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Hydrogen Infrastructure Strategies to Enable Deployment in High-Impact Sectors

2024 Workshop Summary Report

Hydrogen and Fuel Cell Technologies Office

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.

Acknowledgments

The Hydrogen and Fuel Cell Technologies Office (HFTO) would like to thank all the speakers who presented at the workshop:

- Michael (Misho) Penev – National Renewable Energy Laboratory
- Steve Lommele – U.S. Joint Office of Energy and Transportation
- Matthew Post – Hatch
- Mike Veenstra – Ford Motor Company
- Zach Barra – Daimler Truck North America
- Keith Brandis – Volvo Group
- Maarten Meijer – PACCAR
- Tim Brown – FirstElement Fuel
- Luke Wentlent – Plug Power
- Brent West – Fives Cryo Inc.
- Samuel Gage – Energetics/ U.S. Department of Energy, Industrial Efficiency & Decarbonization Office
- Joe Beach – Starfire Energy
- Steve Hammond – National Renewable Energy Laboratory
- Nyla Khan – U.S. Department of Energy, Office of Electricity
- Jim Greer – Advanced Clean Energy Storage (ACES) Delta
- Katrina Regan – Southern California Gas Company
- Travis Wright – QTS Data Centers
- Vincent Holohan – U.S. Department of Transportation, Pipeline and Hazardous Materials Safety Administration
- Hyun Jo (Joe) Jun – ExxonMobil
- Evan Frye – U.S. Department of Energy, Office of Fossil Energy and Carbon Management

HFTO would like to thank all the meeting participants for providing meaningful feedback and engaging in valuable discussions. The organizers would also like to thank all moderators, scribes, and facilitators who assisted during the workshop.

Nomenclature or List of Acronyms

ACES	Advanced Clean Energy Storage
ARL	Adoption readiness level
CAPEX	Capital expenditure
CcH_2	Cryo-compressed hydrogen
CCS	Carbon capture and storage
CO_2	Carbon dioxide
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
ESGC	Energy Storage Grand Challenge
FCHEA	Fuel Cell & Hydrogen Energy Association
FECM	Office of Fossil Energy and Carbon Management
FEF	FirstElement Fuel
FOA	Funding opportunity announcement
GH_2	Gaseous hydrogen
GHG	Greenhouse gas
H_2	Hydrogen
HD	Heavy-duty
HFTO	Hydrogen and Fuel Cell Technologies Office
HRS	Hydrogen refueling station
ICE	Internal combustion engine
IEDO	Industrial Efficiency and Decarbonization Office
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory
LCOS	Levelized cost of storage
LD	Light-duty

LDES	Long duration energy storage
LDSS	Long Duration Storage Shot
LH_2	Liquid hydrogen
MD	Medium-duty
MRL	Manufacturing readiness level
NG-DHT	Natural Gas Decarbonization and Hydrogen Technologies
NH_3	Ammonia
NREL	National Renewable Energy Laboratory
OE	Office of Electricity
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PHMSA	Pipeline and Hazardous Materials Safety Administration
PPE	Personal protective equipment
R&D	Research and development
RD&D	Research, development, and demonstration
SAE	Society of Automotive Engineers
SCS	Safety, codes and standards
TCO	Total cost of ownership
SAF	Sustainable aviation fuel
SHASTA	Subsurface Hydrogen Assessment, Storage, and Technology Acceleration
SNL	Sandia National Laboratories
SoCalGas	Southern California Gas Company
TEA	Techno-economic analysis
TRL	Technology readiness level
UGS	Underground natural gas storage
USCAR	United States Council for Automotive Research
WETO	Wind Energy Technologies Office
ZEV	Zero-Emission Vehicle

Executive Summary

On January 17-18, 2024, the Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE) held an in-person workshop, with a virtual option, focused on strategies to enable hydrogen infrastructure deployment in high-impact sectors. The primary objective of the workshop was to convene stakeholders from industry, academia, national laboratories, and government to explore strategies to develop and demonstrate clean hydrogen storage, delivery, and dispensing infrastructure in three high-impact sectors: medium- and heavy-duty transportation, industrial and chemical manufacturing, and long-duration energy storage.

In total, there were 202 registered attendees for the two-day workshop, with 106 in-person participants and 96 virtual attendees. On the first day, the workshop opened with an introduction from HFTO, a presentation providing an overview of the National Clean Hydrogen Strategy from the National Renewable Energy Laboratory (NREL), and an overview of the Department of Energy's (DOE) Strategy for medium- and heavy-duty (MD/HD) transportation. The workshop continued with two stakeholder presentations on the Joint Office of Energy and Transportation's perspective and that of fleet operators (Hatch). Proceeding a break, a stakeholder panel comprising representatives from Ford Motor Company, Daimler Truck North America, Volvo Group, and PACCAR focused on vehicle Original Equipment Manufacturer (OEM) needs and requirements. There were also several stakeholder presentations focused on infrastructure providers such as hydrogen station providers (FirstElement Fuel), hydrogen providers (Plug Power), and equipment OEMs (Fives Cryo Inc). Lastly, there were two breakout sessions: (1) vehicle, end-user, and fleet requirements, and (2) hydrogen supply, delivery, and dispensing.

Several hydrogen infrastructure challenges were identified during the first day. Regarding vehicle, end user, and fleet requirements, the challenges discussed were cost, lifecycle of tanks and components, hydrogen losses, and reliability of fueling time. The identified research, development and demonstration (RD&D) opportunity areas were materials selection and quality, near-term target frameworks, dispenser innovation, and accelerated testing. In terms of challenges facing end-users and fleets, discussions included cost of onboard storage, energy density, fueling rate, purity, supply, back-to-back fills, scalability, and hydrogen losses. RD&D opportunities included standardization of design and components, specific onboard technology for vehicle classes, cryo-compressed subcooled liquid hydrogen, flexible refueling stations, boil-off management, uptime, resiliency, and multiple fueling options. Regarding hydrogen supply and delivery, the challenges discussed were component reliability, testing component requirements available for liquid hydrogen, liquid hydrogen boil-off handling, pipeline permitting, and liquefaction costs. The identified RD&D opportunity areas included cryopumps, support facilities for accelerated testing, mobile refueling, liquefaction improvements, and economic analysis.

Lastly, regarding station dispensing, the challenges discussed were component reliability, liquid/submerged pumps, testing protocols, lack of hydrogen-specific service components, station measurement, mass balance and flow metering, liquid hydrogen fueling needs, supply chain issues, diaphragm compressors, nozzle freezing, cryogenic valves, and pressure relief valves. The identified RD&D opportunity areas included standardization across all components and testing evaluation facilities, lowering compressor cost, reliability to redundancy, component qualifications, and better transfer pumps to avoid pressure-based liquid hydrogen transfer. For more specifics on these challenges and RD&D opportunities, please refer to section 2.5.

On the second day, the workshop opened with an introduction and presentation from HFTO on the DOE Strategy for Energy Storage and Chemical/Industrial Processes. The workshop then proceeded with stakeholder presentations on industrial/chemical processes, energy storage, and storage and delivery technologies. The stakeholder presentations on industrial/chemical processes included talks on the DOE Industrial Efficiency and Decarbonization Office's perspective (IEDO/Energetics), ammonia (Starfire Energy), and steel (NREL). The stakeholder presentations on energy storage included the DOE Office of Electricity's perspective, subsurface hydrogen energy storage (Advanced Clean Energy Storage), utilities' perspective

(Southern California Gas Company), and data centers (QTS Data Centers). The stakeholder presentations on storage and delivery technologies focused on hydrogen pipelines (DOT Pipelines and Hazardous Materials Safety Administration), pipeline operator's perspective (ExxonMobil), and subsurface hydrogen storage (DOE Office of Fossil Energy and Carbon Management). The second day agenda included two breakout sessions: (1) end user requirements in energy storage and industrial/chemical processes and (2) storage and delivery technology development needs.

First, regarding end user requirements for energy storage, the challenges discussed were understanding end-user demand, variability and cost sensitivity, scalability and availability of storage systems, and hydrogen storage density requirements. The identified RD&D opportunity areas included regulatory pressures/incentives; identifying and accelerating technology, manufacturing, and adoption readiness levels (TRLs, MRLs, and ARLs); validation and demonstration projects; leakage preventative projects; subsurface liquid hydrogen storage tests/experiments; thermal integration; and submerged pump advancements. Second, regarding industrial/chemical end user requirements, the challenges discussed were integration of end uses, hydrogen recovery, ammonia's role, and storage volume required vs geologic constraints. The identified RD&D opportunity areas included low-cost bulk storage, safety considerations, hydrogen recovery from methanol, and metal hydrides. Third, regarding small/mid-scale energy storage, the challenges discussed were system size, accessibility to hydrogen, footprint, and cost of metal hydrides. The identified RD&D opportunity areas were thermal management, compressed gas 350 bar (ability to function at –40°C), and high flow rates.

Fourth, regarding large-scale energy storage, the challenges discussed were subsurface location dependence, lack of safety standards, and workforce development. The identified RD&D opportunity areas were subsurface storage advancements, localized storage solutions, and distribution network improvements. Next, for delivery and transmission, the challenges discussed were the role of ammonia, in-line inspection improvements for detecting hydrogen, and lacking materials test methods/facilities/services. The identified RD&D opportunity areas included pipeline testing, in-line inspection tools, composites, and submerged pumps for subsurface liquid hydrogen. Lastly, for industrial and chemical processes, the challenges discussed were catalyst conversion, sensors, standardization of designs and conditions, and new pipeline off-takers. The identified RD&D opportunity areas were compressors for very high throughput, in-line sensors for hydrogen purity, and industrial centers around pipelines. For specific details on these challenges and opportunities please refer to section 2.5.

The following summary provides additional information on hydrogen infrastructure strategies, key insights from expert presentations and Q&A discussions, and feedback and recommendations gathered through breakout session deliberations. This report, the detailed agenda, speaker information, and the presentation materials can be found at: Hydrogen Infrastructure Strategies to Enable Deployment in High-Impact Sectors Workshop | Department of Energy. The guidance established through this workshop will be considered, along with input from other stakeholder engagements, and past and future workshops, in the formulation of DOE's multi-year RD&D plan on hydrogen infrastructure technologies.

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1 Presentations

1.1 DOE Welcome and Introduction

The Hydrogen Infrastructure Strategies to Enable Deployment in High-Impact Sectors workshop began with a welcome and introduction from Ned Stetson, Hydrogen Infrastructure Technologies Program Manager, HFTO. He discussed the basis for priorities for clean hydrogen (e.g., the H2@Scale initiative, the Biden Administration's Decarbonization goals, and the U.S. National Clean Hydrogen Strategy and Roadmap), the role of the hydrogen infrastructure program, and the scenario planning activities to enable deployment of clean hydrogen. He concluded by delineating the objective of the workshop, which was to provide input on the scenarios being developed to address high-priority needs to enable the use of clean, low-carbon hydrogen in the evolving end-use applications; identify where the scenarios should be revised to match industry's expectations on the direction clean hydrogen deployments are most likely to go; and to help identify the high priority end-use applications most in need of further DOE development support.

The following sections summarize the presentation highlights and Q&A discussions from the workshop sessions. Copies of the speaker presentations can be found on the Workshop Proceedings webpage: Hydrogen Infrastructure Strategies to Enable Deployment in High-Impact Sectors Workshop | Department of Energy. An overview of the workshop speakers and topics is presented in Table 1.

Table 1. Workshop speakers

Topic Area	Speakers	Moderators
DOE Welcome and Introduction	Ned Stetson, HFTO	N/A
Overview of National Clean Hydrogen Strategy	Michael (Misho) Penev, NREL	N/A
DOE Strategy for MD/HD Transportation	Mark Richards, HFTO	N/A
Deployment Activities	Steve Lommele, DOE/DOT Joint Office of Energy and Transportation Matt Post, Hatch	Mark Richards
Vehicle OEMs	Mike Veenstra, Ford Motor Company Zach Barra, Daimler Truck North America Keith Brandis, Volvo Maarten Meijer, PACCAR	Ned Stetson
Infrastructure Providers	Tim Brown, FirstElement Fuel Luke Wentlent, Plug Power Brent West, Fives Cryo Inc	Vicky Olivier-Stevens

DOE Strategy for Energy Storage and Industrial/Chemical Processes	Zeric Hulvey & Marika Wieliczko, HFTO	N/A
Industrial/Chemical Processes	Sam Gage, IEDO/Energetics Joe Beach, Starfire Energy Steve Hammond, NREL	Zeric Hulvey
Energy Storage	Nyla Khan, DOE Office of Electricity Jim Greer, ACES Delta Katrina Regan, SoCalGas Travis Wright, QTS Data Centers	Marika Wieliczko
Storage and Delivery	Vincent Holohan, DOT PHMSA Hyun Jo (Joe) Jun, ExxonMobil Evan Frye, FECM	Kevin Carey

1.2 Overview of National Clean Hydrogen Strategy

Michael (Misho) Penev, Senior Transportation Analyst at NREL, provided an overview of the U.S. National Clean Hydrogen Strategy, which includes three strategies: (1) target strategic, high-impact end uses, (2) reduce the cost of clean hydrogen, and (3) focus on regional networks. Concerning the first strategy, the clean hydrogen use scenarios involve catalyzing clean hydrogen use in existing industries and initiating new uses; scale up for heavy-duty transport, industry, and energy storage; and market expansion across sectors for strategic, high-impact uses. As for the second strategy, he explained how pathways to reduce cost require both manufacturing scale up and continued research and development (R&D). And for the third strategy, regional networks can be built through the planned Regional Clean Hydrogen Hubs authorized under the 2021 Bipartisan Infrastructure Law. He also touched on equity and environmental justice efforts in the Hydrogen and Fuel Cell Technologies Office, such as their six strategies, community benefit plans, resources, and Justice 40 & disadvantaged communities initiatives. He ended his presentation by providing links to resources and opportunities for engagement such as the 2024 DOE Annual Merit Review and Peer Evaluation Meeting in May 2024.

1.3 DOE Strategy for MD/HD Transportation

Mark Richards, Hydrogen Infrastructure Technologies Technology Manager, HFTO, provided an overview of DOE’s strategy for medium- and heavy-duty transportation infrastructure development. The infrastructure components of liquid hydrogen delivery/dispensing and gaseous hydrogen dispensing were discussed. Additionally, the level of challenge, technology readiness, and DOE impact were covered.

1.4 Deployment Activities

Steve Lommele, Communications and Stakeholder Engagement Lead at the Joint Office of Energy and Transportation discussed the infrastructure activities within the Joint Office. The mission of the Joint Office is to accelerate an electrified transportation system that is affordable, convenient, equitable, reliable, and safe.

The vision is a future where everyone can ride and drive electric. Areas of emphasis include technical assistance for zero-emission vehicle charging and refueling infrastructure. The infrastructure programs supported by the Joint Office, with the help of the Infrastructure Investment & Jobs Act (IIJA), include the following: the National Electric Vehicle Infrastructure (NEVI) Formula Program (U.S. DOT), the Charging & Fueling Infrastructure Discretionary Grant Program (U.S. DOT), the Low-No Emissions Grants Program for Transit (U.S. DOT), and the Clean School Bus Program (U.S. Environmental Protection Agency (EPA)).

Matthew Post, Sustainable Fleet Specialist at Hatch, went through Hatch's activities on MD/HD vehicle and infrastructure deployment, more specifically the Island Transit Zero Emission Vehicle Transition Plan. Hatch's transition goal is to go from an all-fossil fuel transit fleet to a 100% zero-emissions transit fleet by 2040, including both battery electric and hydrogen fuel cell electric vehicles. The transition plan, the current state, technology considerations, scenarios, lifecycle costs, and facility considerations were all discussed.

1.5 Vehicle OEMs Panel

Mike Veenstra, Manager of Fuel Cell and Hydrogen Storage Systems at Ford Motor Company, discussed DOE's SuperTruck 3 program. Its project goals are to develop a zero-emission vehicle (ZEV) with a fuel cell propulsion system for Ford Super Duty Chassis Cab for vocation applications; to demonstrate ZEV capability without compromised customer attributes, including 10,000 lb payload, 300-mile range, and SAE J2601 refueling times; evaluate the technology in real-world environments with three fleet customers to provide insight into fuel cell durability, usage, efficiency, refueling, and operating costs; and evaluate greenhouse gases (GHG) and total cost of ownership (TCO) utilizing hydrogen infrastructure and economy projections for comparison with today's internal combustion engine (ICE) products. The relevance and potential impact of the SuperTruck program were discussed. The pilot vehicle attribute priorities were explored as well. Remaining challenges include extreme cold weather operation, Ford Super Duty Lifetime Durability, local infrastructure deployment, and ICE parity in MD commercial vehicle applications. The barriers are hydrogen infrastructure and cost. Lastly, he discussed a whitepaper authored by United States Council for Automotive Research (USCAR) members (Ford, General Motors, and Stellantis); they recognized the commercial MD vehicle market as a critical segment for the economy and emissions reduction. The main takeaway from the whitepaper is that they need a hydrogen station network that is not limited to a vehicle class or application but rather highly compatible, flexible, and reliable to maximize utilization.

Zach Barra, Manager of Advanced Vehicle Energy Systems at Daimler Truck North America, discussed Daimler Truck's vocational and long-haul applications. He compared compressed gaseous hydrogen and liquid hydrogen storage systems for long-haul trucks. Lastly, he discussed subcooled liquid hydrogen (sLH_2) fueling stations for HD land vehicles. Subcooled liquid hydrogen offers high performance for long haul trucks since it is cost-efficient, has high storage capacity, can fuel multiple tanks through just one connection and has fast refueling comparable to conventional fueling. Also, sLH_2 has no hydrogen losses in fueling or operation, doesn't require data transfer, has low energy demand, and no protective clothing is required for its use. Daimler Truck's target is one common sLH_2 refueling standard that is usable industry wide.

Keith Brandis, Vice President of Partnerships and Strategic Solutions at Volvo Group, discussed a three-pillar strategy for decarbonization and a scenario with complementary technologies. He discussed how Volvo Group is testing fuel cell systems in adverse conditions and how the DOE SuperTruck program is advancing key technologies.

Maarten Meijer, Senior Engineering Manager Advanced Technology at PACCAR, discussed hydrogen opportunities, such as tailoring technology to applications. He also elaborated on the efficiency and cost of ownership of hydrogen powertrains, the H_2-ICE indirect benefits, and hydrogen infrastructure needs for commercial vehicles. PACCAR is involved in various programs to build networks of H_2 producers, consumers, and local connective infrastructure.

1.6 Infrastructure Providers

Dr. Tim Brown, Founder and Chief Innovation Officer at FirstElement Fuel (FEF) opened his presentation by sharing FEF's mission statement, overview, and how it is the first mover in the United States for hydrogen refueling stations. He then described the geographic presence and market landscape of hydrogen infrastructure in California. FEF has developed proprietary station designs and fuel delivery systems that have four simultaneous fueling positions, can refuel ~450 vehicles per day, are scalable to meet the needs of HD and commercial vehicles, and are designed for streamlined permitting. He also discussed the FEF Innovation Center, which has in-house capability to repair, rebuild, redesign, and manufacture cryopump station components, and FEF's hydrogen logistics hub in Livermore, California. Also, FEF is working with multiple OEMs to coordinate the rollout of HD trucks. Lastly, he shared that FEF is opening its Oakland HD station in the first quarter (Q1) of 2024.

Dr. Luke Wentlent, Principal R&D Engineer at Plug Power, discussed how higher-density storage will ultimately be required and how the fueling solution for four segments will be unique. These segments are (1) low power/short range mobility, (2) high power/long range mobility, (3) aerospace, and (4) maritime. Regarding the fueling infrastructure ecosystem, a variety of fueling solutions will be required to support a multi-faceted site. Both mobile and stationary refueling infrastructure will be required. He stated that in the near term, 700 bar onboard storage would be a critical transitory technology. Long term, cryogenic-based solutions would be required for more mature market penetration and near-diesel parity. He also discussed how thermal optimization across the liquid hydrogen supply chain is a critical gap. To realize the DOE's performance targets, the entire supply chain would need to be optimized. The supply chain cannot be treated as discrete elements any longer. He covered several current challenges for hydrogen refueling such as plume studies and venting releases, material selections, boil-off management, cryogenic pump reliability, and transfer pumps. Lastly, he discussed how workforce development is critical. In his view, the availability of a trained workforce will quickly become one of the rate limiting factors with regards to the growth and maturation of the hydrogen economy.

Brent West, CEO at Fives Cryo Inc., gave an overview of the company's activities. Fives' hydrogen mission is to be a world class and number one independent provider of key process equipment required to produce, convert, liquefy, and transport hydrogen in its various chemical states, e.g., liquid hydrogen (LH_2), ammonia (NH_3), and gaseous hydrogen (GH_2). Fives' cryogenic pumps will cover all needs, from the liquefaction of hydrogen to its distribution, for mobility applications. Also, Fives develops a comprehensive and fit-to-H_2 range of cryogenic pumps for all applications. He mentioned how the current development relies on strong and superior technological knowledge, applied to the specificities of LH_2. He discussed several challenges such as the evolving market, partnership approaches, and testing.

1.7 DOE Strategy for Energy Storage and Industrial/Chemical Processes

Zeric Hulvey and Marika Wieliczko, technology managers for HFTO's Hydrogen Infrastructure Technologies group, discussed the potential clean hydrogen demand for the industrial/chemical and energy storage sectors. Clean hydrogen demand and costs for market penetration were mentioned. Several scenarios were explored such as pipelines and onsite production.

1.8 Industrial/Chemical Processes

Sam Gage from the Industrial Efficiency and Decarbonization Office (IEDO), discussed the development of a roadmap and strategy for industrial decarbonization. The U.S. industrial sector accounts for 33% of the nation's primary energy use, 30% of carbon dioxide (CO_2) emissions, and the anticipated industrial sector energy demand growth of 30% by 2050 could result in a 17% CO_2 emissions increase. He also discussed systemic barriers to industrial decarbonization. The vision of IEDO is an efficient and competitive industrial sector with net-zero greenhouse gas emissions by 2050. IEDO's mission leads the development and accelerates the adoption of sustainable technologies that increase efficiency and eliminate industrial greenhouse gas emissions. He touched on the DOE Industrial Decarbonization Roadmap and its four pillars covering several focus areas. These pillars include energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources; and carbon capture, utilization, and storage. The sector focus areas are iron and steel, chemicals, food and beverage, petroleum refining, and cement. He discussed how hydrogen and other low-carbon fuels and feedstocks are crucial to decarbonize refining. The roadmap's recommendations are to advance early-stage research, development, and demonstration, invest in multiple process strategies, achieve scale through demonstrations, address process heating, decarbonize electricity sources, integrate solutions, conduct modeling and system analyses, engage communities, and develop a thriving workforce.

Joe Beach, CEO and co-founder at Starfire Energy, discussed hydrogen needs for making ammonia into the new petroleum. He mentioned that ammonia is not just for fertilizer anymore; it has pending markets such as seasonal storage, grid firming, marine shipping, heavy equipment, aviation, building and water heat, and hydrogen delivery. He elaborated on how ammonia can solve hydrogen's storage and transport problems and how it allows terawatt-hour (TWh)-scale energy storage anywhere. The benefits of ammonia include that it liquefies easily, requires inexpensive steel tanks and pipes, possesses a strong detectable odor, is nearly impossible to detonate, and has an already developed global distribution network. Lastly, he discussed several hydrogen technology needs such as flexible electrolysis that can track wind power, at least 30 bar hydrogen output pressure, at least 99.99% hydrogen purity, modular packaging that can live outdoors, low capital expenditure (CAPEX), and low maintenance modules.

Steve Hammond, Senior Research Advisor at NREL, gave an outline on iron/steel fundamentals, hydrogen production, and industry end use. He discussed the two routes for U.S. steel production, namely blast furnace and electric arc furnace, and their challenges. The challenge is to develop cost competitive, zero-emission technologies and infrastructure appropriate for U.S. feedstocks and the full spectrum of steel end use products. The high-level view of iron/steel involves developing alternatives to the ~30 U.S. blast furnaces, scaling up the use of direct reduction using hydrogen rather than methane, and improving the approach to scrap preparation to remove impurities. He mentioned that by "using hydrogen for iron ore reduction, economic viability is reached at a hydrogen procurement cost of $1.70 per kg, while achieving a CO_2 emissions reduction of 76% at the plant site" (Rosner, et al., 2023). Furthermore, he discussed the "green steel" project funded by HFTO and the Wind Energy Technologies Office (WETO) with national laboratories such as NREL (lead), Argonne National Laboratory (ANL), Lawrence Berkeley National Laboratory (LBNL), Oak Ridge National Laboratory (ORNL), and Sandia National Laboratories (SNL). The project's vision is to develop a national roadmap and reference designs for purpose-built off-grid, gigawatt-scale hybrid energy systems, tightly-coupled with green hydrogen production, co-located with industry end uses, that can accelerate the path to decarbonization. He walked through the GreenHEART model's fully integrated system (renewables to hydrogen to storage to steel) and the initial techno-economic analysis (TEA) of five land-based locations. Lastly, he mentioned how the Inflation Reduction Act policy is a game changer for hydrogen production.

1.9 Energy Storage

Nyla Khan, Energy Storage Materials & Systems Engineer at the U.S. Department of Energy's Office of Electricity (OE), gave an overview of the Office of Electricity's storage activities. She discussed the energy storage landscape and the path to 2030. She explained how grid storage deployment is projected to rapidly grow and that diverse technology options provide a means to improve the resiliency of grid storage supply chains. Additionally, DOE supports a variety (30+) of storage technologies. More specifically, OE's storage division accelerates bi-directional electrical storage as a key component of the future-ready grid. She then highlighted the Energy Storage Grand Challenge (ESGC), which accelerates the development, commercialization, and utilization of next-generation storage solutions. She then discussed the Long Duration Storage Shot (LDSS), which aims to reduce storage costs by 90% from a 2020 lithium-ion battery baseline storage system that delivers 10+ hours of duration in one decade. Business-as-usual conditions alone won't achieve the necessary $0.05/kWh levelized cost of storage (LCOS). The improved LCOS for hydrogen storage could drop to ~$0.11kWh (cavern) and $0.16/kWh (tank). Investment to reach those 2030 LCOS levels could range from ~$100M-$900M and take 7-12 years. Lastly, she shared how the Grid Storage Launchpad is a new signature facility for storage advancement.

Jim Greer, Project Director at Advanced Clean Energy Storage hub (ACES Delta), shared an overview of ACES Delta Hub's first phase. First, he discussed various energy storage use cases, such as lithium-ion batteries for short-duration energy storage and hydrogen for long-duration storage. Then, he discussed hydrogen production and storage sizing. Renewable power surplus is a key variable to understanding when to produce hydrogen for storage and when to use hydrogen for power generation. It drives the sizing criteria for hydrogen production and storage facilities. He then discussed underground storage basics. The two most prevalent storage types are depleted reservoirs and solution-mined salt caverns. Lastly, he gave an overview of the technical and operational challenges facing ACES Delta Hub Phase I.

Katrina Regan, Angeles Link Development Manager – Engineering & Technology at Southern California Gas Company (SoCalGas), gave an overview of the role of hydrogen and pipeline infrastructure in achieving California's net-zero climate goal. She discussed how hydrogen may be the only scalable solution to address long-term energy storage needs. Storing energy in chemical form as hydrogen or synthetic methane is scalable and maintains its energy potential, irrespective of elapsed time. She then went on to discuss planning for reliability. Prioritizing the development of clean, flexible resources like hydrogen generation could advance California's electric sector decarbonization goals while maintaining a reliable electric system. Lastly, she shared SoCalGas' multiple initiatives such as Angeles Link, California Direct Air Capture Hub, [H_2] Innovation Experience, and the Joint Hydrogen Blending Injection Standard.

Travis Wright, Vice President of Energy and Sustainability at Quality Technology Services (QTS) Data Centers, provided an overview of the data center perspective on hydrogen energy storage. He mentioned the trends driving the growth of macro data centers. He discussed using hydrogen for backup power and its storage challenges. Then he discussed using hydrogen for prime power; on-site microgrids can eliminate the need for backup generation.

1.10 Storage and Delivery Technologies

Vincent Holohan, Senior Engineer at the Pipeline and Hazardous Materials Safety Administration (PHMSA) in the U.S. Department of Transportation, gave an overview of hydrogen pipeline safety and challenges. He stated that there are 1,585 miles of hydrogen gas transmission pipelines in the U.S. He also discussed the current transportation regulations which are unique to hydrogen gas pipelines such as 49 CFR Part 192. PHMSA has regulated the transportation of hydrogen gas by pipeline since 1970. There are limited regulatory differences between hydrogen and natural gas pipeline transportation. As of now, blends of hydrogen and natural gas are not defined or specifically captured in the available data. He discussed PHMSA's Hydrogen R&D Initiative. The output of the initiative is knowledge/technology project reporting about hydrogen safety in transporting/storing underground. The outcomes would be a revision of industry standards and PHMSA regulations regarding hydrogen. As for ongoing hydrogen pipeline research, there are currently 11 active projects related to hydrogen pipelines with a total of $10.6 million in PHMSA funding and an additional $2.5 million in cost sharing. He also touched on past hydrogen pipeline research. The presentation concluded with links to R&D resources.

Hyun Jo (Joe) Jun, Advanced Research Associate at ExxonMobil, gave an overview of ExxonMobil's work on hydrogen pipeline transport. The key objective of ExxonMobil's low carbon solutions is to provide decarbonization solutions in hard-to-abate sectors and there is a focus on carbon capture and storage (CCS), hydrogen, and lower emissions fuels. He discussed how the transportation infrastructure is integral to hydrogen and CCS value chains. He then gave an overview of background, opportunities, and key challenges concerning hydrogen pipeline transport. He mentioned the current efforts to understand and manage integrity threats. He also discussed hydrogen pipeline infrastructure challenges including pipeline integrity in the presence of hydrogen (e.g., hydrogen embrittlement and material compatibility), codes and standards being overly conservative, and industrial practices/technologies for commercial scale hydrogen pipeline transport.

Evan Frye, Natural Gas Decarbonization and Hydrogen Technologies Program Manager at U.S. Department of Energy's Office of Fossil Energy and Carbon Management (FECM), provided an overview of the Natural Gas Decarbonization and Hydrogen Technologies (NG-DHT) Program; the program coordinates with other DOE offices to support the transition towards a clean hydrogen-enabled economy through the decarbonization of natural gas conversion, transportation, and storage. He then discussed FECM's FOA2400, a funding opportunity announcement (FOA) which focuses on fossil energy-based production, storage, transport, and utilization of hydrogen approaching net-zero or net-negative carbon emissions.

The Subsurface Hydrogen Assessment, Storage, and Technology Acceleration (SHASTA) project's objective and goals were also shared. This project aims to identify and address key technological hurdles and develop tools and technologies to enable broad public acceptance for subsurface storage of pure hydrogen and blends of hydrogen and natural gas. The goals of the project are to quantify operational risks, quantify the potential for resource losses, develop enabling tools/technologies/guidance documents, and develop a collaborative field-scale test plan in partnership with relevant stakeholders. The advantages of underground gas storage (versus storage in above-ground tanks) are storage capacity, storage cost, surface footprint, and storage safety. The four possible storage reservoir types are salt caverns, hard rock caverns, depleted reservoirs, and brine aquifers. Underground natural gas storage (UGS) sites are distributed throughout the United States and are often located near large population centers where natural gas demand is greatest. There is hydrogen energy storage potential in existing UGS facilities. There is lots of interest in blended storage (hydrogen and natural gas), where many facilities operate below their maximum volume. However, there may be a need for new sites depending on the demand scenario. The key considerations for subsurface hydrogen storage are well integrity, microbiology and geochemistry, managing reservoir flow dynamics, and techno-economics. Deliverables coming out of SHASTA include a code comparison study for reservoir simulation, geologic screening study for several locations, multiphase flow studies in rocks, material performance in hydrogen environments, material performance for reservoir caprock under abiotic and biotic conditions, continuous updates to the SHASTA help tool, and community engagement plans. SHASTA's goal is to enable field testing.

2 Breakout Sessions

On each day, attendees were divided into four rooms for parallel breakout session discussions following the speaker presentations. The two-day workshop included four breakout session periods with a total of 16 discussion sessions that were moderated by a set of HFTO and national lab experts. The first day included two breakout discussion periods on the following topics: vehicle requirements, end user/fleet requirements, hydrogen supply and delivery, and station dispensing. On Day Two, the topics were end user requirements in energy storage and industrial/chemical processes, and technology development needs for small/mid-scale energy storage, large-scale energy storage, delivery/transmission, and industrial/chemical processes. Each breakout session was 60 minutes long. The breakout session topics as well as the moderator(s) for each session are shown in Table 2.

Table 2. Breakout Sessions

Breakout Sessions	Topics of parallel sessions	Moderators
Breakout Session 1	Vehicle requirements 1 Vehicle requirements 2 End user and fleet requirements 1 End user and fleet requirements 2	Cassidy Houchins, Ned Stetson, Marika Wieliczko, Amgad Elgowainy, Mark Richards, Brian James, and Zeric Hulvey

Breakout Session 2	Hydrogen supply and delivery 1 Hydrogen supply and delivery 2 Station dispensing 1 Station dispensing 2	Krishna Reddi, Marika Wieliczko, Kevin Simmons, Mark Richards, Shaun Onorato, Zeric Hulvey, Will James, Brian Hunter, and Jesse Adams
Breakout Session 3	End user requirements: energy storage 1 End user requirements: energy storage 2 End user requirements: industrial/chemical 1 End user requirements in industrial/chemical 2	Nyla Khan, Ned Stetson, Abhi Karkamkar, Marika Wieliczko, Hanna Breunig, Zeric Hulvey, Katie Hurst, and Mark Richards
Breakout Session 4	Small/mid-scale energy storage Large-scale energy storage Delivery and transmission technologies Industrial/chemical processes	Genevieve Saur, Marika Wieliczko, Dan Leighton, Brian Hunter, Chris San Marchi, Mark Richards, Peng Peng, and Zeric Hulvey

2.1 Vehicle, end user, and fleet requirements

Vehicle requirements

This breakout session focused on the technical requirements of onboard storage in hydrogen-powered MD/HD vehicles. The objective was to glean from the participants phase-neutral targets (i.e., irrespective of whether H_2 is gas, liquid or as materials-based storage) that would establish benchmarks for the development and demonstration of onboard storage. A vehicle OEM representative suggested 600 km as a desirable range target though it might be too early to give an exact figure for fuel capacity (kg of H_2) due to pending advances in powertrain efficiency and electric/fuel cell switching algorithms. The discussion also touched on how an onboard storage capacity target (e.g., 100 kg for class-8 trucks) imposes trade-offs on vehicle weight that may not be easily resolved with current regulations. OEMs generally design trucks with the maximum legal weight per axle, then size the powertrain and other components accordingly. Another challenge is that onboard storage tanks cannot easily be filled to 100% in a reliable manner, though it is not clear if this is an issue that can be resolved through R&D interventions on the vehicle side or the station side. There was also discussion on how the size of H_2 storage systems can require lengthening the wheelbase, which affects performance such as turning radius. Thus, higher storage densities are preferable. Throughout the discussion, fuel capacity, cost, reliability, tank lifetime, and fill time were identified as parameters to be included in the target-setting effort. Generally, attendees were wary of setting specific targets and instead suggested opting for ranges and tailoring targets to the wide variety of vehicle systems. The use of thermodynamic targets such as energy density, energy efficiency, utilization rate, and flow rate that remain agnostic of vehicle type and can also be extended to off-road vehicles with atypical duty cycles was suggested. The conversation shifted later to refueling stations; the topic of the high cost and inadequate reliability of refueling systems was brought up. Another consideration was the temperature range set by current refueling codes and standards, which was criticized as being too restrictive. As liquid hydrogen is heavily favored for station storage and may also be used for onboard storage, there was some discussion on the need to invest in improving the reliability of cryogenic components such as pumps.

In discussing components/technologies needed to scale up MD/HD vehicle deployment, a lot of development still needs to occur. Applications need to be more specific and require less maintenance. For cryogenic components, 3D printing materials or applications can change the cost of materials.

Specific items suggested to be addressed include:

- HD fuel capacity range of 60-120 kg, with an initial target of 80-100 kg;
- Improved reliability of fueling connectors;
- Eliminating the need for precooling to -40 °C for fueling;
- Increasing the allowable maximum temperature for tanks;
- Improving consistency of complete fills;
- Increasing maximum allowable electrified truck weights from the additional 2,000 lbs to 8,000-10,000 lbs (i.e., max weight of 88,000-90,000 lbs versus 82,000 lbs)

A sizable portion of the discussion focused on whether 10 kg/min is a realistic refueling rate. Most attendees seemed to agree that this rate is reasonable. NREL's heavy-duty hydrogen fast flow refueling station can handle 10 kg/min fills with 1 inch and ¾ inch 20,000 psig-rated stainless steel tubing and air-operated valves. The discussion then steered into questioning what is included in the refueling time. Some participants did not consider conditioning as part of the fueling time.

End user/fleet requirements

The objectives of this session were the following: identify the primary requirements for fleet operation, both onboard the vehicle and refueling infrastructure including, onboard storage (e.g., fuel capacity, mass and volume constraints, performance requirements, cost) for which targets should be set; identify the key requirements for the fueling infrastructure (e.g., fueling rates, fuel costs, station dispensing capacity) for which targets should be set. Lastly, there was a discussion on the key differences between fleets and non-tethered vehicles and if there were any areas the DOE should work on that were not identified in the current scenarios.

First, onboard storage requirements were discussed. There is currently a tradeoff between the different types of refueling offered, whether liquid hydrogen, 700 bar gaseous, or 350 bar gaseous hydrogen. It would be more advantageous to design a refueling station that could handle all three forms. The discussion then switched to the cost constraints for different technologies and the opportunities of different technologies. Cost was also discussed. Cost is always a factor alongside the "fitness for use." However, if the application or technology doesn't work, then the cost is irrelevant. Also, basing the equivalence of diesel to hydrogen on today's fuel price was discussed, as well as the fuel economy ratio of diesel to hydrogen. Each light, medium or heavy-duty application is unique, so the ratio will change with each type. Both onboard storage and fuel cost must be considered together when discussing R&D opportunities.

The session then turned to the question of whether there have been migrations away from private fueling and if fleet operators would be amenable to doing their own fueling. Mobile refuelers was suggested as an attractive option and there is a need for mobile fueling solutions. The subsequent question is whether a single mobile solution can be created to support 350 bar, 700 bar, and liquid H_2. DOE is currently funding development of a mobile refueler that will be able to dispense liquid and gaseous hydrogen.

Barriers that fleet operators faced were also discussed. These include cooling, purity standardization, back-to-back fueling rates, fuel flow rate, high throughput compressors, and the need to reduce labor. The opportunities for future development, from a fleet operator perspective, are addressing hydrogen leakage, standardization of components and how they are built into the stations, improvements in uptime, resilience and maintenance costs, enabling direct fills, fleet versus public options, and automation.

2.2 Hydrogen supply, delivery and station dispensing

Hydrogen supply and delivery

This breakout session focused on the feasibility of different modes of hydrogen supply and delivery for MD/HD refueling stations, as well as the components that need further development to facilitate hydrogen delivery and dispensing. Generally, there are three options for hydrogen delivery to stations: compressed gaseous H_2 in tube trailers, liquid H_2 in tankers or compressed gaseous H_2 in pipelines. An ammonia industry representative highlighted ammonia as a largely overlooked fourth option which may be economical in off-road vehicle applications, such as in remote mining operations, where transporting and storing the required quantities of hydrogen may be challenging and expensive.

The attendees, for the most part, agreed that pipeline delivery is the industry-preferred option and is generally cheaper than liquefying and trucking cryogenic hydrogen. Facilitating the buildout of a hydrogen pipeline backbone that connects low-cost production centers to stations and truck distribution hubs could be key to enabling the reliable and low-cost dispensing of the large quantities of hydrogen needed in MD/HD stations. Pipelines can be planned by anticipating where the demand centers will be located, and long-term purchasing agreements can be established to guarantee demand consistency and incentivize pipeline developers. Otherwise, if demand is not consistent, then liquid hydrogen delivery is the preferred option, though boil-off management remains challenging. One attendee indicated that while boil-off management is feasible at large volumes (e.g., at export terminals), it may become uneconomical at station-level volumes.

The conversation also shifted towards co-locating hydrogen production and refueling stations. Although MD/HD stations could dispense dozens of metric tons of hydrogen per day, which would require very large electrolyzers, there is interest in using co-located electrolysis or methane pyrolysis as an economic approach to serve refueling points in remote areas. However, one attendee disagreed with the co-location idea, indicating that supply to remote communities is not a priority problem to solve. It is more important to scale up the market and develop conventional off-takers and associated business models.

The conversation ended with a discussion on station and delivery components. One attendee mentioned high-flow electrochemical compressors as a possible R&D opportunity, while another highlighted the need for investment in developing more reliable diaphragm compressors that are designed for intermittent operation, instead of their traditional use in continuous operation applications.

Station dispensing

The session’s objectives included: identify the key requirements for stations to meet the refueling/dispensing needs for MD/HD vehicles, identify the status of the current state-of-the-art components and processes, identify the gaps for components and processes for hydrogen fueling stations, and identify the highest priority needs that the DOE should focus on.

The session started off by discussing the underlying issues of reliability and whether hydrogen is really that difficult to work with. The difficulties of pumps and compressors for liquid hydrogen were brought up. Thermal shocks and their subsequent leaks were discussed as well. All types of pumps/parts will need to avoid thermal cycling. Then, attendees suggested ways DOE could help drive solutions such as developing a FOA for station-of-the-future concepts, standardizing pumps, and testing facilities. Also, various components that need to be prioritized in development were discussed such as liquid hydrogen nozzles, valves, check valves, and accuracy around mass custody transfer during filling. Communication interfaces need to be prioritized as well. The tank and dispenser sides need to work on the communication interface problem. Also, the major cost drivers on the station dispensing were discussed. The pumps themselves are a major component. Pumps are not expensive, but they are also not reliable. Compressors are expensive and needed for the pumps. The CAPEX for both should be considered.

A challenge that was discussed throughout the session was the reliability of all components. Concerning reliability, it is best achieved through theory and practice. There needs to be test facilities, statistically relevant data, and experience. Also, redundancy is the best way to achieve reliability. A RD&D opportunity would be standardization across all components and testing and evaluation facilities, and collaborating with safety, codes and standards (SCS) teams for testing standards for various components/interfaces.

2.3 End user requirements in energy storage and industrial/chemical processes

End user requirements – energy storage

In this session, discussions on scalability and practical demonstrations were identified and prioritized. Concrete data from demonstration projects is needed to scale up energy storage solutions effectively, especially for the middle range of storage where solutions are lacking. Utilization and availability remain significant challenges, with varying demand and market competitiveness necessitating a spectrum of solutions. Technology readiness levels (TRL) of different storage methods vary, with some, like small liquid hydrogen storage and large caverns, being more mature. Facilitating and driving R&D projects can increase TRLs and demonstrations to bridge gaps. Discussions turned to turbines and pipelines and how, although there is limited experience, they are still considered a potential solution, particularly in line packing analysis for hydrogen. Large-scale GH_2 storage presents economic and technological challenges, necessitating further exploration. Furthermore, the utility industry could benefit significantly from hydrogen storage but requires lower costs and more information on hydrogen applications. Overall, a comprehensive approach is needed to address these challenges and optimize energy storage applications effectively.

End user requirements – industrial/chemical processes

This breakout session focused on identifying industrial applications, processes, and components that could benefit from R&D investment to accelerate the utilization of hydrogen to decarbonize industrial and chemical processes.

The provision of high-quality process heat was identified as a promising area for hydrogen use. Glass and ceramic manufacturing require heat at temperatures up to 2400 °F, which is currently delivered using natural gas combustion in pure oxygen. Hydrogen burns at comparable temperatures, but reducing the cost of its production, storage, and delivery is critical to enable its use in industrial heat applications which tend to be very cost-sensitive. Alternatively, one attendee noted that hydrogen may interact with industrial/chemical processes in unintended ways (e.g., hydrogen can introduce moisture into asphalt processing), so more R&D attention should be given to chemical engineering and processing considerations.

Investment in the demonstration of bulk storage of hydrogen was another major area of discussion. Reducing the cost of subsurface and high-capacity hydrogen storage technologies can incentivize industry to switch away from natural gas in industrial heat applications. The development of these storage technologies can be done within industrial parks where the storage serves multiple off-takers in its vicinity. Multiple attendees agreed that the Regional Clean Hydrogen Hubs program was a valuable opportunity to develop co-located bulk storage and industrial parks. Carbon capture can also be integrated to provide streams of high-purity carbon dioxide that can be combined with hydrogen to produce useful fuels and chemical products. This conversation on integration of industrial processes with hydrogen storage and carbon capture led several national lab representatives to mention possible interest in modeling and demonstrating the time matching of hydrogen availability with industrial processes, as both can fluctuate at time scales ranging from hours to seasons.

Ammonia and its place within the hydrogen ecosystem was discussed, as well as issues surrounding the safety considerations with integrating hydrogen alternatives such as ammonia and methanol. Improving the ammonia cracking process such as lowering the required temperature was identified as a potential RD&D opportunity area.

Finally, several industry representatives noted the poor communication, in their opinion, of R&D results from both national labs and the private sector. One attendee suggested the use of large language models to mine research databases and synthesize results in an easily digestible fashion.

2.4 Storage and delivery technology development needs

Small/mid-scale energy storage

In this session, various gaps, barriers, and key challenges were discussed including:

- compressed gas above ground moderate compression,
- risk of long-term investments,
- accessibility to hydrogen (delivery methods), and
- barriers to adoption, such as footprint of gaseous versus liquid hydrogen and existing infrastructure.

In turn, several RD&D opportunity areas were identified including:

- defining boundaries,
- 350 bar compressed gas and the ability to function at -40 ^{o}C,
- small-scale demos,
- thermal management and heat recovery,
- cycle times,
- scalability,
- high flow rates,
- modeling, and
- thermal insulation.

Other topics for consideration were

- trade regulations,
- mining operations,
- number of buses,
- buying commercially available systems,
- low-cost margins, and
- fully charged life cycle of tanks.

Large-scale energy storage

The gaps, barriers, and key challenges discussed in this session included:

- the fact that subsurface storage is location dependent,
- the lack of safety, codes and standards for large-scale hydrogen storage,
- deliverability,
- supply chain and domestic manufacturing,
- application/end-use specific needs, and
- workforce development.

Furthermore, the following RD&D opportunity areas were identified:

- advancements in engineered subsurface storage,
- localized hydrogen storage solutions,
- “last mile” solutions such as a hydrogen distribution network, and
- development of submerged pumps for subsurface liquid hydrogen storage.

Other topics discussed included the following:

- long lead times for hydrogen storage tanks,
- storage needed to match intermittent renewable energy,
- whether ammonia solves many hydrogen storage barriers,

- centralized versus distributed storage,
- environmental concerns (e.g., venting), and
- contamination in bulk storage environments.

Delivery/transmission

This breakout session focused on identifying hydrogen delivery R&D needs for large off-takers in the power and industrial sectors. While pipelines are an obvious, relatively mature delivery option, the moderators tried to steer the conversation towards discussing other delivery options such as chemical carriers (e.g., ammonia) and rail. Several industry representatives pushed back against the use of ammonia noting that both pipeline and rail operators would avoid it due to its toxicity. On the other hand, transporting liquid hydrogen by rail received significant interest. While there is an existing code for such rail transport, it is not practiced today though rail cars have the potential to transport up to 9 tons of liquid hydrogen each and could provide significantly greater geographical reach compared to pipelines. R&D work could focus on improving rail car insulation and couplings.

The discussion shifted eventually to pipelines. Attendees noted the need to improve crack detection technology to qualify existing pipelines for hydrogen service, consistently report the characteristics of vintage pipelines, develop more efficient turbo-compressors, build facilities for hydrogen in-situ testing, and further develop and standardize the manufacturing and joining of fiber-reinforced composite pipelines.

Industrial/chemical processes

The session started with a focus on pipelines and how repurposing natural gas pipelines may be a blending concern. In the case of blending, there should be on injection point. There is a struggle with mapping hydrogen pipeline networks with high volume users like refineries. However, this could be an analysis opportunity for potential high-volume users, as well as a R&D opportunity for developing critical infrastructure for these areas.

Second, better integration of onsite production was discussed. Catalyst degradation and aggregation pathways was mentioned as an area in need of further investigation, with the conversion to methanol being a prominent example on the process side.

Other gaps, barriers, and key challenges that were discussed were the following:

- catalyst conversion for processes using hydrogen
- sensors for leak detection and in-line integration of electrolyzers
- new pipeline off-takers (leaks, hardware, and operation)
- standardization of designs and conditions.

The subsequent RD&D opportunity areas identified and prioritized were:

- compressors for very high throughput
- compressors tailored to optimize pipeline operation
- in-line sensors for hydrogen purity
- locating industrial centers around pipelines

2.5 Breakout Session Report-out

Following the breakout sessions on each day, the moderators of each session provided a summary of the key topics discussed in their groups. The report-out slides from each breakout group are shown in Tables 3-19.

Table 3. Breakout Session 1: Vehicle Requirements (1) Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)

Cost and weight of onboard storage tanks		Set vehicle levels targets for different use cases (i.e., vehicle vocations, storage system types, liquid hydrogen vs. compressed gas)
Determining the range vs. capacity		Look into adjusting the standard ranges of temperature
Understanding the lifecycle of tanks and components		
Volumetric density of system		
Consistency/reliability of fueling time		

Table 4. Breakout Session 1: Vehicle Requirements (2) Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)
Materials Availability - Materials and components can be more expensive when sourced domestically. Long lead times	Materials selection and material quality for use in cryogenic environments	Fueling times less important than getting consistent full fills
Cost – cost penalties of various fueling requirements	Developing frameworks for near term targets	
Conditioning – Novel ways to recirculate and recover hydrogen losses	Divergent (or convergent?) metric for MD and HD	
Reliability and durability of components	Innovation at dispenser and accelerated testing	
Power requirements of high-flow refueling stations		
Ease of station deployment		

Table 5. Breakout Session 1: End-User, Fleet Requirements (1) Storage Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)

Cost of onboard storage	Impact on infrastructure	Daily vehicle miles travelled (VMT)
Energy density	Identify specific onboard technology for each vehicle class and use case	Fuel economy – needed for each class of vehicle
Volume/mass constraints	Conformable storage	Fuel economy ratio – function of onboard sizing, fuel cost
TRL	Cryo-compressed (CcH_2), subcooled liquid hydrogen, liquid hydrogen	

Table 6. Breakout Session 1: End-User, Fleet Requirements (1) Infrastructure Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)
Precooling	Flexible hydrogen refueling station (HRS) for various onboard storage	Hydrogen supply form to HRS (e.g., CcH_2 vs. LH_2)
Flexibility	LH_2 supplied HRS	Utilization
Purity	Boil-off management/utilization	
Back-to-back fills	Standardization of design and components	
Fueling rate	Novel concepts	
Hydrogen losses	Direct fills	
Resilience and reliability	Automation	
Utilization – fleet vs. public	Uptime, resilience, reliability	
Supply chain		

Table 7. Breakout Session 1: End-User, Fleet Requirements (2) Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)
Redundancy, resiliency	Eliminate boil-off losses (entire pathway)	Parity with diesel or incumbent technologies

Back-to-back fill/state-of-fill, fast fill	Ensuring multiple fueling options	Cost of hydrogen
Ensuring a diversity of platforms/flexibility	Compression and pre-cooling tech	TCO
Modularity/Scalability		
Hydrogen source and location		

Table 8. Breakout Session 2: Hydrogen Supply and Delivery (1) Report Out

Gaps, barriers, and key challenges	**RD&D opportunity areas, identified, prioritized**	**Other considerations (special topics)**
Component reliability (e.g., diaphragm compressors)	Boil-off handling strategies	Ammonia as H_2 carrier
Testing components requirements available for LH_2	Approved materials for better diaphragms	
Market framework of industry	Cryopumps and advanced technologies	
LH_2 boil-off handling strategies	Develop ties with liquefied natural gas processes	
Backbone pipeline infrastructure to support liquefaction sites	Support facilities for accelerated testing	
	Mobile refueling as potential way to support station deployment	

Table 9. Breakout Session 2: Hydrogen Supply and Delivery (2) Report Out

Gaps, barriers, and key challenges	**RD&D opportunity areas, identified, prioritized**	**Other considerations (special topics)**
Pipeline permitting and approvals	Novel methods for delivery	Energy demands of hydrogen delivery and liquefaction
Sizing is dependent on the specific station needs	Liquefaction improvements	Onsite hydrogen production for fueling stations likely not feasible at MD/HD scales
Educate public on hydrogen pipelines	Economic analysis for delivery and supply scenarios	How do early adoption needs vary from long term solutions

Liquefaction costs – Other opportunities besides economies of scale		Electricity input is a key cost driver for electrolyzer hydrogen production
Station design is dependent on delivery/supply method		

Table 10. Breakout Session 2: Station Dispensing (1) Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)
Reliability of all components	Standardization across all components and testing evaluation facilities	How can we leverage existing industry testing facilities?
Many H_2 components aren't specifically designed for H_2 service	Lower cost or facilitated component testing (maybe lab-industry collaborations for testing)	Standardization could help with supply chain issues and cost
Liquid/submerged pumps	Collaborating with SCS for testing standards for various components/interfaces – to simplify the testing problem	
Testing protocols and standardized test stands	Lowering compressor cost	
Hydrogen station measurement/mass balance/flow metering		

Table 11. Breakout Session 2: Station Dispensing (2) Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)
Reliability, cost performance GH_2	Reliability to redundancy; direct fills (eliminate compressor, cascade storage and pre-cooling)	Commissioning
Diaphragm compressor; point of sale and nozzle freezing; cryogenic valves and pressure relief valves	Factory acceptance testing; station components	Knowledge sharing between stations

Supply chain challenges; equipment and components coming from European Union	Supplies need component qualifications (DOE could potentially offer assistance)	Big target goals to guide component suppliers; 3D-printed components, Fuel Cell & Hydrogen Energy Association (FCHEA) provide list approved components
LH_2 fueling needs	Fueling protocols; H_2 loss management' nozzle, PPE; gas flow metering: mass flow metering	LH_2 ISO SAE DOE collaboration; white paper already exists; a liquid H_2 testing facility at National Labs
	Better transfer pumps to avoid pressure-based LH_2 transfer	DOE perspective overall regarding H_2, no mixed messaging

Table 12. Breakout Session 3: End User Requirements – Energy Storage (1) Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)
Establishing/understanding end user demand/market of storage infrastructure	Engaging with end users, creating resources to better understand existing and emerging markets	Encouraging dialogue across sectors, optimization exercise when considering H_2
Variability and cost sensitivity/needs of industry stakeholders	Understanding the end user's timeline, regulatory pressures/incentives, and capacity	Extending cost spending horizons (i.e., 2030/2050 constraint)
Scale, utilization, and availability of storage systems	Identify and accelerate technology, manufacturing, and adoption readiness levels (TRLs, MRLs, and ARLs)	Limited experience on turbines running on H_2
Balancing storage with peaking and acute needs (duration and trending)	Identify specific emerging needs of end user	
Move beyond conversation into more demonstration projects	Validation and demonstration projects	
Environmental compliance of leakage prevention	Leakage preventative projects	

Emerging technological storage systems and components	Facilitate and drive R&D projects to increase TRLs, and demonstration to bridge gaps (i.e., geological formations opportunity space)	Line packing

Table 13. Breakout Session 3: End User Requirements – Energy Storage (2) Report Out

Gaps, barriers, and key challenges	**RD&D opportunity areas, identified, prioritized**	**Other considerations (special topics)**
Value of long duration energy storage (LDES) by sector and duration	Subsurface liquid hydrogen storage tests and experiments	Above ground elevated (canopy) storage in space limited areas
Hydrogen storage density requirements will be dictated by sector. Footprint	Subsurface storage demonstrations needed	Hydrogen reserves
Cost – materials, thermal management (economies-of-scale do not apply)	Thermal integration	Articulate sizing requirements for various applications
Subsurface storage maintenance challenges	Submerged pump advancements	Synthetic fuels as a storage method
Ammonia has major environmental concerns	N/A	Safety, codes and standards need to be defined for new applications (subsurface, canopy)

Table 14. Breakout Session 3: End User Requirements – Industrial/Chemical (1) Report Out

Gaps, barriers, and key challenges	**RD&D opportunity areas, identified, prioritized**	**Other considerations (special topics)**
H_2 not necessarily a perfect drop-in for natural gas heat	Glass/ceramics/fiberglass omitted (high quality heat applications)	Shipping fuels/sustainable aviation fuels (SAFs)
Integration of end uses, storage, electrolyzers	Low-cost bulk hydrogen storage	Uses for separated oxygen (or other co-products)
Information about usage profiles for industrial/chemical processes	Analysis or modeling for energy parks/hubs/co-located facilities (helps on both delivery and storage sides)	Integrated approach to pipeline planning and geographic considerations

Electrical demand info	Lifecycle considerations and safety	Data aggregation
Hydrogen recovery		

Table 15. Breakout Session 3: End User Requirements – Industrial/Chemical (2) Report Out

Gaps, barriers, and key challenges	**RD&D opportunity areas, identified, prioritized**	**Other considerations (special topics)**
Ammonia – place within the H_2 ecosystem	Improving ammonia cracking process – specifically lowering the temperature required	Combine processes between industries to share costs where possible
Safety consideration with H_2 alternative integration (e.g., ammonia and methanol)	H_2 recovery from methanol	Water availability and cost for H_2
Steel – intermittency concerns of electrolyzers	Methane pyrolysis	Develop utility/industry working group to work backwards (end use → production cost)
Benchmarking H_2 and power cost among different regions	Metal hydrides & carriers for storage of H_2	Decoupling H_2 production from utilities to secure a fixed cost
Storage volume required vs. geologic constraints		TEA – carbon capture, regionality, storage capacity

Table 16. Breakout Session 4: Small/Mid-Scale Energy Storage Report Out

Gaps, barriers, and key challenges	**RD&D opportunity areas, identified, prioritized**	**Other considerations (special topics)**
Size of system 9 mBTU/MWh 70 kg/MWh (200 MW frame 14000 kg/hr)	Define boundaries (application specific)	Trade regulations; homeland security review 10 tons/site
Compressed gas above ground moderate compression	Compressed gas 350 bar (ability to function at -40 ^{o}C)	Mining operations
Risk of long-term investments, prefer off the shelf system	Small scale demos, R&D support for utilities	Number of buses (100 buses, 1/3 of which are fuel cell-powered)

Accessibility to hydrogen (delivery method)	Thermal management; heat recovery	Buy commercial systems
Barriers: footprint (gaseous vs. liquid); existing infrastructure	Cycle time	Low-cost margins, subsidy
Cost: for metal hydride and minimal energy	Scalability, high flow rates, modeling, thermal insulation	Fully charged, life cycle of tanks
		Time, space, money

Table 17. Breakout Session 4: Large-Scale Energy Storage Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)
Subsurface is location dependent	Engineered subsurface storage advancements	Long lead times for hydrogen storage tanks
Lack of safety, codes and standards large-scale hydrogen storage	Localized hydrogen storage solutions	Storage needed to match intermittent renewable energy
Deliverability	"Last mile" solutions – hydrogen distribution network	Does ammonia solve many hydrogen storage barriers?
Supply chain and domestic manufacturing	Submerged pumps for subsurface liquid hydrogen	Centralized vs. distributed storage. Storage along the pathway and phased solutions
Needs are application/end-use specific		Contamination in bulk storage environments
Workforce development (manufacturing, safety, testing facilities, etc.)		

Table 18. Breakout Session 4: Delivery and Transmission Report Out

Gaps, barriers, and key challenges	RD&D opportunity areas, identified, prioritized	Other considerations (special topics)
What is the role of ammonia in transmission and delivery?	Pipeline testing needed – potential for use as hydrogen hubs start to build out/connect	Community engagement
Data gaps – do we have the pipelines characteristics for repurposing?	Fiber reinforced polymers, composites, new pipe	Leak detection and safety

	materials, joining and integration regulations, TEA	
Plastic pipe material characteristics are different between each manufacturer	National inventory and mapping of pipeline tool, in-line inspection tool	Carriers: used as-is or converted to H_2 at the end use site?
In-line inspection improvements for detecting hydrogen sensitive flaws	Submerged pumps for subsurface liquid hydrogen	Hydrogen Hubs have the potential for small-scale deployments
LH_2 rail cars, are they possible?		
Materials test methods, facilities, and services are lacking		
Pipeline ancillary equipment, suitability for hydrogen (e.g., turbo machinery)		

Table 19. Breakout Session 4: Industrial and Chemical Processes Report Out

Gaps, barriers, and key challenges	**RD&D opportunity areas, identified, prioritized**	**Other considerations (special topics)**
Catalyst conversion for processes using H_2	Compressors for very high throughput	Purity requirements
Sensors (leak detection, in-line)	Compressors tailored to optimize pipeline operation	Cement
Integration of electrolyzers	In-line sensors for hydrogen purity	
New pipeline off-takers (leaks, hardware, and operation)	Industrial centers around pipelines (maybe focused on “other” industrial/chemical processes like cement or glass)	
Standardization of designs and conditions		

3 Conclusions and Recommendations

Ned Stetson, HFTO, provided closing remarks. He thanked presenters, attendees, organizers, moderators, and scribes for their valuable contributions. Participants appreciated the opportunity to engage with DOE and the wider hydrogen infrastructure community. Participants were also invited to attend the follow-up workshop, Hydrogen Infrastructure Priorities to Enable Deployment in the High-Impact Transportation Sector.

This workshop had a very high level of interest, with over 200 in-person and virtual attendees over the course of two days. The workshop achieved its objective to convene a wide range of stakeholders to explore strategies to develop and demonstrate clean hydrogen infrastructure in three sectors: medium- and heavy-duty transportation, industrial and chemical manufacturing and long-duration energy storage.

Notably, many of the experts in attendance highlighted the need for further investments in reducing the cost and weight of onboard storage tanks, improving the uptime and reliability of fueling systems, and standardizing the designs of systems and components in MD/HD vehicle refueling stations. The use of mobile refuelers was also repeatedly mentioned as a cost-effective way to accelerate the deployment of hydrogen fueling infrastructure. Additionally, several industry stakeholders emphasized the importance of transitioning towards higher-TRL investments and demonstrations. The conversation on industrial and chemical processes highlighted the need for low-cost, high-volume delivery of hydrogen either via pipeline or rail, as well as the importance of workforce development, hydrogen recovery technologies, and co-location of delivery infrastructure and end-users. Ammonia garnered significant attention as a hydrogen delivery and storage option that remains relatively poorly explored due to safety concerns.

The high level of engagement from external stakeholders confirms their confidence in hydrogen as an important part of a net-zero-emissions energy economy and their interest in helping DOE shape future pathways to achieve common goals. The presentations on relevant topic areas were valuable in setting the stage for productive discussions within and outside the breakout sessions. The participation of workshop speakers during the breakout sessions was especially beneficial as many questions and discussions were discussed based on the content of their presentations. Together, the presentations and breakout discussions will allow DOE to better understand the various challenges and opportunities for hydrogen infrastructure.

References

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Appendix

This appendix provides a summary of the workshop agenda.

Day 1

8:00 – 8:30 *Breakfast*
8:30 – 8:45 DOE Welcome and Introduction – **Ned Stetson**, HFTO
8:45 – 9:15 Overview of National Clean Hydrogen Strategy – **Misho Penev**, NREL
9:15 – 9:35 DOE Strategy for MD/HD Transportation – **Mark Richards**, HFTO
9:35 – 10:15 Stakeholder Presentations: Deployment Activities
- DOE/DOT Joint Office of Energy and Transportation Perspective – **Steve Lommele**, Joint Office
- Fleet Operators - **Matt Post**, Hatch

10:15 – 10:30 *Break*
10:30 – 11:30 Stakeholder Panel: Vehicle OEMs
- **Mike Veenstra** (Ford Motor Company), **Zach Barra** (Daimler Truck North America), **Keith Brandis** (Volvo Group), **Maarten Meijer** (PACCAR)

11:30 – 11:40 *Transition to breakout rooms*
11:40 – 12:40 Breakout sessions - 1: Vehicle, end user, and fleet requirements
12:40 – 1:40 *Lunch*
1:40 – 2:50 Stakeholder Presentations: Infrastructure Providers
- Hydrogen Stations - **Tim Brown**, First Element
- Hydrogen Providers - **Luke Wentlent**, Plug Power
- Equipment OEMs - **Brent West**, Fives Group

2:50 – 3:00 *Break*
3:00 – 4:00 Breakout sessions - 2: Hydrogen supply, delivery, and dispensing
4:00 – 4:10 *Transition to general session room*
4:10 – 4:55 Report-outs from breakout sessions
4:55 – 5:00 Summary/End-of-day remarks

Day 2

8:00 – 8:30 *Breakfast*
8:30 – 8:35 Introduction and Day 2 Agenda – **Zeric Hulvey**, HFTO
8:35 – 8:50 DOE Strategy for Energy Storage and Chemical/Industrial Processes Scenarios – **Zeric Hulvey** & **Marika Wieliczko**, HFTO
8:50 – 9:50 Stakeholder presentations: Industrial/Chemical Processes
- DOE Industrial Efficiency and Decarbonization Office Perspective – **Sam Gage**, Energetics
- Ammonia - **Joe Beach**, Starfire Energy
- Steel – **Steve Hammond**, NREL

9:50 – 10:05 *Break*
10:05 – 11:25 Stakeholder Presentations: Energy Storage
- DOE Office of Electricity Perspective – **Nyla Khan**, Office of Electricity
- Subsurface Hydrogen Energy Storage - **Jim Greer**, Advanced Clean Energy Storage – Delta, UT
- Utilities Perspective - **Katrina Regan**, Southern California Gas Company
- Data Centers - **Travis Wright**, QTS Data Centers

11:25 – 11:35 *Transition to breakout rooms*
11:35 – 12:35 Breakout sessions - 3: End user requirements in energy storage and industrial/chemical processes

12:35 – 1:35	*Lunch*
1:35 – 2:35	Stakeholder presentations: Storage and Delivery Technologies • Hydrogen Pipelines – **Vincent Holohan**, DOT Pipelines and Hazardous Materials Safety Administration • Pipeline Operator Perspective – **Joe Jun**, ExxonMobil • Subsurface Hydrogen Storage – **Evan Frye**, DOE Office of Fossil Energy and Carbon Management
2:35 – 2:45	*Transition to breakout rooms*
2:45 – 3:45	Breakout sessions - 4: Storage and delivery technology development needs
3:45 – 3:55	*Transition to general session room*
3:55 – 4:35	Report-outs from breakout sessions
4:35 – 4:45	DOE Outlook – **Ned Stetson**, HFTO
4:45	*End of workshop.*

U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

For more information, visit:
https://www.energy.gov/eere/fuelcells/hydrogen-infrastructure-strategies-enable-deployment-high-impact-sectors-workshop

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