U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Hydrogen Infrastructure Priorities to Enable Deployment in the High-Impact Transportation Sector

2024 Workshop Summary Report

Hydrogen and Fuel Cell Technologies Office

U.S. Department of Energy

February 27–28, 2024

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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:

- Amgad Elgowainy – Argonne National Laboratory
- Shaun Onorato – National Renewable Energy Laboratory
- Dionissios Papadias – Argonne National Laboratory

Additionally, HFTO would like to thank all the workshop participants for providing meaningful feedback and engaging in valuable discussions, as well as all moderators, scribes, and facilitators who contributed to the success of this workshop.

Nomenclature or List of Acronyms

AMR	Annual Merit Review and Peer Evaluation Meeting
ANL	Argonne National Laboratory
cH_2	Compressed hydrogen
CcH_2	Cryo-compressed hydrogen
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
FOA	Funding opportunity announcement
GHG	Greenhouse gas
HD	Heavy-duty
HFCEV	Hydrogen fuel cell electric vehicle
HFTO	Hydrogen and Fuel Cell Technologies Office
LD	Light-duty
LH_2	Liquid hydrogen
MD	Medium-duty
NFPA	National Fire Protection Association
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory

R&D	Research and development
RD&D	Research, development, and demonstration
RDD&D	Research, development, demonstration, and deployment
SBIR	Small Business Innovation Research
SCS	Safety, codes, and standards
sLH_2	Sub-cooled liquid hydrogen
TRL	Technology readiness level

Executive Summary

On February 27–28, 2024, the Hydrogen and Fuel Cell Technologies Office (HFTO) within the U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) held an in-person workshop focused on identifying and prioritizing the research, development, and demonstration (RD&D) needs and targets for enabling the deployment of medium- and heavy-duty (MD/HD) vehicles and fueling infrastructure. In attendance were 83 participants representing industrial firms, national laboratories, government contractors, and government agencies.

On the first day, the workshop opened with brief introductory remarks from DOE's Hydrogen Program Coordinator and HFTO Director Dr. Sunita Satyapal, followed by a presentation providing an overview of the *U.S. National Clean Hydrogen Strategy and Roadmap* and workshop objectives from Ned Stetson, program manager for Hydrogen Infrastructure Technologies in HFTO. Mark Richards, an HFTO technology manager, then presented DOE's scale-up scenario for hydrogen-powered MD/HD transportation. After the HFTO presentations, three national laboratory experts delivered in-depth technical presentations about different aspects of the MD/HD transportation ecosystem. Amgad Elgowainy from Argonne National Laboratory (ANL) presented on hydrogen supply and delivery to refueling stations, Shaun Onorato from the National Renewable Energy Laboratory (NREL) presented on hydrogen dispensing at refueling stations, and Dionissios Papadias from ANL presented on vehicle integration and onboard storage. The remainder of the first day was dedicated to breakout-room discussions, which focused on different RD&D needs, priorities, and performance metrics within the MD/HD transportation space.

On the second day, discussions continued and focused on RD&D priority areas that were identified on the first day. The discussions among the various stakeholders on both days allowed HFTO to identify RD&D needs that require priority investment to accelerate the deployment of MD/HD hydrogen fuel cell electric vehicles (HFCEVs) and their associated refueling infrastructure.

In short, **testing and validation facilities**, **boil-off management**, and **cryogenic infrastructure** were identified as primary areas needing attention and progress to enable the deployment of reliable refueling stations and hydrogen-powered MD/HD vehicles.

This workshop summary report provides additional information on hydrogen infrastructure strategies, key insights from expert presentations and Q&A discussions, and feedback and recommendations gathered via the breakout session deliberations. This report, the detailed agenda, speaker information, and the presentation materials can be found at: Hydrogen Infrastructure Priorities to Enable Deployment in the High-Impact Transportation Sector Workshop. The information and insights emerging from this workshop are complemented by the outcomes of similar activities focused on clean hydrogen storage, delivery, and dispensing infrastructure. Additional workshops in this area may be held in the future, as technologies and market conditions evolve.

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1 Presentations

The following sections summarize the presentation highlights from the workshop sessions. Copies of the speaker presentations can be found on the Workshop Proceedings webpage: Hydrogen Infrastructure Priorities to Enable Deployment in the High-Impact Transportation Sector Workshop. An overview of the workshop speakers and topics is shown in Table 1.

Table 1. List of Speakers

Topic Area	Speakers	Moderators
DOE Welcome and Introduction	Sunita Satyapal, HFTO	N/A
Overview of Workshop Objectives	Ned Stetson, HFTO	N/A
DOE Strategy for MD/HD Transportation	Mark Richards, HFTO	N/A
Stakeholder Presentation: Hydrogen Fueling Cost Analysis of Various Onboard Storage Technologies	Amgad Elgowainy, ANL	Marika Wieliczko, HFTO
Stakeholder Presentation: Medium- and Heavy-Duty Dispensing	Shaun Onorato, NREL	Marika Wieliczko, HFTO
Stakeholder Presentation: Onboard Cryogenic Hydrogen Storage Performance and Cost Analysis	Dionissios Papadias, ANL	Marika Wieliczko, HFTO

1.1 DOE Welcome and Introduction

The workshop began with a welcome and introduction from Dr. Sunita Satyapal, director of HFTO. Dr. Satyapal opened with a broad exposition of the U.S. energy and greenhouse gas (GHG) emissions landscape, then outlined the role of hydrogen in enabling not only reductions in GHG emissions, but also in providing economic opportunities and supporting energy security. In discussing the *U.S. National Clean Hydrogen Strategy and Roadmap*, she also emphasized the efforts of the U.S. government in accelerating hydrogen deployment through three strategies: (1) targeting strategic, high-impact end uses, (2) reducing the cost of clean hydrogen, and (3) focusing on regional networks. The first strategy involves market expansion across sectors for strategic high-impact uses, including catalyzing clean hydrogen use in existing industries and initiating new uses, particularly in the heavy-duty transport and industrial sectors, and for long-duration energy storage. The second strategy invests in pathways to reduce cost through both manufacturing scale up and continued research and development (R&D). And the third strategy will be addressed by investing in regional networks, including the seven selected Regional Clean Hydrogen Hubs. She highlighted the whole-of-government approach to clean hydrogen, and the role of the hydrogen infrastructure program and the scenario planning activities in enabling deployment of clean hydrogen.

Finally, Dr. Satyapal highlighted the significant growth in new hydrogen projects across the world including gigawatt-scale production sites, industrial and mobility applications, and infrastructure deployments. The continuation of this growth sets hydrogen to contribute to 10–20% of GHG emissions reductions worldwide. Dr. Satyapal concluded by encouraging the participants to provide meaningful and honest input on the R&D needs within their respective organizations and technology focus areas, and highlighted opportunities for further engagement with HFTO and the U.S. Department of Energy.

1.2 Overview of Workshop Objectives

Dr. Ned Stetson, program manager for Hydrogen Infrastructure Technologies at HFTO, focused on the mission of HFTO's Hydrogen Infrastructure Technologies Program and the objectives of the workshop. The program's mission is to support RD&D efforts for technologies with the potential to enable successful deployment of hydrogen in applications that help meet the aggressive national decarbonization goals. These efforts are supported primarily through cooperative agreements and grants selected through competitive funding opportunity announcements (FOAs) and the Small Business Innovation Research (SBIR) program, and through consortium efforts at the national laboratories. These efforts typically span the technology readiness levels (TRLs) of 2 through 6. FOA and SBIR topics are developed with consideration of congressional direction, HFTO's *Multi-Year Program Plan*, and stakeholder feedback captured through various channels including this workshop. Targets or performance metrics are used to measure progress and are ideally developed in concert with expert stakeholders via workshops and dedicated meetings.

In his talk, Dr. Stetson outlined the objectives of this workshop which included identifying key focus areas and RD&D needs, prioritizing focus areas with due consideration of deployment timelines, and developing targets and performance metrics for the MD/HD transportation sector. He also emphasized the important role of the participants in providing expert input that could be used in the development of HFTO's Infrastructure Technologies' five- to 10-year RD&D plan for the program. This plan would help enable successful deployment of MD/HD vehicle and refueling infrastructure and support success of the selected Regional Clean Hydrogen Hubs.

1.3 DOE Strategy for MD/HD Transportation

Mark Richards, a technology manager for Hydrogen Infrastructure Technologies at HFTO, provided an overview of DOE's strategy for MD/HD transportation infrastructure development. Under this strategy, DOE foresees that hydrogen will mostly be delivered as a liquid, which then affords the flexibility of dispensing the hydrogen to the vehicles as either a cryogenic liquid (LH_2) or a compressed gas (cH_2). The different components and systems involved in LH_2 delivery/dispensing and cH_2 dispensing were discussed. Additionally, Mr. Richards highlighted the level of challenge, technology readiness levels, and the key metrics that DOE will be targeting to measure the impact of its RD&D investments.

1.4 Hydrogen Fueling Cost Analysis of Various Onboard Storage Technologies

Dr. Amgad Elgowainy, senior scientist and group leader at Argonne National Laboratory (ANL), presented results of analysis conducted on the refueling costs associated with various vehicle onboard storage technologies. He opened by explaining how hydrogen fuel cells can offer a lower-cost alternative to battery electric vehicles when daily energy use is high. Considering different refueling station configurations as determined by the type of hydrogen supply (gaseous or liquid) and the type of hydrogen dispensed (350 bar gaseous, 700 bar gaseous, 350 bar cryo-compressed, and low-pressure liquid), Dr. Elgowainy explained how the ANL analysis found stations with liquid supply and liquid dispensing to be the lowest cost option. However, if gaseous dispensing is inevitable due to the onboard vehicle storage, 350 bar gaseous would significantly lower costs compared to 700 bar, especially for buses and other MD vehicles.

The analysis of Dr. Elgowainy and his team also found that although the cost contribution of a liquid/liquid station configuration is low (< $1/kg), liquefaction is quite energy intensive and could contribute at least $2/kg

to the cost of dispensed hydrogen. Additionally, boil-off losses during liquid hydrogen dispensing can be difficult to predict and could add as much as $6/kg if not mitigated properly.

1.5 Medium- and Heavy-Duty Dispensing

Shaun Onorato, systems engineering researcher at the National Renewable Energy Laboratory (NREL), discussed current progress on refueling protocols, dispensing hardware, communications, and station architecture and their effects on tailoring codes and standards to the requirements of MD/HD hydrogen refueling. Mr. Onorato also highlighted the work done by NREL in developing, demonstrating, and modeling MD/HD refueling. Notably, this work included the establishment of the Hydrogen Infrastructure Testing and Research Facility (HITRF), which enabled, among many achievements, the demonstration of fast flow 700 bar hydrogen refueling at an average rate of 12.6 kg/min and a peak rate of 23 kg/min. Finally, Mr. Onorato discussed the development of tools to estimate the economic costs of stations and MD/HD vehicles and noted further opportunities to improve refueling protocols and control valve technologies.

1.6 Onboard Cryogenic Hydrogen Storage Performance and Cost Analysis

Dr. Dionissios "Dennis" Papadias, researcher at Argonne National Laboratory (ANL), discussed the performance metrics and cost modeling for three onboard storage options in MD/HD vehicles: LH_2 with and without an on-board pump, cryo-compressed hydrogen (CcH_2), and sub-cooled liquid hydrogen (sLH_2). The modeling indicated that CcH_2 and sLH_2 are attractive options for HD trucks if the fuel cell system accepts hydrogen at 5 bar. Alternatively, if the fuel cell system requires hydrogen at higher pressure (15 bar or above), CcH_2 might be the only viable option as it uses substantially less carbon fiber per unit mass of stored hydrogen compared to cH_2. He also indicated that the development of onboard booster pumps can increase the competitiveness of low-pressure LH_2 onboard storage.

2 Breakout Sessions and Discussions

On the first day, after the presentation session concluded, the participants were divided into two breakout groups: one focused on onboard requirements and one focused on offboard or station requirements. These breakout discussions included the use of online polling to aggregate stakeholder feedback and provide the opportunity for anonymous input. On the second day, these discussions continued but in a large-group format where all the participants were informally grouped around roundtables in a single room (6-8 participants per table), with a scribe assigned to each table. Discussions alternated between roundtable-centric conversations and large-group discussions, which allowed both focused deliberations amongst stakeholders from the same sector, as well as cross-pollination between stakeholders from disparate areas of expertise. These Day Two discussions focused on three specific priority areas that were identified on Day One: testing and validation facilities, boil-off management, and cryogenic infrastructure, with the aim of identifying and prioritizing RD&D needs and performance metrics that would guide HFTO investments within the MD/HD transportation space.

The breakout session topics, as well as the moderators for each session are shown in Table 2. Below we provide a summary of the discussion outcomes in each of the five topic areas on which the breakout sessions and discussion were focused: onboard requirements, offboard requirements, testing and validation facilities, boil-off management, and cryogenic infrastructure.

Table 2. Breakout Sessions

Breakout Sessions	Topic	HFTO Moderators
Breakout Session 1	Onboard requirements	Zeric Hulvey, Asha-Dee Celestine

Breakout Session 2	Offboard requirements	Marika Wieliczko, Mark Richards
Large Group Discussions	Testing and validation facilities, boil-off management, and cryogenic infrastructure	Zeric Hulvey, Mark Richards

2.1 Onboard Requirements

This breakout session focused on identifying key considerations for developing and demonstrating hydrogen MD/HD HFCEVs. First, the moderator polled the attendees on the vehicle vocations that should be prioritized in future DOE-funded work. Class-8 long-haul sleeper trucks had the highest number of votes, while class-8 regional-haul trucks, class-8 city buses, and class-5 service vehicles were equal in second place. Participants then discussed various characteristics and performance requirements for each of these vehicle vocations, and the characteristics of the refueling infrastructure needed for each vocation.

Several attendees highlighted the need for redundancy and near-100% reliability in HD refueling and the importance of prioritizing technical solutions that reduce cost of ownership and achieve cost parity with diesel. Opportunities for rapid vehicle deployment enabled by mobile refuelers which can be especially valuable for fleet operators was also a key concern. Some vehicle manufacturer representatives also argued for increased prioritization of demonstration and high-TRL activities to meet the accelerated timeline for vehicle manufacturing deployment that the industry is currently planning.

2.2 Offboard Requirements

This breakout session focused on identifying and prioritizing the needs of MD/HD hydrogen refueling stations. There was broad agreement that unless stations are served by high-capacity pipelines, which is the industry-preferred option and is generally the cheapest delivery method, truck delivery of hydrogen in cryogenic liquid form is the only feasible option. Consequently, the discussion focused on the need to accelerate the development and demonstration of cryogenic components and systems, and to establish appropriate testing and validation facilities to this end. These facilities should allow access to LH_2 and enable the provision of standardized certifications. Several attendees highlighted the need to prioritize the reliability of critical components including sensors and pumps, especially since 700-bar dispensing in HD vehicles places much greater demands on these components than 350-bar dispensing for smaller vehicles.

A valuable RD&D opportunity would be standardization across all components and testing and evaluation facilities, and collaborating with safety, codes, and standards (SCS) teams to establish testing standards for various components and refueling interfaces.

2.3 Large Group Discussions

On the second day, attendees were divided into roundtables within a single large room. The discussions focused on three priority areas identified during the first day of discussions and breakout sessions: testing and validation facilities, boil-off management and hydrogen storage, and cryogenic infrastructure.

Testing and Validation Facilities

A significant number of industry stakeholders argued for the need to prioritize the establishment of testing and validation facilities, especially to facilitate the demonstration and certification of cryogenic components. When asked about which materials, components, or systems should be tested, participants mentioned pumps (including piston rings), compressor diaphragms, and high-flow control valves. Some participants noted the current dearth of LH_2 testing capabilities, while others argued for testing to be focused on components and materials, rather than entire systems.

When asked about the parameters and metrics that would guide the testing, most participants agreed that accelerated testing methods need to be developed and standardized. Ultimately, the aim should be to design testing and validation methods (and establish supporting facilities) to qualify entire MD/HD refueling stations. Various entities should be involved in supporting these methods and facilities including national laboratories, the U.S. Department of Transportation (DOT), the National Fire Protection Association (NFPA), universities, in addition to industrial and commercial firms. National laboratories were preferred as centralized providers of component testing services and as trusted interfaces between component manufacturers and end users, while neutral non-profit third parties were preferred for qualification and validation of industry testing. As safety is paramount to ensuring widespread social acceptance of hydrogen and its associated infrastructure, the Hydrogen Safety Panel and other safety-focused governmental and non-governmental entities should also be involved.

Boil-off Management and Hydrogen Storage

Boil-off mitigation was mentioned during the first day's presentations and discussions as critical to reducing economic losses during the delivery, storage, and dispensing of cryogenic hydrogen for the refueling of MD/HD vehicles. The second day's discussions on this topic highlighted that R&D investment is required to minimize losses at all transfer points including interfaces between the delivery truck and the station storage, and between the dispenser and the onboard vehicle storage. These boil-off losses can be quite severe at all transfer points when using LH_2 and are generally higher in mobile refuelers compared to stations.

The participants then discussed methods to capture and re-utilize boil-off hydrogen with many highlighting the need to redesign tanks, rethink standard hydrogen management practices, optimize trailer delivery processes, and re-use vented hydrogen for power either in delivery trailers or on-site. Other participants that are familiar with DOT regulations mentioned that increasing trailer pressure limits could also lead to substantial reductions in hydrogen venting. As for the performance metrics governing hydrogen boil-off and capture, participants discussed the need to improve the methods used to determine the location and quantity of releases, as well as develop monitoring tools and methods for refueling stations.

Cryogenic Infrastructure

On the first day, there was broad agreement that refueling stations will require LH_2 deliveries to meet the large volumes required by HD vehicles. As such, industry stakeholders identified cryogenic infrastructure as an area that requires priority RD&D investments. Specifically, participants identified RD&D gaps and opportunities in seals, valves, cryopumps, flowmeters, small-scale liquefiers, cryocoolers, and onboard storage. To assess RD&D progress in this area, participants highlighted the importance of comparing to the economics and experience of diesel, as well as establishing targets for costs, efficiency, and hydrogen losses.

3 Conclusions

Closing remarks were given by HFTO's Ned Stetson, who 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.

The discussions throughout the two-day workshop provided valuable insights on stakeholders' concerns and perspectives surrounding hydrogen infrastructure for the transportation sector, including the current challenges and opportunities to enable large scale deployment of MD/HD vehicles. Stakeholder input will help DOE's efforts to prioritize the RD&D areas needing attention and progress to enable the deployment of reliable refueling stations and hydrogen-powered MD/HD vehicles.

Topics that elicited the most discussion included **testing and validation facilities, boil-off management,** and **cryogenic infrastructure.** The concerns surrounding these three topics strongly indicate that DOE needs to

extract more information from relevant stakeholders in future workshops and/or other stakeholder engagement activities.

Attendees provided the following key recommendations for DOE:

1) Continue near-term focus on the MD/HD transportation sectors.

2) Investigate additional RDD&D opportunities in the MD transportation sector.

3) Mitigate industrial uncertainty by providing strategic roadmaps and other guidance on long-term outlooks, specifically on infrastructure issues.

4) Develop intermediate targets that support market liftoff, rather than market maturity, with appropriate consideration for economic constraints, customer needs, and technology limitations.

5) Strengthen the domestic supply chain of high-quality materials and components.

6) Support development of the skilled workforce needed to produce, assemble, install, and maintain hydrogen infrastructure.

7) Increase support for collaborative partnerships among hydrogen producers and end users, to facilitate infrastructure development, testing, and demonstrations.

In addition to these specific recommendations, discussion themes suggested that DOE continue to evolve its long-term outlook for large-scale hydrogen-transmission scenarios. This could include strategies for deploying and repurposing pipelines, enabling transmission connections to remote areas and export terminals, and ensuring the reliability of transmission networks. This could also involve developing a better understanding of the impact market dynamics will have on future infrastructure needs.

Appendix

This appendix provides a summary of the workshop agenda.

Day 1

8:00 – 8:30 Breakfast

8:30 – 8:40 DOE Welcome & Introduction - Sunita Satyapal, HFTO

8:40 – 9:10 Overview of Workshop Objectives and Goals – Ned Stetson, HFTO

9:10 – 9:20 MD/HD Transportation Scale-up Scenario – Mark Richards, HFTO

9:20 – 10:40 MD/HD Transportation Stakeholder Presentations
- Hydrogen supply and delivery – Amgad Elgowainy, ANL
- Hydrogen stations and dispensing – Shaun Onorato, NREL
- Onboard storage and vehicle integration – Dionissios Papadias, ANL
- Q&A

10:40 – 10:55 Break

10:55 – 12:25 Breakout Session 1 – Needs and Priorities for MD/HD Transportation Scale-up

12:25 – 1:25 Lunch

1:25 – 2:25 Large Group Discussion

2:25 – 2:40 Break

2:40 – 4:10 Breakout Session 2 – Key Performance Requirements for MD/HD Transportation

4:10 – 4:25 Summary/End-of-day Remarks

Day 2

8:00 – 8:30 Breakfast

8:30 – 8:40 Day 1 Recap and Forecast for Day 2 – Zeric Hulvey, HFTO

8:40 – 10:10 Large Group Discussion

10:10 – 10:25 Break

10:25 – 11:25 Large Group Discussion

11:25 – 11:40 DOE Outlook and Wrap Up – Ned Stetson, HFTO

11:40 – 1:00 Lunch and Networking

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

DOE/EE-2858 ▪ July 2024