Hydrogen Fuel and Infrastructure Research & Development Workshop Report

This report was compiled and written by the Fuel Cell and Hydrogen Energy Association (FCHEA).

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Introduction

On November 15, 2018, the U.S. Department of Energy's (DOE) Fuel Cell Technologies Office (FCTO), in collaboration with the Fuel Cell and Hydrogen Energy Association (FCHEA), hosted a workshop, with both in-person and web-based participation, on Hydrogen Fuel and Infrastructure Research & Development (R&D). Such workshops are one of several mechanisms through which the DOE solicits industry feedback to help inform future priorities for R&D. By engaging with the private sector, the DOE seeks to identify the most critical early-stage R&D needs and help determine low value activities which may be discontinued.

FCHEA represents leading companies and organizations that are advancing innovative, clean, safe, and reliable energy technologies with a focus on hydrogen and fuel cells. FCHEA is the national association for the fuel cell and hydrogen industry which provides a cohesive industry voice on various issues related to hydrogen and fuel cells.

This workshop presented a forum for FCHEA industry representatives to discuss current needs and challenges pertaining to hydrogen infrastructure deployment as well as production, delivery and storage that could be addressed by DOE with either funding directives via Funding Opportunity Announcements (FOAs), cost-share of demonstration projects, or leadership and direction in bringing key stakeholders together.

The DOE also discussed its H2@Scale Cooperative Research and Development Agreement (CRADA) call, as well as provided various National Laboratories an opportunity to highlight the capabilities and programs that are available.

The workshop concluded with a facilitated discussion among the participants on perceived R&D needs.

Objectives

The objectives of the Hydrogen Fuel and Infrastructure R&D workshop were to:

- Provide input into prioritization of R&D challenges related to hydrogen production, storage, and infrastructure;
- Assess and inform cost and performance targets for hydrogen fuel technologies;
- Facilitate collaboration between laboratory researchers and industry stakeholders to inform R&D; and
- Discuss the roles of government and the private sector in supporting R&D activities, including an overview of current capabilities within National Laboratories and opportunities for collaboration.

Introductory Remarks

Sunita Satyapal, Director of the DOE FCTO provided an overview of the Program's R&D focus areas and impact. FCTO leads the Hydrogen and Fuel Cell Program at the DOE and has been funding between approximately $100M and $250M per year of hydrogen and fuel cell R&D over the last decade. She discussed examples of R&D, including those related to H2@Scale, Platinum Group Metal (PGM)-free catalysts, durable membrane electrode assemblies (MEAs), electrode performance, hydrogen production pathways, hydrogen delivery components, advanced materials for storage, hydrogen safety, and hydrogen manufacturing. FCTO funding has helped achieve a 60% reduction in fuel cell cost, a fourfold increase in fuel cell durability, and an 80% reduction in electrolyzer costs. FCTO has also enabled 738 U.S. patents through its funding and the commercialization of more than 30 technologies by private industry through 2018. Other highlights included activities beyond early-stage R&D, such as: developing the Hydrogen Station Equipment Performance (HyStEP) device to verify fueling protocols, cost-sharing the development of next generation mobile hydrogen fuelers, providing the $1 million H2Refuel H-Prize for a small scale hydrogen fueler using only water and electricity, and conducting modeling and experimental work on liquid hydrogen releases, reducing station footprints, and enabling the use of fuel cell vehicles on bridges and in tunnels.. More information can be found online at: https://www.energy.gov/eere/fuelcells/fuel-cell-technologies-office.

Industry Overviews

Industry presentations included leading automotive, fuel cell and hydrogen industry representatives detailing specific R&D priorities and challenges as well as progress updates and market status, where applicable.

Summaries of the presentations are provided below. The full presentations can be found online at https://www.dropbox.com/sh/qx7ueaz8tbqqf70/AACfdTZlTdzpdhfMC5UVBHr6a?dl=0.

Stephen Ellis, Manager of Fuel Cell Marketing, Honda Motor Company

Stephen Ellis provided an update on Honda's fuel cell vehicle developments, primarily with respect to its Clarity vehicle series. Honda's research priorities have focused on reducing the size of its fuel cell stack by 33% while increasing its power output, hydrogen safety design, and improving consumer hydrogen station experience.

Honda's industry challenges and R&D priorities include:

- **Vehicle Cost** – Material-level research to reduce cost and increase durability of fuel cells; onboard vehicle hydrogen storage advancements
- **Hydrogen Station Cost** – Station-level hydrogen storage advanced research

- **Hydrogen Production** – Dedicated supply of hydrogen for vehicle purposes, rather than tapping off existing supply resources
- **Renewable Hydrogen Supply** – Larger scale and lower cost renewable hydrogen pathways including electrolysis, biogas, and biomethane
- **Fuel Cost** – Hydrogen fuel cost at parity with gasoline, if not lower
- **Hydrogen Scale** – 1,000 to 2,000 kilogram/day high-capacity, high throughput station demonstrations
- **Demonstration Transition** – Transitioning of projects to industry following successful demonstrations

David Edwards, Director of Hydrogen Energy, Air Liquide

David Edwards provided an overview of how hydrogen can enable broad energy decarbonization and renewable energy utilization. Air Liquide characterized market success for the hydrogen industry as utilization of hundreds of tons of hydrogen per day (with a robust and resilient supply chain), ~1,000 kilograms a day hydrogen station capacity able to conduct hundreds of fuelings per day, hydrogen fuel cost comparable to gasoline and diesel, and expanded production of renewable hydrogen – all of which will need significant market investments and policies to support these developments.

Air Liquide's technology and project challenges are related to:

- **Hydrogen Production at Scale** – Electrolyzer system scaling; energy storage, grid integration and design, load balancing, and frequency management
- **Renewable Hydrogen** – Balancing the requirements of renewable hydrogen development with low-cost pathways for hydrogen to enable scale; support of all options for renewable and carbon free hydrogen
- **Uninterruptible Hydrogen Supply** – Uninterruptible supply of hydrogen that includes sufficient storage, production overcapacity, and regional coordination
- **Hydrogen Liquefiers** – Higher capacity and efficiency next-generation liquefaction plants
- **Large-Scale Hydrogen Storage** – Liquid storage facility expansion; new means of gaseous hydrogen storage
- **Hydrogen Pipelines** – New hydrogen pipeline cost and technical challenges; demonstration and implementation of at scale conversion of existing natural gas pipelines
- **Hydrogen Stations** – Higher station capacities; more robust back-to-back fueling capabilities; more fueling positions
- **Hydrogen Fuel Cost** – Reduction in the cost of hydrogen fuel, which will require significant investment and time to develop
- **Hydrogen Value for Grid** – Evaluation of the value of hydrogen energy storage for the grid; demonstration of hydrogen energy storage at scale
- **Hydrogen Station Regulation** – Streamlining of site permitting and other gating regulatory processes, especially when crossing jurisdictions and regions; market needs for redundancy and resiliency in supply from the onset of a project

Kathy Ayers, Vice President of Research and Development, Proton OnSite/NEL Hydrogen

Kathy Ayers provided an overview of NEL Hydrogen's overarching R&D goal, which is reducing the overall cost of ownership (capital cost and operating cost) of electrolyzer systems. NEL Hydrogen identified R&D improvements needed in terms of cost reduction and efficiency, specifically for the fuel cell stack. NEL is targeting a reduction in cell stack costs of over 50%.

While part of this reduction will be possible through scale (cell stacks larger than 1 megawatt), other improvements will be needed through areas such as R&D in materials and manufacturing, including:

- **Membrane Electrode Assembly (MEA) Manufacturing** – Dry MEA fabrication; higher speed/roll-to-roll processes (e.g., slot die, reverse gravure) manufacturing methods
- **Membrane Electrode Assemblies** – Thinner, high-strength membrane when saturated; low creep at high load, with low hydrogen permeation to mitigate crossover; porous transport layer for the anode
- **Advanced Catalyst Electrode Fabrication** – Automated manufacturing; lower catalyst usage
- **Reduction of PGM Content** – Blended alloys and novel structures
- **Low-cost Alternative Coatings for Porous Transport Layers (PTLs)** – Microporous layers for both carbon and metal PTLs; elimination of electroplating; alternative surface treatments
- **Optimization** – Interface and catalyst support

The challenges faced in the electrolysis market were highlighted in the presentation:

- **Technology Supply Chain** – Underdeveloped/immature supply chain with many materials not optimized for electrolyzer requirements
- **Testing Infrastructure** – Large-scale testing infrastructure availability and cost
- **Grid-integration** – Electrolysis modules power quality; system input and output; rate of load changes
- **Government Support** – Funding elements are spread across multiple programs and agencies
- **International Competition** – Rapidly increasing competition from overseas investment

Regarding energy storage and grid integration, the group discussed specific load following characteristics of electrolyzer systems, particularly in terms of response time. More analysis is needed both on what is required from the grid, as well as how the electrolyzer systems perform. DOE has identified several areas in which hydrogen energy storage can provide support and add value to the grid, but those valued services depend on the response time of the hydrogen energy systems. In order to integrate electrolyzers with the grid, response characteristics need to be understood.

Gerry Conway, Vice President of Government Affairs, and Tim Cortes, Vice President of Hydrogen, Plug Power

Gerry Conway and Tim Cortes described Plug Power's business sectors related to the hydrogen industry, both the deployment of hydrogen-powered fuel cell material handling equipment and other vehicles, as well as the hydrogen stations to support these vehicles. Plug Power is exploring other hydrogen fuel cell applications, including fleet vehicles, drones, buses, taxis, medium-duty delivery trucks, and more.

Plug Power's challenges and research needs include:

- **Hydrogen Cost** – Hydrogen delivery cost at scale; prices are currently unpredictable and are not tied to other energy indexes
- **Hydrogen Compression** – Reliable and cost-effective compression technology
- **Hydrogen Production** – Demand for liquid hydrogen is outpacing capacity expansion and is at approximately 85% of current production levels; need more hydrogen and more renewable hydrogen production; medium-term scalable hydrogen generation from 50 to 1,000 kilograms/day
- **Distributed Hydrogen Generation** – High-purity hydrogen production at point of use to offset prohibitively high distribution costs in some areas; $5/kilogram price point would be ideal for market competitiveness
- **Unreliable Hydrogen Supply** – Ubiquitous and available hydrogen supply to alleviate customer concerns
- **Hydrogen Storage** – Low-pressure, high-density, economical, and safe hydrogen storage technologies
- **Supply Chain** – Supply chain technologies and products are needed across the United States and globally, particularly in compression and reformation
- **Electrolyzer Technology** – Electrolyzer-sourced hydrogen infrastructure development
- **Liquid Hydrogen** – Cryogenic cooling of liquid hydrogen at the site to increase pump performance; liquid hydrogen trailers to improve hydrogen infrastructure network reliability; dynamic model development and experimental verification of liquid hydrogen infrastructure; cost-effective integration of liquid hydrogen pump performance enablers
- **Hydrogen Refueling** – Pod refueling technology development; hybrid cascade refueling technology development; autonomous hydrogen fueling are also considerations

Charles Freese, CEO, GM Defense LLC[1]

Charles Freese discussed General Motors' fuel cell technology development, particularly its focus on the defense market, which could offer another opportunity for large-scale hydrogen utilization outside of the consumer vehicle market.

[1] *Note, at the time of publication of this report, Charles Freese's position has changed to Executive Director of Global Fuel Cell Business for General Motors (GM).*

General Motors fuel cell challenges and R&D priorities are focused on addressing pain points within the military, such as:

- **Detection and Stealth** – Reductions in sound, heat, and odor detection
- **Range** – Time on station; flexibility to use in-theater energy sources; energy storage density
- **Performance** – Torque and mobility
- **Electrical Power Availability** – Availability of exportable power
- **Logistics** – Fuel, power, water, and air transportability to reduce the logistics burden
- **Autonomy** – Leader/follower functionality; full autonomy in off-road environments; option to remotely pilot vehicles; autonomous sensors
- **Infrastructure Solutions** – Containerized reformer systems located at forward operating bases

GM identified the following areas where DOE can provide R&D support:

- **Material Advances** – Leverage National Laboratory capabilities for areas such as water imaging and site operation of fuel cells
- **Refine Modeling** – Develop more confidence in analytical modeling of FCEV components and performance, to increase technology development and bring technology to market faster without having to rely on physical testing
- **Accelerated Testing** – Prove extended durability in a shorter time
- **Codes and Standards** – DOE plays a key role in ongoing bridge and tunnel technical support
- **Hydrogen Production** – Cost-competitive delivered hydrogen; need to transition from subsidized hydrogen to hydrogen at scale with a sustainable business model
- **Hydrogen Storage and Transport** – Affordability and cost-effectiveness

Robert Wimmer, Director of Energy & Environmental Research, Toyota Motor North America

Robert Wimmer provided an update on Toyota's fuel cell vehicle development, as well as its hydrogen and infrastructure R&D needs.

Toyota's technology challenges and R&D priorities are:

- **Heavy-Duty Hydrogen Infrastructure** – New high-capacity hardware; codes and standards such as heavy-duty fueling protocols
- **Hydrogen Station Cost** – Reductions in capital costs and operating expenses
- **Hydrogen Components** – Improve efficiency, reliability, and durability of hydrogen station components, including compressors, chillers, and nozzles
- **Hydrogen Delivery** – Carbon fiber trailers for gaseous hydrogen delivery; regulatory changes
- **Hydrogen Storage** – Liquid and gaseous hydrogen storage

- **Electrolyzers** – Low-cost small to mid-size electrolyzers for on-site generation
- **Regulatory Coordination** – Coordination between U.S. and international standard bodies to ensure there is one set of open (non-proprietary) global standards

FCTO Overview of H2@Scale CRADA Call Opportunity

Elizabeth Connelly, Management and Operations Contractor, DOE FCTO

The National Renewable Energy Laboratory (NREL) issued a Cooperative Research and Development Agreement (CRADA) call to double the impact of its applied research funding to accelerate technology advancement in support of the H2@Scale objectives and to increase industrial and stakeholder engagement in the H2@Scale initiative.

The CRADA projects are collaborations between industry and National Laboratories to address key challenges associated with wide-scale production and use of hydrogen to tackle critical issues such as enabling grid resiliency, energy security, domestic job creation, and leadership in innovation.

Current CRADA project topics include:

- Hydrogen Quantitative Performance Analysis and Operation R&D
- Advanced Hydrogen Production Concepts R&D
- Hydrogen Distribution Component Development R&D
- Hydrogen Integration with Energy Generation R&D

Key focus areas of the H2@Scale effort include increased low-cost hydrogen production, more efficient hydrogen transmission, low cost value-added applications, and flexible low-cost bulk storage technologies.

To learn how a company can initiate a partnership with one of the National Laboratories and propose an H2@Scale CRADA project, please visit H2atScale@doe.gov.

A detailed overview of the various National Laboratory capabilities available via CRADAs were expanded on in the following presentations.

National Laboratory Capability Overviews

While FCTO funds a number of National Laboratories, including the consortia focused on early-stage R&D, this workshop focused on infrastructure and therefore four examples of relevant Labs and their capabilities were presented.

Amgad Elgowainy, Team Leader/Principal Energy Systems Analyst, Argonne National Laboratory

Amgad Elgowainy, Energy Systems Division for Argonne National Laboratory (ANL), provided an overview of the various models available for hydrogen and fuel cell applications, including the Hydrogen Delivery Scenario Analysis Model (HDSAM) and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model.

ANL's hydrogen delivery modeling encompasses all components or systems involved after production to vehicle refueling and regarding station configurations. The Hydrogen Refueling Station Analysis Model (HRSAM) was developed specifically for light-duty fuel cell electric vehicle refueling stations and the Heavy-Duty Refueling Station Analysis Model (HDRSAM) specifically for heavy-duty fuel cell electric vehicle fleet refueling stations. HDSAM estimates costs for hydrogen delivery and dispensing, for a number of variable scenario parameters.

These models incorporate a number of market, technical, and economic user defined inputs, including:

- Market size
- Station capacity
- Station utilization rate
- Mode of hydrogen delivery
- Delivery distances
- Fueling speed
- Hourly fueling demand
- Rate of return on investment
- Analysis period
- Production volumes

The outputs for these models include hydrogen delivery cost, capital cost, station cost, and cash flow for these various hydrogen delivery scenarios.

ANL detailed several key takeaways from these models:

- In the near term or when there is small market demand, trucking hydrogen to the point of use is the lowest cost option. Pipeline delivery would be the lowest cost option in cases with a large market demand (long-term).
- The primary cost drivers of hydrogen fueling are currently compressors, storage technology, dispenser, refrigeration, controls, and electrical equipment, with the compressor being the most significant component related to cost and reliability.
- Station utilization has a large impact on hydrogen refueling cost for light duty vehicle stations, at present accounting for as much as $6/kilogram of hydrogen today at low utilization. With further R&D and increased utilization, the cost of refueling has the potential to drop to $2/kilogram in the future. There are similar potential impacts of

fueling rate and utilization rate on the cost of hydrogen refueling cost for heavy duty vehicle stations.

These models are publicly available for download and use online at https://hdsam.es.anl.gov/.

Keith Wipke, Fuel Cell & Hydrogen Technologies Program Manager, National Renewable Energy Laboratory

Keith Wipke, Fuel Cell & Hydrogen Technologies Program Manager for the National Renewable Energy Laboratory (NREL), provided an overview of NREL's hydrogen fuel and infrastructure research.

NREL's current hydrogen systems capabilities include a range of hydrogen infrastructure projects:

- Hydrogen fueling protocols at both 35 and 70 MPa
- Hydrogen storage for high throughput experiments
- Hydrogen station component monitoring, analysis, and validation – including compressors, meters, hoses, detectors, and dispensers
- Customizable hydrogen station operation
- Wind-to-hydrogen production
- Hydrogen contaminant detection
- Hydrogen delivery

NREL also offers electrolysis and energy storage services, in collaboration with Idaho National Laboratory, including:

- **Grid services** – Dispatchable loads (electrolyzers and stations) for grid services
- **Renewables with Electrolysis** – Transient operation with AC and DC power operation and analysis
- **Electrolyzer System Control / Operation** – Power conversion; system integration; remote, real-time response, stimulation, demand response, and safety
- **Cell and Stack Testing** – Multiple stack test beds capable of variable sizes and operation conditions, including balance of plant
- **Power to Gas** – Reaction of carbon dioxide with hydrogen to make synthetic natural gas for power to gas applications

Other innovative hydrogen infrastructure capabilities include:

- **Life-Cycle Testing** – Autonomous "arm" capability to accelerate life cycle experiments for hydrogen station components and dispenser reliability
- **Benchmarking** – Performance with near-term and future operating conditions
- **Station Operation** – Power, energy, demand, and operation optimization experiments

- **Failure Investigation** – Root cause investigation
- **Prototype** – Development and evaluation of emerging technologies

NREL is also able to conduct hydrogen safety R&D, including:

- **Integration** – Safety codes and standards integration
- **Components** – Component performance and failures from the field and in the laboratory
- **Sensors** – High-accuracy and low-cost prototype sensors
- **Monitoring** – Requirements for safe operation, handling, and use of hydrogen

NREL is home to the National Fuel Cell Technology Evaluation Center (NFCTEC) as part of its Energy Systems Integration Facility (ESIF), which supports NREL's independent third-party data collection, analysis, and results sharing. The NFCTEC is designed for secure management, storage, and processing of proprietary data from industry. NFCTEC provides aggregated data for public sharing, as well as confidential data for contributing companies.

Chris LaFleur, Hydrogen Safety, Codes, and Standards Program Lead & Joe Ronevich, Staff Scientist, Sandia National Laboratories

Chris LaFleur, Lead for the Hydrogen Safety, Codes, and Standards Program for Sandia National Laboratories (SNL) discussed various hydrogen risk research areas at SNL, including:

- **Tunnel Modeling** – Risk and modeling efforts for fuel cell vehicles in tunnels for the Northeast Corridor
- **Hydrogen Risk Assessment Model (HyRAM) 2.0 Development** – Expanded Quantitative Risk Analysis (QRA) for a wide variety of hydrogen applications and improvements to the user interface; incorporation of liquid and cryogenic hydrogen release behavior models and risk analysis; generation data and probabilities for liquid hydrogen systems (including component failures, leak frequencies, detection effectiveness, etc.); future analysis of different fuels (CNG, LNG, and LPG)

Chris LaFleur also highlighted SNL's efforts on liquid hydrogen release behavior R&D.

Joe Ronevich, Staff Scientist for SNL, discussed hydrogen materials compatibility efforts at SNL, carried out by several Laboratories:

- **Hydrogen Effects on Materials Laboratory** – In situ mechanical testing in hydrogen
- **Computational Hydrogen Materials Science Laboratory** – Multi-physics, multi-length scale modeling tools
- **Hydrogen Transport and Trapping Laboratory** – Hydrogen permeation and thermal desorption spectroscopy

- **Hydrogen-Surface Interactions Laboratory** – Specialized tools and capabilities to detect hydrogen-surface interactions

Joe Ronevich also discussed the Hydrogen Materials (H-Mat) Consortium. The Consortium was developed by DOE to conduct fundamental studies on hydrogen materials compatibility and lead that research towards advances in technology (e.g. improved materials, cost, and reliability). The Consortium includes SNL, Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL), Savannah River National Laboratory (SRNL), and ANL. H-Mat includes the following R&D objectives:

- Develop new polymeric formulations for high-pressure applications
- Identify microstructural characteristics that increase toughness of high-strength steels to enable their use in pressure vessels
- Advance the technical basis for high-strength aluminum alloys in hydrogen components
- Formalize mechanisms of crack formation in steels to increase life of piping and pressure vessels
- Identify mechanisms of degradation in welds to enable cryogenic applications

SNL is also engaged in several collaborations and partnerships on topics including:

- **Materials Performance and Testing** – Steels for advanced high-pressure storage
- **Codes and Standards** – Materials qualification methodologies to harmonize materials selection for vehicle fuel systems with the Society of Automotive Engineers (SAE) codes and United Nations Global Technical Regulations
- **Pipeline Steels** – Advanced pipeline materials and welding technologies for hydrogen delivery
- **Polymers** – Damage mechanisms in polymer materials due to pressure cycling

Jamie Holladay, Senior Research Engineer, Pacific Northwest National Laboratory

Jamie Holladay, Senior Research Engineer at Pacific Northwest National Laboratory (PNNL) discussed PNNL's fuel cell and hydrogen efforts, including the Hydrogen Safety Panel, catalysis of methane to products, magnetocaloric gas liquefaction, energy storage grid and cost analysis, and solid oxide electrolysis.

PNNL provides a wide variety of hydrogen safety resources, including: the Hydrogen Safety Panel, Hydrogen Tools web portal, hydrogen lessons learned, hydrogen best practices, national emergency response training resources, online awareness training, classroom training, and other tools.

PNNL recently formed a partnership with the American Institute of Chemical Engineers (AIChE) to develop the global Center for Hydrogen Safety (CHS), which includes the Hydrogen Safety Panel and hydrogen emergency response training resources. The CHS will streamline the process for industry engagement and has access to 110 countries and 60,000 members through AIChE.

The Hydrogen Safety Panel provides design and document reviews, participation in or review of risk assessments, and site reviews. These resources are targeted at private and commercial installers, federal agencies, state agencies, code officials, and permitting authorities.

PNNL's Institute for Integrated Catalysis has over 150 scientists and engineers engaging in catalysis development and reactor design, spanning from basic sciences to deployment.

PNNL supports R&D on direct conversion of methane to fuels, with the potential for new opportunities for hydrogen production with low carbon emissions, including two types of conversion R&D: methane to hydrogen and solid carbon, as well as methane to hydrogen, benzene, toluene, and xylene (BTX).

PNNL is actively involved in developing innovations for highly-efficient magnetocaloric small-scale hydrogen liquefaction. PNNL has demonstrated a world record temperature decrease and this has significant impact potential in the long term.

PNNL supports efforts to understand and model the electric grid, including:

- **Energy Storage Analytics** – Analysis of benefits that hydrogen energy storage can add to the grid (economics, cost and performance characterization, control systems, and distribution system integration, etc.)
- **Distribution and Demand Response** – Smart grid simulation and analysis
- **Transmission Reliability** – Planning models and decision support tools
- **Cybersecurity** – Cybersecurity risk information sharing program

PNNL is also working on solid oxide technology development, from materials synthesis to fuel cell and electrolyzer stack manufacturing and design.

The Discussion Topics

Sunita Satyapal facilitated the discussion portion of the workshop and asked several questions to participants. FCTO Program Managers Eric Miller and Ned Stetson also provided perspectives.

The overarching theme from industry is the need for projects that demonstrate 'scale' – showing capability to produce, distribute and store large enough quantities of hydrogen to support demand and an increase in fuel cell passenger vehicles as well as other transportation and stationary/portable applications. These additional applications include, but are not limited to, heavy-duty trucking, material handling, marine, rail, unmanned vehicles. In some applications, new regulations, codes and standards may need to be developed, or existing documents may need to be revised to include these new applications. In many cases, requirements are being put in place already to cover new applications.

The value in having DOE lead these efforts is that once feasibility/viability is demonstrated, it is easier for companies to secure "buy in" and move from "inside the fence" to "outside the fence" for real world deployment.

Another recurring message was the need to support DOE-led demonstration projects once completed – transitioning them into marketplace or continuing to expand on the work once the projects have ended.

What are examples of first-of-a-kind, multi-stakeholder demonstration projects that would be beneficial to advancing hydrogen technologies?

Scaling up existing technology with innovative new concepts to create integrated demonstrations that would include distribution, production, and storage with a focus on regional (outside California) approach. Isolating a region that already has significant renewable penetration (e.g. wind in Texas, solar in southwest) and integrating hydrogen in the region. Attracting new partners – utilities, nuclear companies, systems integration – adding grid stabilization, pipeline research, other areas for implementation of technologies.

Taking current technology (small-scale) and expanding it to scale at a facility with multiple end-use applications – seaports, airport, trucking depots would be of value.

Hydrogen Fueling Stations:

- **1000+ kg/day Hydrogen Station** – No technology breakthrough needs to occur; need to scale up stations, including generation, compression, and storage capacity
- **Station Throughput** - Multiple hydrogen fueling dispensers and nozzles to fuel more than one fuel cell vehicle at a time (at multiple stations)
- **Increasing Renewable Hydrogen Supply** – Capture value of electrolyzers and renewable energy; value of system integration with various options – renewables, nuclear, etc.
- **Codes and Standards** – Feedback of real-world operating data and failure mode analysis to improve next-generation codes and standards, which leads to more robust future stations and components

Liquid Hydrogen:

- **Small-Scale Liquefiers** – Develop and deploy small modular liquefiers to improve the supply reliability of liquid sources; large-scale liquefier failures take a significant amount of capacity out of the network and can be down for longer periods of time, small modular liquefiers could provide capacity redundancy and improve network availability
- **Large-Scale Liquefiers** – Increase liquefiers from small-scale to 100 ton/day

- **Underground Liquid Storage** – Utilize learning from Benning Road (DC) first of its kind use and others

Pipelines:

- **Natural Gas Pipeline Conversion** – Feasibility of natural gas to hydrogen pipeline conversion
- **Pipeline Steels** – Higher strength materials
- **Buried Pipelines** – Buried vacuum recovery pipelines

Biofuels:

- **Hydrogen Production from Biofuels** – Deploy distributed biofuel derived hydrogen generation corresponding to regional production volumes to take advantage of lower-cost feedstock and reduced distribution costs

Are there examples of pre-competitive R&D where collaboration across industry stakeholders is feasible?

- **Systems integration R&D** – Bringing in renewables, nuclear-based hydrogen generation, energy storage, grid services
- **Regulations, Codes and Standards** – Technical Committee collaboration and information sharing to inform working groups
- **Hydrogen Storage** - Low-pressure, high-density hydrogen storage technologies
- **Compressors and Reformers** - Reliability and cost improvements
- **Hydrogen Purification** – Low-cost purification of hydrogen
- **Green Hydrogen** - Hydrogen production from renewable sources

What are examples of National Lab capabilities that would be beneficial to expand to support industry-led R&D projects?

- **Fuel Cell Mining Applications** – Need to define scale and region
- **Modeling** – The modelling work presented by Sandia noted the HyRAM fault tree analysis can now be edited to calculate risk for any system or application and is being expanded to address other alternative fuels
- **Hydrogen Liquefaction** – Small, modular liquefiers
- **Compressors and Reformers** – Reliability and cost improvements
- **Pipelines** – Research converting existing pipelines to hydrogen distribution
- **Hollow Carbon Fibers for Hydrogen Storage** – Continue and accelerate work on hollow carbon fibers (e.g., existing DOE projects at University of Kentucky and National Laboratories) to reduce carbon fiber costs on Type III and IV tanks; carbon fiber currently represents over 50% of the cost of hydrogen tanks

What are some examples of R&D priorities that require government support in the near term and why?

In addition to the priorities listed in individual presentations, industry participants discussed specific examples of focus area priorities that require R&D in the near-term to address issues and challenges:

- **Cost Reduction**
  - Hydrogen fueling station components – nozzles, hoses, dispensers
  - Hydrogen storage - onboard vehicles (700 bar) and at stations
  - Hydrogen supply – scaling up renewable pathways, biogas/biomethane
  - Fuel cell system – materials
  - Tanks, cylinders – carbon fiber

- **Component R&D** – Membranes, catalysts, porous transport layers, manufacturing
- **Power Electronics** – Next-generation power electronics
- **Supply Chain** – Supply chain manufacturing challenges
- **Station components** – Compression and reformation
- **Hydrogen Storage** – Tanks and cylinders for drones and backup power need to be able to swap easily, increase storage capacity onsite
- **International Coordination** – Coordinate with ongoing efforts in Europe to transfer learnings such as the European HyTunnel and other Fuel Cells and Hydrogen Joint Undertaking (FCH JU) projects. FCH JU is developing a database to document regulatory barriers in Europe - https://www.hylaw.eu/ and https://hydrogeneurope.eu/hylaw.

Conclusion and Next Steps

Sunita Satyapal provided concluding remarks detailing the recent efforts, in addition to this workshop, by DOE FCTO to gain industry feedback and input on its programs through Requests for Information and other workshops. Dr. Satyapal detailed that a future workshop on fuel cells is in development that will also be undertaken in coordination with FCHEA. Additional future workshops could be considered to provide greater examination of certain specific areas, for example one that is focused solely on hydrogen on- and off-board storage and hydrogen liquefaction.

Dr. Satyapal and Morry Markowitz thanked the attendees for their participation in the workshop and detailed that a report would be developed to capture the discussion and input provided.

Appendix A – List of Participants

Over 120 attendees across nearly 50 organizations participated in this workshop. Please see the list of participating organizations below.

AECOM

Air Liquide

Ames Laboratory

Argonne National Laboratory

BMW

Brookhaven National Laboratory

California Air Resources Board

California Energy Commission

California Fuel Cell Partnership

Catalyxx

Connecticut Center for Advanced Technologies

CSA Group

CSRA

Denver Government

Doosan Fuel Cells

Fuel Cell and Hydrogen Energy Association

FuelCell Energy

FuelScience LLC

General Motors

H2B2

H2PowerTech

Haskel

Hexagon Lincoln

Honda Motor Company

Hydrogenics

Hypersolar

Idaho National Laboratory

IGX Group

Intelligent Energy

Lawrence Berkeley National Laboratory

Lawrence Livermore National Laboratory

Linde

Los Alamos National Laboratory

Massachusetts Hydrogen Coalition

National Renewable Energy Laboratory

NEL Hydrogen

Nikola Motors

Oak Ridge National Laboratory

Pacific Northwest National Laboratory

Plug Power

Sandia National Laboratory

Santa Barbara County Air Pollution Control District

SLAC National Accelerator Laboratory

SQI

Toyota Motor Company

U.S. Department of Energy

W.L. Gore