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Bulk Storage of Gaseous Hydrogen

2022 Workshop Summary Report

Hydrogen and Fuel Cell Technologies Office & Office of Fossil Energy and Carbon Management

U.S. Department of Energy

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Preface

Prepared by: U.S. Department of Energy/Office of Energy Efficiency and Renewable Energy/Hydrogen and Fuel Cell Technologies Office in coordination with the Office of Fossil Energy and Carbon Management.

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The Hydrogen and Fuel Cell Technologies Office (HFTO) and the Office of Fossil Energy and Carbon Management (FECM) would like to thank all of the speakers who presented at the workshop:

- Serge van Gessel – Netherlands Organization for Applied Scientific Research
- Eric Lewis – National Energy Technology Laboratory
- Raja Amirthalingham – Plug Power
- Tony Leo – FuelCell Energy
- Michael DeBortoli – Northern California Power Agency
- Upshur Quimby – Microsoft
- Hilary Petrizzo – SoCalGas
- Greg Wright – Wabtec
- Nico Bouwkamp – California Fuel Cell Partnership
- Robert Smith – Pipeline & Hazardous Materials Safety Administration
- Vincent Holohan - Pipeline & Hazardous Materials Safety Administration
- Nik Huerta – Pacific Northwest National Laboratory
- Tim Reichwein – Lane Power and Energy Solutions
- Mariel Schottenfield – Air Products
- Kevin Harris – Hexagon Purus
- Brian Weeks – GTI
- Claudio Lanzarini – FIBA Tech

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Nomenclature or List of Acronyms

ASME	American Society of Mechanical Engineers
CCS	Carbon capture and sequestration
DOE	U.S. Department of Energy
DOT	Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
FECM	Office of Fossil Energy and Carbon Management
HFTO	Hydrogen and Fuel Cell Technologies Office
LLNL	Lawrence Livermore National Laboratory
NETL	National Energy Technology Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	Research and development
RDD&D	Research, development, demonstration, and deployment
SNL	Sandia National Laboratories
SOEC	Solid oxide electrolyzer cell
SHASTA	Subsurface Hydrogen Assessment, Storage, and Technology Acceleration
SMR	Steam methane reforming
tpd	Tonnes per day

Executive Summary

On February 10-11, 2022, the Hydrogen and Fuel Cell Technologies Office (HFTO), within the Office of Energy Efficiency and Renewable Energy (EERE), and the Office of Fossil Energy and Carbon Management (FECM) jointly held a virtual workshop focused on the bulk storage of gaseous hydrogen. The primary objective of the workshop was to bring together industry partners, end-users, and government stakeholders with those involved in active large-volume storage operations or research, development, demonstration, and deployment (RDD&D) projects, to better understand the various challenges and opportunities for hydrogen in meeting future energy storage demand.

In total, there were 1141 registrants for the two-day workshop, with 743 and 578 attendees participating on each respective day. The workshop opened with introductions from HFTO and FECM, a presentation providing European perspective on hydrogen from the Netherlands Organization for Applied Scientific Research, and an overview of integrated pathway analyses for meeting the Hydrogen Energy Earthshot, from the National Energy Technology Laboratory (NETL). The workshop continued with industry expert presentations in five focused topic areas: Hydrogen Production (Plug Power, FuelCell Energy), Energy Storage (Northern California Power Agency, Microsoft, SoCalGas), Transportation & Export (Wabtec, California Fuel Cell Partnership, Pipeline & Hazardous Materials Safety Administration), Subsurface Storage (Pacific Northwest National Laboratory, Lane Power and Energy Solutions, Air Products), and Surface Storage (Hexagon Purus, GTI, FIBA Tech).

The workshop continued with breakout sessions that allowed attendees and speakers to discuss the technology needs for the focus area, identify technology gaps and needed R&D. The key outcomes of the workshop were open discussion on the state-of-the-art (SOA) of current technologies between current, future, and potential stakeholders; identification of RDD&D gaps; exploration of innovative concepts; and review of safety and analysis activities. These discussions potentially provide insight that may be beneficial for guidance of DOE activities relating to surface and subsurface bulk gaseous hydrogen storage that are necessary to further enable a decarbonized energy economy. Key recommendations for DOE are to collect and share cost and performance data with stakeholders, to establish cost and performance targets for both surface and subsurface storage technologies, to enable RDD&D to reach those targets, and to support refinements to regulations, codes, and standards requirements and their harmonization across governing bodies, both domestically and globally.

The following summary provides additional information on bulk gaseous hydrogen storage, key insights from expert presentations and Q&A discussions, and the feedback and recommendations gathered through breakout session deliberations. This report, the detailed agenda, speaker information, and the presentation materials can be found at: https://www.energy.gov/eere/fuelcells/bulk-storage-gaseous-hydrogen-workshop. The guidance established through this workshop is complemented by the outcomes of similar activities focused on the storage of liquid hydrogen, as well as past and future workshops focused on hydrogen production technologies.

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1 Introduction

As part of the U.S. Department of Energy (DOE) Hydrogen Program, a primary objective of the Office of Energy Efficiency and Renewable Energy (EERE) - Hydrogen and Fuel Cell Technologies Office (HFTO) and the Office of Fossil Energy and Carbon Management (FECM), is advancing the current state of hydrogen-based technologies. Among other activities, HFTO and FECM plan and support workshops that bring together members of the stakeholder community from academia, industry, and government. Workshops provide an opportunity to gather input from stakeholders to identify, discuss, and prioritize key aspects of individual components within the overall vision for wide-scale use of hydrogen-based technologies, a concept referred to as H2@Scale. One such aspect of the larger system is storage within the overall infrastructure in moving the hydrogen from the point of production to the point of end use, including at the site of ultimate end use. In order to address the current status of bulk gaseous hydrogen storage, identify barriers to further development and strategies for overcoming them, and guide directions and targets for future work, HFTO and FECM jointly hosted the Bulk Storage of Gaseous Hydrogen Virtual Workshop on February 10-11, 2022. The workshop included plenary sessions, expert panel presentations, and breakout sessions. This report summarizes the outcomes and achievements of the workshop that provide input to help guide future work by HFTO and FECM.

1.1 Background on Hydrogen Storage

Hydrogen is a unique and flexible energy carrier due to the diversity of domestic options for hydrogen production as well as the broad spectrum of industrial end uses, as shown in the H2@Scale vision illustrated in Figure 1. Production pathways include utilization of natural gas, coal, water, biomass, nuclear power, electricity, and direct sunlight. Regardless of how the hydrogen is produced, its storage is a crucial part of its application, and the specific end use case significantly influences the storage method that provides the best cost and performance.

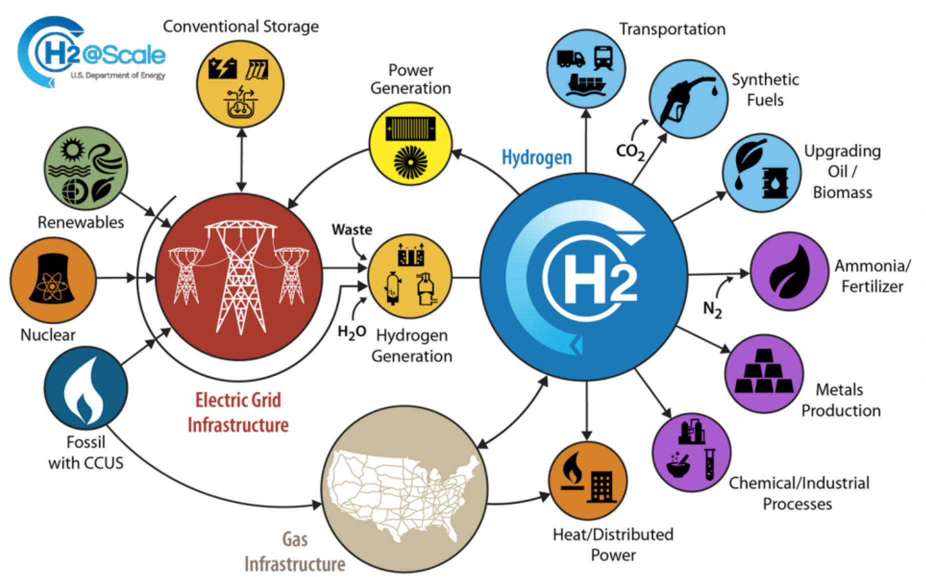

Figure 1. The H2@Scale Vision: Hydrogen can be produced from diverse domestic resources and is a central input to many important end uses in the industrial, chemical and transportation sectors.

Hydrogen has about three times higher energy content by mass than gasoline or natural gas but has low energy density by volume. A challenge for hydrogen storage is to store it in a manner that increases the energy density. As a compressed or cold/cryo-compressed gas, vessels capable of withstanding high pressures are required. Gaseous hydrogen storage is particularly challenging in space-limited applications such as light-duty fuel cell electric vehicles (FCEVs) where hydrogen gas is stored in high-pressure onboard tanks three to four times larger than typical gasoline tanks. These 700 bar compressed Type III (metal liner) or type IV (plastic liner) tanks are overwrapped by carbon fiber (CF) composite material that is both lightweight and extremely high-strength, but costly.

Liquid hydrogen has a normal boiling point of 20 K, and therefore requires advanced technology for its liquefaction and storage. Liquid storage is being investigated for onboard applications like medium-and heavy-duty trucking, rail, and marine transport, and off-board applications, such as larger-scale bulk or stationary storage. Though liquid hydrogen is typically employed for the storage of large amounts of hydrogen, the high energy input required for liquefaction and the need for special, highly insulated vessels impose significant costs. Additionally, liquid hydrogen suffers from boil-off losses such that hydrogen is lost to the environment over time, so it may not be amenable to long-term storage, such as for offloading seasonal energy production and demand.

As hydrogen is largely produced in gaseous form, bulk storage of gaseous hydrogen will become increasingly important as production expands. Though bulk gaseous storage may be less constrained by the space limitations of applications such as vehicles, significant cost and performance challenges remain for large, suitable vessels. These include cost and availability of suitable materials which can sustain high pressure, pressure cycling, and chemical compatibility with hydrogen for long periods, as well as sufficient, but non-excessive safety regulations, codes, and standards that dictate their installation and use. End-of-life considerations also contribute to lifetime costs as these vessels must be disposed of and replaced.

The geologic storage of hydrogen in formations such as underground salt caverns, lined hard rock caverns, depleted oil and natural gas fields, and aquifers, among others, is an emerging option with potential to provide low-cost and large-scale bulk storage of hydrogen. Such storage, however, is limited by the geographic availability of suitable geologic formations, the need for geologic characterization, as well as limited examples to model additional installations.

Above-ground, surface storage of large volumes of gaseous hydrogen in manufactured vessels, as well as underground, subsurface hydrogen storage in natural geologic or engineered formations are both relevant to a hydrogen economy that spans and serves the needs of the United States. The DOE Hydrogen Program recognizes this need for diverse and accessible options for the bulk storage of gaseous hydrogen. To accelerate the RDD&D needed to ensure these options are available to a growing hydrogen economy, HFTO and FECM jointly conduct activities relating to all aspects of bulk gaseous hydrogen storage, which is agnostic of the hydrogen production pathway.

2 Presentations

The workshop began with opening remarks and an introduction and overview of the DOE Hydrogen Program from Ned Stetson, Hydrogen Technologies Program Manager, HFTO. He gave an overview of the Program's priorities on the production of low-cost, clean hydrogen; low-cost, efficient, and safe hydrogen delivery and storage; and enabling end use applications at scale for impact. He explained the Hydrogen Energy Earthshot Initiative as well as highlights for hydrogen in the Bipartisan Infrastructure Law, which includes $9.5B for clean hydrogen and requires the development of a National Hydrogen Strategy and Roadmap. He concluded by explaining the Workshop objectives: to identify bulk hydrogen storage needs for upcoming, large-scale applications; to review current state-of-the-art bulk hydrogen storage technologies; to identify performance gaps of current technologies and application needs; to identify R&D needs to narrow performance gaps; to identify innovative concepts to pursue for bulk hydrogen storage; and to address any additional relevant considerations of concern to the Program's mission.

Tim Reinhardt, Director of the Division of Methane Mitigation Technologies within the Office of Resource Sustainability, gave an overview of FECM's perspectives on clean hydrogen. FECM aims to minimize the environmental impacts of fossil fuels and achieve net-zero emissions. Priority technology areas should support legacy communities and address the hardest-to-decarbonize applications in the electricity and industry sectors. He explained FECM's near-, mid-, and long-term strategy to achieve its mission with hydrogen and described the main thrusts of the current R&D for hydrogen production, transportation, and storage the Office is focused on. He gave more detail on specific focus areas within these three areas: transformative natural gas to hydrogen production, hydrogen in natural gas pipeline infrastructure, and hydrogen storage R&D needs. Challenges for storage include determining the viability, safety, and reliability of storing pure hydrogen and hydrogen/natural gas blends in subsurface environments.

Serge van Gessel provided a European perspective on hydrogen from the Netherlands Organization for Applied Scientific Research. He described predictions for growing demand for hydrogen in the Hydrogen Roadmap Europe – A Sustainable Pathway for the European Energy Transition [1]. He described the demand predictions in the Netherlands and bulk storage options under consideration, which include surface tanks, lined rock and salt caverns, and gas fields and aquifers. Salt caverns are proven at a pilot/demonstration technology readiness level, and several pilots are underway in Europe. Porous reservoirs are another option that may be explored in the near future. He described several initiatives in Europe that attendees could investigate for more information: Hydrogen Underground Storage in Porous Reservoirs [2], Hydrogen Storage in European Subsurface [3], and the IEA Hydrogen Technology Collaboration Program – Task 42: Underground H2 Storage [4]. He concluded with a positive and optimistic outlook that hydrogen will be an important part of Europe's commitment to sustainability, security, and affordability.

An overview of integrated pathway analyses for meeting the Hydrogen Energy Earthshot goal, presented by Eric Lewis of the National Energy Technology Laboratory (NETL), followed. The presentation outlined a completed study that compared the commercial, state-of-the-art, and fossil-based hydrogen production technologies as well as ongoing work focused on providing screening analysis for the Hydrogen Energy Earthshot Initiative. The comparison study objectives were: 1) develop a reference of hydrogen production pathways using current, commercial technologies with emphasis on coal gasification, co-gasification of coal with an alternative feedstock, and natural gas technologies using the levelized cost of hydrogen as the figure of merit; and 2) identify areas of R&D to further improve the performance and cost of fossil fuel-based hydrogen production, including follow-on analysis. Results from the study indicated that the lowest cost case per kilogram of hydrogen is steam methane reforming without carbon capture, and the highest being "net-zero" coal/biomass. The key objective for the screening analysis study is to identify potential pathway scenarios to meet the Hydrogen Energy Earthshot production cost goal of $1/kg hydrogen. Several pathways will be explored, from evaluating feedstocks to advancements in contemporary commercial technologies, in order to provide an informative framework for FECM hydrogen R&D.

Following introductory presentations, the workshop progressed into the panelist sessions. The sessions were broken up into five topic areas that spanned over the remainder of day 1 and into the first half of day two. Each session was comprised of 2-4 experts in the field. The panel sessions consisted of each panelist providing a short presentation on their company's or agency's relevant activities and perspectives on the topic area, followed by a question and answer (Q&A) and discussion period. Questions were posed by session moderators and attendees were able to submit additional questions through the virtual platform chat function for speakers and other participants to reply in writing. The speakers and affiliations who provided their perspectives are listed in Table 1, and key takeaways from presentations and Q&A for each topic area are summarized in the following sections.

Table 1. Focused topic area panel speakers

Topic Area	Speakers	Moderator
Hydrogen Production	Raja Amirthalingam, Plug Power Tony Leo, FuelCell Energy	Ned Stetson
Energy Storage	Michael DeBortoli, Northern California Power Agency Upshur Quinby, Microsoft Hilary Petrizzo, SoCalGas	Asha-Dee Celestine
Transportation & Export	Greg Wright, Wabtec Nico Bouwkamp, California Fuel Cell Partnership Robert Smith, U.S. Department of Transportation - Pipeline & Hazardous Materials Safety Administration Vincent Holohan, U.S. Department of Transportation - Pipeline & Hazardous Materials Safety Administration	Martin Sulic
Subsurface Storage	Nik Huerta, SHASTA, PNNL Tim Reichwein, Lane Power and Energy Solutions Mariel Schottenfeld, Air Products	Jared Ciferno
Surface Storage	Kevin Harris, Hexagon Purus Brian Weeks, GTI Claudio Lanzarini, FIBA Tech	Zeric Hulvey

2.1 Hydrogen Production Presentations

Speakers in the Hydrogen Production panel represented commercial hydrogen producers active in production technology development and deployment. Both described emerging and currently employed methods for commercial hydrogen production and the current status of their respective underlying technologies and provided insight into their companies' priorities and planned activities.

2.1.1 Hydrogen Production Priorities and Plans

Plug Power is a leading provider of hydrogen fuel cell turnkey solutions, providing fuel cell and electrolyzer products. The company is looking to become a hydrogen supplier with a main goal to produce a large quantity of hydrogen. While bulk production allows for economies of scale, frequent transport is difficult. The company sees the future of hydrogen production transforming from a few industrial gas companies to more, smaller-scale hydrogen production at refineries, mobile hydrogen consumers, and other chemical companies. Current consumers do not want to depend on industrial gas companies and there are new hydrogen consumers that will enter the market.

FuelCell Energy produces carbonate fuel cells. They produce two high temperature electrochemical platforms that can be operated reversibly. In a Reforming/Electrolysis/Purification (REP) system, a combination of reforming and electrolysis using standard carbonate fuel cell stacks can be operated in reverse mode to accomplish electrolysis, which uses less fuel than pure reforming and less power than pure electrolysis. The company is interested in trigeneration systems, which can operate on biogas and produce water. The company is pursuing a 250 kW demonstration SOEC system that can produce 150 kg/day H_2, and which will be integrated with a nuclear power source. With a reversible solid oxide fuel cell (RSOFC), energy storage in hydrogen is significantly less expensive than battery systems for long duration systems.

2.1.2 Hydrogen Production Q&A

Plug Power has several large multi-megawatt electrolyzer projects in the process of being installed. What is the primary need for hydrogen storage for these large electrolyzer installations and what are the key attributes of those facilities?

Raja Amirthalingham, Plug Power: It will be key to streamline production in relation to the demand for hydrogen. To help drive demand, Plug Power will engage new customers. While Plug Power will be primarily focused on mobile applications, conversations are also taking place with ammonia producers (presumably on stationary storage). The goal is to sell excess hydrogen while Plug Power scales up. The intent is to use hydrogen storage at the scale and location that customers demand.

From a FuelCell Energy perspective, what are the most important storage aspects that are needed to support your systems?

Tony Leo, FuelCell Energy: Cost is key. Targets of $19/kWh for industrial scale and $5/kWh for geologic scale are sound, but if storage costs are much more than that, the advantage of hydrogen storage is minimal. The footprint of the storage system plays a substantial role in cost. The most important question is whether those storage prices hold true for storage at reversible electrolyzer plants.

2.2 Energy Storage Presentations

Speakers represented utilities aiming to make hydrogen a part of the energy mix they provide to customers for direct use, and the datacenter sector where hydrogen has significant potential for backup power applications.

2.2.1 Energy Storage Priorities and Plans

Northern California Power Agency is a 16-member agency of power, transit, and government entities, and leads the Lodi Energy Center Pilot Concept. The Lodi Energy Center was recently upgraded to support hydrogen development. The project includes a combustion turbine, grid/market integration, and storage. Both above- and below-ground hydrogen storage options are under consideration. Policy support is needed over the next 10-15 years to address key issues such as the Low Carbon Fuel Standard, Renewable Emissions Credits, and Independent System Operator market demonstration and delivery of renewable resources.

Microsoft is aiming to eliminate its dependency on diesel fuel by 2030. Diesel fuel is used for backup power, but has several disadvantages in addition to emissions. The company has been exploring fuel cell research since 2017, starting with solid oxide fuel cells using natural gas. The company's more recent 250 kW fuel cell demonstration to provide 48 hours of power has garnered significant media attention and public interest. The company is currently part of a DOE-funded project with Caterpillar, Ballard, and NREL to demonstrate a 1.5 MW fuel cell to meet data center requirements.

SoCalGas is a utility company that has been operating for over 140 years and provides natural gas to more than 20 million customers. Hydrogen is of interest for meeting long-term energy storage needs that cannot be met by batteries or pumped hydro power, and geologic storage of hydrogen is a viable option. The company has multiple hydrogen projects underway including a training facility for blending hydrogen and a *Hydrogen*

Home concept. The company also aims to develop hydrogen infrastructure solutions for the 2028 Olympic Games in Los Angeles and establish a hydrogen industrial cluster by 2030.

2.2.2 Energy Storage Q&A

What are the most critical needs your companies have to advance their hydrogen storage projects?

Hillary Petrizzo, SoCalGas: In California, a key need is a regulatory environment to support the development of hydrogen, such as a hydrogen injection standard. This would allow all of the California utilities to inject hydrogen into their systems. SoCalGas’ transmission system would allow for hydrogen to be stored in their fields. Pilot projects and extensive research and field work are important especially with respect to injection.

Michael DeBortoli, Northern California Power Agency: Grants are important because these projects are very expensive and energy intensive. Currently hydrogen is not cost competitive with other fuels, such as natural gas. Support for low carbon fuel standards and renewable energy credits is also important in lowering costs.

Upshur Quimby, Microsoft: Getting the market up to scale is the most important thing.

Why is Microsoft currently using hydrogen instead of solar panels for their datacenters?

Upshur Quimby, Microsoft – Solar panels on the roof of datacenters would provide a very small amount of power relative to the energy a datacenter consumes. It could also harm their customers’ proprietary data if the panels were to cause a fire. Microsoft has renewable power purchase agreements that include large scale solar projects.

Can you tell us more about the hydrogen home which has been developed by SoCalGas?

Hillary Petrizzo, SoCalGas: It’s a new home but it will have the same appliances as regular homes. They are looking to fuel the house with a 20% hydrogen blend which should be compatible with the SoCalGas system.

Can you discuss the cost model your company is using for your compressed hydrogen model? Some attendees think it seems high.

Michael DeBortoli, Northern California Power Agency: We worked with Black and Veatch to develop the cost model. It covers the cost over the life of the asset. Operation and maintenance should be factored in.

Can you share some information on safety and flammability issues with respect to blending hydrogen into pipelines? Would the flame be a different color if it is blended?

Hillary Petrizzo, SoCalGas: SoCalGas works with the Center for Hydrogen Safety and has done other safety trainings as well. The University of California – Irvine, Southwest Gas, and PG&E have done some good research on how flames change with hydrogen blending at different concentrations; Southwest Gas has a video online that demonstrates these changes. SoCalGas also uses blended hydrogen to cook hamburgers for employees; higher blends have longer cooking times.

Can salt caverns handle all hydrogen storage needs? What can pipelines handle? How much will new hydrogen storage in salt caverns cost?

Michael DeBortoli, Northern California Power Agency: The salt caverns are not in the Northern California Power Agency (NCPA) service area so if we used them, we would need large pipelines to bring them into California. We are looking at other solutions that are local.

Hillary Petrizzo, SoCalGas: The pipelines will be able to handle some storage as hydrogen is transported.

What plans does Microsoft have for hydrogen storage?

Upshur Quimby, Microsoft: Our goal is to use fuel cells as a substitute for diesel. We would look for partners that can provide hydrogen just over the fence on a large scale.

2.3 Transportation & Export Presentations

Presenters gave insight on the current status and needs of hydrogen for automotive transportation as well as rail, where emissions reductions are desired by replacing the use of diesel fuel. Hydrogen fuel cells are a future option for electric locomotives where very large batteries are needed, but energy density is still a concern. The refueling station is an important element of both. Presenters also gave an overview of pipeline regulations and past and current R&D on dedicated hydrogen pipelines and blends into natural gas pipelines.

2.3.1 Transportation & Export Priorities and Plans

Wabtec is a rail technology company, where a key competitor is the trucking industry. The first battery locomotives have been demonstrated in California, but the battery requirement is very large, and hydrogen fuel cells are a longer-term option for replacing diesel locomotives. The roadmap to zero carbon anticipates a hydrogen fuel train by 2030 with zero carbon emissions. A typical locomotive would need approximately 5000 kg of hydrogen, so energy density is critical, and since both gaseous and liquid hydrogen have lower volumetric energy density than diesel, this is the greatest barrier to adoption.

The California Fuel Cell Partnership is focused on fuel cell automobile transportation. They have a map available on their website, which at the time shows 50 public retail hydrogen refueling stations. They envision 1000 light duty retail stations for 1 million fuel cell vehicles by 2030. They also envision one third of the transit buses in California using fuel cells, and 200 public heavy-duty fueling stations for trucks. They estimate a demand for hydrogen of 2.4 million kg/day for California. Fuel cell buses would use 25 kg/day but stations would be private because they are fueled behind the fence. Pipelines for the refueling network could be used for both transport and storage.

The U.S. Department of Transportation Pipeline & Hazardous Materials Safety Administration (PHMSA) regulates transport through the Office of Pipeline Safety. Their mission is to protect people and the environment through regulations that pipeline operators must follow. They have conducted some hydrogen pipeline research in the past and aim to remove technical and regulatory barriers through R&D. Research has been focused on materials and welding for hydrogen pipelines, and this information will now be considered for hydrogen/natural gas blends. Gas leak detection is another area of concern and development for blends.

2.3.2 Transportation & Export Q&A

With the wide range of applications represented, is your definition of "bulk" storage?

Greg Wright, Wabtec: For a locomotive it is 5000+ kg.

Nico Bouwkamp, California Fuel Cell Partnership: For automotive, it depends on the vehicle, but the bulk storage consideration is really fueling stations, i.e., rail would need a lot more than 5000 kg at an operational yard. It depends on space available on site for cars, and typically goes as large as 100-1000kg. Trucking depends on footprint, with a minimum of 1000kg. Buses don't have much space and use liquid hydrogen tanks with horizontal or vertical 12,000-25,000 gallon liquid hydrogen storage tanks; gas needs more space.

Vincent Holohan, PHMSA: Depends on if its feeding into pipeline but can't give a number, any amount of H2 that entered a pipeline would involve their office, no matter the amount

Is leakage a concern in the community?

Greg Wright, Wabtec: New technology often scares people, but education can help and familiarity can lead to a bubble of safety. Our approach is to start with educating first responders. Users and regulators are seen as biased and less trusted by the public about hydrogen, but first responders are trusted members of the community.

Robert Smith, PHMSA: We echo the first responder approach. We have a liaison that gets trained by them to tell the people because sometimes they won't listen to regulators.

Nico Bouwkamp, California Fuel Cell Partnership: Informing first responders can help all around.

Are pipelines above ground and underground the same?

Vincent Holohan, PHMSA: Most above ground pipes we deal with are in plants and are much easier to monitor than underground pipelines. The major difference in the two pipeline locations is monitoring practices and not so much in material changes.

In moving containers across the country, and considering batteries can only get you so far, is there a plan for cross country infrastructure so there are more refueling points?

Greg Wright, Wabtec: The largest hurdle to adoption is the current range of trains, which is limited by refueling stations. We have to consider how we can start building that network. We will need a staged approach.

What is the main reason for causality of storage? Is there a way to bring more visibility to refueling stations?

Nico Bouwkamp, California Fuel Cell Partnership: We do what we can to help people be informed. Challenge is that they don't have control over sales of vehicles, fuel cell vehicle salesmen don't always give great information – this happened with battery electric vehicles too. People don't know where to refuel, or how to refuel. A question for us is, how far do we go to make sure people are informed?

From a pipeline materials point of view, up to how much can we increase the level of hydrogen by blending into natural gas pipelines?

Vincent Holohan, PHMSA: That remains to be determined; there are no current restrictions in blending, current data suggests there isn't any blended gas in pipelines, but they do not specifically collect this information

Nico Bouwkamp, California Fuel Cell Partnership: That depends on what part of the country as well. The Pacific Northwest has a new pipeline network that's mostly polyethylene, while the deep south and east coast have cast iron networks that are older.

2.4 Subsurface Storage Presentations

The subsurface presentations gave insight into the use of geological formations, which include salt and rock caverns, depleted oil and gas fields, and saline aquifers, as well as engineered subsurface storage such as wells or silos. Presenters illustrated the geographic distribution of and design requirements for suitable formations and described geologic studies that can be used or are needed to increase the use of salt caverns and implement emerging types of subsurface storage.

2.4.1 Subsurface Storage Priorities and Plans

The Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) project, which includes PNNL, NETL, LLNL, and industry partners, aims to address technological hurdles and develop technologies to enable public acceptance of subsurface storage of pure hydrogen and hydrogen/natural gas mixtures as a safe and effective bulk energy storage option. This work includes risk quantification, enabling technologies, and stakeholder engagement. Existing natural gas infrastructure to enable blends with hydrogen, or pure hydrogen, are being investigated. Reservoir performance will depend on rock and fluid properties. The possible impacts of microbial interactions and biogeochemical processes is an important consideration. Durability of well construction materials, leakage along wellbores, and testing and surveillance approaches are all aspects for consideration in the use of existing or construction of new wells for hydrogen storage. SHASTA is also looking at social, regulatory, and technoeconomic considerations as part of its objective.

Lane Power and Energy Solutions has extensive experience with hard rock caverns and salt caverns, including one hydrogen cavern. Though there are numerous hard rock caverns globally, used for storage of crude and light oil, and liquid petroleum gas (LPG), there are none presently used for hydrogen. The company presented estimates for the capital costs of salt and hard rock cavern hydrogen storage. The costs are region dependent for salt caverns and are lower in the Gulf Coast region compared to similar caverns in Appalachia. The company also introduced and presented cost estimates for an underground hydrogen silo option, which may be a flexible, customizable option with diameter, depth, and number to suit storage volume requirements.

Air Products is a major player in the current hydrogen market with experience in salt cavern storage. Salt tectonics, the geological study of how salt bodies evolve over time and space, is important for pinpointing where suitable saline aquifers for gas storage may be found. Understanding fault distribution around salt bodies is important as these can create fluid escape pathways. Salt tectonics principles, which have historically been used to search for hydrocarbons, can be used to locate saline aquifers that could be used for hydrogen storage.

2.4.2 Subsurface Storage Q&A

What is the priority focus for geology in SHASTA research?

Nik Huerta, SHASTA/PNNL: Sandia National Laboratories has done a good amount of work on salt cavern storage. Therefore, SHASTA has focused on porous media storage given the research constrained environment. In terms of deployment, it depends on the availability of samples to study. Research will grow organically and workshops, such as the one being held today, are very helpful in opening doors to get the necessary samples to move the research forward.

What are the risks to population centers that are near subsurface storage? Are microseismic incidents a concern?

Nik Huerta, SHASTA/PNNL: We are more concerned with well integrity/well failure. We want to get a better idea if hydrogen can move through cement. SHASTA is not well suited to do risk assessments to determine the possibility of incidents, but rather is looking at applied fundamental aspects.

Can you expand on the concerns with microbials in underground storage?

Nik Huerta, SHASTA/PNNL: Microbials consume hydrogen and this can be an asset. Microbials can also negatively impact wellbore integrity and plug and/or foul wells if they grow too much. I am not a microbiologist, but there could be several reactions that may or may not be problematic. The oil and natural gas industry has techniques to mitigate any issues but doing an assessment to understand what may be problematic is important. The timescale is also important to understand.

Does SHASTA focus on oil and natural gas reservoirs or salt caverns?

Nik Huerta, SHASTA/PNNL: It currently focuses on porous media storage. There is value in looking at existing facilities that can store natural gas because this will be helpful with blending hydrogen and natural gas.

What would be the ideal field site for SHASTA to do research?

Nik Huerta, SHASTA/PNNL: An ideal site would be one that has a strong partner who is willing to work with us and interested in helping educate the community about the project. The geologic conditions would be a secondary consideration. Public acceptance will be critical to advancing storage.

The three salt caverns in the U.S. are in brine. Have you looked at the impact of hydrogen on hard rock?

Tim Reichwein, Lane Power and Energy Solutions: We have not had the opportunity or need to do that. Our preference would be creating a hard rock cavern in shale because of the nature of its impermeability. They are impermeable and dry, but they can still be designed for hydrostatic transport. We'd design these with a working pressure less than hydrostatic head. They are at great depths at about 2,000 feet, so we can get maximum 800 psig – they reserve about 100 psig base gas in the cavern, so you get enough pressure to work with. These are not compensated hard rock caverns.

How does salt shifting (brine compensation) impact the capacity of a cavern?

Tim Reichwein, Lane Power and Energy Solutions: Our Gulf Coast caverns are very large and can store 4-5 bcf of hydrogen. They are dry gas caverns and are non-compensated. In a compensated cavern, brine will displace the hydrogen. The only impact would be, if you are pumping in one well and trying to pull hydrogen from the same well through the inner string, there will be pull limitations on that cavern. With a given size well, you would not have that with a dry gas cavern.

Why has the life of caverns been set at 40-50 years? What determines that?

Tim Reichwein, Lane Power and Energy Solutions: We design hard caverns for a 50-year life. So far, the caverns that have not lasted this long are those that have been intentionally taken out of service.

Is there a density contrast between salt and sediments?

Mariel Schottenfield, Air Products: Seismic is used to identify density contrasts and where both salts and sediments are. Sediments have very linear features all around them in a seismic line because of density contrasts. This is how we find sediment for aquifer storage.

2.5 Surface Storage Presentations

Speakers in the Surface Storage session gave an overview of the currently available surface storage and transport options, their advantages and disadvantages, and insights into innovations being pursued.

2.5.1 Surface Storage Priorities and Plans

Hexagon Purus is a supplier of high-pressure vessels, fuel storage systems, and distribution systems for hydrogen. They specialize Type IV high-pressure vessels made from carbon fiber rated for pressures ranging from 250 bar to greater than 950 bar. They also supply hydrogen distribution solutions across North America at a range of pressures (250-950 bar), hydrogen capacities (25-1000 kg), and distribution methods.

GTI is a not-for-profit R&D institution with a portfolio of services includes research and development, program management, and consulting across energy supply, conversion, delivery, and utilization processes. Long-duration energy storage was presented as a critical need to achieve decarbonization goals as reliance on renewable energy sources increases, and hydrogen was presented as a promising and cost-effective energy storage medium. Pipelines can be considered a hydrogen storage vessel, and line pack in the pipeline can provide instantaneous response for energy storage.

Fiba Tech is using finite element analysis (FEA) to model material integrity. Extensive characterization of Type I and Type II cylinders has shown that fatigue crack growth rates are 10-100x greater in hydrogen environments than air. Examining the local stress/strain on materials includes elastic-plastic analysis, cyclic stress/fracture mechanics, and global loading. Plugs and vessels are both examined. The material must be prepared for non-linear characterization, where analysis is especially important. Refinement of the mesh to capture local strain is necessary to ensure reliable results.

2.5.2 Surface Storage Q&A

Has 950 bar transport been approved by the Department of Transportation (DOT)?

Kevin Harris, Hexagon Purus: Yes, it was approved circa 2018, and we already have units in the field.

Can you provide more detail on the specific end-users of drop-and-swap options for gaseous hydrogen?

Kevin Harris, Hexagon Purus: It's currently not being used much in the hydrogen sector and is primarily something we have used for our compressed natural gas (CNG) customers. A trailer is brought to the site and parked, and used until it is depleted, at which point it can be exchanged for another trailer.

What sort of R&D is needed to reduce costs?

Kevin Harris, Hexagon Purus: For Type IV cylinders, the carbon fiber is the largest part of the cost, at 50-60%. Reducing the cost of the carbon fiber would lower the vessel cost significantly. The DOE is currently supporting a project at the University of Kentucky on the development of hollow carbon fibers. My understanding is that the majority of the strain is on the outside of the fiber. Approaches such as this would reduce the mass and consequently the cost of the carbon fiber.

Claudio Lanzarini, FIBA Tech: Regarding Type I and Type II vessels, the company is developing new technology that it is unable to disclose at this time. Generally, there is a need to improve crack detection onsite. Detecting smaller cracks earlier may help to extend the life of the vessel.

What are the limits of blending hydrogen into the natural gas infrastructure?

Brian Weeks, GTI: Hydrogen can be blended with natural gas, but the percentage depends on the pipeline network. Some natural gas pipelines are being suggested for conversion to hydrogen or blending, but some pipelines won't be able to transfer any hydrogen at all. There is ongoing R&D to determine which pipelines can be used, such as through the DOE HyBlend initiative. Natural gas pipeline variance is important and needs to be looked at more closely. Installation of 100% hydrogen pipeline in an existing natural gas right-of-way could be important.

3 Breakout Sessions

The two hour breakout sessions gave users and providers an opportunity to discuss the technology needs, current status and identify technology gaps and RD&D needs. Day two attendees were permitted to select from either a surface or subsurface storage breakout topics. There were two rooms for each topic to allow for more participation from more individuals. One moderator facilitated discussion while two scribes took notes on the conversation in each breakout session. Moderators were asked to craft report slides based on the following general topics:

- Application areas discussed
- Technology Gaps for State-of-the-Art Technologies
- R&D areas identified
- Innovative Concepts discussed
- Other considerations identified

Sections 3.1 and 3.2 contain narrative summaries of the discussions. Following the breakout sessions, attendees returned to the main session and each moderator reported on the discussion in their breakout room. The key points presented in the report out for each breakout session topic are compiled in Table 2.

3.1 Subsurface Storage Breakout Session

Between 60-80 attendees participated in each Subsurface Storage breakout session. Discussion topics included caverns and porous-rock storage; natural gas, carbon dioxide, hydrogen, town gas industries; monitoring programs from heavy oil and natural gas; and coupled physics and modeling of caprock and fault integrity from carbon dioxide storage. There was significant discussion on technical gaps for subsurface storage. Within technical gaps, there was general discussion on the lack of knowledge of hydrogen interaction with various subsurface storage materials and cyclability of underground storage. Additionally, there were comments on regulations, codes, and standards related to underground storage and novel underground storage methods. There was also general discussion on how to leverage knowledge and resources from multiple groups. The DOE convened this group to facilitate discussion across geologic media, varying supply chains, and storage opportunities for hydrogen and other gases in the subsurface.

3.1.1 Technology Gaps and R&D Needs

Because hydrogen storage in the subsurface at scale, is currently limited to commercial operations in salt caverns, major technology gaps remain across varying geologies and storage infrastructure. For example, there is a lack of knowledge in the performance metrics of different well and injection designs. Additionally, some research shows that diffusivity and losses change if you inject vertically or laterally in the formation. The need for pilot demonstration to reconcile lab-based predictive modeling in order to optimize the safe storage of hydrogen at scale.

Audience participants brought empirical operational experience to the discussion. Topics included acceptable cycling rates, plume migration, and recoverability. One attendee noted that they have demonstrated 12/12 and 16/8 hour cycling and have maintained pressure for 60 cycles in their small hydrogen to gas turbine and storage facility. This work is ongoing and current modeling is focused on modeling diffusivity for hydrogen and cushion gas within a storage reservoir.

Participants discussed trap integrity, casing, coatings, liners, and seal characterization at length. Some important characteristics of seals include resiliency during cycling (changes in pressure) and formation deformation. Knowledge on what types of operational conditions and materials could improve seals and polymer performance, is needed. No one proposed current state-of-the-art seals for this application, but it was noted that are major distinctions between cementing and seals for surface equipment. It was noted that industry participants use a very high degree of seal-ability because hydrogen is such a small and mobile molecule.

Cushion gases which are required to maintain storage reservoir pressure, in terms of type and scale were also discussed. Nitrogen and carbon dioxide were suggested as possible cushion gases alternatives to methane. It was noted that the mixture of cushion and hydrogen and its interactions with the surrounding equipment is not well studied. R&D is needed for gas interactions with cycling at multiple system (and time) scales. This area of interest will impact optimization of storage and more research is fundamentally needed. Other geochemical reactions must be identified, with the cushion gas in mind, in order to avoid degradation of the storage formation. The synergistic effect of material/cavern degradation with simultaneous hydrogen exposure and cycle loading is another, more difficult research area to study that may show effects greater than seen for individual research subjects.

Another knowledge gap is to test the mechanical integrity of salt caverns throughout their operational life. A conversation on whether over- or under-pressurization of salt caverns lead to poorer performance concluded that it was not an issue to formation performance. The testing of cavern structural stability relates to the acceptable leakage rate for hydrogen. This leakage rate needs to be determined within evaluation of prospective storage sites. Someone noted that an acceptable leakage rate is 'one that cannot be read by the instrument.' There is R&D at NREL on hydrogen sensors for remote and large-scale detection, but again unclear if those instruments are designed with a specific acceptable leakage rate in mind.

Greater investment in related R&D is needed to more fully determine the feasibility of underground hydrogen storage and across different geologies and geographies. Guidance is needed on which locations are best suited to pair with geomechanical models, characterize the fluids present, determine reactions with surrounding environment, etc. to predictively understand storage in the subsurface. There is also no information on seismic or geophysical responses of mixed natural gas and hydrogen or mixed methane and hydrogen. These needs may suggest critical requirements to establish testing standards for caverns to determine if they are suitable for storage. The need for scaling is understood and attendees were hopeful that we could engineer subsurface storage facilities in new locations or expand on existing storage opportunities and leverage existing infrastructure.

3.1.2 Regulations, Codes, and Standards

There are concerns about how we would detect hydrogen leaks and fires, particularly considering the transparency of hydrogen flames.

Codes and standards need to be developed around hydrogen reactivity with relevant materials, such as seals, geological formations, cushion gases, and these materials in combination. The American Institute of Chemical Engineers (AIChE) is a good resource for this reactivity information and could be used as a basis for regulations, codes, and standards. Carbon sequestration storage is well monitored and would be a good guidance as to the safeguards that need to be put in place, as opposed to natural gas storage which is not heavily monitored. There were concerns that monitoring rules that were in place do not define what adequate monitoring is, and more guidance is required.

3.1.3 Infrastructure and Resources

This conversion focused mostly on locations and types of subsurface hydrogen storage. There is a limitation on hydrogen storage in salt dome due to location constraints and porous media, which includes aquifers and depleted oil and gas fields, offers a wider geographical capacity. Use of porous storage media introduces contamination issues which will require more hydrogen purification infrastructure.

There are currently no standards for the placement of hydrogen storage salt caverns. Guiding principles in placing natural gas caverns is a pillar to diameter ratio of 2:1, as recommended by industry. Most operators, however, option for a higher ratio to improve the process of watering the cavern and brine extraction. Proximity of salt caverns is a concern as well. Placement too close to adjacent caverns runs the risk of degrading cavern integrity and limits the excavation process for new caverns. It is also important to properly plan out caverns before building above ground structures.

3.1.4 Innovative Concepts

Participants noted that there wasn’t any discussion on hydrogen storage in deep water. Deep water can enable high pressure, stable, hydrogen storage. There are R&D areas that need to be addressed to make this a viable option including the mineralization of hydrogen. NREL is currently evaluating the techno-economics of deep water storage. This method can be suitable for long-duration, grid-scale, and seasonal storage. Additionally, it can provide an alternative when other storage options are too expensive and/or not available.

3.2 Surface Storage Breakout Sessions

Between 60-80 attendees participated in each Surface Storage breakout session. Throughout the discussion, discourse returned to regulations, codes, and standards as both the major challenge, and opportunity area identified by current users and suppliers of surface hydrogen storage technologies. While attendees discussed costs, much of these were directly related to regulations, codes, and standards requirements. Opportunities to reduce costs of materials and manufacturing are overshadowed by the need to reduce costs imparted by testing, certification, and compliance for the storage and transport, whose governance falls under different bodies with different protocols and requirements. R&D opportunities largely related to extending acceptable lifetime of tanks, improving testing to reduce the burden of certification, and reducing restrictions on transport and storage. Attendees encouraged DOE to lead codes and standards reform and harmonization. Attendees held the

DOE accountable for collecting, analyzing, and sharing cost data, and establishing targets for cost and performance for bulk gaseous hydrogen storage. Attendees also gave suggestions for some potential R&D areas that might be of interest to DOE.

3.2.1 Cost Data and Targets

DOE does not currently have any established cost or performance targets for bulk gaseous hydrogen storage. Current targets are for onboard hydrogen storage for vehicles. Targets for stationary applications may need to be independent of onboard applications. Attendees agreed that currently available cost data varies significantly depending on which consultancy provides the analysis, and there is need for consistency in cost data. This kind of data is readily available for batteries and should be available for hydrogen. The attendees overall agreed that the DOE setting cost and performance targets would be of value, where cost targets alone may not be valuable to academia. They agreed that the DOE should provide guidance on whether volume should be more important than weight, and which metrics, such as $/kg or $/kWh, should be used. The DOE should determine these targets and provide guidance on how far they are from being met.

Targets for stationary storage should consider the role of geologic vs. tank storage. It would be helpful to understand the difference in cost. Geologic storage may be ideal for very large volumes but taking into account the time cost for implementation would be beneficial. Packed pipeline may be an option, but similarly the timeline is quite far out. For tanks, the primary costs are steel, shipping, and manifolding. All aspects should be studied to determine where capital expenditure can be reduced.

Currently, the cost of large stationary tanks is burdensome and is a potentially limiting factor to increasing production volumes. For example, a 2 tonne per day (tpd) production capacity facility wishes to increase to 32-48 tpd; having incurred a capital cost of ~$4M for 500 bar Type I tanks to meet current levels, and without subsurface storage available, the capital expenditure necessary for additional storage to accommodate 1 weeks' worth of production at future projections is worrisome. While 200 kg tube trailers may be an option, the hydrogen silo concept presented by Lane Power and Energy Solutions is a very attractive option for consideration as an alternative.

The needs for stationary storage and transportation differ, in aspects such as the required pressure. In many cases liquid storage may not be an option. There is a need for above-ground gaseous storage options larger than the 1-2 tonne ranges available now, that aren't cost-prohibitive. 5-20 tonnes or more may be needed. Currently, costs might be on the order of $1800-2000/kg while <$1000/kg would be ideal. This approximate estimate is for capital costs and does not consider operational expenses.

3.2.2 Application Areas

Participants discussed the limitations of gaseous hydrogen for large scale applications and a point at which liquid hydrogen may be preferable even with technology improvements. It is likely that there will always be a need for gaseous hydrogen, for example with ammonia production, which itself may be used as an energy carrier in large aviation or ocean-going vessels. Application areas where surface bulk storage may be relevant include jets and large aviation, offshore wind vessels, mining, and rail refueling. It is likely that most of these requiring very large volumes of 1000 kg or more will resort to liquid hydrogen.

There is significant interest in hydrogen for the mining industry in particular. A large truck can use 1 tpd of hydrogen and a typical mine might have 25 trucks and maintain a weeks' worth of fuel stored onsite. Several mines have announced plans to go carbon neutral by 2030, and this may be influenced by regulations that limit diesel use. Companies are considering the feasibility of onsite hydrogen production, and the most economical source of electricity. They must balance the costs of running transmission lines out to a mine site compared to installing solar or wind facilities. Companies are generally agnostic to the exact fuel if it is clean. For example, clean methanol produced from hydrogen or otherwise would be easier to store and transport.

The general consensus is that while there will continue to be a need for gaseous hydrogen, surface storage of very large volumes is likely to be superseded by liquid storage. Gaseous storage currently outweighs cost and performance gaps in hydrogen liquefaction and will be needed until such limitations can be overcome. The subsurface alternative will likely be preferred for bulk storage of gaseous hydrogen, especially for long-term energy storage. There was concern over whether long duration hydrogen energy storage is worthwhile if geologic storage is not available. Cryogenic storage is an option but is not as efficient as gaseous storage, but there could be space for more exploration there. Depleted reservoirs, where there is an integrated network, might be suitable until other issues can be resolved.

3.2.3 Regulations, Codes, and Standards

Regulatory and other influential bodies include ASME, OSHA, DOT, and the Compressed Gas Association (CGA). In terms of design, high pressure tanks must be tested for impact and explosive threats. Smaller tanks for vehicles undergo gunfire tests to determine threats for different applications. Larger diameter imparts impact resistance and gives more robust containers. See appendix for additional information.

Participants said there is a gap between usage, transport, and storage of hydrogen in terms of regulations, codes, and standards. There is a need for more clarity on the risks of collocating. Approval requirements for the ASME, which can include various cycling and empirical testing, are very onerous to users. If users were allowed to use DOT standards this would move the industry forward. These standards should be harmonized and interchangeable, as separating transport and storage into different governing jurisdictions is prohibitively burdensome.

The European Union (EU) is more lenient on restrictions in transportation standards. For instance, the EU uses metric tons while the DOT uses imperial tons. It would be beneficial if DOT could relax the regulations to allow more hydrogen to be transported at a time on the road. One route to that would be lobbying Congress, which is outside the actionable activities of DOE.

EPA's ALOHA software [5] allows for a simple determination of appropriate setback distances. There is ongoing analysis work at Sandia National Laboratories (SNL) to reduce setback distances for gaseous hydrogen similar to work underway for liquid hydrogen. It may be difficult to deploy a simple application as it would be prone to error as every site and storage situation is different.

The testing and recertification of tanks is a tremendous burden. Taking tanks out of service while undergoing recertification is a major disruption, and the cost to ship tanks from Hawaii to the mainland is exorbitant (on the order of $50,000). There may be some options available for onsite testing that could alleviate this burden. Hexagon Purus has an acoustic emission technique, Digital Wave, which is used on Type IV tanks. This allows a team to go onsite and complete the necessary testing in 1-3 days.

The current requirement for a 5-year recertification cycle, and a 15-year lifespan need to be revisited. Tanks that will expire because of these restrictions will ultimately be sent to a landfill unless there is an option for repurposing or recycling. This is a major capital investment loss in a growing hydrogen industry. Sandia National Laboratory may benefit from receiving these tanks to conduct further studies on the effects of hydrogen exposure and additional environmental factors that may affect material resiliency, such as exposure to sunlight and humidity. The user must make such arrangements for transfer with little if any benefit to their business. The inspection and requalification are also issues for testing end connectors that are sealed with O-rings. More work to enhance sealing and test for leaks here would be worthwhile. This type of failure at joints may not be specific to hydrogen, but reliability is important.

There was interest in the possibility of storage tank health monitoring or telemetry-type systems that could be integrated into a "smart tank" design. There may have been some similar technologies used for liquid nitrogen, but it was not certain if this has been deployed successfully. Monitoring each individual storage vessel could be costly to implement, but this could be matched or even outweighed by lower insurance or inspections costs and could provide a market acceptance value from a public safety perspective. There is a gap in pressurization cycle counting technology. Some may not be counting accurately, as this isn't automated. It may be problematic if hydrogen ground storage cycling is not accurate, as permitting officials will question this. There may be some software available for performing cycle counting and monitoring that could potentially be expanded to the hydrogen space.

Much of the work on hydrogen safety is focused on vessels as opposed to materials. There are kinetic and explosive safety concerns for high pressure storage vessels. Solid state storage, like magnesium borohydrides, may have lower concerns than gaseous hydrogen storage and could allow for bulk storage of hydrogen. DOE has done a lot of work on sorbent-type storage. For most of these, cryogenic temperatures are required, which would then require double-wall vessels for insulation. Higher capacities are possible at room temperature but when compared to 250 or 500 bar pressures typically used, they do not provide an advantage.

Storage pipelines may be an avenue to reducing storage costs. Currently, under OSHA standard 1910.103(b)(2)(i)(c), pipeline systems shall not be located beneath electric power lines. This restriction must be considered when determining where substations can be located. These standards should be revisited. Harmonization of standards for hydrogen transport in existing pipelines between the U.S. and EU is also an area of focus.

3.2.4 Innovative Concepts

Discussions of blending hydrogen with natural gas emerged from other topics. There is work underway through the National Laboratories as well as international organizations working in this effort. Limits must be established and are highly dependent on the existing infrastructure and the end use application. Up to 20% is the number that many seem to be coalescing around.

Participants discussed advanced and automated manufacturing to bring overall costs down. While there has been some success on this front in the propane tank realm, it is not expected to make a major cost reduction for hydrogen tanks. At the scales needed, it is difficult to automate much of the manufacturing. The large diameters require thicker and heavier materials to be formed, which becomes difficult to automate. The major cost is those materials, and a major factor is the lack of domestic supply. For Type IV tanks, the major cost is carbon fiber. In either case, automating and minimizing the manufacturing cost is negligible compared to the cost of the actual material.

The development of a universal hydrogen tank, not for long term storage, but as a swappable tank concept for applications such as aircraft could potentially be considered. This would be dependent on the time saved by swapping compared to refilling, and the associated implications of a refilling infrastructure or the cost of multiple tanks. Advanced manufacturing techniques may allow for 3D-printed tank concepts. Super large balloons, which have been seen in some underwater storage applications, could be explored for use in areas like the countryside. Additionally, old rail lines could be repurposed to be used for storage vessels, similar to tube trailer arrangements that function as stationary storage.

R&D for technology inside the pressure vessel or additional work on ultrasonic testing may be of interest; Digital Wave acoustic technology has been used but does not allow for sizing of cracks or leaks. More work for materials property testing for polymer materials in particular, is needed to develop standards for hydrogen environments.

There may be value in co-storage of hydrogen and oxygen, particularly for reversible electrolysis cells. High purity oxygen streams yield improved efficiency as opposed to using air as the oxidant source. There may be merit in developing large-scale systems with these capabilities.

Whether or not odorants, such as hydrogen sulfide, would be used to detect hydrogen leaks was debated. While some attendees believed that the industry would rely more on hydrogen-specific sensors to detect leaks, others had heard of odorants already being added to hydrogen supply lines for certain applications. Those applications were likely only where hydrogen would be combusted (e.g., power generation, industry), as odorants would contaminate fuel cells. Low-cost leak detection methods that can be widely deployed across the hydrogen supply chain is a potential area of further development.

3.2.5 Workforce Development

There is high demand for employees in the hydrogen industry that is not being met by the current supply of candidates. The supply of potential members of the workforce has remained consistent but is outpaced by rapid growth of the hydrogen industry. There is competition for engineers, and people with engineering backgrounds are expected to continue to be in high demand in the future. Ways to address this increasing demand or to increase the supply of candidates were not discussed.

3.3 Breakout Session Report-out

Upon reconvening in the main session, moderators from each breakout session gave a short report of the main discussion points to all attendees. The report-out highlights are compiled in Table 2.

Table 2. Summary of the report slides produced by breakout session moderators.

Discussion Topic	Subsurface	Surface
Application Areas Discussed	Regulatory needs for hydrogen storage Leverage technology developed for oil and gas, carbon storage, compressed air, hard rock technologies, work on liquid and gas product storage in caverns in water curtains – lessons learned from gas storage – all applicable to H2 storage in porous media and caverns	Stationary (e.g., mining applications) & tube trailers Regulations, codes, and standards The use of pipelines for H2 storage Many on-board applications will require liquid
Technology Gaps for State-of-the-art Technologies	Reservoir imaging and data acquisition Access to core (destructive/non-destructive) Leakage Utilizing oil fields specifically (for EOR or otherwise) Other storage mechanisms Well designs and injection designs affect performance – vertical vs lateral injection Maintaining cycle rates for hydrogen storage and use Monitoring needs for hydrogen	Reducing the cost of carbon fiber (material cost and conversion) Extend the life of storage systems through code changes, health monitoring, life extension inspections Durable components and conveyance technologies for high transfer rate (e.g., high pressure) Large scale (>5 tons) above-ground storage options at affordable cost Need a 50-75% reduction in cost More sophisticated inspection technologies for H2 vessels

	Odorant injection for leak detection Salt Cavern design and spacing restraints – no standard available Characterization of seals	Improved cycling and monitoring methodologies Pressure volume constraints for gaseous H2 storage (compressors) More refined and standardized approach for the qualification of new materials (domestic vs international) Existing codes/standards to be reviewed and updated and made available to stakeholders
R&D Areas Identified	Microbial conversion Suitability of caverns for different end uses Producibility/cycling rates Best resources for buffer demand storage Understanding cushion gas dynamics Hydrogen utilization and safety Address seals for permeability and cycling of pressurization, engineering more stable seals. Limited information about reactivity of H2 in porous media – how do Impurities affect hydrogen storage (oil) H2 interaction with surface equipment, casings, impact integrity. Seal integrity and interaction with cement barriers- pyrite Cushion gas type (H2, NG, CO2, N2), control of pressure, reactivity, operations of these are not well studied. R&D needed at multiple scales with cycling	Lifetime extension of tanks (needs regulatory change as well) Assess the value of vessel health monitoring to see if there is a cost benefit, or improves public perception Suggestions heavily “infrastructure” focused – discussion provided a new perspective from DOE Transition from analog to digital measuring and monitoring and controls

	Mechanical integrity testing of caverns Acceptable leak rates for H2 H2 embrittlement – steel liner	
Innovative Concepts	Competition for CCS and pore space Competition for other commodities Cost drivers Ability to store H2 in deep water: for long duration, grid scale, or seasonal storage Characterization of seismic and geophysical responses of H2 and NG Using engineering design to improve subsurface volume other than search for other storage sites	Non-traditional containment (e.g., steel coated concrete vessels) Swappable volume tanks for regional aircrafts 3D printed H2 tanks Cryogenic storage Super balloons in countryside Old rail lines to be used as stationary storage vessels (transport H2 when and where needed)
Additional Considerations	Public education of new energy systems American and European views on storage in salt domes, arising from models adopted in past and different geologies in the different countries Storage tradeoffs (methane vs. hydrogen vs. ammonia) H2 Hub and the impact to subsurface projects Hydrogen exports Leveraging existing knowledge base (geology) What are the impacts of H2 losses or effect on surrounding area Safety concerns due to transparent H2 flame	Need to define targets for H2 storage technologies that are application space specific (e.g., size, pressure, stationary vs. mobile) Desire for published cost curves for stationary H2 storage at large volumes Harmonize codes between DOT and ASME

	Every storage formation will behave differently Lessons learned from fields not suitable for CO2 storage, may not be good for H2 either. Injectivity and productivity is small	

4 Conclusion and Recommendations

Closing remarks were given by Ned Stetson, HFTO. He thanked presenters, attendees, organizers, moderators, and scribes for their valuable contributions. Participants gave positive feedback on the workshop and were appreciative of the opportunity to participate in the informative and engaging event. Participants were also invited to engage in upcoming workshops on liquid hydrogen and electrolysis.

This workshop had a very high level of interest, with over 1100 attendees who registered and participation from 842 total attendees over the course of two days. The workshop achieved its objective to bring together industry partners, end-users, and government stakeholders with those involved in active large-volume storage operations or RDD&D projects. The high level of engagement from external stakeholders confirms their confidence in hydrogen as an important part of the energy economy and allowed DOE to include them in helping to shape future pathways to achieve common goals. The breakout sessions were of particular value, as were having the presentations on relevant topic areas set the stage for productive discussions. The participation of speakers in the breakout sessions was especially valuable as many questions and discussions arose from the content of their presentations. Together, the presentations and breakout discussions will allow DOE to better understand the various challenges and opportunities for hydrogen in meeting future energy storage demand.

Topics that elicited the most discussion were the gaps and challenges with geologic storage, hydrogen blending with natural gas for both storage and transport, and regulations, codes, and standards. This indicates that additional stakeholder engagement around these topics is needed and suggests that focused workshops and continued or increased DOE support for these topics are warranted. Major stakeholder concerns are the burden of testing/certification, outdated, conflicting, or lacking codes, standards, and regulations, and the need for reliable and accurate cost data and performance metrics or targets. Additionally, the growing demand for a skilled workforce is already presenting a challenge that is expected to worsen if the supply of trained workers remains at constant levels. Importantly, these concerns about testing, regulations, and workforce, are not specific to bulk storage of gaseous hydrogen, or hydrogen storage in general, and apply to production and delivery as well.

Key recommendations for DOE: 1) collect and share cost and performance data with stakeholders; 2) establish cost and performance targets for both surface and subsurface storage technologies; and 3) enable RDD&D to reach those targets. DOE should also consider some of the innovative concepts suggested for future inclusion in funding opportunities as appropriate. More broadly, DOE should support R&D to inform regulators to regulations, codes, and standards requirements and their harmonization across governing bodies, both domestically and globally. Funding to advance technologies that would facilitate such refinements, such as for better testing and monitoring, would be beneficial. Lastly, DOE should support workforce development across hydrogen and fuel cell technologies, including leveraging transferrable skills from the current workforce in natural gas and other sectors. These activities will provide the strong foundational support system on a Federal level that will allow hydrogen to flourish in the future energy market and fulfill the mission of the DOE to ensure America’s energy and environmental security.

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Appendix

This appendix provides a summary of regulations that were not discussed explicitly during the workshop breakout sessions, but may be of interest to readers. The full record of regulations: https://energy.sandia.gov/wp-content/uploads/2021/03/H2-Regulatory-Map-Report_SAND2021-2955.pdf

Regulation of hydrogen storage systems:

Regulatory primacy can vary by system location and purpose.

- Regulation of a hydrogen storage system is dependent on the purpose of the storage system and whether the hydrogen is stored in gaseous or liquid form.
- The U.S. Department of Labor Occupational Safety and Health Administration (OSHA) regulates hydrogen storage through 29 CFR Part 1910 Subpart H – Hazardous Materials.
  - This Code of Federal Regulation (CFR) provides the safety requirements of the structural components and operations of gaseous and liquid hydrogen in terms of storage as well as delivery.
- For aircraft and spacecraft launch sites, DOT Federal Aviation Administration (FAA) regulates hydrogen storage through 14 CFR Part 420.
  - Dictates the separation distance requirements between the storage of liquid hydrogen and any incompatible energetic liquids stored within an intraline distance (the minimum distance permitted between any two explosive hazard facilities in the ownership, possession, or control of one launch site customer).
- There are several codes and standards related to hydrogen storage for distribution that are subject to approval from state or local authority having jurisdictions which would adopt and enforce these as regulations.

Blending of Hydrogen into Natural Gas Supply Value Chain:

- The blending of hydrogen and natural gas is regulated based on where it is used and where hydrogen is added to the natural gas supply value chain.
- FERC would regulate the import/export of blended fuels.
- Once blended hydrogen and natural gas is introduced into the pipeline system, PHMSA OPS, BSEE, and USCG would regulate the pipeline based on whether it is onshore or offshore.
- FERC regulates fuel used in combustion systems for power generation and FERC regulates fuels used for heating systems.
- DOE EERE regulates heating appliances where this blended fuel may be used in certain applications DOE FECM also regulates alternative fuels through 10 CFR Part 503 and 504.
  - These regulations include using blends stated in Part 503 for new facilities and Part 504 for existing power plants.

    - These requirements are set for facilities required to meet Title VIII of the National Energy Conservation Policy Act (42 USC Chapter 91) which prohibits a power plant from burning natural gas or petroleum as its primary energy source.
    - There is guidance on allowed exemptions to operate using fossil fuels either permanently, temporarily, or due to an emergency.
- Additionally, blended hydrogen and natural gas used as a fuel source are subject to state/local regulation.

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For more information, visit:
https://www.energy.gov/eere/fuelcells/hydrogen and fuel cell technologies office

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