Moving Hydrogen from Here to There: The Distribution and Storage of Hydrogen Fuel

June 17, 2025

MESSY MIDDLE BOOTCAMP

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NACFE NORTH AMERICAN COUNCIL FOR FREIGHT EFFICIENCY

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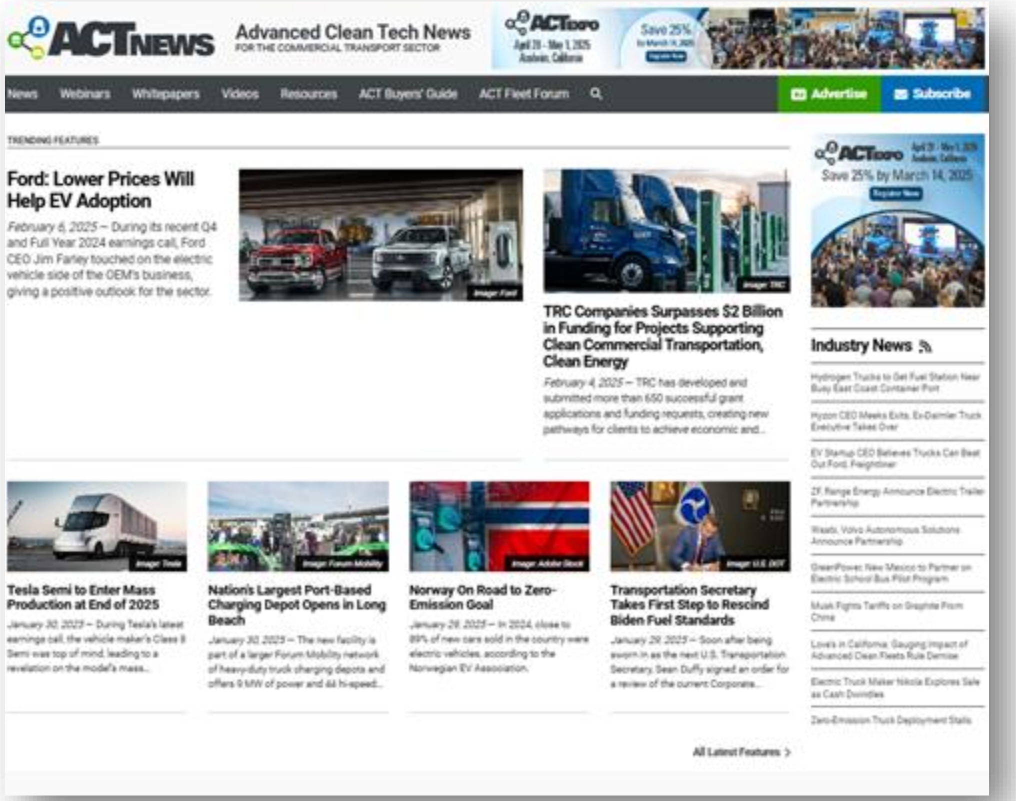

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2023 Bootcamp is still available at: https://runonless.com/electric-depot/

Update from the Run...

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Quiz for Today's Session

Completing Today's Quiz:

- Go to runonless.com and click back into the session
- Click 'Take Quiz' button
- Create username and password to keep track of your progress
- Provide your name and email to enter a drawing for a Run on Less - Messy Middle swag bag

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What You Should Know

Q&A

Submit your questions to the host using the Q&A box in the upper right-hand corner

Recording

A recording of today's webinar will be available on runonless.com

Technical Issues

Contact Stephane Babcock at **sbabcock@trccompanies.com**

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Today's Bootcamp Speakers

Moving Hydrogen from Here to There: The Distribution and Storage of Hydrogen Fuel

Des Carlisle
Executive Director
Southeast Hydrogen Energy Alliance (SHEA)

Eugene Reyes
Hydrogen Commercial Mobility Lead, Renewables & Energy Solutions
Shell

Charles Sanders
Vice President of Business Development
Air Liquide

Paul Sandsted
Director of Technology and Sustainability
The Transport Project

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SHEA

Southeast Hydrogen Energy Alliance

How do we get hydrogen from here to there

SHEA’s Pursuits

Drive Innovation & Collaboration

Focus Areas:

- Connect members to opportunities by providing key connections and resources
- Create an environment conducive to startups of mature and nascent technologies
- Maximize hydrogen innovation through local, state, and federal investment dollars
- Highlight hydrogen businesses/ uses in a focused campaign for other businesses to join the region
- Make collaboration the way of business, not the exception, resulting in expansive commerce
- Creating an organization that is a tool for companies rather than an obligation to join

Increase Education & Awareness

Focus Areas:

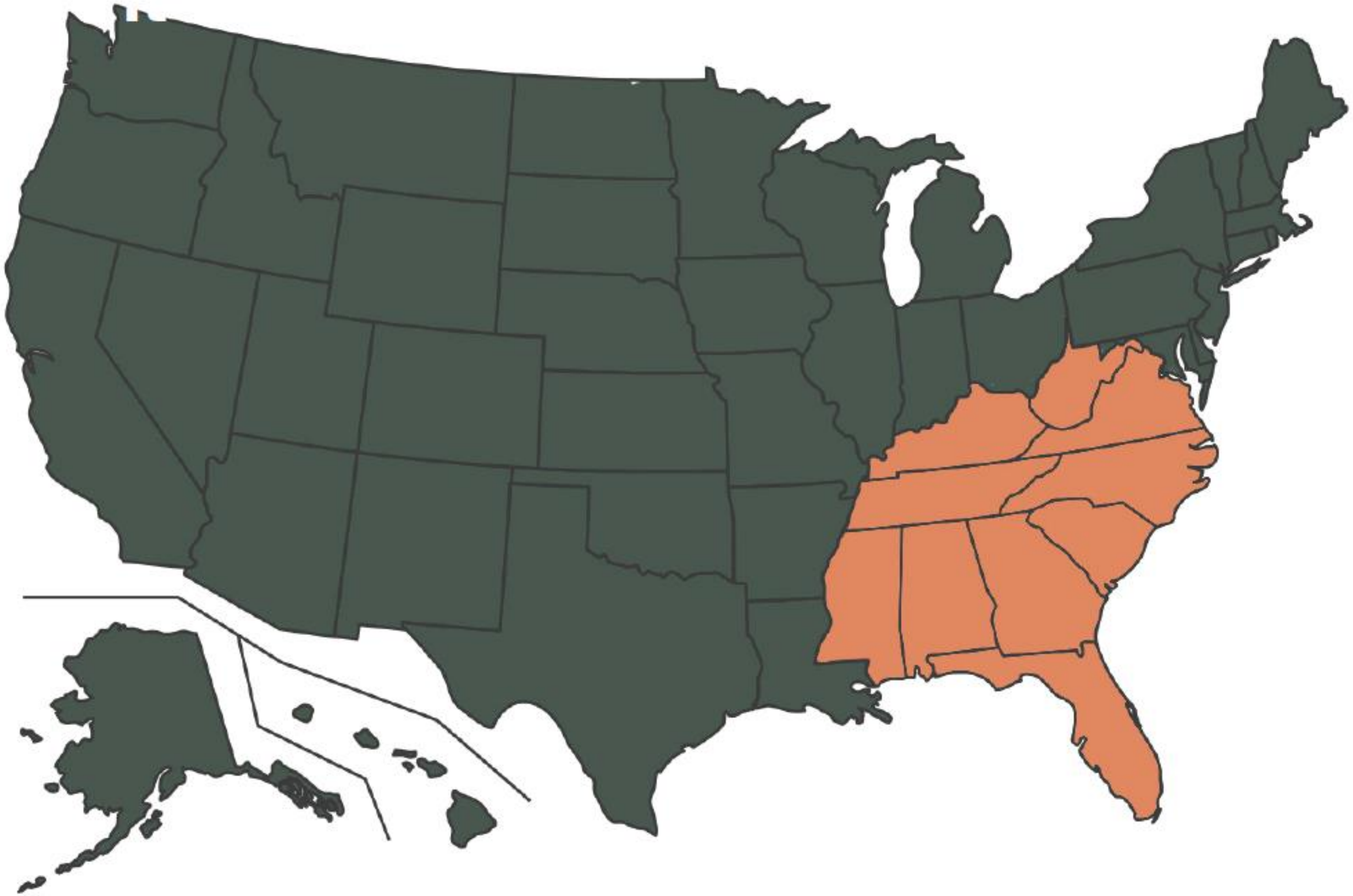
- Provide credible, trustworthy and transparent education on the hydrogen industry
- Train workforces of all sizes and backgrounds
- Partner with academia at each level of the education spectrum to create curriculum and opportunities to grow Hydrogen education
- Create partnerships with national labs
- Develop recognizable branding and marketing efforts
- Host, contribute, and attend educational webinars
- Launch educational and promotional campaigns to target specific areas and raise awareness

Enable Change & Adoption

Focus Areas:

- Partner with local and state governments to mobilize opportunities
- Establish connections with the Federal government where appropriate, including linkage to incentives and permitting opportunities
- Streamline hydrogen agenda across all 10 states and local municipalities
- Engagement directly with staff & membership
- Foster coordination across each state’s key organizations, such as the Clean City Coalitions and the State Energy Offices
- Inform and uplift the Southeast communities about their key role in hydrogen development

SHEA's Geographical Footprint



Headquartered in Nashville, TN

Hydrogen

Stored ● Delivered ● Case Study

Hydrogen Storage

Geological Storage

Hydrogen can be stored as a gas underground in empty salt caverns, depleted aquifers, or retired oil and gas fields. In fact, there's a long precedent of storing gasses underground like this. It's an ideal option for storing hydrogen for long periods of time. It's one of the cheapest and largest scale options today, but it's not available everywhere.

Compressed Gas

Like any gas, hydrogen can be compressed and stored in tanks. But hydrogen requires very high pressure tanks that hold a limited quantity of energy. Whether we're talking about above ground tanks or tube trailers, compressed gas is one of the most expensive and least energy dense options we have today, but it's also one of the simplest.

Liquid & Cryogenic Storage

Hydrogen is much more energy dense as a liquid, offering greater efficiency for storage and transport. However, achieving this state requires cooling it to near absolute zero, necessitating significant energy input and the use of sophisticated, highly insulated tanks to maintain its low temperature and ensure safety.

Material Storage

Hydrogen is stored in materials like metal hydrides, which absorb and release hydrogen through chemical reactions. This method allows for compact, safe storage, ideal for high-density energy needs, and releases hydrogen on demand, typically by applying heat.

Hydrogen Delivery

Pipelines

There are approximately 1,600 miles of hydrogen pipelines across the U.S. Hydrogen can be blended into existing natural gas pipelines with modifications.

Over the road cryogenic liquid tanker trucks

These specialized vehicles are designed to transport liquefied gases at extremely low temperatures.

Over the road tube trailers

These mobile transportation units are equipped with high-pressure cylinders carrying compressed gases.

Real World Application Deployments

Class 8 Fuel Cell Trucks

Class 8 fuel cell trucks are at the forefront of transforming the heavy-duty transport industry by using hydrogen to power long-haul operations with zero emissions. Companies like Nikola Motor and Hyundai are leading manufacturers in this space, developing advanced fuel cell technologies to increase the range and efficiency of these heavy trucks.

Fuel Cell Transit Buses

Fuel cell electric buses have been in operation across the United States for over a decade, demonstrating the viability and durability of hydrogen-powered public transportation. Currently, there are hundreds of these buses deployed in various cities, providing daily service and showcasing the longstanding commitment to hydrogen fuel technology in transit systems.

Fuel cell technology is revolutionizing the material handling industry by powering forklifts, offering increased efficiency and zero emissions in warehouses and distribution centers. Companies such as Plug Power and Toyota Material Handling are leading the way in manufacturing fuel cell forklifts, enhancing operational productivity with faster refueling and longer run times compared to traditional battery-powered forklifts.

Light Duty Fuel Cell Electric Vehicle (FCEV)

Light-duty fuel cell trucks are being developed to offer sustainable transportation solutions with zero tailpipe emissions for lighter commercial activities. Manufacturers like Toyota and Hyundai are at the forefront, producing vehicles like the Toyota Mirai and Hyundai Nexo, which combine the efficiency and quick refueling capabilities of hydrogen with the versatility needed for light-duty tasks.

Additional Applications: Hydrogen 101 - SHEA (seh2.energy)

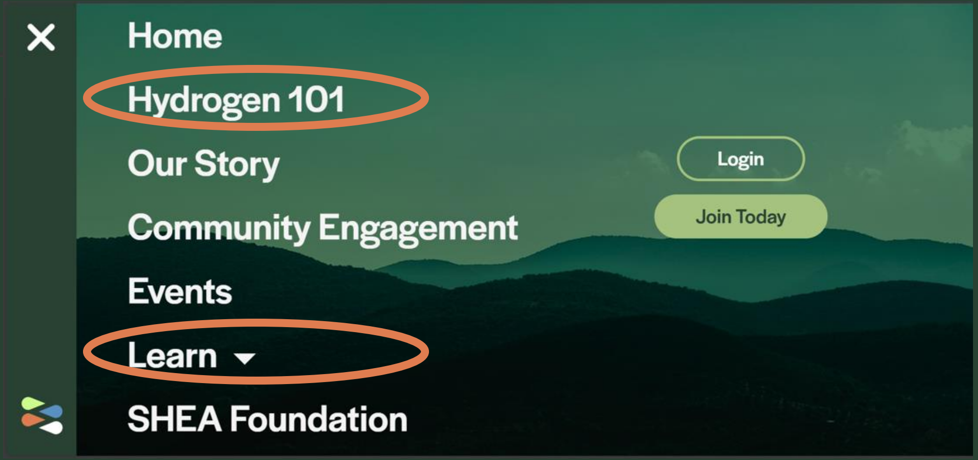
Tools to Learn & Grow

Tools to Learn & Grow

www.seh2.energy

Hydrogen 101 – learning tools and printable PDFs

Learn – Resources & News: updated weekly



SHEA

Southeast Hydrogen Energy Alliance

Find out more:
www.seh2.energy
learnmore@seh2.energy

Hydrogen Fuel Distribution and Storage

NACFE Hydrogen Bootcamp

Paul Sandsted

Director of Technology and Sustainability

THE TRANSPORT PROJECT

17JUN2025

Discussion Topics

- Hydrogen Delivery Pathways
- CH2 vs LH2
- Mobile Transport Trailers
- Hydrogen Filling Considerations and Storage

- As The Transport Project becomes increasingly focused on hydrogen fueled powertrain solutions to decarbonize the heavy-duty transportation sector, storage and transportation aspects of hydrogen as a fuel are a critical factor. Whether hydrogen will be delivered to end use applications via pipeline or tube trailer, it is important for producers, transporters, and equipment engineers to understand the technical distinctions that exist between gaseous compressed hydrogen and liquefied hydrogen.

Hydrogen Production Pathways and Storage Solutions

Challenges and Opportunities for Gaseous and Liquefied Hydrogen to Fuel Commercial Trucks

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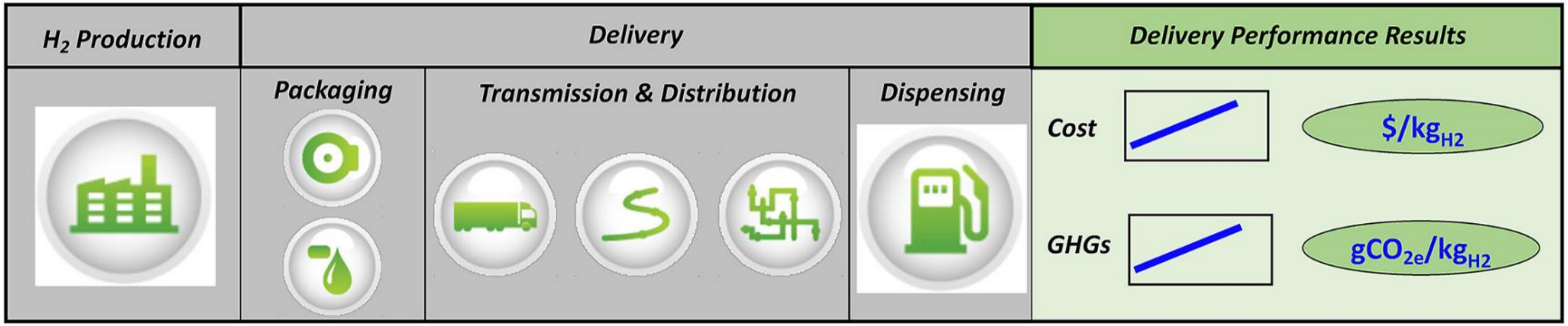
Hydrogen fueling challenges to overcome

Inefficient power consumption	Compressed H2 systems are inherently power inefficient due to the total compression horsepower and chilling required for vehicle fueling
Lower reliability	Diaphragm compressors offer low MTBF in medium pressure applications leading to unknown times between failure
Frequent maintenance intervals	Conventional liquid pump cold ends require service in as little as 500 operational hours or 100 pump starts requiring cool down
Longer fill times	Fill times are driven by the size of the precool equipment. Precool equipment doesn't scale well with flow rate versus cost
Limits on successive fills	Both external liquid pumps and compressors require ground storage of pressurized gas which greatly decreases the number of fills available
High complexity and expense	Traditional hydrogen fueling systems consist of a myriad of components leading to a complicated system with many high-cost components

Analysis of Production and Delivery Options



Source: Edward D. Frank, Amgad Elgowainy, Krishna Reddi, Adarsh Bafana
Life-cycle analysis of greenhouse gas emissions from hydrogen delivery: A cost-guided analysis
International Journal of Hydrogen Energy; Volume 46, Issue 43; 2021

LH_2 Carbon Intensity

COMPARISONS FROM THE VARIOUS PRODUCTION PATHWAYS AND HOW THEY COMPARE WITH GH2

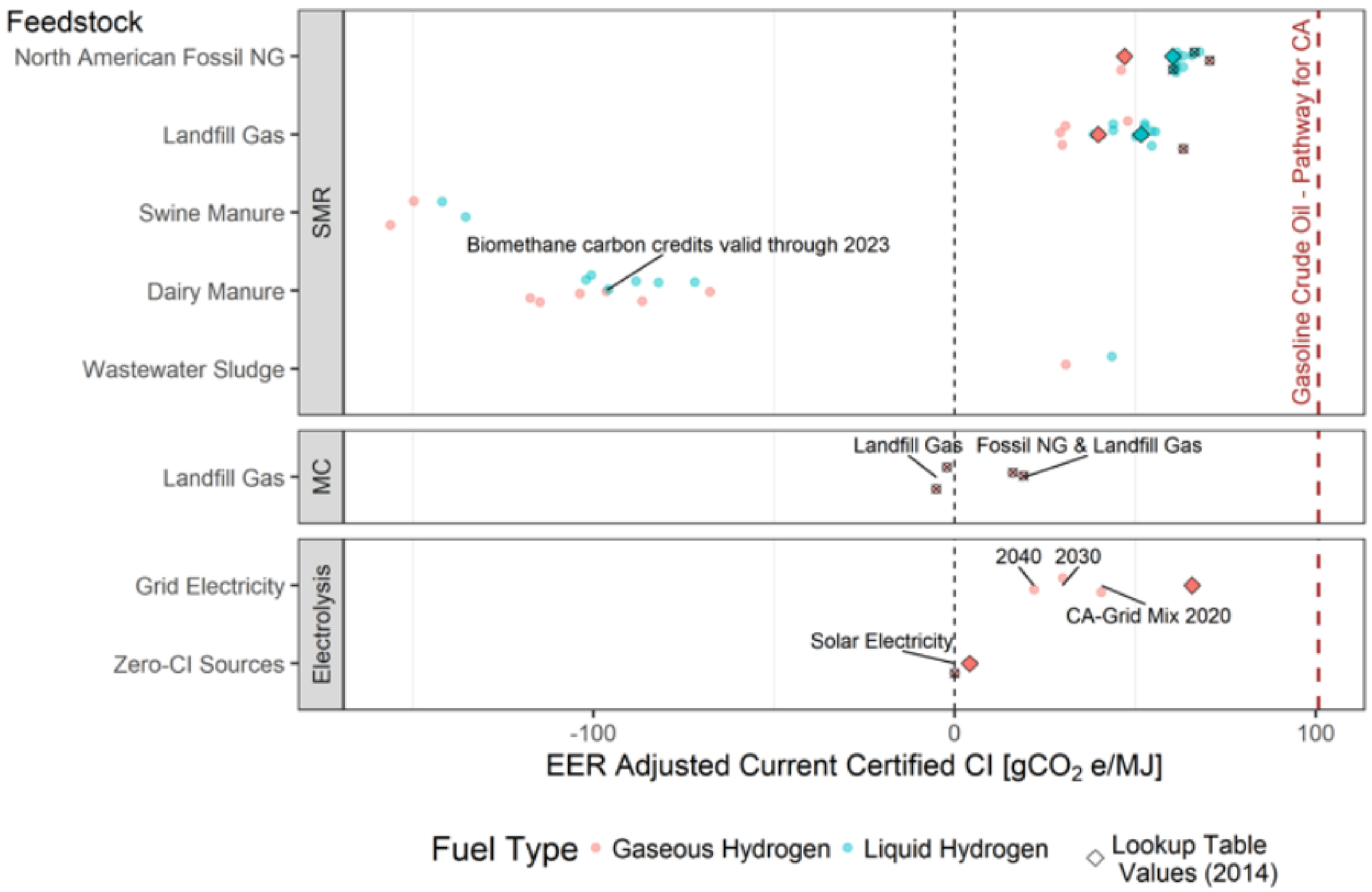


Figure 3: CI Scores of Main Hydrogen Production Pathways as Used in Transportation Applications. Source: Compiled by UC ITS from California Air Resources Board June 2022 data. Notes: MC is methane cracking; NG is natural gas. Carbon intensity values are from: ww2.arb.ca.gov/es/resources/documents/lcfs-pathway-certified-carbon-intensities.

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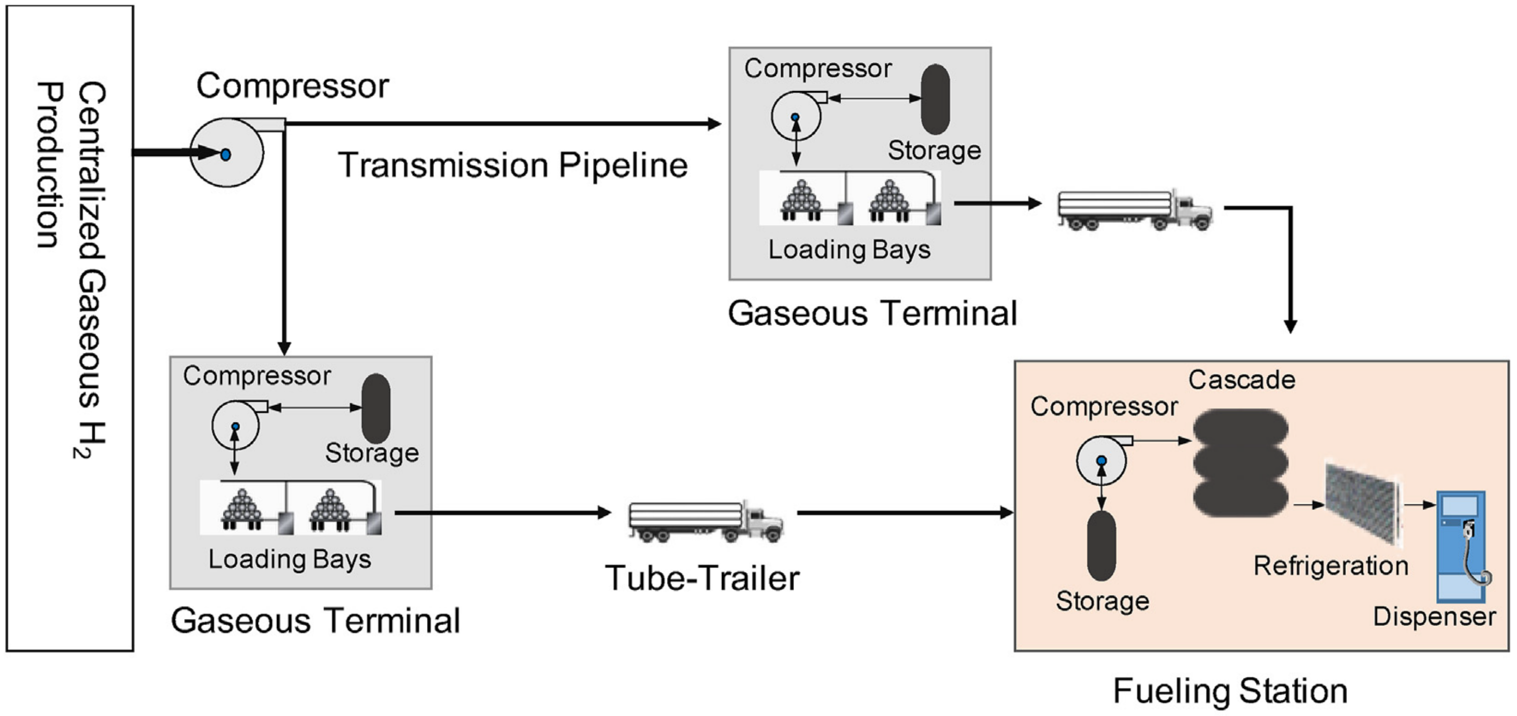
Typical CH_2 Distribution System



Source: Edward D. Frank, Amgad Elgowainy, Krishna Reddi, Adarsh Bafana
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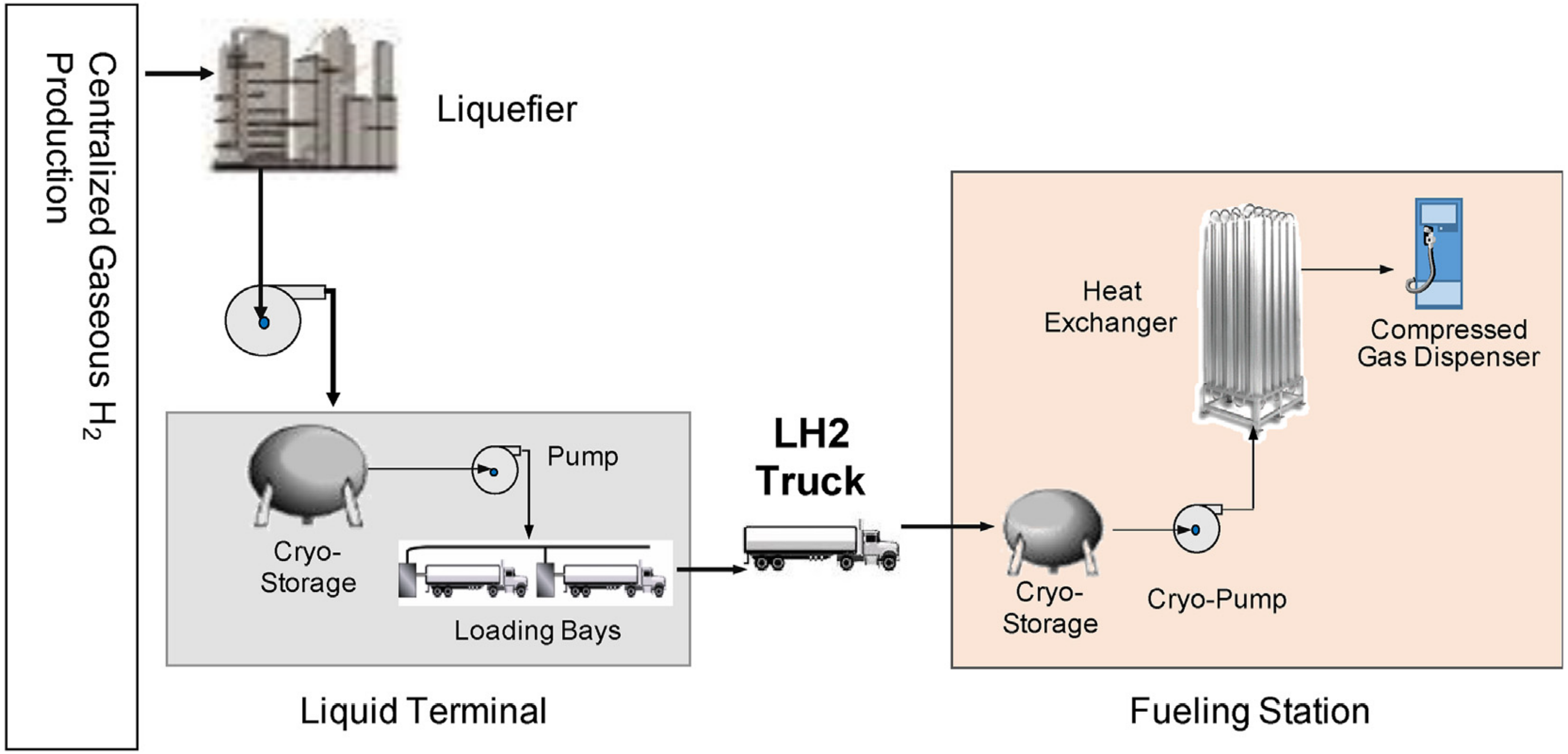
Typical LH_2 Distribution System



Source: Edward D. Frank, Amgad Elgowainy, Krishna Reddi, Adarsh Bafana
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Gaseous Hydrogen Storage

- ☐ Energy density
- ☐ Fuel cost
- ☑ Fuel availability
- ☐ Onboard vehicle storage
- ☑ Long-term storage
- ☑ Carbon intensity

10000 PSI GHG

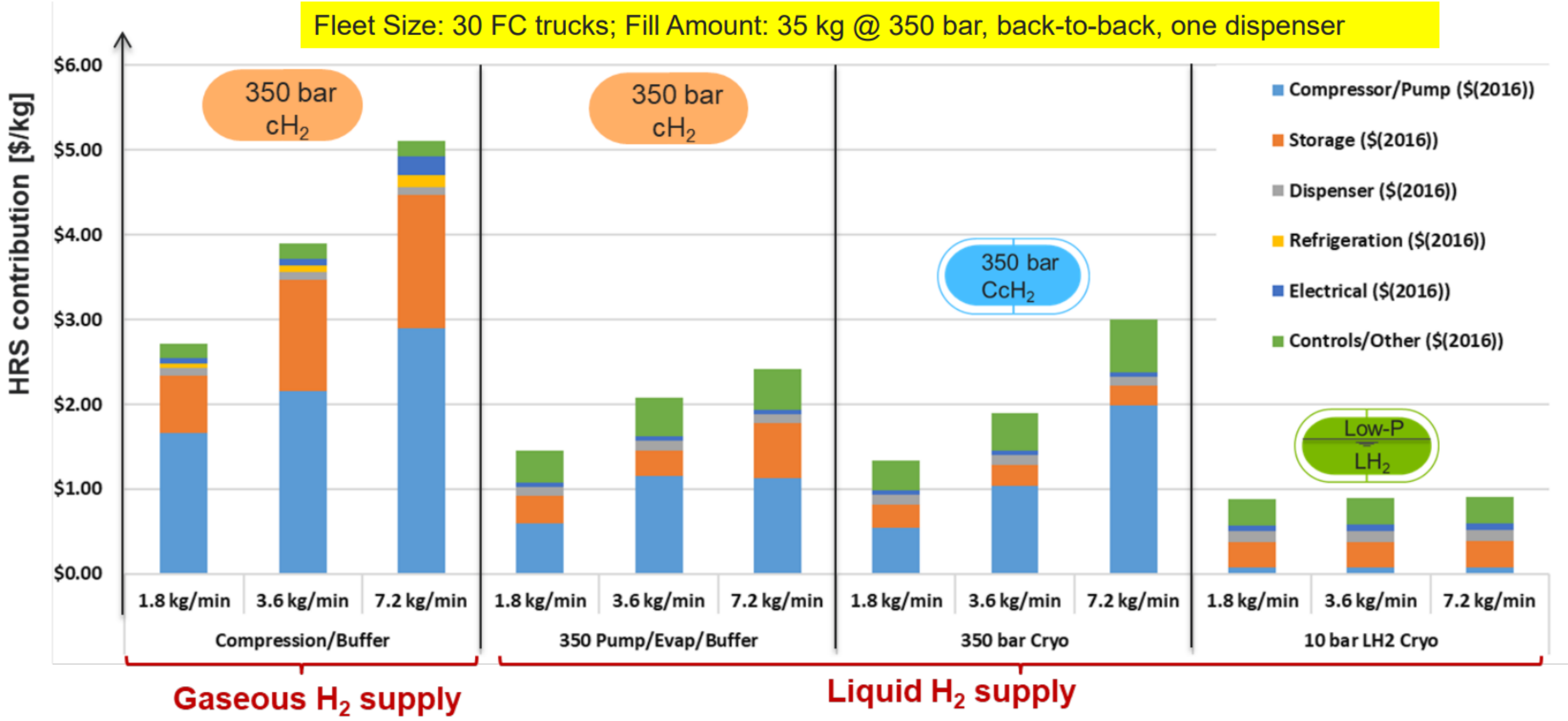
Liquefied Hydrogen Storage

- ☑ Energy density
- ☑ Fuel cost
- ☐ Fuel availability
- ☑ Onboard vehicle storage
- ☐ Long-term storage
- ☐ Carbon intensity

LH_2

Cost Comparison

Liquid H_2 supplied stations can handle faster fills with lower cost compared to gaseous H_2 supply



➢ Compression and pumping are key cost drivers

Compressed Hydrogen Transport Trailers

Bulk Transportation Perspectives on Trailer Design, Operation, and Filling

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CH2 Transport Trailers Available Today in Various Sizes and Volume Capacities

Liquid Hydrogen Transport Trailers

Bulk Transportation Perspectives on Trailer Design, Operation, and Filling

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Why Liquid Hydrogen?

Volumetric Energy Density at atmospheric pressure

- Liquid Hydrogen
  - Much higher energy density (8,500 MJ/m³) compared to gaseous hydrogen
- Gaseous Hydrogen
  - Lower energy density (10-11 MJ/m³) but can be increased significantly by compression (up to 5,300 MJ/m³ at 700 bar)

LH_2 IS 800+ TIMES THE ENERGY DENSITY OF ATMOSPHERIC H_2!

Implications for Storage and Transport

- Liquid Hydrogen
  - More efficient for storage and transport due to higher volumetric energy density
  - Requires cryogenic temperatures (-253°C) and specialized containers
- Gaseous Hydrogen
  - Requires substantial compression to achieve higher volumetric energy density, making storage and transport less efficient at atmospheric pressure

Liquid Hydrogen

70+ GRAMS PER LITER
0.26 KG PER GALLON

LIQUID IS 4+ TIMES THE DENSITY!

Gaseous Hydrogen

12-20 GRAMS PER LITER
0.06 KG PER GALLON

Fill Considerations

Purging and Cooling	• The filling hose and trailer must be purged and cooled before filling to prevent damage, prevent contamination, and ensure the integrity of the hydrogen.
Temperature and Pressure Control	• Liquid hydrogen must be maintained at extremely low temperatures (around -253°C) and appropriate pressures during filling to prevent evaporation and ensure safe handling.
Flow Rate and Filling Time	• The flow rate and filling time must be carefully controlled to prevent over-pressurization, manage heat, and ensure efficient filling.
Safety Protocols	• Strict safety protocols must be followed, including the use of protective equipment and adherence to emergency procedures.
Monitoring	• Monitoring systems are used to track temperature, pressure, and flow rate during the filling process.
Environmental Considerations	• Measures must be taken to minimize environmental impact, such as preventing hydrogen leaks and managing boil-off gas.

Mode of Supply	LH2	CH2
Time to Fill*	4 – 6 Hours	~4 Hours
Capacity*	>3,000 kg	~300 kg
Pressure	110 – 150 psi	2,400 psi
Off-Load Time*	1 – 2 Hours	30 – 45 Mins

** Size dependent*

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Appendix

Supplemental Information

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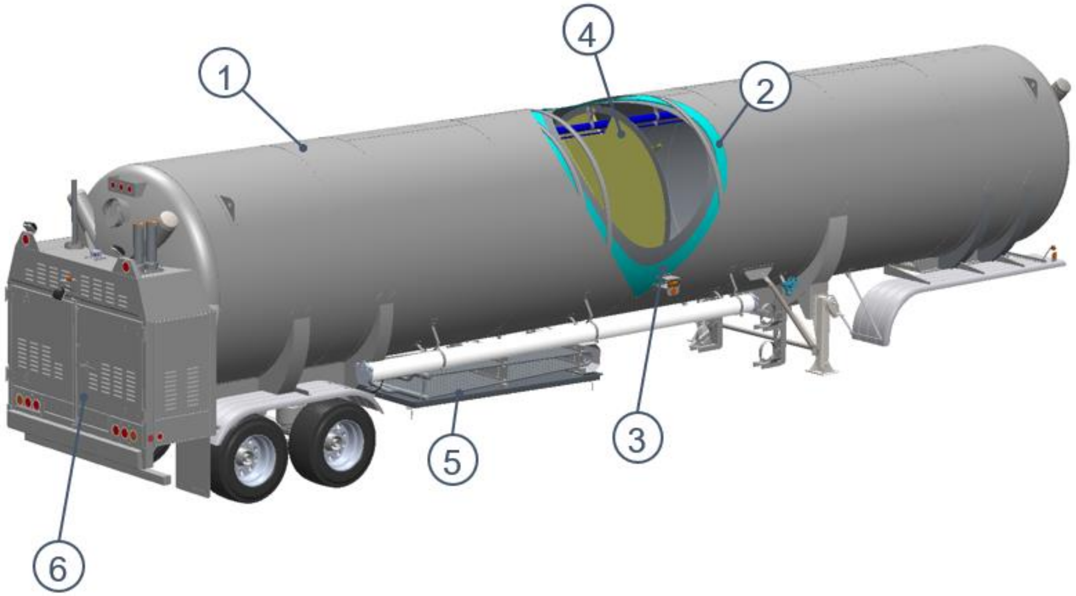
Widespread demand for hydrogen energy

Transit	Refueling of bus fleets – up to 70 kg in 10 minutes at 350 bar
Trucking	Regional and long-haul trucks – 100 kg in 15 minutes at 700 bar
Light rail	Refueling multiple times per day – 70 kg at 350 bar in 10 minutes
Locomotive	Fuel tender recharging – 1,000 kg at 700 bar
Marine	Bunkering of ferries and tow boats – 500 kg at 700 bar
Aerospace	Technology demonstration projects across classes of equipment
Pipeline	Blending into natural gas supplies typically lower pressure but much higher volumes with continuous demand
Industrial	Process-specific supply at required pressure and volume for each application

The HPES liquid hydrogen pumping system will be targeted at high performance applications hydrogen supply, i.e., requiring medium pressure, up to 900 bar, and medium flow, up to 10 kg per minute

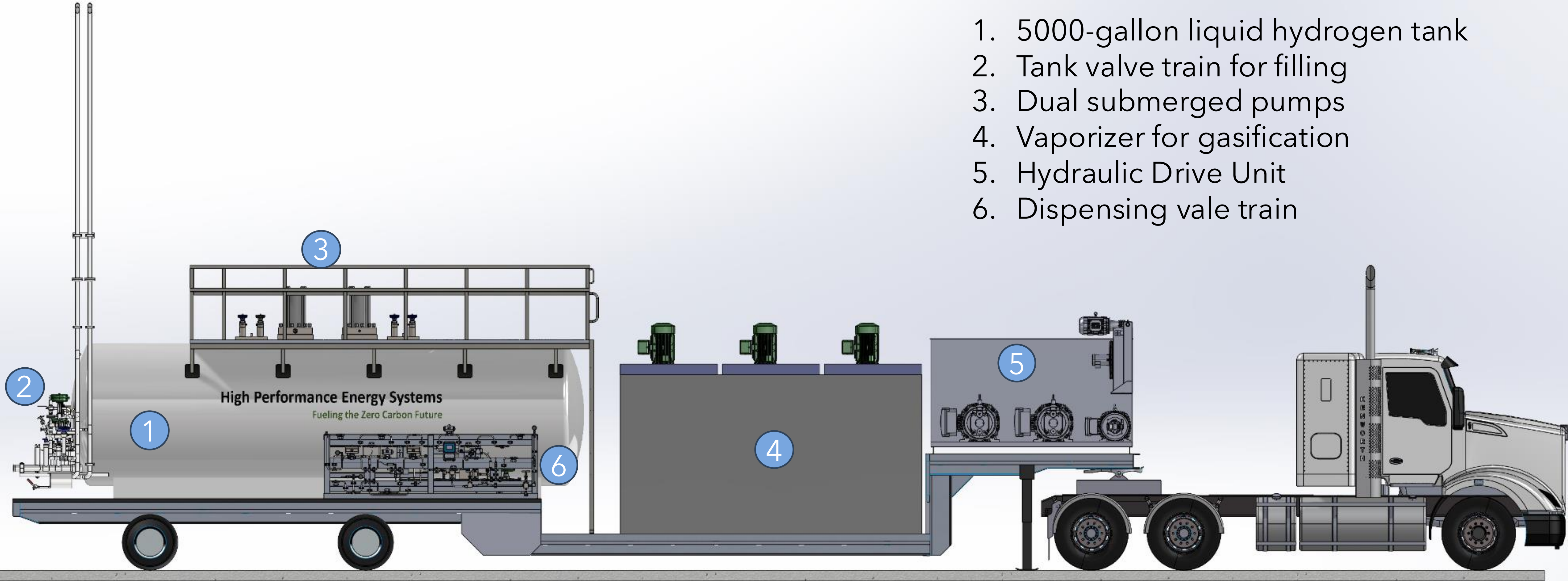
LH2 Tank Trailer Design Considerations

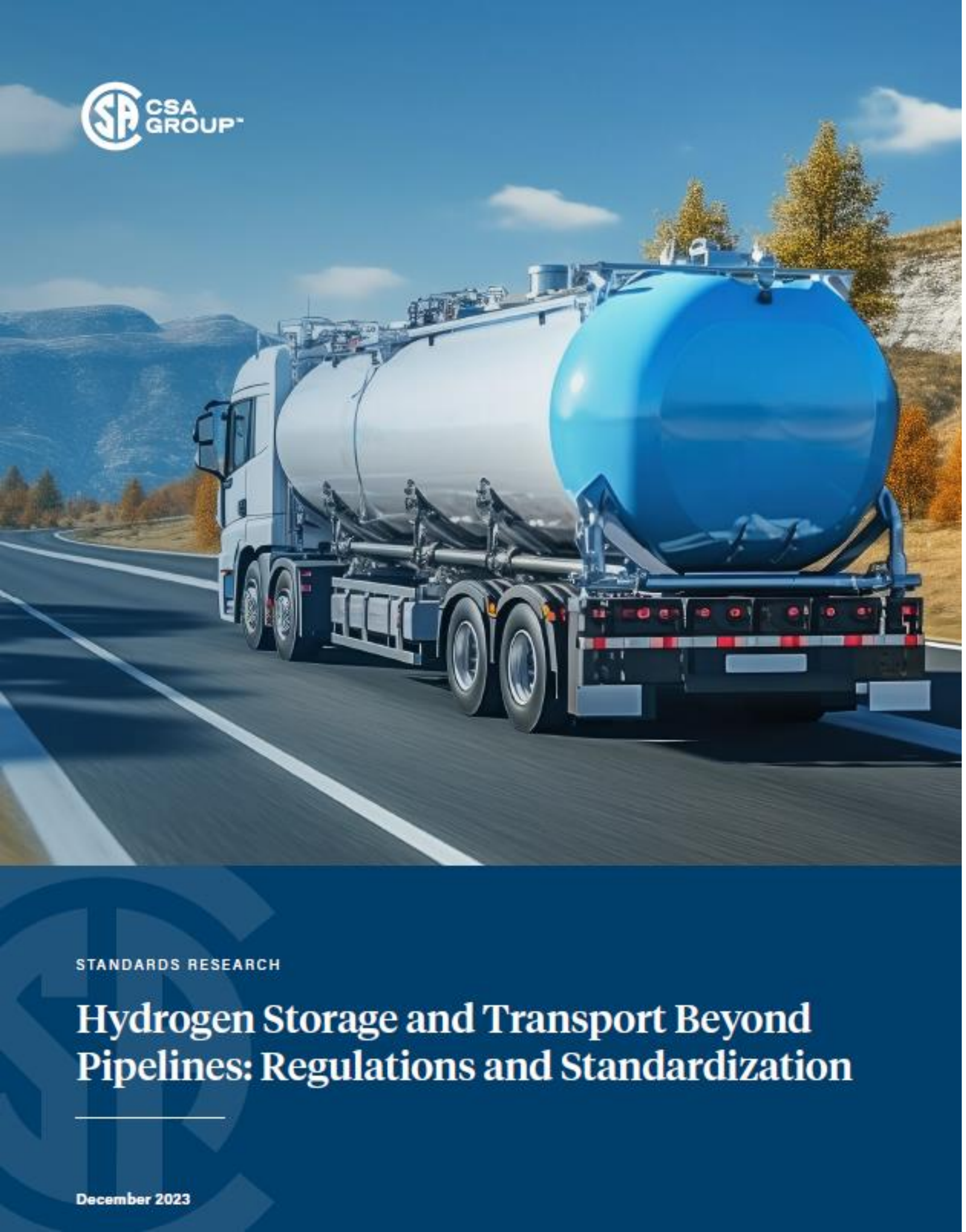
1. Outer Jacket
   - Stainless and Carbon Steel
   - Designed for external pressure
   - Vacuum between vessels removes air and reduces heat transfer by **convection**
2. MLI Insulation
   - Reduces the transmission of heat by **radiation**
3. Inner Vessel
   - Stainless Steel
4. Inner Support
   - Invisibly suspends inner vessel shielding it from heat by **conduction**, and ensures safe storage with engineering wizardry
5. Baffles
   - Reduce surge from waves of liquid when vehicle slows down
6. Pressure Building Coil
   - Located in front of the rear tires and is used to convert liquid to gas to build pressure inside inner vessel so that the liquid can be pushed out to fill customer tanks
7. Plumbing Cabinet
   - Protected by frame rails and bumper



Product in development

1. 5000-gallon liquid hydrogen tank
2. Tank valve train for filling
3. Dual submerged pumps
4. Vaporizer for gasification
5. Hydraulic Drive Unit
6. Dispensing vale train



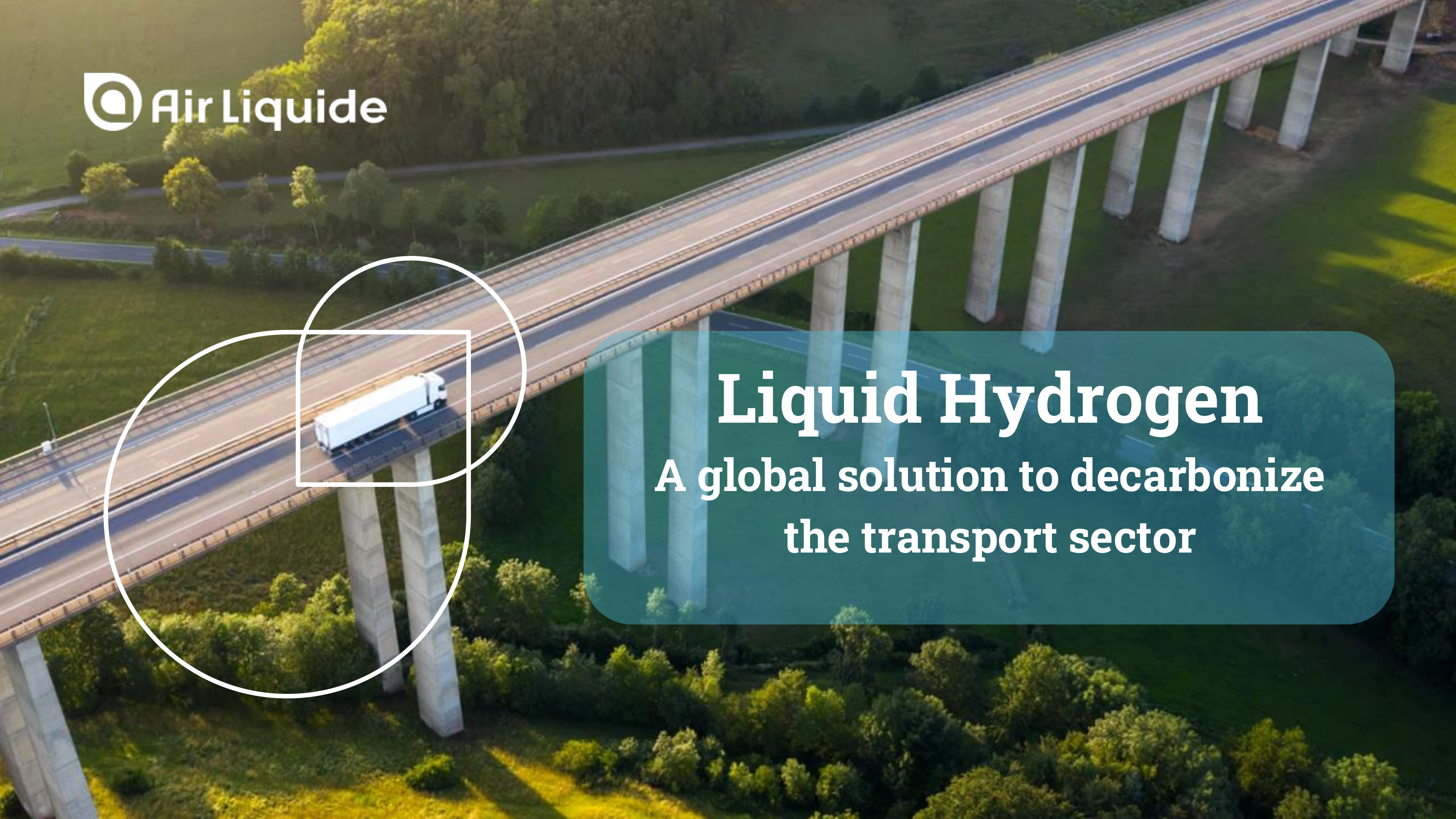


- Canadian Federal, Provincial, and Territorial Regulations for hydrogen transportation and storage.
- US Federal and State Regulations for hydrogen transportation and storage.
- Harmonization Between Regulations to ensure consistency across different jurisdictions.
- Hydrogen Codes and Standards for Transport and Storage of hydrogen by road, maritime, and rail.
- Regulation/standardization Gaps, Challenges, and Recommendations
- Full report available for download at https://www.csagroup.org/article/research/hydrogen-storage-and-transport-beyond-pipelines-regulations-and-standardization/

Safety Training

AVAILABLE FROM THE CENTER FOR HYDROGEN SAFETY

- Safety Considerations for Liquid Hydrogen Systems
  - https://www.aiche.org/ili/academy/courses/ela206/safety-considerations-liquid-hydrogen-systems



Liquid Hydrogen

A global solution to decarbonize the transport sector

Air Liquide's long track record with hydrogen

60+
years of expertise

1.2 Mt
annual production

€2.2 bn
annual sales

~1,000
employees in hydrogen

~2,000
km of pipelines

240+
stations delivered

Air Liquide Hydrogen Energy & Mobility

Fuel Production & Distribution

Dedicated Hydrogen Mobility Team

Air Liquide works transparently and collaboratively with mobility customers and stakeholders open to working outside of traditional industrial gas models

Solution Oriented

With our capacity to innovate, we invest in solving problems & optimizing costs within the hydrogen industry

Strong Partners & Network

Active in the DOE Hydrogen Hubs, strong relationships with retail partners and OEM's to develop the market

Hydrogen Expertise & Safety

With over 60 years of experience in hydrogen, Air Liquide is an expert in hydrogen production, liquefaction, distribution, storage, and refueling stations

Reliable Supplier

Delivering liquid hydrogen with a 98+% reliability supporting the California mobility market safely

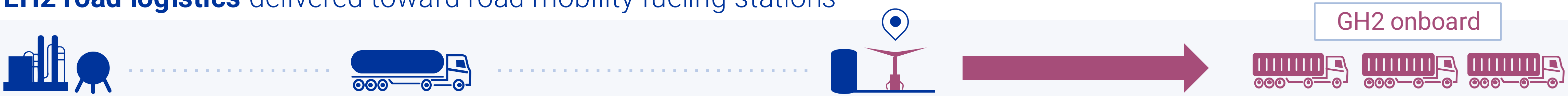
Low Carbon Solutions

We offer a comprehensive portfolio of low-carbon technologies and service solutions to support customers' decarbonization efforts

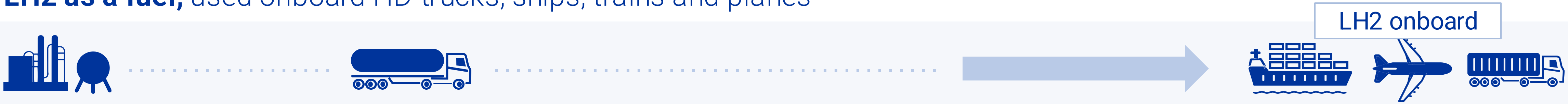
3 key uses for liquid hydrogen (LH2) in mobility

DOMESTIC usage

1 **LH2 road logistics** delivered toward road mobility fueling stations



2 **LH2 as a fuel,** used onboard HD trucks, ships, trains and planes



INTERNATIONAL supply chain (for EU & ASIA)

3 **LH2 export,** for use in power generation or onboard vehicles

Air Liquide

LH2 unique benefits: enhancing the potential of hydrogen!

HIGHER ENERGY DENSITY & HIGHER PERFORMANCE

vs battery-electric & vs GH_2

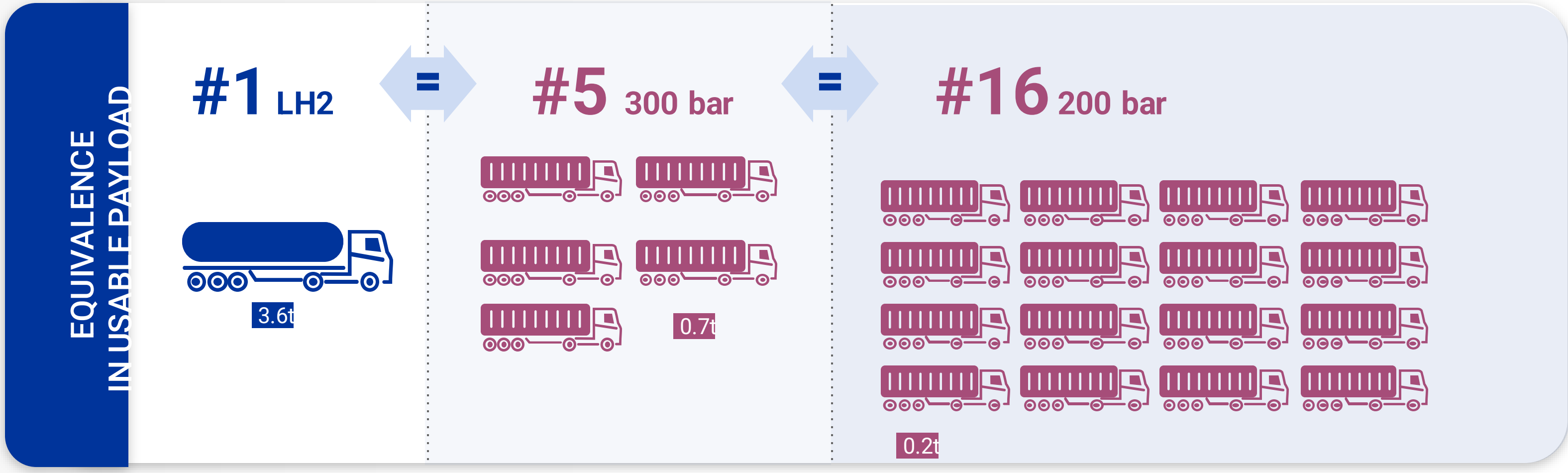
MOST COMPETITIVE TCO

for distances greater than ~200 miles

OPERATING RELIABLY AT SCALE TODAY

Road logistics: more viable at scale vs GH_2

Minimum storage & transport costs



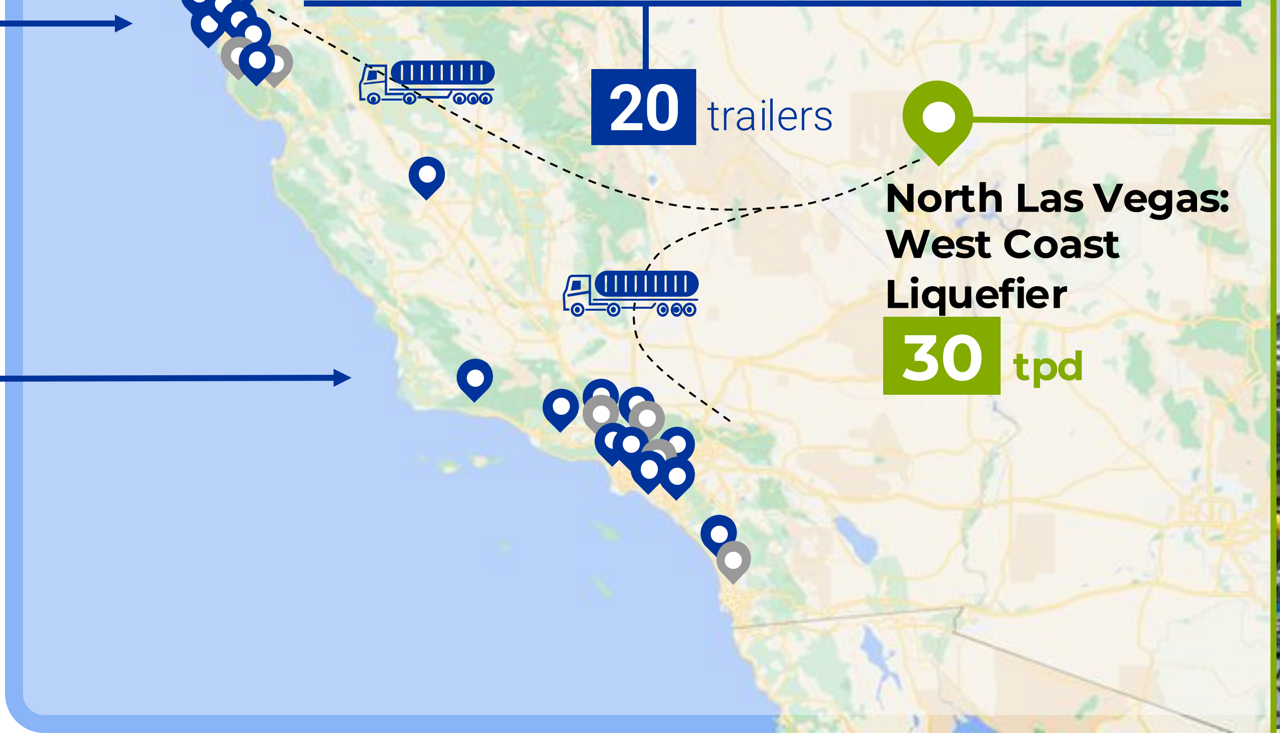
Air Liquide

Cryogenic storage of LH2 => a safe, mature, robust technology

vertical storage tanks

West Coast: a platform to optimize the LH2 supply chain

40 Liquid to Gas stations



20 trailers

North Las Vegas: West Coast Liquefier

30 tpd

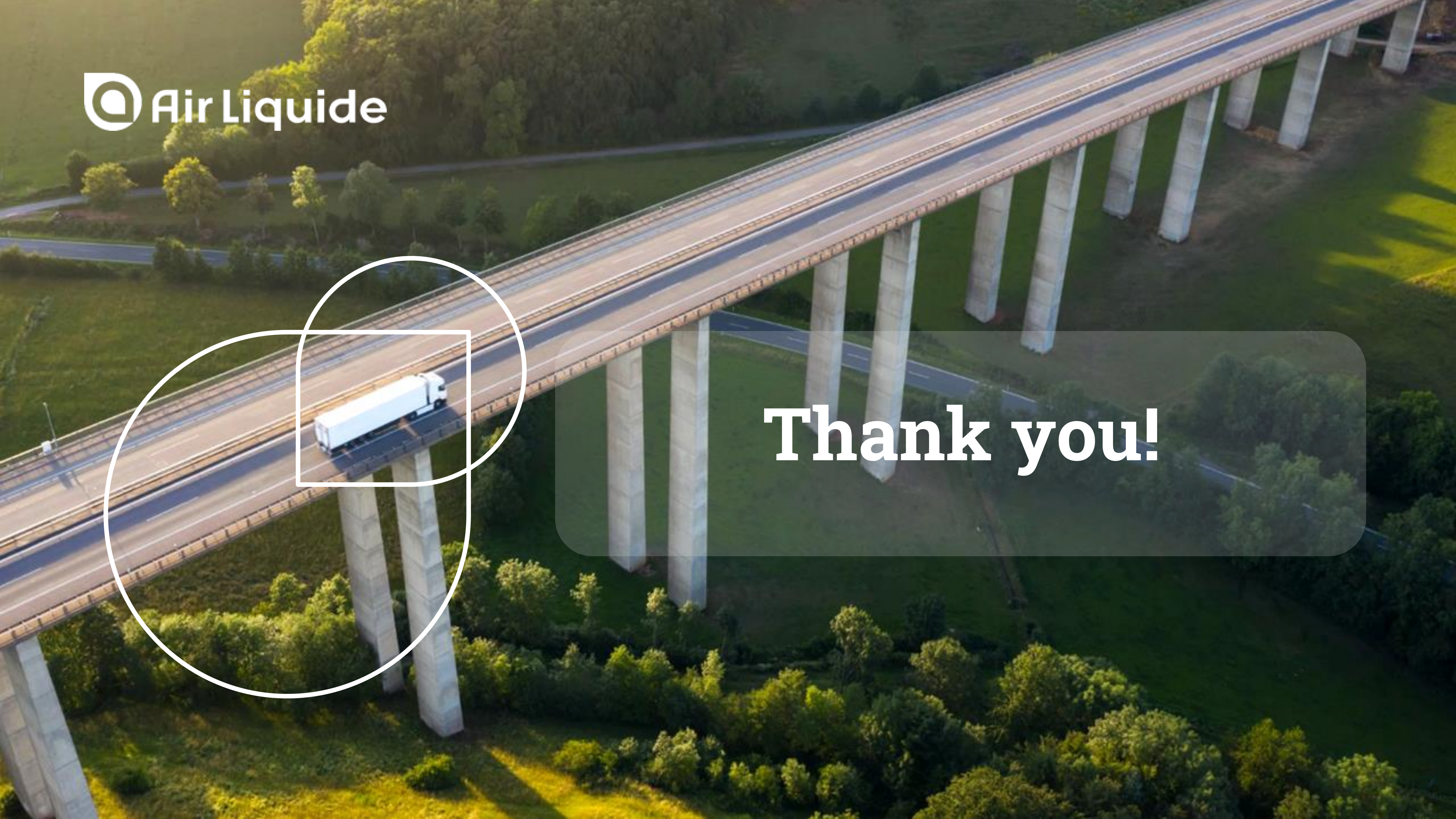
Air Liquide

Did you know there are losses in the liquid hydrogen supply chain?

Air Liquide's hydrogen expertise can help you understand and mitigate them

Currently, a significant amount of product loaded on trailers from the plant is **lost** during **distribution and dispensing**

Why?	***Resulting in …***	***The solution?***
Ambient heat is introduced via exchanger in order to build pressure in the trailer so it can be transferred to the customer's tank	*A higher* **Dispensed Unit Cost**	*Air Liquide's patented* **Advanced Delivery System (ADS)**
When heat is introduced, some of the cryogenic liquid hydrogen boils, turning into a gas		
Gaseous hydrogen is then vented from both the customer's tank and the trailer		



Thank you!

Shell Hydrogen – North America

Eugene Reyes
Hydrogen Commercial Mobility Lead, Low Carbon Solutions
Shell

Hydrogen has 2 key roles, and 3 key challenges

Decarbonise hard-to-abate end-uses

Decarbonising grey H2 **feedstock** in refineries, chemical industries & fertilisers

Decarbonising **industry** energy use replacing coal and other fossil fuels

Decarbonising **building** heat and power leveraging existing gas infrastructure

Decarbonising **transportation** leveraging higher energy density uses

Enables renewable-based energy system

Enabling renewables-based energy system, by acting as a **buffer or storage** to overcome supply demand mis-match and increase resilience

Allows renewable energy to be **transported** from renewables long regions to renewables short demand centers

Global Proof points

Develop key **applications** of hydrogen – HD mobility, marine, steel

Develop hydrogen **infrastructure** to connect supply with customers

Make hydrogen **competitive** by scaling-up, technology and initial support

Shell Hydrogen – History of Refueling Stations

SHELL HYDROGEN STATIONS IN CALIFORNIA

Santa Monica Boulevard | Torrance | Newport Beach

	Santa Monica	Torrance	Newport Beach
Start up	2008	2010	2012
Supply	Alcaline electrolysis	H2 Pipeline	On site reforming
Delivery pressure	350 bar	350 / 700 bar	350 /700 bar

SHELL HYDROGEN STATIONS

California Hydrogen Refueling Station Archetypes

- ❑ California Light Duty Stations: 2008-2023
  - Northern and Southern California
  - Different Station Supply Archetypes
    - On-site Supply SMR
    - Pipeline
    - Delivered Midstream GH2
- ❑ California Heavy Duty Stations: 2020-Present
  - Southern California – Ports/Inland Empire

Distribution – Midstream Gaseous Delivered

- ❑ Supply On-site Storage
- ❑ Two Lanes: 2x H70 Dispensers & 1x H35 Dispenser
- ❑ Equipment Type: Diaphragm Compressors/ On-site Storage
- ❑ Supply On-site Production/Pipeline/Delivered Mid-stream
- ❑ Hydrogen Gas vs. Liquid

Shell Hydrogen – North America – California Heavy Duty

Southern California HD Hydrogen Refueling Stations: Ontario, Long Beach Wilmington and the Port of Long Beach

- ZANZEFF HD H2 Stations (2020): Class 7 - 8 FCET & FCEBs – Drayage Ops at the Ports
- Each station has a modelled capacity plate of ~1 Tonne Per Day (TPD)
- Two Lanes: 2x H70 Dispensers & 1x H35 Dispenser
- Equipment Type: Diaphragm Compressors/On-site Storage supplied via gaseous trailers

Long Beach Wilmington (2021)

Port of Long Beach (2021)

Ontario (2020)

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DIESEL NATURAL GAS BATTERY ELECTRIC HYDROGEN FUEL CELL

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