) Grid simulation and electrolyzer testing, and
4) Hydrogen risk assessment and planning

The consortium structure would follow that of other recently launched consortia within the DOE's Energy Materials Network, which aims to make lab capabilities more accessible to industry and academia. Dr. Satyapal concluded with a summary of DOE's activities regarding H2@Scale to date, including the original concept pitch at the Lab Big Idea Summit, stakeholder engagement, an ongoing technoeconomic analysis project, development of an H2@Scale research, development, and demonstration (RD&D) roadmap, and grid simulation and testing work. The next steps for DOE are to complete the H2@Scale Roadmap, using input from stakeholders at the workshop and at the Annual Merit Review to help prioritize efforts, and to explore release of a cooperative research and development agreement (CRADA) call to solicit engagement of industry and academia with the H2@Scale consortium.

Overview of H2@Scale Concept and Preliminary Analysis

Mark Ruth, **National Renewable Energy Laboratory**

Mr. Ruth presented an overview of the H2@Scale concept. Mr. Ruth commenced by describing the massive scope of the energy sector, both in terms of energy produced and employment, and enumerated key challenges, such as energy independence and emissions reduction. He explained that transformation of the power grid to meet or exceed DOE's 2050 goals for solar and wind penetration is extremely challenging due to the resulting needs for grid services and energy storage. The H2@Scale vision is premised on the ability of hydrogen to address many energy sector challenges simultaneously.

In 2017, the national laboratories began a technoeconomic analysis task to characterize the technical potential of hydrogen demand from current and emerging industries (e.g. FCEVs for transportation and direct reduction of iron via hydrogen), as well as the technical potential of hydrogen supply from domestic resources, including renewable power, nuclear power, natural gas, and coal. Mr. Ruth presented preliminary results of the analysis of technical potential, concluding that the U.S. has sufficient domestic resources to meet aggressive growth in hydrogen demand. Mr. Ruth then explained that hydrogen production from water at large scales will require reductions in the cost of water splitting. Electrolyzers may be able to achieve these goals through a combination of research investments that lower their capital costs and through dynamic integration with the power grid, such that they utilize low-cost power during off-peak times and/or receive capacity payments. Other areas of research that will need to be addressed for wide-scale hydrogen deployment include high-temperature hydrogen production processes that can be integrated with industrial heat, hydrogen storage and distribution infrastructure, and value-add applications for hydrogen.

Strategies and Technologies to Enable Resiliency of the Power Grid

Sandip Sharma, **Electric Reliability Council of Texas (ERCOT)**

Mr. Sharma discussed how ERCOT evolved the Texas grid to manage the increase in power supplied by renewables, from only 0.008% in 1999 to 17.4% in 2015. The majority of renewables penetration in Texas is currently wind power, but over 1,500 megawatts (MW) of solar are also expected to connect to the grid by the end of 2017. Substantial renewable generation has been located in the western region of the state, while demand is centered in the East. To manage this mismatch between supply and demand, ERCOT invested nearly $7 billion in installing new transmission lines, through the Competitive Renewable Energy Zone (CREZ) project completed in 2014. ERCOT has also created new regulatory requirements for renewable generators, to mitigate risks of grid instability. Renewable generators must now:

- Be capable of "primary frequency response" to the power grid. Renewable generators are now effectively required to employ technologies (e.g. governors) that can mitigate frequency disruptions. These disruptions may be exacerbated under high penetrations of renewables due to: 1) mismatch between power supply and demand, and 2) loss of real inertia on the grid as conventional synchronous generators are replaced with wind and solar plants. ERCOT also reduced the maximum dead-band permissible for governors from 36 mHz to 17 mHz, to generate frequency response at smaller disturbances than was previously the case.
- Stay online during faults that cause sudden drops or increases in voltage. This "voltage ride-through" requirement prevents large amounts of renewables from tripping offline simultaneously during a fault.
- Provide voltage support services, in the form of producing or absorbing reactive power when needed.
- Implement controls that restrict their ramp rate to 20% of their nameplate capacity.

Regulations were also enacted to ensure that the ancillary services procured each year are sufficient to manage system faults:

- As of 2017, "regulation service" (i.e. reserves that add or shed load from the grid within seconds) are procured based on calculations of grid variability that include forecasts of solar power; previously, variability only accounted for wind.
- As of 2015, "responsive reserves" (i.e. reserves used to stabilize grid frequency) are procured annually based on estimates of the amount of inertia the grid is likely to have, given historical data; previously, responsive reserves were procured based on the size of the two largest generating units on the ERCOT grid. This change was made to ensure that the quantity of reserves available could stabilize the grid (i.e. prevent "under frequency load shedding"), even under the extreme scenario wherein ERCOT's two largest generators trip offline while the grid's inertia is already low.
- As of 2016, the procurement of "non-spinning reserve services" (NSRS, i.e. reserves brought online within about 30 minutes to address loss of generating capacity, errors in load forecasts, risks of rapid fluctuations in net load, or insufficiency in generating capacity) incorporates calculations of the risks of net load ramp (e.g. if wind power declines down while power demand rises) and load forecast error.

The success of these regulatory and technological measures is demonstrated by the fact that steady increase in ERCOT's Control Performance Standard 1 (CPS1) score from 2008-2017, and by the steady decrease in average hourly "regulation up" reserves needed from 2011 to 2016; wind penetration in Texas was steadily increasing during this time. The CPS1 score is indicative of frequency error on the grid, and regulation up reserves indicate the need for additional generating capacity online. The ERCOT Reliability Risk team has additional ongoing goals to improve the accuracy of renewable forecasts, and maintain sufficient reserves to manage fluctuations in frequency, forecast errors, and rapid ramps in load.

Mobile Source Emissions at Port Houston - Can Hydrogen Help?

Ken Gathright, **Port Houston**

The Port of Houston Authority owns and operates cargo terminals that account for about 15% of the total tonnage transported through the Port of Houston. Port Houston is within a non-attainment area for ground level ozone, making nitrogen oxide (NOx) and volatile organic compound (VOC) emissions of particular concern. Heavy duty diesel vehicles (HDDVs) account for about 14% of the NOx emissions and 22% of the VOC emissions at Port Houston from goods transport. These trucks are owned by a diverse range of companies; 622 different trucking companies visited the Barbours Cut and Bayport container terminals (within Port Houston) in 2016. Additionally, NOx emissions of these vehicles can vary widely depending on their age. As an example, a diesel engine released in 2010 has 95% lower NOx emissions than an engine in a truck released between 1998-2003; about 32% of trucks in Port Houston have engines with model years from 1998-2003. Hydrogen fueled drayage trucks have the potential to essentially eliminate those emissions.

Hydrogen fuel cells have been deployed in several port drayage demonstration projects, including:

1. Toyota's Project Portal to deploy fuel cell powered drayage trucks in the Ports of Long Beach and Los Angeles.
2. Fuel cell powered drayage trucks being deployed in the Ports of Long Beach and Los Angeles by U.S. Hybrid and Jiangsu Dewei Advanced Materials Co.

3. Fuel cell powered drayage trucks being deployed in the Ports of Long Beach and Los Angeles by Kenworth Trucks.
4. Fuel cell trucks being developed by Nikola Motor Company.
5. Fuel cell drayage trucks being developed by the Gas Technologies Institute and U.S. Hybrid for use at Port Houston.

Barriers to growth of hydrogen fuel cell powered drayage trucks in Houston include:

- Insufficient regulatory or market forces to incentivize replacement of conventional trucks.
- The reduction in NOx enabled by a fuel cell truck relative to a new diesel truck is marginal.
- Fuel cell trucks are significantly more expensive than relatively new used diesel trucks.
- Lack of hydrogen fueling infrastructure.
- Lack of training of first responders in hydrogen.

Mr. Gathright identified possible mechanisms to incentivize use of hydrogen powered trucks, including:

- Cargo and freight owners requiring that their cargo be shipped via zero emission vehicles.
- Use of grants to cover the costs of transitioning fleets.
- Government implementation of a "mobile source emission reduction credits" system for trucks.
- Offers of discounts by marine terminals if zero emission vehicles are used.

Mr. Gathright concluded by highlighting other potential applications for hydrogen and fuel cells at the port: trains, cargo handling equipment, harbor vessels (e.g. tour boats), ocean going vessels, and energy storage applications.

Plenary Questions and Answers

1. Is energy storage recognized as an independent component within the electricity grid, and are there taxes or levies placed on its use of electricity?
    a. No, ERCOT treats energy storage as an ancillary service that has access to wholesale load, not subject to retail tariffs.

Session I: Hydrogen's Current Usage in Industry and Transportation

Hydrogen Use at Refineries, & Drivers for Expected Growth

Aimee LaFleur, **Shell**

Ms. LaFleur presented on hydrogen's use in refineries and connections to H2@Scale. First, she gave an overview of how refineries operate, as a refinery's configuration and feedstock dictate its hydrogen demand. The main roles of hydrogen in refining are: 1) hydrotreating to remove impurities, such as sulfur, aromatics, and olefins and 2) hydrocracking hydro-cracking, to break larger molecules into smaller, higher-value molecules (e.g. diesel, kerosene, and jet fuel). The primary sources of hydrogen at a refinery are the catalytic reformer, which produces hydrogen as a by-product of producing gasoline, and the steam methane reformer, which is used to produce hydrogen from natural gas. Hydrogen is also produced through gasification/partial oxidation of petroleum residuals, and as a by-product of "steam cracking" of long chains of hydrocarbons. These hydrogen streams are supplemented with purchase of hydrogen from third parties (industrial gas companies). Refineries optimize their hydrogen use based on the processes they implement and the pressures and temperatures at which these processes require hydrogen.

Ms. LaFleur concluded by framing the role of H2@Scale in refineries' supply of hydrogen. In order to displace SMR, any new hydrogen production technology should be targeted to achieve comparable cost, purity, reliability, and integration with refinery configurations. At Shell, methods to achieve decarbonization are being explored, such as capture of carbon from flue gas. Decarbonization could also be achieved through use of greener methods of hydrogen production, and/or use of hydrogen as a combustion fuel (instead of natural gas). As older refinery infrastructure ages, companies may be more willing to invest in such new technologies if they are competitive with alternatives.

Current Use of Hydrogen in Ammonia Production and Research Needs

Steve Szymanski, **Proton Onsite**

Mr. Szymanski presented on the role green ammonia can have in H2@Scale. Megawatt-scale electrolyzers were used to make ammonia in the early- to mid-1900s, and they have again been deployed in specific chemicals production applications in recent years. About half of hydrogen consumption worldwide is for ammonia production; in the U.S. this hydrogen accounts for about 4% of industrial natural gas consumption. Of the 18 chemicals that account for 80% of the chemical industry's global energy demand, ammonia production is the largest energy consumer. Furthermore, the ammonia market is growing steadily, and it is expected to continue to grow at around 1.3% per year through 2050.

Mr. Szymanski then discussed the role that renewable hydrogen could play in the ammonia industry. Distributed, small-scale ammonia production plants, such as the 25 ton/year plant at the University of Minnesota, can leverage available renewable resources for hydrogen production; in the U.S., many of these resources are also in regions of the country that have large ammonia demand. Moreover, the applications of ammonia can extend beyond its conventional use as fertilizer: ammonia can be used to transport hydrogen cost-effectively long distances (e.g. to hydrogen fueling stations, where it would be dehydrogenated to release hydrogen), to store energy at a smaller footprint than possible with batteries, or to produce power through direct use in fuel cells. Ammonia can therefore serve as an energy carrier that connects renewable power generation and energy-intensive industries located throughout the world. Mr. Szymanski concluded by outlining research needs to enable large-scale deployment of ammonia, including:

- Catalysis to enhance the efficiency of ammonia production,
- Reductions in the capital cost of electrolysis,
- Durability, stability, and efficiency of electrochemical ammonia synthesis,
- Improvements in the efficiency of hydrogen production from ammonia through electrochemical cells,
- Development of fuel cells and turbines that can run directly on ammonia.

Innovative Uses of Hydrogen in Iron-Making

Dr. Jayson Ripke, **Midrex**

Dr. Ripke reviewed the role that hydrogen can play in steelmaking in the U.S. The primary methods of steel production currently rely on either: 1) basic oxygen furnaces (BOFs), or 2) electric arc furnaces (EAFs). Significant differences in these processes are that:

- BOFs are supplied by liquid iron that is produced from blast furnaces (BFs). BFs refine iron ore using coke (produced from coal in coke ovens), which reacts with the hot air blast to reduce the iron ore to iron and melt it.

- EAFs use scrap metal and reduced iron (i.e. pig iron, direct reduced iron [DRI], or hot briquetted iron [HBI]) as feedstock; these feedstocks are melted using electricity. The reduced iron is produced using iron ore and reformed natural gas or coal.

In the early 2000s, EAFs overtook BOFs as the dominant method of steel production in the U.S. EAFs operate more efficiently and produce less emissions than BOFs; the performance of each depends on the feedstock used. While the process of direct reduction of iron (DRI) conventionally relies on reformed natural gas or coal, it can also be performed using hydrogen as the reductant.

A Midrex HBI plant is currently being built in Corpus Christi, TX for the steelmaker Voelstapine. This plant will rely on reformed natural gas, but could be converted to use hydrogen, in which case it would consume over 300 tons of hydrogen per day. Dr. Ripke then identified numerous efforts worldwide to reduce the emissions from steelmaking along with remaining R&D needs. With respect to use of hydrogen in DRI, R&D is needed on: 1) control of the physical and metallurgical quality of iron ore reduced in higher concentrations of hydrogen, 2) characterizing risks of hydrogen embrittlement of both the iron ore and the equipment utilized, and 3) optimization of flowsheet, mass & energy balances, and techno-economic assessment (including CAPEX & OPEX). R&D should also be performed on the viability of hydrogen as a supplement to coke in reducing iron ore in BFs.

Session I Questions and Answers

1. Does increasing the percentage of hydrogen in a reducing environment produce superior iron?
    a. Not necessarily – replacing carbon monoxide (CO) with hydrogen does not improve purity of the product.

2. What would be the driver for three industrial sectors to adopt/use more expensive green hydrogen?
    a. For refineries, there must be a financial incentive. Government pressure, perhaps through a carbon tax will help. Aging infrastructure also creates a huge opportunity for replacement. Alignment of the timing of these efforts and opportunities is important.
    b. For ammonia production, the development of cost-competitive distributed Haber-Bosch plants would help. Incentives for companies to use green ammonia would also help. An example could be the ability to charge a premium for sustainable food produced with green fertilizer.
    c. For steelmaking, hydrogen must be cost-competitive to displace alternatives. The impact of using hydrogen in plant footprint is also important. Other parts of the world have carbon taxes, which create an incentive. To that end, international customers may create pressure on U.S. steelmakers.

3. What is the minimum purity required for hydrogen from natural gas reforming to be utilized?
    a. Higher purity is always better, as it minimizes the use of pressure swing adsorber (PSAs), which take up space. However, lower purity hydrogen will be used in combination with PSAs if necessary.

4. What is the round trip efficiency of hydrogen storage with ammonia? Can a Haber-Bosch plant operate at 20% capacity or is that not sufficient?
    a. While the round-trip efficiency is relatively low, the primary interest in use of ammonia as a hydrogen carrier is due to its density relative to transport of hydrogen gas long distance. Ammonia can be stored and transported at relatively low pressure, and it is an efficient hydrogen carrier.

5. If a hydrogen economy took off, what would be the impact on demand for petroleum products that drive refineries' use of hydrogen?
    a. Shell is trying to take a broad approach to be prepared and have a strategy. Looking at FCEVs too. Looking at near and long-term, participating in hydrogen stations and infrastructure.

6. How does electricity usage vary between iron production techniques?
    a. Steelmaking by DRI/EAF (a.k.a. mini-mills) is 12.5% more energy efficient, per ton of liquid steel, than the BF/BOF (a.k.a. integrated steelmaking). EAFs and DRI consume much less energy than BFs. Of course, electric arc furnaces (EAFs) consume more electricity than BF/BOFs because BF/BOF uses predominantly coal/coke instead of electricity.

7. What are the drivers for EAFs to overtake blast furnaces in US?
    b. Fewer emissions (55% less CO_2 per ton of liquid steel), and the ability to avoid building a coking facility.

Session II: Hydrogen Delivery & Grid Infrastructure

Current Status and Research Needs for Hydrogen Infrastructure (Pipelines, Liquefiers, Tube Trailers, and Fueling Stations)

Aaron Harris, **Air Liquide**

Mr. Harris presented that changing transportation fuel at scale is possible; it was done to remove lead from fuel, and can similarly be done to decarbonize. For electrolysis to be viable, the scale must increase by orders of magnitude while costs decrease. Electrolyzers must be at capacities relevant to grid operators (100-200 MW) to support grid stability while supplying low-cost hydrogen. A significant challenge in growth of hydrogen at scale is that it is currently not sold as a commodity, but a service. Additionally, policy measures will be necessary to prevent conflicting incentives and to promote electrolytic hydrogen. As an example, significant hydrogen can also be produced from the biogas industry, which may have more incentives than electrolysis. Furthermore, the distribution costs for transporting hydrogen are not trivial, particularly since centralized production facilities are concentrated in the Gulf Coast while growing markets for hydrogen in fuel cell vehicles are along the Northeast and West coasts.

Mr. Harris argued that the DOE should encourage industry relationships for high risk research and deployment opportunities. The DOE can identify and collaborate with other key user communities in federal government, such as the Department of Defense (DOD) and National Aeronautic Space Agency (NASA). R&D priorities could include large-scale electrolysis, large-scale reforming of biogas, reduction in the scale of liquefaction, and safety R&D. With respect to safety, reduction in the footprints of liquid storage at urban station, gaseous stations, promulgation of safety information, and increase in public confidence are needed. Finally, distribution costs of trailers, terminals, and hydrogen fueling stations must be reduced.

Hydrogen Safety, Risk Assessment, and Material Compatibility R&D

Dr. Christopher Moen, **Sandia National Laboratories**

Dr. Moen presented on safety, codes, and standards for hydrogen technology. The goal of research in these areas at Sandia National Laboratories (SNL) is to facilitate the safe use of hydrogen technologies by understanding and mitigating risk. Over time, Sandia's quantitative risk analysis (QRA) of hydrogen releases has informed modifications to codes and standards that govern designs of hydrogen facilities, such as the National Fire Protection Association (NFPA) 2 code, and they have also resulted in the development of a publicly available tool, HyRAM, that characterizes the risks of user-defined designs of hydrogen facilities. Sandia's QRA resulted in indoor fueling of fuel cell vehicles (forklifts) to be permissible per NFPA-2. In 2014, Sandia also analyzed the impacts of the 2011 revision of NFPA-2 on the footprint of hydrogen fueling station designs. Their analysis indicated that 20% of gasoline stations in California had sufficient land area to accommodate hydrogen dispensers. Sandia is now developing models of cryogenic hydrogen behavior, with the goal of informing the design requirements of liquid hydrogen storage.

Sandia is also a leader in the evaluation of materials for use in hydrogen service. Sandia's evaluations of steels and polymers have resulted in publication of numerous technical references and development of testing protocols, as well as informed component design codes. Their test capabilities range from coupon specimens to full components, such as pressure vessels for hydrogen storage. Their research is being performed in collaboration with the international community to coordinate R&D, and support international consensus on codes and standards.

Dr. Moen concluded with safety, codes, and standards needs for H2@Scale. These include protocols for distributed production and power systems integration, oxygen management in distributed systems, metrology at scale, purity requirements and purification techniques, gas segregation in mixed gas systems, assessment of leakage from bulk storage, materials compatibility in infrastructure, requirements for hydrogen combustion, safety requirements for underground hydrogen storage, standards for maritime shipping of hydrogen, and safety standards for shipment of liquid hydrogen.

Role of Electrolyzers in Grid Services

Dr. Rob Hovsapian, **Idaho National Laboratory**

Dr. Hovsapian presented on the role that electrolyzers play in the H2@Scale concept. Electrolyzers have potential to supply grid services, such as load and frequency management, as a form of responsive load. Responsive loads are technologies that consume power from the grid on the basis of grid signals; other examples include residential and commercial equipment, such as air conditioners and refrigerators, that are programmed to draw power based on grid signals, to support grid stability. Dr. Hovsapian reviewed experimentation performed by Idaho National Laboratory (INL) and the National Renewable Energy Laboratory (NREL) to evaluate the viability of electrolyzers as responsive load. Testing has showed that electrolyzers can fluctuate their power intake from 25% to 100% of their rated power within sub-seconds. Due to this ability, specific services that electrolyzers can provide to the grid include:

- Reduction of peak loads on the grid: electrolyzers can reduce their power intake when demand for power is high.
- Support in management of power prices: electrolyzers can selectively consume energy when the price of power is low, freeing energy when the price of power is high
- Regulation: electrolyzers can ramp their power intake up or down to mitigate the impacts of short-term mismatches between power supply and demand on the grid.
- Spinning Reserve: if a power generator trips off the grid, electrolyzers can rapidly reduce their power intake to mitigate the impacts of the fault on stability.
- Ramping: electrolyzers can fluctuate their power intake to counter-balance rapid changes in power supply on the grid.

- Artificial inertia: in the event that the frequency of power supply on the grid is irregular (e.g. due to a fault in a generator), fleets of electrolyzers can rapidly fluctuate their power intake to stabilize frequency.
- Voltage management: an electrolyzer can vary its power consumption to correct irregularities in voltage on the grid.
- Autonomous response: if connected with an intelligent controller, an electrolyzer can identify the grid services it should supply autonomously (without guidance from utility signals).

The objectives of ongoing R&D being performed by INL and NREL are to:

- Characterize the technical and economic potential of electrolyzer use in grid services, and in supplying hydrogen to fueling stations.
- Validate electrolyzer performance in conditions that mimic grid signals.
- Determine the communications and controls technologies needed for electrolyzer integration with the grid.

INL and NREL have tested electrolyzer response, startup, and shutdown times for 200 hours to date, under various simulated grid conditions. They are now testing the performance of electrolyzers under simulations of the PG&E electricity grid as well.)

Session II Questions and Answers

1. On risk assessment – are consequence analysis and probability assessment taking into account that hydrogen is completely different from other fuels? Reliability issues are important.
    a. Probability is hard to evaluate because there is not a large amount of time and experience with hydrogen infrastructure to gather data from. Today, probabilities of failures are often approximated from analogous materials and gases.
    b. Reliability of hydrogen refueling technologies is a significant issue, and is being addressed by tasks within the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project.
    c. It is important to note that equipment in high-pressure hydrogen service has historically undergone extreme testing for acceptance– drop testing, gunfire testing, etc. Additionally, DOE assembles and publicizes lessons learned from incidents with hydrogen through www.h2tools.org The H2Tools portal hosts information anonymously, and DOE strongly encourages members of the hydrogen community to contribute to its database.

2. Is there interest in use of liquefiers as responsive load on the grid?
    a. Liquefiers cannot respond to fluctuations in power signals rapidly enough.

3. There has been a lot of talk about hydrogen generation, but not much on storage. When does liquefaction make more sense for hydrogen storage than compressed gas?
    a. DOE has on-going work on storage and delivery. Vehicles currently utilize high-pressure tanks, but DOE is researching numerous hydrogen storage technologies, as well as approaches to efficient liquefaction, such as use of magnetocaloric materials.

4. What are the materials compatibility issues in applications other than refueling stations (refineries, etc).?

    Embrittlement is a concern in many applications where metals are exposed to hydrogen. Examples of other applications include cost optimization of pipelines through material selection, as well as assessing compatibility of existing infrastructure (e.g. natural gas pipelines) with hydrogen service.

Breakout Session: Discussion on H2@Scale Lab Capabilities

In small groups, feedback was gathered on laboratory capabilities in the areas of:

1. *Hydrogen Materials Compatibility*
2. *Hydrogen Risk Assessment and Safety R&D*
3. *Grid Simulation and Electrolyzer Integration*
4. *Modeling and Analysis*

Key Takeaways from the Breakout Session:

1. **Interest in lab capabilities is evenly distributed across the categories listed above.**

2. **The largest barrier identified to the use of national laboratory capabilities was a lack of familiarity regarding lab expertise.** Other important barriers identified were cost, the long time frame required to execute contracts, and perception of intellectual property (IP) risk.

3. **Feedback on working with labs overall**: Many industry players are unaccustomed to collaborating with the national laboratories, and are hampered by the complexity and "red tape" involved. Moreover, R&D at the labs is often on applications that are higher risk than those relevant to the business world. Industry would only leverage very specific capabilities that the labs already have, as generation of new capabilities is difficult and riskier than other business agreements. However, collaboration with labs is beneficial in that it adds confidence in in R&D results. The laboratories are able to operate as an "honest broker" of R&D results.

Participants were also asked the following questions:

1. **What areas of technological progress and/or R&D are not currently being addressed at your organization due to lack of technological expertise and capability?**

A. Risk Assessment and Safety R&D
   a. Validation of electrolyzers at scale, and integrated in grid conditions
   b. Development of odorants to detect hydrogen leaks

B. Grid Simulation and Electrolyzer Integration
   a. Concepts to enable "massive electrification" that could largely displace fossil fuels
   b. Engineering integration issues associated with electrolysis
   c. Utilization of waste heat to generate hydrogen when power is being curtailed

C. Modeling and Analysis
   a. Development of fueling protocols for efficient fueling
   b. Financial modeling and assessment of business cases for new applications for hydrogen and hydrogen infrastructure
   c. Assessment of regulatory structures to ensure that supply on the power grid is deployed to match demand, and to enable business cases for new hydrogen concepts
   d. Evaluation of possible sites for geologic storage

D. Other
    a. Development of chemical carriers for hydrogen
    b. Technologies to enable efficient electricity storage
    c. Testing of advanced hydrogen equipment as well as equipment in high-pressure conditions (e.g. hydrogen storage vessels)
    d. Improvements in fuel cell efficiency and vehicle refueling times

2. Can you give specific examples of projects or research areas where collaboration with the labs could be beneficial to you? (i.e. "R&D Wish List")

a. Improving the economics and reliability of small-scale steam methane reformers.
a. Testing of nuclear small modular reactors.
b. Development of power electronics to integrate electrolyzers with the grid
c. Understanding the typical service conditions that electrolyzers integrated with the grid will face, as well as the extremes of operation.
d. Simulations of power grids.
e. Development of novel compression technologies.
f. Testing of advanced hydrogen concepts.
g. Development of electrochemical separators.
h. Evaluation of approaches that integration with electrolyzers with the grid can provide monetary value.
i. Utilization of national laboratory supercomputing capabilities.

Session III: Hydrogen Production in the Near-term

Scalable, Economic Hydrogen Generation from Natural Gas

Dr. Jeff Mays, **Gas Technologies Institute**

Dr. Mays discussed the Compact Hydrogen Generator (CHG) technology being developed by the Gas Technologies Institute (GTI) is for large-scale hydrogen production (i.e., >2 million standard cubic feet per day) and carbon dioxide capture at lower capital costs and footprint than steam methane reforming. The CHG comprises a novel fluidized bed reactor (FBR) that generates hydrogen from steam reforming of methane. Calcium oxide is also injected into the FBR and reacts with the CO2 that results from reforming to form calcium carbonate. The calcium carbonate is subsequently separated out of the gas stream and heated in a calciner to release the CO2. The calcium oxide can then be reused in the system. As part of this project, GTI completed technoeconomic analyses of the CHG system. The cost of the CHG system is driven by capital, but the system is more cost-effective than integration of natural gas combined cycle (NGCC) turbines with amine-based carbon capture technologies. The components within the CHG system are currently at mid- to high technology readiness levels, and require a demonstration to establish their true value proposition. Of relevance to this project is that DOE's Office of Fossil Energy has been funding the development of turbines that can operate efficiently in high-temperature (> 3100°F) hydrogen or natural gas service.

Questions

1. How many hours of operation have the calcium cycles been tested in?
    a. GTI has not completed long-duration testing yet. However, if the system can run 500 cycles before renewing the calcium, then renewal will only account for 1% cost of the cost of hydrogen; i.e., not a significant impact.
2. Has the dynamic performance of the CHG been evaluated, as it has for electrolyzers?
    a. This has not been done. The intended application of this plant is to supply large, baseload volumes of hydrogen. The turbine could serve peaking demand on the grid.
3. Is GTI developing its own hydrogen turbine, or using another company's?
    a. NETL is developing a turbine with GE and Siemens.
4. What level of carbon taxes or credits would be required for the CHG to achieve parity with SMR?
    a. Please see the cost charts in the slides.

Resourcing Byproduct Hydrogen from Industrial Operations for Emerging Hydrogen Markets

Dr. Amgad Elgowainy, **Argonne National Laboratory**

Dr. Elgowainy opened by explaining that demand for hydrogen due to fuel cell electric vehicles (FCEVs) will ramp in the near-term, and may require growth in hydrogen supply. FCEVs in California alone could consume 20 tons of hydrogen per day by 2022, based on forecasts of vehicle deployments. Possible approaches to meet this demand include: 1) construction of new steam methane reformers (SMRs), 2) deployment of electrolyzers at fueling stations, 3) use of spare capacity in SMRs near FCEV markets, which will be located in California and the Northeast in the near-term, and 4) recovery of hydrogen that is currently released as a by-product of chemical production processes. Construction of new SMRs will be challenged by the capital intensity of these plants, deployment of electrolyzers at fueling stations will be challenged by both their costs and impacts to station footprint, and existing SMRs near FCEV markets may not have sufficient spare capacity to meet demand. Recovery of hydrogen from chlorine and petrochemical cracking plants may, however, be a viable approach. It is important to note that the deployment of these plants is spread throughout the country, and is increasing due to the abundance of low-cost natural gas.

The ethane, propane, and butane cracking plants expected to be installed by 2020 will produce about 8,000 tonnes of hydrogen per day as a by-product. By-product hydrogen is ordinarily burned as fuel in cracking plants. If these plants instead burned natural gas as fuel and recovered and purified the hydrogen, the marginal cost of the hydrogen would be less than $1.00/kg. Moreover, this hydrogen would have a lower carbon intensity than conventional hydrogen produced from SMR, and may therefore be able to take advantage of financial incentives from regulations such as California's Low Carbon Fuel Standard (LCFS). In conclusion, growth in domestic petrochemical cracking is creating an opportunity to capture low-cost abundant hydrogen supply to meet growing needs of the FCEV market.,

Questions and Answers

1. Are there any other industrial processes that produce hydrogen as a by-product?
    a. There are some, but they produce lower concentrations of hydrogen. Moreover, chlorine production and petrochemical cracking will produce more than the hydrogen demand of FCEVs in the near term.

2. What are barriers to use of by-product hydrogen in industry?
    a. By-product hydrogen is used in some applications, but greater use is challenged by the cost of transporting the hydrogen to centers of demand, and by lack of certainty on whether use of such low-carbon hydrogen will be credited by existing regulations (such as LCFS).

Water Electrolyzer Technology: Status and Challenges

Dr. Monjid Hamdan, **Giner**

Dr. Hamdan presented background on the history and status of electrolyzer technologies. The most mature approaches to electrolysis involve: 1) use of alkaline electrolytes, or 2) use of proton exchange membranes (PEM). Capacities of PEM electrolysis are currently growing, and currently range from <1 kg-H_2/hour to > 20 kg-H_2/hour. Current markets for large-scale electrolyzers worldwide include hydrogen fueling stations and utilities. Emerging markets worldwide include use of excess electricity on the grid to produce: 1) synthetic fuels (i.e. power-to-gas or power-to-mobility), or 2) hydrogen. These markets require larger stacks, and Giner is therefore targeting development of a 5-MW electrolyzer by 2018/19.

Dr. Hamdan discussed remaining R&D challenges in electrolysis. Lack of high-volume manufacturing technologies for membranes, membrane electrode assemblies, electrodes, plates, and other cell components challenge the amount of time and money that stacks take to develop. Lack of quality inspection and assembly technologies create similar challenges. Increasing the capacity of electrolyzers to megawatt scales is challenged by lack of cell support materials, tooling, and supply chain. Scaling is also challenged by lack of test facilities that can verify the performance of electrolyzers at higher differential pressures and with large current draws, and by the difficulty of transporting large-scale electrolyzers to test facilities themselves. Giner currently relies on the National Laboratories to test their stacks.

Dr. Hamdan then discussed emerging electrolyzer technologies and challenges, including for low temperature electrolysis (AEM) and high temperature electrolysis. These approaches require improvements in efficiency and durability, including identification of degradation mechanisms. Electrolyzer stacks in general should be improved to reduce part counts, which will reduce their labor and fabrication costs. Integration of electrolyzers with the grid requires R&D to develop power electronics that allow for rapid control of electrolyzers, and reduce costs of integrating electrolyzers with the grid. Finally, coordination between electrolyzer manufacturers, utilities, regulatory bodies, and FCEV manufacturers is a large challenge. Dr. Hamdan believes a roadmap is needed for renewable electrolysis to align the needs of diverse stakeholders.

Questions and Answers

1. When will electrolyzers transition from laboratory testing to actual integrations with the grid?
    a. This is a complex topic, and will require input from industrial gas companies.
2. Are the costs of electrolyzer testing standardized across industry?
    a. Standardization is challenging because of the many improvements that have occurred in the past several years in electrolyzer technologies, particularly with respect to membranes. Difference in technologies across companies makes standardization challenging.
3. Are accelerated test protocols for electrolyzers being developed?
    a. Giner has a goal to do this, in concert with other electrolyzer companies and laboratories.

Session IV: The Role of Hydrogen in the Future of Energy

Current and Future Markets and Challenges for Onshore and Offshore Wind in Texas

Dr. Carsten Westergaard, **Texas Tech University's National Wind Institute**

Dr. Westergaard reviewed some of the history of onshore and offshore wind technologies, along with the grid simulation and testing capabilities and R&D at Texas Tech University. Wind power has grown aggressively in Denmark since the 1990s, with wind energy producing about 40% of the country's power demand on average. Worldwide, capacity factors of wind turbines have increased over time, largely due to increases in rotor size; larger rotor sizes increase the energy a turbine can produce under given wind conditions. The capacity factor of turbines in the U.S. is, on average 32.9%; capacity factor in Texas specifically is 34.5%. Texas is currently the fifth largest wind generator in the world.

Throughout the U.S., median wind plant capacity factors can vary from 20% to 35% depending on the regions. Remaining challenges to greater penetration include: 1) transmission costs from generators to locations of power demand, 2) need to define requirements for energy storage and grid services, 3) need to optimize the mix of generators on the grid (wind, solar, fossil, and nuclear), 4) capital costs of generation, 5) power pricing and generator ownership structures, and 5) forecasting of wind generation.

Questions and Answers

1. Are there synergies between power electronics for wind turbines and those for electrolyzers?
    a. There may not be synergies, but these are both applications that need to be developed for greater renewables penetration and hydrogen energy storage.

2. What is the installed cost for an 8-MW wind turbine?
    a. A turbine itself costs $1.2M per MW for machinery. Deployment of turbines offshore has a substantial infrastructure cost.

3. How common is curtailment in the US for a wind park, and is there compensation to the owner? If not is there a need for storage?

a. Curtailment has been a big issue in the past, but is currently less than 2% in Texas. Compensation models for generators are regional.
b. Sometimes, thermal plants (e.g. nuclear) also get curtailed because of the production tax credits wind plants receive.

4. Denmark is about the size of Houston – how can we relate successes in Denmark to land area the size of Texas?
   a. A large challenge in managing wind power is connecting unpopulated areas to cities. Texas successfully accomplished this through the buildout of transmission lines in the Competitive Renewable Energy Zones (CREZ) program.

Integrating Next Generation Nuclear Generators with Hydrogen Production

Dr. Noah Meeks, **Southern Company**

Dr. Meeks gave an overview of Southern Company's service area. Their mission is to provide clean, safe, reliable and affordable energy for customers and communities. Dr. Meeks focused on advanced nuclear reactors, but noted that Southern Company is interested in all energy resources. Dr. Meeks explained that Southern Company is interested in hydrogen because it is a storable energy carrier that may enable a utility to provide energy with a high capacity factor to existing customers, as well as open up new markets. Utilities could participate in the hydrogen economy by using it for energy storage and grid services, reducing the carbon footprint and maximizing the heat value for green natural gas, and selling hydrogen for dispatchable distributed generation as well as transportation.

Dr. Meeks then described the options in nuclear reactor design. Key defining aspects of a technology include:

1) The "moderator" material chosen to control the speed of fission
2) The level of plutonium the reactor produces in generating power
3) Whether the fuel supplied to the reactor is in solid pellet form, or carried by liquids
4) Whether the fuel supplied is thorium or uranium
5) The material chosen as the reactor coolant, and the temperature and pressure at which it operates

Defining features of next-generation advanced reactor designs include:

1) Operation at high temperatures (to drive greater efficiency of power generation)
2) Ability to refuel the reactor while it is in operation
3) Ability to recycle spent fuel to generate power
4) Smaller footprints
5) Autonomous shut-down capabilities, enhancing safety

Southern Company is currently being funded by the DOE to develop a molten chloride fast reactor (MCFR) in combination with TerraPower, the Electric Power Research Institute (EPRI), Oak Ridge National Laboratory, and Vanderbilt University. The MCFR will operate at temperatures high enough that it can be integrated with hydrogen production technologies, such as the thermochemical hydrogen production cycles. In this integration, the heat from the reactor would be used to produce hydrogen when the reactor's electricity is not needed on the grid; this approach would therefore minimize generator curtailment. Thermochemical cycles are currently in early stages of research, and involve hydrogen production at temperatures ≥800C. Southern Company is considering integration of the "hybrid sulfur" thermochemical hydrogen production cycle with their advanced MCFRs. Dr. Meeks concluded by mentioning that a roadmap should be developed to outline research needs that align nuclear power with the changing energy landscape

Questions and Answers

1. Is Southern Company interested in pebble-bed reactors?
    a. They have considered them. Safety measures to allow use of high pressure gas could drive costs.

2. While Southern Company operates in a regulated market, would the concepts they're proposing also be viable in an unregulated market?
    a. EPRI is currently working with utility advisory boards to assess integration issues between renewables and flexible power generators.

3. Does Southern Company have an interest in integrating electrolyzers with nuclear power?
    a. This is an interesting concept, but they do not necessarily see the value proposition.

4. What will be scales of next generation nuclear reactors?
    a. Southern is evaluating 1000 GW class reactors. These reactors may particularly have viability as carbon constraints challenge coal plants. Moreover, scaling down in size is challenging for nuclear reactors.

Fundamental Hydrogen Production Research Needs being addressed by the HydroGEN R&D Consortium, within DOE's Energy Materials Network

Dr. Eric Miller, **U.S. Department of Energy's Fuel Cell Technologies Office**

Dr. Miller presented on the Energy Materials Network (EMN) at DOE, and how the structure of EMN consortia can be leveraged by the H2@Scale consortium now being developed. The goal of the EMN is to accelerate development and deployment of novel materials into clean energy products using national lab consortia centered around specific materials classes. Seven consortia have been launched to date, three of which involve hydrogen technologies. Each of these consortia have four defining features:

1. World-class capabilities in specific areas of materials research
2. Development of portals to allow sharing of materials data and analysis tools
3. A clear point of engagement (i.e. "concierge) that supports external stakeholders in working with the consortium
4. Short-form contractual agreements that can expedite access to member national laboratories (i.e. "streamlined access")

The three EMN consortia launched by FCTO are:

1. ElectroCat[2]: Focused on platinum group metal (PGM)-free catalysts for fuel cells
2. HyMARC[3]: Focused on advanced materials for hydrogen storage
3. HydroGEN[4]: Focused on advanced water splitting materials for hydrogen production

[2] http://www.electrocat.org
[3] https://hymarc.org/
[4] https://www.h2awsm.org/

The “concierge” and “streamlined access” capabilities of the EMN consortia could be leveraged as best practices by the H2@Scale consortium, as they expedite and ease collaboration between industry and national laboratories.

Questions and Answers

1. Comment: Storage and compression of hydrogen will be important in the H2@Scale vision.
2. Who is the POC for each consortium?
    a. There is contact information for a “concierge” on each consortium website. The concierge facilitates identification and communication with relevant POCs within each national laboratory, depending on the stakeholders needs.

Breakout Sessions: Feedback on H2@Scale RD&D

Feedback was collected on gaps in the H2@Scale R&D Roadmap Draft (May 2017 Version), and has been used to update the roadmap draft. Feedback was also gathered on R&D needs wherein there was interest in industry collaboration. This feedback is summarized below.

Question: Which H2@Scale R&D needs would you be interested in supporting?

A. Hydrogen Integration with the Grid
  a. Development of technoeconomic models on energy storage and electrolyzer integration with the grid. Data could be shared across utilities with non-disclosure agreements (NDAs) in place.
  b. Development of cross-cutting components for hydrogen production, such as balance-of-plant components
  c. Evaluation of electrolyzer membrane performance (e.g. accelerated stress tests)
  d. Development of manufacturing technologies for high-volume production of electrolyzer stacks.
  e. Evaluation of the impacts of grid services on electrolyzer durability and performance.

B. Industrial End Uses for Hydrogen
  f. Advanced electrochemical approaches to produce acetic acid
  g. De-carbonizing point sources of emissions at refineries using hydrogen as a fuel
  h. Pipeline materials compatibility in hydrogen
  i. Development of hydrogen leak detectors
  j. Production of hydrogen from biomass
  k. Safety, kinetics, and quality of direct reduction of iron (DRI) in hydrogen
  l. Techno-economic analysis and mass flows of DRI in hydrogen
  m. Commercial demonstration of DRI in hydrogen
  n. Increasing the round-trip efficiency of fuel cells for energy storage
  o. Facilitate market appeal for hydrogen processes through outreach
  p. Near-term approaches to decarbonization, such as lowering the cost of small-scale steam methane reforming
  q. Enhancing the dynamic performance of steam methane reformers to mitigate the need for hydrogen storage
  r. Capture of carbon by-product from hydrogen production, and subsequent use in industries (e.g. tire manufacturing, electronics, building materials)

C. Hydrogen Infrastructure
  a. Development of technologies and protocols to fill hydrogen tube trailers
  b. Development of durable polymers for hydrogen seals.
  c. Development of underground hydrogen storage vessel for fueling stations
  d. Development of novel, large- and small-scale non-mechanical technologies for hydrogen compression
  e. Development of purification technologies for hydrogen.
  f. Development of strategies to eliminate the need for pre-cooling at hydrogen fueling stations.
  g. Development of approaches to reduce setback distances at liquid hydrogen fueling stations.

h. Development of strategies to reduce boil-off from liquid hydrogen stations.
i. Development of chemical carriers for hydrogen.
j. Development of technologies that can assess hydrogen purity.

Question: Which H2@Scale R&D needs would you not be able to support (e.g. too early-stage), but still think have value:

a. Coupling of solid oxide electrolysis with nuclear reactors.
b. Development of thermochemical cycles for hydrogen production.
c. Testing at high pressures, powers, and flow rates.
d. Guidance on optimal integration of electrolyzers with the power grid.
e. Development of a national energy strategy.
f. Development of computational models for complex electro-chemistries.
g. Evaluation of historical shifts in national infrastructure, and how lessons learned can be applied to hydrogen.
h. Challenges in blending hydrogen into natural gas (e.g. safety and/or metering of the fuel).
i. Capture and use of boil-off from liquid hydrogen equipment.
j. Development of advanced insulation for liquid hydrogen equipment.

The Infrastructure breakout session also conducted voting on which R&D areas were the highest priorities to advancing the H2@Scale concept. Participants were asked to vote for their top three priorities. Results are summarized below:

A. Gaseous Equipment
   a. Novel non-mechanical compression (4)
   b. Underground storage (3)
   c. Pre-cooling elimination (3)
   d. Protocols for fueling trailers (1)

B. Liquid Equipment
   a. Reduced hydrogen station footprint (4)
   b. Analysis of hydrogen purities (4)
   c. R&D for separation of ortho and para molecules of hydrogen (2)
   d. Development of chemical carriers (1)
   e. R&D on polymeric materials for hydrogen seals (1)
   f. Behavior of cryogenic hydrogen at ultra-low temperatures (1)
   g. Strategy to eliminate boil off (0)