Project 099 Conceptual Analysis of Cryogenic Hydrogen Distribution to Airports

Washington State University

Project Lead Investigator

Jacob Leachman
Professor and HYPER Laboratory Director
School of Mechanical & Materials Engineering
Washington State University
Pullman, WA 99164
509-335-7711
Jacob.leachman@wsu.edu

University Participants

Washington State University (WSU)

- P.I.: Dr. Jacob Leachman
- FAA Award Number: 13-C-AJFE-WaSU-050
- Period of Performance: September 18, 2024, to December 31, 2025
- Tasks:
  1. Contribute to the State of the Technology Analysis considering current efficiencies, realistic 5-year efficiencies, and ideal/limiting efficiencies
  2. Site Selection Analysis to supplement/complement the ongoing National Laboratory of the Rockies (NLR) study
  3. Cryogenic hydrogen effects on demand modeling
  4. Cryogenic hydrogen fueling analysis including needs for technology development
  5. Cryogenic hydrogen infrastructure sizing estimates
  6. Cryogenic hydrogen infrastructure safety analysis

Project Funding Level

The Federal Aviation Administration (FAA) provided $199,910 in funding. Airbus Americas is the cost share partner, partnering with NLR for the previous infrastructure study and investing over $1M in WSU's HYPER Laboratory over the last couple years.

Investigation Team

Jacob Leachman, PI, Washington State University (WSU)
Kazunori Nagasawa, co-PI, National Laboratory of the Rockies (NLR)
Kyle Appel, Research Scientist, Washington State University – Responsible for conducting the research under all tasks
Justin Bracci, Hydrogen Delivery Scenario Analysis Model (HDSAM) modeling, National Renewable Energy Laboratory – Conducted HDSAM modeling under Tasks 2 and 3

Project Overview

This project partners with an existing project funded by the FAA at the NLR to analyze gaseous hydrogen delivery to airports. The goal of this project is to add corresponding cryogenic hydrogen infrastructure analysis to a previous study conducted at the NLR. This previous study, sponsored by the FAA, investigated hydrogen implementation at the Seattle-Tacoma Internation Airport (SEA), Portland International Airport (PDX), San Francisco International Airport (SFO), and Los Angeles International Airport (LAX), primarily focusing on gaseous hydrogen delivery and conducting technoeconomic, emissions, safety, and job analysis. NLR, WSU, and FAA agreed to this ASCENT project to complement the previous study by evaluating cryogenic hydrogen implementation. The following specific objectives were pursued:

1. Contribute to the State of the Technology Analysis by reviewing conceptual hydrogen delivery pathways to airports including liquid hydrogen tankers, trains, and liquid and or cryogenic gaseous pipelines. The analysis considered current efficiencies, realistic achievable efficiencies for technologies developed in the next five years, and ideal/limiting efficiencies.
2. Site Selection Analysis for suitability to cryogenic hydrogen deliveries. The site selection analysis was limited to no more than three sites from the current NLR study for ease of comparison. The analysis applied the realistic technology delivery pathways identified in the prior objective to the sites with information to supplement/complement the ongoing NLR study.
3. Cryogenic hydrogen effects on demand modeling. This considered the effects of boil-off and transfer losses of cryogenic hydrogen and the effects on demand.
4. Cryogenic hydrogen fueling analysis including needs for technology development. This objective considered needs for cryogenic technology development and interviewed key industrial players to verify the technology development needs.
5. Cryogenic hydrogen infrastructure sizing estimates. This objective considered differences in sizing/scaling of cryogenic hydrogen infrastructure for refueling stations relative to gaseous hydrogen and applying these to airport infrastructure.
6. Cryogenic hydrogen infrastructure safety analysis relevant to codes and standards. WSU considered the American Institute of Aeronautics and Astronautics (AIAA) and the National Fire Protection Association (NFPA) hydrogen safety codes specific to cryogenic hydrogen for setback and other safety requirements.

Task 1 – Contribute to the State of the Technology Analysis Considering Current Efficiencies, Realistic 5-year Efficiencies, and Ideal/Limiting Efficiencies

Washington State University

Objective

The objective of this task is to contribute to the State of the Technology Analysis by reviewing conceptual hydrogen delivery pathways to airports including liquid hydrogen tankers, trains, and liquid and or cryogenic gaseous pipelines. The analysis considered current efficiencies, realistic achievable efficiencies for technologies developed in the next five years, and ideal/limiting efficiencies.

Research Approach

An investigation into the state of cryogenic hydrogen technology was conducted through a literature review, exploring conceptual hydrogen delivery pathways for airports. Table 1 was created to compare the conceptual pathways discussed in previous studies. Based on the results of the literature review, delivery pathways of liquid hydrogen (LH_2) ships, rails, and cryogenic/cryo-compressed pipelines should be analyzed in Task 2.

Table 1. Previous hydrogen delivery pathway studies found in the literature.

Author	Year	Airport	LH_2 Ship	LH_2 Train	LH_2 Truck	Cryo-Pipeline	Onsite Liquefaction
Brewer [1]	1975	San Francisco	×	✓	✓	✓	✓
Boeing and Nasa [2]	1976	O'Hare	×	×	×	×	✓
Alder [3]	1987	Zurich	×	×	×	×	✓
Gretz [4]	1994	Conceptual	✓	×	×	×	×
Sefain [5]	2006	Conceptual	×	×	×	✓	✓
Stadler [6]	2014	Conceptual	✓	×	✓	×	×
Amy [7]	2019	Conceptual	×	×	×	×	✓

Author	Year	Airport	LH_2 Ship	LH_2 Train	LH_2 Truck	Cryo-Pipeline	Onsite Liquefaction
Clean Sky 2 JU and FCH 2 JU [8]	2020	Conceptual	×	×	✓	×	✓
Marksel [9]	2020	Tromso	×	×	✓	×	✓
ATI-ACI [10]	2021	Conceptual	×	×	✓	✓	✓
Alexandrou [11]	2022	Toulouse Blagnac	×	×	✓	×	✓
Hoelzen [12]	2022	Conceptual	✓	×	✓	×	✓
Degirmenci [13]	2023	Conceptual	✓	✓	✓	✓	✓
Dijk [14]	2024	Rotterdam	✓	×	✓	×	✓

Relevant metrics for current, 5-year, and limiting efficiencies for cryogenic hydrogen technologies were recorded as part of the literature review. Efficiencies are defined differently for storage, liquefaction, or cryo-compression. For hydrogen storage efficiency is defined by boil-off losses, which is hydrogen unutilized due to venting or transfers. This is also associated with a heat leak entering the tank that causes a normal background boil-off rate. The efficiency for hydrogen liquefaction is defined by the energy required to liquefy one kilogram of hydrogen, expressed as the Specific Energy Consumption (SEC) in kWh/kg. Cryo-compressed hydrogen efficiency can be measured by SEC required to compress and cool the hydrogen or by heat loss of the pipeline. These metrics are used in Task 2 to predict the levelized cost of hydrogen (LCOH) for each conceptual pathway with the advancement of technologies and scaling. The metrics are shown in Table 2.

Table 2. Current, 5-year, and limiting efficiencies for truck, rail, marine, cryo-compressed pipelines, and onsite liquefaction.

	Truck	Rail	Marine	Onsite Liquefier	Cryo-compressed pipeline
Current Losses	3.0 wt% [15]	1.0 wt% [16]	1.0 wt% [16]	-	-
5-year Losses	0.3 wt% [16]	0.3 wt% [16]	0.3 wt% [16]	-	-
Limiting Losses	0 %	0 %	0 %	-	-
Current Power Requirement	-	-	-	12.3 kWh/kg [17]	6.42 kWh/kg [18]
5-year Power Requirement	-	-	-	6.7 kWh/kg [17,19]	5.62 kWh/kg [18]
Limiting Power Requirement	-	-	-	2.98 kWh/kg [20]	-
Current Heat Leak to Fluid	300-400 W	300-400 W	300-400 W	-	1.0 W/m [21]
5-year Heat Leak to Fluid	126-168 W [22]	126-168 W [22]	126-168 W [22]	-	0.42 W/m [22]
Limiting Heat Leak to Fluid	0 W	0 W	0 W	-	0 W/m

Milestone

This task is complete and documented in a draft NLR report.

Major Accomplishments

Literature revealed with analyzed conceptual cryogenic hydrogen delivery pathways and estimated efficiency metrics for current, 5-year, and limiting cryogenic hydrogen technologies. Conceptual hydrogen delivery pathways and associated assumptions will be used for modeling analysis in Task 2.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work was completed in December 2025 and a thorough report for publication is in progress in collaboration with NLR.

References

[1] Brewer G.D., Morris RE, Lange RH, Moore JW. LH2 Airport Requirements Study. 1975 Jan.

[2] Boeing, NASA. A N EXPLORATORY STUDY TO DETERMINE THE INTEGRATED TECHNOLOGICAL AIR TRANSPORTATION SYSTEM GROUND REQUIREMENTS OF LIQUID-HYDROGEN-FUELED SUBSONIC, LONG-HAUL CIVIL AIR TRANSPORTS NATIONAL AERONAUTICS AND SPACE ADMINISTRATION. 1976.

[3] Alder H. Hydrogen in air transportation. Feasibility study for Zurich airport, Switzerland. Int J Hydrogen Energy. 1987;12(8):571–85.

[4] Gretz J, Drolet B, Kluyskens D, Sandmann F, Ullmann OI. Status of the Hydro-Hydrogen Pilot Project (EQHHPP). Vol. 19. 1994.

[5] Sefain MJ. Hydrogen Aircraft Concepts & Ground Support. Cranfield University; 2000.

[6] Stadler P, Caliandro P, Leonardi C, Van Herle J. Cost evaluation of large scale hydrogen production for the aviation industry. Master Semester Project. 2014;

[7] Amy C, Kunycky A. Hydrogen as a Renewable Energy Carrier for Commercial Aircraft. 2019; Available from: https://www.researchgate.net/publication/336551230

[8] Clean Sky 2, Fuel Cells and Hydrogen 2 JU. Hydrogen-powered aviation. 2020;

[9] Marksel M, Brdnik Prapotnik A, Kamnik R, Hanžič K, Letnik T, Božičnik S, Rok Kamnik Ds, Katja Hanžič Ds, Stanislav Božičnik Ds. Adaptation of Airport Infrastructure for Operation of ICE-Hybrid and Fuel-Cell Aircraft. 2000.

[10] ACI-ATI. Integration of Hydrogen Aircraft into the Air Transport System. 2021.

[11] Alexandrou S. Comparative Analysis of On-site vs Off-site green-Hydrogen Value Chain Scenarios to cover projected Aviation demand A case for Toulouse Blagnac Airport in France. KTH School of Industrial Engineering and Management; 2022.

[12] Hoelzen J, Flohr M, Silberhorn D, Mangold J, Bensmann A, Hanke-Rauschenbach R. H2-powered aviation at airports – Design and economics of LH2 refueling systems. Energy Conversion and Management: X. 2022 May 1;14.

[13] Degirmenci H, Uludag A, Ekici S, Hikmet Karakoc T. Analyzing the hydrogen supply chain for airports: Evaluating environmental impact, cost, sustainability, viability, and safety in various scenarios for implementation. Energy Convers Manag. 2023 Oct 1;293.

[14] Dijk D, Ebrahim H, Jooss Y, Bodal EF, Hjorth I. Integrating liquid hydrogen infrastructure at airports: Conclusions from an ecosystem approach at Rotterdam The Hague Airport. 2024 Apr.

[15] Zhang F, Zhao P, Niu M, Maddy J. The survey of key technologies in hydrogen energy storage. Int J Hydrogen Energy. 2016 Sep 7;41(33):14535–52.

[16] Borsboom-Hanson T, Patlolla SR, Herrera OE, Mérida W. Point-to-point transportation: The economics of hydrogen export. Int J Hydrogen Energy. 2022 Aug 29;47(74):31541–50.

[17] Al Ghafri SZ, Munro S, Cardella U, Funke T, Notardonato W, Trusler JPM, … May EF. Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities. Vol. 15, Energy and Environmental Science. Royal Society of Chemistry; 2022. p. 2690–731.
[18] Wang H, Zhao Y, Dong X, Yang J, Guo H, Gong M. Thermodynamic analysis of low-temperature and high-pressure (cryo-compressed) hydrogen storage processes cooled by mixed-refrigerants. Int J Hydrogen Energy. 2022 Aug 5;47(67):28932–44.
[19] Zhang T, Uratani J, Huang Y, Xu L, Griffiths S, Ding Y. Hydrogen liquefaction and storage: Recent progress and perspectives. Vol. 176, Renewable and Sustainable Energy Reviews. Elsevier Ltd; 2023.
[20] Valenti G, MacChi E, Brioschi S. The influence of the thermodynamic model of equilibrium-hydrogen on the simulation of its liquefaction. Int J Hydrogen Energy. 2012 Jul;37(14):10779–88.
[21] Demaco. Vacuum Insulated Transfer Lines (VIP). 2025.
[22] Yin L, Yang H, Ju Y. Review on the key technologies and future development of insulation structure for liquid hydrogen storage tanks. Vol. 57, International Journal of Hydrogen Energy. Elsevier Ltd; 2024. p. 1302–15.

Task 2 – Site Selection Analysis to Supplement/Complement the Ongoing NLR Study

Washington State University, National Laboratory of the Rockies

Objective

The objective of this task is to perform site selection analysis for suitability to cryogenic hydrogen deliveries. The site selection analysis was limited to no more than three sites from the previous NLR study for ease of comparison. The analysis applied the realistic technology delivery pathways identified in the prior objective to the sites with information to supplement/complement the ongoing NLR study.

Research Approach

HDSAM[1] is used to estimate the LCOH for the hydrogen delivery pathways. The technoeconomic analysis was conducted by Justin Bracci (NLR) utilizing the pathways, assumptions, and metrics generated in Task 1. The analysis includes conceptual pathways to deliver cryogenic hydrogen to the SEA, PDX, SFO, and LAX independent of location. Truck tanker and gaseous pipeline pathways assume hydrogen production and liquefaction is 50 km from any one of the airports. The rail tanker pathway assumes production and liquefaction are 1,000 km from the airport with last mile trucking from a rail spike near the airport. The ocean tanker pathways assume production and liquefaction are 10,000 km from the airport with last mile trucking from a marine port to the airport. In the analysis different station throughput capacities are used, evaluating the effect of scale on dispensing cost. The effect of technology advancement is analyzed utilizing the metrics of current, 5-year, and limiting efficiencies. The results of the analysis are shown in Figure 1 with 80% utilization and throughput capacity of 6, 12, and 24 metric tonnes per day (MTPD) for all delivery pathways. LCOH is shown on the y-axis and delivery method on the x-axis. Based on the assumptions made, the plot shows that delivering LH_2 via truck tankers currently yields the lowest LCOH, with onsite production and liquefaction as a close second lowest. For both the 5-year estimate and limiting efficiencies, the LCOH from rail and ocean tankers is less than that of truck tankers.

---

[1] https://hdsam.es.anl.gov/index.php?content=hdsam

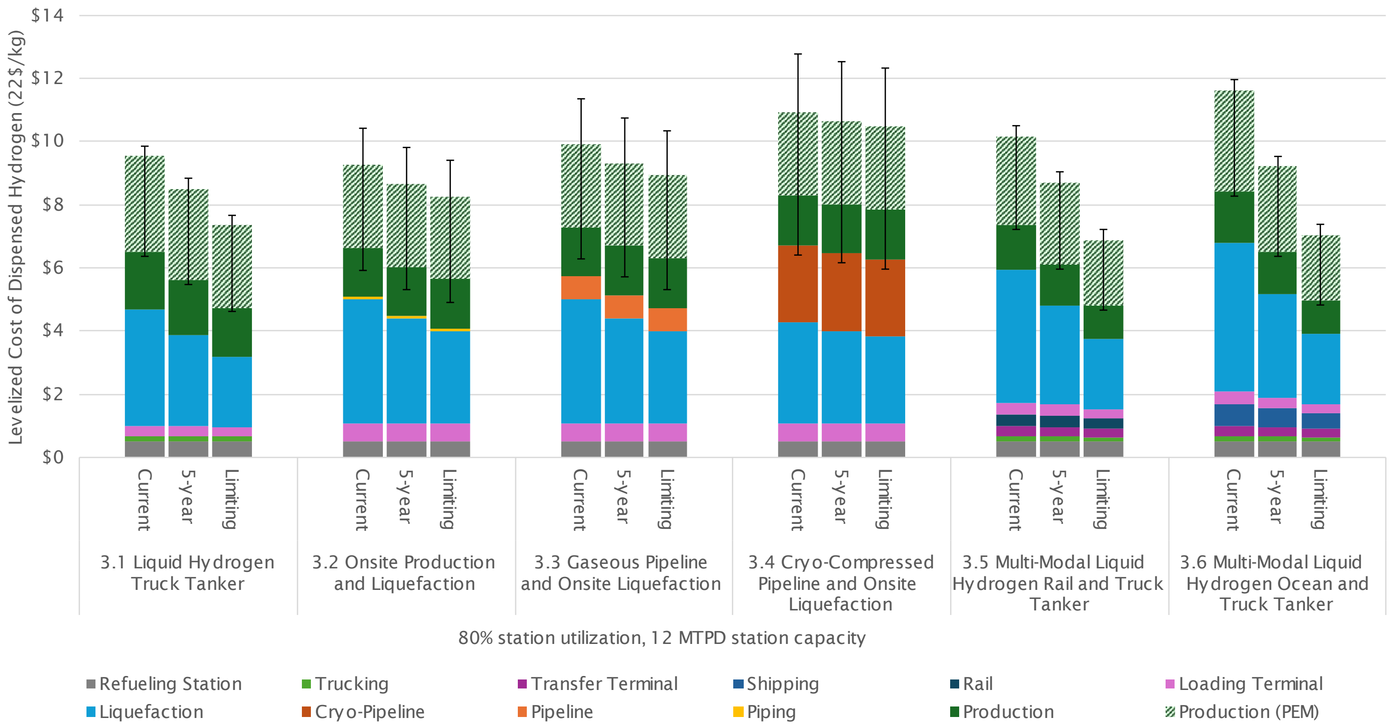

Figure 1. Results of Task 2 showing six delivery methods for LH_2, 80% utilization of the refueling station, and current/5-year/limiting losses and efficiencies.

Milestones

This task is complete.

Major Accomplishments

Levelized the cost of hydrogen estimates obtained via modeling in HDSAM by Justin Bracci and various altered assumptions and delivery pathway development. Effects of future technological development and scaling of LH_2 usage on LCOH are included.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work was completed in December 2025 and a thorough report for publication is in progress in collaboration with the NLR.

References

[23] https://hdsam.es.anl.gov/index.php?content=hdsam

Task 3 – Cryogenic Hydrogen Effects on Demand Modeling

Washington State University

Objective

The objective of this task is to identify the cryogenic hydrogen effects on demand modeling. This considered the effects of boil-off and transfer losses of cryogenic hydrogen and the effects on demand.

Research Approach

Using HDSAM, sensitivity studies are conducted evaluating the effect of boil-off and transfer losses, SEC of liquefaction, and capital cost of liquefaction plants on LCOH. The results are shown in Table 3.

Table 3. Sensitivity analysis on the levelized cost of hydrogen (LCOH) with different boil-off and liquefaction parameters for liquid hydrogen (LH_2). SEC: Specific Energy Consumption.

Scenario #	Delivery Method	Altered parameter	Parameter % change	LCOH % change	LCOH % / Input %
3.1	LH2 Truck Tanker	Liquefier SEC	-45.53	-7.28	0.160
3.1	LH2 Truck Tanker	Liquefier capital cost	-9.99	-2.20	0.220
3.1	LH2 Truck Tanker	LH2 unloading losses	-23.08	-2.98	0.129
3.1	LH2 Truck Tanker	Truck LH2 boil-off rate	-66.67	-0.69	0.010
3.5	LH2 Rail Tanker	LH2 unloading losses	-23.08	-5.69	0.247
3.5	LH2 Rail Tanker	Rail LH2 boil-off rate	-70.00	-0.51	0.007
3.6	LH2 Marine Tanker	LH2 unloading losses	-23.08	-5.78	0.250
3.6	LH2 Marine Tanker	Marine LH2 boil-off rate	-70.00	-8.04	0.115

Additionally, a numerical model which was previously validated and used to predict boil-off losses for in-service LH_2 tanks [24,25], was used to predict the number of tanks required to supply airport throughput. The model was used to evaluate single spherical tanks that would only be refilled once per day, sized to fit the airport throughput capacities of 6, 12, and 24 MTPD. Vertical or horizontal cylindrical tanks were also modeled using 2-12 tanks in a storage system. The total losses and number of times the tanks required refilling over a 6-day period were predicted. Losses and number of fills are shown below in Figure 2 and Figure 3 for horizontally oriented tanks.

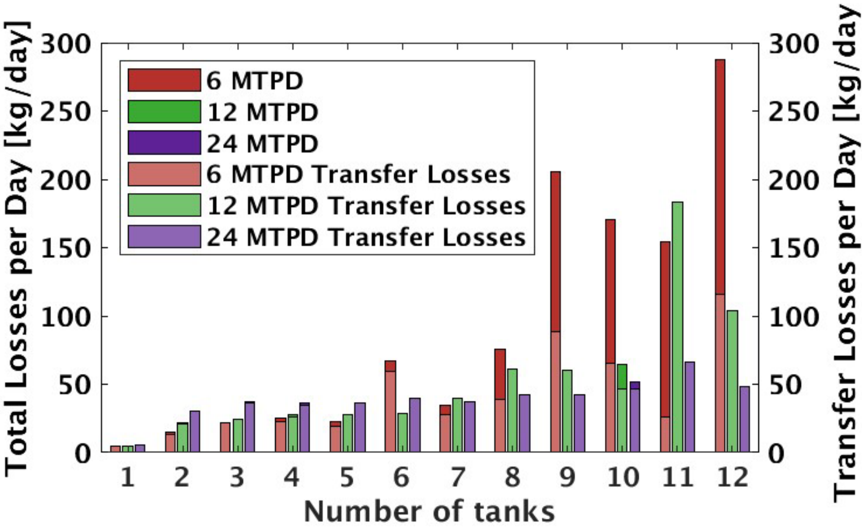

Figure 2. Average daily boil-off losses for a varied number of horizontal tanks for Cases 3.1-3.6 scenarios with 6, 12, and 24 metric tonnes per day (MTPD) refueling capacity.

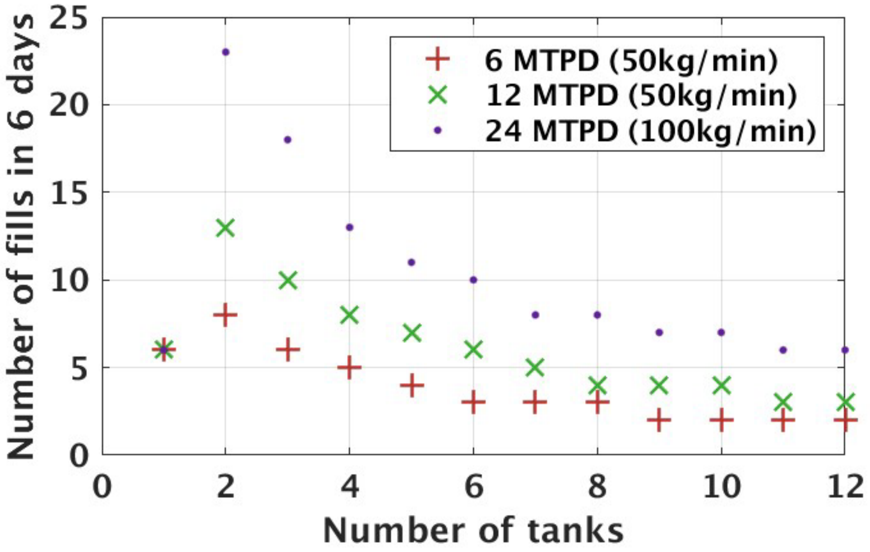

Figure 3. Number of fills per tank during the six-day simulation for a varied number of tanks for Cases 3.1-3.6 scenarios with 6, 12, and 24 MTPD refueling capacity.

Milestones

This task is complete.

Major Accomplishments

The sensitivity of the LCOH is evaluated by altering boil-off and transfer losses, liquefaction SEC, and liquefaction capital cost for scenarios 3.1, 3.5, and 3.6. The unloading losses and liquefier capital cost were both highly related to the LCOH, meaning decreasing these losses and costs will result in lower LCOH. The numerical model predicted 3 and 6 tanks are enough to service 6 and 12 MTPD capacities regardless of tank orientation. For 24 MTPD station capacity 11 horizontal tanks or 13-14 vertical tanks are needed. The results of this analysis can be used to estimate the spatial requirement for airports using LH_2 storage vessels.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work was completed in December 2025 and a thorough report for publication is in progress in collaboration with the NLR.

References

[24] Appel K. Numerical Modeling of Liquid Hydrogen Storage Tanks for the Reduction of Boil-Off Losses [Thesis]. [Pullman]: Washington State University; 2024.

[25] Appel KR, Matveev KI, Leachman JW. Modeling the effects of liquid hydrogen tank operations on boil-off losses. Cryogenics (Guild). 2025 Sep 15;150.

Task 4 – Cryogenic Hydrogen Fueling Analysis Including Needs for Technology Development

Washington State University

Objective

The objective of this task is to perform cryogenic hydrogen fueling analysis including needs for technology development. This objective considers needs for cryogenic technology development and during this task, key industrial players were interviewed to verify the technology development needs.

Research Approach

Analysis of current liquid hydrogen refueling technologies was conducted through literature review. Several technologies were identified that require advancement before commercial use in airports.

- High efficiency hydrogen production
- High efficiency cooling technologies
- Boil-off management systems
- LH_2 pumps
- LH_2 hydrant systems
- Mobile refuelers
- Mobile refueler safety devices
- Standardized refueling procedures

Industry partners including ZeroAvia, Airbus, and Joby Aviation were interviewed for their perspective on the technological advancement needed for LH_2 implementation. As part of this interview, a new list containing technological advancements industry believes is needed was created.

- LH_2 transportation and logistics
- Boil-off gas capture

- Liquefaction technologies
- Operational study of interim LH_2 integration
- Pumps and heat exchangers for refueling control
- Zero venting transfer line chill down
- Refueler sizing
- Advanced leak detection
- Easily manageable transfer lines
- Onsite production and liquefaction efficiency
- Hydrogen vent stack burn-off
- Standardized refueling components
- LH_2 storage tank materials and designs

Milestones

This task is complete.

Major Accomplishments

Several technologies have been identified by industry for improvement to enable LH_2 integration with airport infrastructure.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work was completed in December 2025 and a thorough report for publication is in progress in collaboration with the NLR.

Task 5 – Cryogenic Hydrogen Infrastructure Sizing Estimates

Washington State University

Objective

The objective of this task is to complete cryogenic hydrogen infrastructure sizing estimates. This objective considered differences in sizing/scaling of cryogenic hydrogen infrastructure for refueling stations relative to gaseous hydrogen and applying these to airport infrastructure.

Research Approach

Using the estimated number of tanks required for 6, 12, and 24 MTPD throughput capacity from Task 3, the space required for storage is estimated. This estimation requires use of the NFPA-2 hydrogen codes for setback distances and local Washington and California state codes for the minimum distance between LH_2 storage tanks [26-29]. Three example layouts for LH_2 storage tanks are shown in Figure 4 below with horizontal tanks arrayed in one or two rows or as vertical tanks. The spatial requirement for singular spherical tanks or equivalent gaseous hydrogen storage tubes was also estimated. Table 4 shows the comparison of the different hydrogen storage methods.

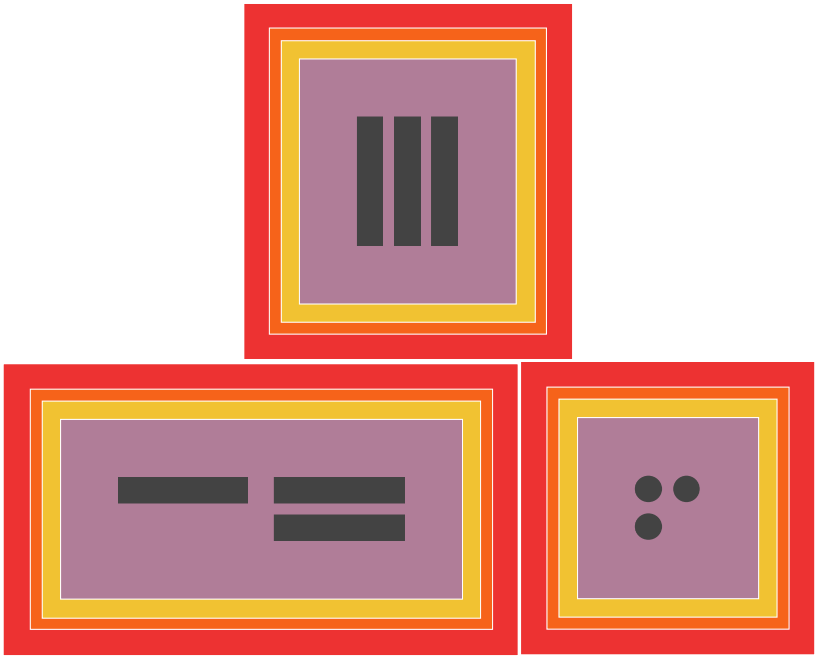

Figure 4. Single row of horizontal LH_2 tanks (top), two rows of horizontal LH_2 tanks (bottom left), two rows of vertical LH_2 tanks (bottom right).

Table 4. Spatial estimate for 6, 12, and 24 metric tonnes per day (MTPD) throughput with different LH_2 storage options. GH_2: gaseous hydrogen.

Refueling Capacity	One Spherical LH_2	Horizontal One/Two Line LH_2	Vertical LH_2	GH_2 Tube Array
6 MTPD	1397 m^2	2017 m^2/2567 m^2	1459 m^2	2380 m^2
12 MTPD	1533 m^2	2710 m^2/2896 m^2	1646 m^2	4369 m^2
24 MTPD	1695 m^2	3861 m^2/3877 m^2	2433 m^2	6750 m^2

Milestones

This task is complete.

Major Accomplishments

Spatial requirements for multiple LH_2 tank configurations and one array for gaseous hydrogen (GH_2) have been estimated as shown in Table 4.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work was completed in December 2025 and a thorough report for publication is in progress in collaboration with the NLR.

References

[26] NFPA 2: Hydrogen Technologies Code, 2023 Edition.
[27] Washington State Legislature. Liquified hydrogen systems. WAC296-24-31505. 2023.
[28] Washington State Legislature. Gaseous hydrogen systems. WAC 296-24-31503. 2023.
[29] State of California Department of Industrial Relations. Subchapter 7. General Industry Safety Orders Group 20. Flammable Liquids, Gases and Vapors Article 138. Hydrogen. In: Cal/OSHA - Title 8.

Task 6 – Cryogenic Hydrogen Infrastructure Safety Analysis

Washington State University

Objective

The objective of this task is to perform cryogenic hydrogen infrastructure safety analysis relevant to codes and standards. WSU considered the AIAA and NFPA hydrogen safety codes specific to cryogenic hydrogen for setback and other safety requirements.

Research Approach

Setback distance analysis was conducted as part of Task 5 to evaluate infrastructure required for LH_2 implementation at airports. Extensive safety analysis was conducted in the previous NLR report. The final report published with NLR may consider the following potential safety analyses:

- Excess fuel reserves
- Additional space required for LH_2 pumps, plumbing, and vaporizers
- A high-level overview of explosion distancing
- Needs for LH_2 aircraft fueling with passengers aboard
- Latest activities in LH_2 codes and standards

Milestones

This task was completed in December 2025.

Major Accomplishments

Spatial requirements are estimated and include NFPA-2 guidelines for LH_2 storage tank setbacks.

Publications

This work is included in a final report detailing all the studies to be published in cooperation with NLR.

Outreach Efforts

Presented at the spring and fall ASCENT meetings in 2025.

Awards

None.

Student Involvement

None.

Plans for Next Period

None. The scope of work was completed in December 2025 and a thorough report for publication is in progress in collaboration with the NLR.

Summary and Recommendations for Future Research

This study partnered with NLR to analyze conceptual liquid hydrogen delivery scenarios to airports, expanding on a prior study completed by NLR for gaseous hydrogen distribution. SEA, PDX, SFO, and LAX were considered for refueling of liquid hydrogen aircraft at 6, 12, and 24 MTPD. Several new conceptual delivery pathways were considered that had not previously been analyzed in the literature. Modifications were made to the HDSAM tool developed by the U.S. Department of Energy for uniform comparison between pathways. A recently developed boil-off model was adapted to analyze losses from on-site storage and filling for various numbers and configurations of on-site tanks. An industrial survey for technology development needs was conducted, identifying high-efficiency hydrogen production and cooling technologies as the primary needs. A safety codes analysis completed for the NLR gaseous hydrogen study was extended to liquid hydrogen.

Several opportunities for technology advancement were identified during this program and warrant consideration for future research. High-efficiency cooling technologies to maintain liquid hydrogen in a sub-cooled state to eliminate boil-off would increase technology performance and reduce losses for all pathways considered. These cooling technologies, also known as cryocoolers, reduce losses from any cryogenic fuel (hydrogen or natural gas) and have yet to be comprehensively surveyed for terrestrial applications to determine a design specification, including price points, capacities, and efficiencies.