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The Feasibility of Onboard Liquid Hydrogen Class 8 Trucks in the United States

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Executive Summary

Class 8 trucks have proven difficult to transition to zero emission technology due to the rigorous duty cycles that they serve. Both battery electric and gaseous hydrogen are not able to replicate the performance that diesel can. Liquid hydrogen, however, offers a higher volumetric density than gaseous hydrogen and can help to bridge the gap between gaseous hydrogen and diesel. Fuel cell trucks can be designed to accommodate onboard liquid hydrogen storage, which is cheaper and weighs less than an equivalent gaseous hydrogen storage system. However, liquid hydrogen's cryogenic conditions introduce unique design and safety challenges that must be addressed. These trucks will also require access to a liquid hydrogen fueling network. Liquid hydrogen fueling stations are less complex and lower capital costs than a gaseous hydrogen fueling station. Liquid hydrogen fueling stations can be served by an existing centralized hydrogen liquefaction network.

Keywords: Fuel Cell Electric Vehicles, Heavy Duty Electric Vehicles & Buses, Fuel Cell Systems

1 Introduction

The state of California has enacted policies, such as the Advanced Clean Truck and Advanced Clean Fleet rules to encourage a transition to zero emission trucks. This effectively requires that fleets transition to battery electric trucks (BET) or fuel cell electric trucks (FCET) over time. While major fleets have begun to adopt zero emission technology for medium-duty trucks, such as cargo vans, adoption in the heavy-duty trucking sector has moved slower. This is especially true for the Class 8 tractor-trailer sector, which as of June 2024 has only deployed 867 zero emission vehicles [1].

There are several barriers to decarbonizing the Class 8 tractor sector. The first challenge is that Class 8 tractors serve a very rigorous duty cycle. These vehicles oftentimes carry shipping containers, which can be very heavy. Furthermore, these vehicles oftentimes have lengthy routes and might have to drive up to 500 miles per day. As a result, meeting these performance requirements with zero emission powertrains can be challenging. To meet these performance requirements, industry has proposed deploying liquid hydrogen (LH2) onboard a Class 8 truck.

Cummins Electrified Power NA Inc. (Cummins) has been involved in the development of Class 8 FCETs. Cummins received funding from the California Energy Commission, under Commission Agreement Number PIR-21-001, to carry out the Hydrogen Fuel Cell Truck project. Under this project, Cummins will develop and demonstrate two Class 8 FCETs. The vehicles are designed to operate using gaseous hydrogen. However under this project, Cummins will also investigate the feasibility of integrating onboard LH2 storage on the vehicles. Cummins contracted with CALSTART to carry out this analysis. This report investigates the vehicle and infrastructure requirements for deploying onboard LH2 storage on an FCET.

2 Zero Emission Fuels

There are two options for powering a Class 8 truck with a zero emission powertrain. The first option is to use a battery-powered drivetrain. To date, BETs have been the dominant zero emission technology. This has occurred because batteries are cheaper and more commercialized than fuel cells. However, batteries have a low volumetric density, meaning that they cannot store very much energy per unit of volume. This is problematic because it limits how much energy can be stored on a BET, which ultimately limits the vehicle's range.

Gaseous hydrogen is an alternative to battery electric technology because it has a higher volumetric density (though still very low in comparison with diesel). As a result, FCETs have a longer range and can serve more rigorous duty cycles than their battery electric counterparts. While fuel cell vehicles have a greater range than battery electric vehicles, they typically do not have the same range as an equivalent diesel-powered vehicle. As a result, industry is seeking an alternative that can achieve a better range than gaseous hydrogen.

LH2 can help to bridge the gap between diesel and gaseous hydrogen. LH2 is a cryogenic fluid that is produced through a process called liquefaction. LH2 can store significantly more energy content per unit of volume, which can increase vehicle range beyond that of gaseous hydrogen. Several companies have started experimenting with this technology. Daimler and Linde [2] have developed demonstration Class 8 FCETs with onboard LH2 storage. Hyzon Motors had also demonstrated an LH2 FCET before the dissolution of the company [3]. The maritime industry is also investigating LH2 as a fuel for commercial harbor craft [4].

Table 1: Class 8 Truck Fuel Comparison

Attribute	Diesel	Battery	Gaseous Hydrogen	Liquid Hydrogen
Range	1,000 miles	200 – 300 miles	300 – 500 miles	Estimated > 600 miles
Charging/fueling time	20 minutes	150 minutes	30 minutes	Estimated 10 – 15 minutes
Volumetric Density	High	Extremely low	Very low	Low
Infrastructure Development	Mature	Under construction	Early stages of development	No commercial option

Industry expects that LH2 Class 8 trucks can achieve a range of over 600 miles. This is important for transitioning long-haul trucking to zero-emission technology. LH2 can also facilitate faster fueling. LH2 does not have temperature changes during fueling, meaning that it does not face the same fueling rate constraints as gaseous hydrogen. Recent technology demonstrations indicate that LH2, with current technology, can be dispensed at 8 kg per minute, meaning that it could fuel an 80 kg tank in ten minutes. Given these advantages, onboard LH2 storage is being considered for vehicle segments such as Class 8 trucks.

The main drawback to LH2 is thermal management. To remain in liquid form, the hydrogen must be kept in dewars, or double-walled containers with vacuum insulation, to keep the fluid cold and to slow the rate of evaporation. Boiloff of LH2 is common and it must be consumed by the vehicle, vented to the environment, or reliquefied to prevent pressure from building in the tank. However, boiloff concerns are likely to be limited because the LH2 is expected to be consumed quickly as the vehicle is driven.

Hydrogen Properties and Safety

Most transportation fuels are combustible substances and must be handled in a safe manner to avoid fire or explosion risks. Common transportation fuels, such as natural gas and gasoline, are evaluated by properties such as flammability range (the range of fuel concentrations at which the fuel can ignite), ignition energy (the minimum energy required to cause combustion), relative vapor density, and flame speed. These properties have a major influence on how likely the fuel is to combust and how much damage can occur if combustion happens.

Gaseous hydrogen, which is the phase that a fuel cell can use hydrogen, is flammable. Gaseous hydrogen has a much wider flammability range than other fuels and can combust at concentrations (by volume) of 4% to 75%. It also has a much lower ignition energy, meaning that far less energy is required to cause gaseous hydrogen to combust [5]. This combination of properties means that hydrogen is very flammable, which introduces fire and explosive atmosphere are risks.

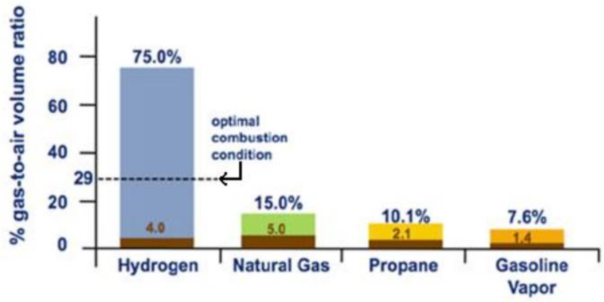


Figure 3. Flammability Range

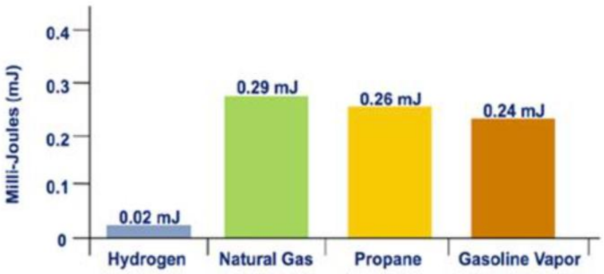


Figure 4. Minimum Ignition Energy

Figure 1: Hydrogen Flammability Range and Ignition Energy [6]

Gaseous hydrogen also introduces additional risks. First, the flame produced by a hydrogen fire is nearly invisible under daylight conditions and the heat doesn't radiate which means that it is difficult to feel the heat it emits from far away [7]. Second, hydrogen also has a higher flame speed at most concentrations. This property means that when ignited, hydrogen tends to ignite in a rapid manner. This increases the risk that an ignition event can cause an explosion. Lastly, hydrogen if it fills an enclosed area poses asphyxiation risks.

Gaseous hydrogen also has a low relative density. This means that gaseous hydrogen is much less dense than air and therefore is a very buoyant gas. This property means that if released, hydrogen will rise quickly and disperse. If released in an open area, the hydrogen will disperse quickly, and concentrations will drop below the concentrations required for ignition. However, if released in an enclosed and unventilated area, gaseous hydrogen will be trapped and concentrations can rise quickly, creating a fire risk [8].

Hydrogen can also be used in liquid form. LH2 forms when hydrogen is cooled to -253°C. At this temperature, LH2 reaches cryogenic conditions and becomes a liquid. LH2 has its own unique safety issues. Since its boiling point is at an extremely low temperature, heat ingress is a major threat. As heat moves from the ambient environment into the LH2, the material the LH2 comes in contact with will experience rapid cooling. This is problematic because these cryogenic temperatures can cause cryogenic burns if people are exposed to them. LH2 is also colder than the condensation point of atmospheric oxygen. As a result, exposure LH2 can cause oxygen droplets to form, which is a major fire risk. To prevent this, all piping and containers that carry LH2 needs vacuum-jacketing to insulate the ambient air from these temperatures.

Heat ingress also creates fire risks. LH2 cannot directly ignite or burn. However, since LH2 has such a low boiling point, it will rapidly vaporize and convert to gaseous form if exposed to the ambient environment. When in gaseous form, the risk of ignition is reintroduced. LH2 is also 858 times more dense than gaseous hydrogen and as a result, hydrogen will expand as it vaporizes. If large amounts of LH2 vaporize in an enclosed space or container, the expansion will cause pressure to increase. If pressure increases in an uncontrolled manner, the container holding LH2 can experience a catastrophic failure. The worst-case scenario is a boiling liquid expanding vapor explosion (BLEVE), where a tank ruptures and its contents ignite explosively. Measures will need to be taken to prevent this [9].

3 Onboard LH2 Integration

Onboard LH2 FCETs are currently under development. Despite LH2's promise, it is important to note that this technology is still in the demonstration phase and is not yet technologically mature. Technology development can be assessed through a metric called technology readiness level (TRL). TRL is measured on a scale of 1 to 9. A score of 1 means that there is scientific evidence for a potential innovation or technology. A score of 9 indicates that the technology is a commercialized product, meaning that it is generally available for use, has begun serial production, and has been successfully operated in an uncontrolled commercial environment [10]. At the time of writing, CALSTART assesses that this technology has a technology readiness level of between 6 (early-stage demonstration phase) and 7 (advanced technology demonstration phase).

3.1 Gaseous Hydrogen FCET Design

The gaseous hydrogen version of the FCET is built on a Class 8 Freightliner P4 Cascadia truck platform. The vehicle is built on a chassis platform that is converted to an electronic rolling chassis by installing an electric drivetrain system (which includes electric axles), fuel cell system, and hydrogen storage. The gaseous hydrogen version vehicle is fitted with 700 bar hydrogen storage tank systems to maximize the amount of hydrogen it can carry and to allow the vehicle to obtain a range of more than 300 miles. The FCET also includes an electronic power takeoff unit to provide power for offloading cryogenic gases.

There are a few key design constraints that Cummins navigated. One consideration is the location of the fuel tanks. FCETs can accommodate the tanks based on two configurations: frame rail-mounted or behind the cab. Cummins opted to place the hydrogen storage tanks behind the cab. Cummins deployed a mounting system to hold the 700 bar hydrogen storage tanks. However, if necessary, Cummins can modify the vehicle to adopt a frame rail-mounted design. Another constraint relates to aerodynamics. Cummins added a roof cap to the truck to improve the aerodynamics for the vehicle. As a result, there are height limits for all components behind the roof cap. No component, especially the hydrogen tank mounting, can be taller than the roof cap.

3.2 Onboard LH2 Integration

There are a lot of similarities between an LH2 FCET and a traditional FCET as they both contain a fuel cell and electric drivetrain. The main difference is that an LH2 FCET has cryogenic hydrogen storage tanks instead of gaseous hydrogen tanks. Since LH2 is a cryogenic gas, the tanks are insulated to prevent heat ingress. Heat ingress is problematic because it causes the LH2 to convert to gaseous hydrogen, which can result in boiloff losses. To prevent this, LH2 storage tanks consist of an inner tank, which contains the LH2, and an outer tank, which protects the inner tank. The annular space between the tanks is evacuated to prevent heat transfer via convection. The tanks have a line that runs to the fill receptacle, which allows LH2 to enter the tank when the truck is refueling. The tanks also have an outlet line, through which hydrogen can exit the tank and be sent to the fuel cell. The fill lines and the outlet lines are vacuum-jacketed to provide insulation, which prevents the liquefaction of atmospheric oxygen on the external part of the line. The LH2 tank transfers hydrogen to the fuel cell by vaporizing some of the LH2 inside of the tanks. The vaporized hydrogen, which is now in gaseous form, increases pressure inside the tanks which is used to push LH2 out of the tanks. The LH2 travels through vacuum-jacketed piping to a vaporizer where it is converted to gaseous hydrogen. It is then sent onwards to the fuel cell where it is converted to electricity to power the vehicle [11].

As with gaseous hydrogen tanks, an onboard LH2 storage system can be integrated as either frame rail-mounted or behind the cab. Under a frame frail-mounted configuration, the LH2 storage tanks are mounted on the sides of the vehicle to the chassis. This configuration usually contains two tanks – one on each side of the chassis. This configuration is commonly used in diesel Class 8 trucks. Alternatively, the onboard LH2 storage tanks can be deployed behind the cab. In this configuration, the onboard LH2 storage tanks are mounted using a racking system.

CALSTART identified the onboard LH2 tank products and investigated the feasibility of integrating them onto an FCET. Chart Industries has developed an onboard LH2 storage system, which is sold as the HLH2. This system is based on the design of their onboard liquefied natural gas storage system. The HLH2 system consists of a tank that contains 35-40 kg of LH2. Multiple tanks can be deployed on a single vehicle to increase storage capacity. The HLH2 system operates at a pressure of 3 – 8 bar. Chart Industries has deployed the HLH2 on the Hyzon Motors FCET, which recently completed a demonstration of this technology.

Chart Industries offers an LH2 storage system that consists of multiple LH2 tanks. Chart Industries can fit up to three 40 kg LH2 storage tanks onto a truck in a behind the cab configuration. Under this configuration, the LH2 storage tanks are mounted using a racking system that keeps the tanks in a horizontal arrangement. Chart Industries typically works with the truck manufacturer to co-develop the racking system. The racking system typically contains all the cryogenic components including the LH2 storage tanks, vacuum-jacketed piping, and the vaporizer. The racking system also contains a vent stack to ensure that vented hydrogen is kept away from ground level. The racking system is then connected to the vehicle. There are two main points of connection. The first point is to connect the vaporizer to the gaseous hydrogen piping on the vehicle. This point of connection is used to transfer the hydrogen to the fuel cell. The second point of connection is a coolant loop. The coolant loop from the fuel cell is used to provide heat for the vaporizer. The onboard LH2 storage tanks can also be mounted on the frame rails. The LH2 storage tanks are relatively easy to mount in this configuration. Diesel Class 8 trucks already have a standard mounting system that is used to integrate diesel tanks to the frame rails. The onboard LH2 storage tanks can use a similar system to integrate the tanks to the frame rail.

Onboard LH2 storage has ramifications for the weight of the vehicle. The onboard LH2 storage tanks weigh significantly less than the equivalent gaseous hydrogen storage. As a result, transitioning to LH2 storage can decrease the total weight of the vehicle. There are some weight tradeoffs between behind the cab and frame rail-mounted configurations. The frame rail-mounted configuration will weigh less because it can be mounted with standard components. The behind the cab configuration will require a mounting rack to be deployed, which adds to the weight. However, despite this tradeoff, both configurations are expected to result in weight reductions as compared to an equivalent gaseous hydrogen storage system. The LH2 hydrogen storage system in the behind the cab configuration is expected to weigh approximately 20-30% less than an equivalent gaseous hydrogen storage system.

3.3 Onboard LH2 Costs

The onboard LH2 storage system is still in the early stages of commercialization, meaning that it is still produced in low quantities. As a result, the current price for an onboard LH2 storage system is approximately $750 - $1,000 per kg of storage capacity. Industry expects that this cost will decrease as economies of scale are reached. The main cause of the high cost is that the components that go into the onboard LH2 storage tanks, such as valves and heat exchangers, are not typically built for this size of tank. These components are typically built for larger tanks. As a result, the supply chain for smaller tanks needs to be developed. After this supply chain is developed, industry believes that the onboard LH2 tank cost will decrease. Industry estimates that prices can fall to approximately $300 per kg of storage capacity. This price would be comparable to (but slightly higher) than a liquefied natural gas tank.

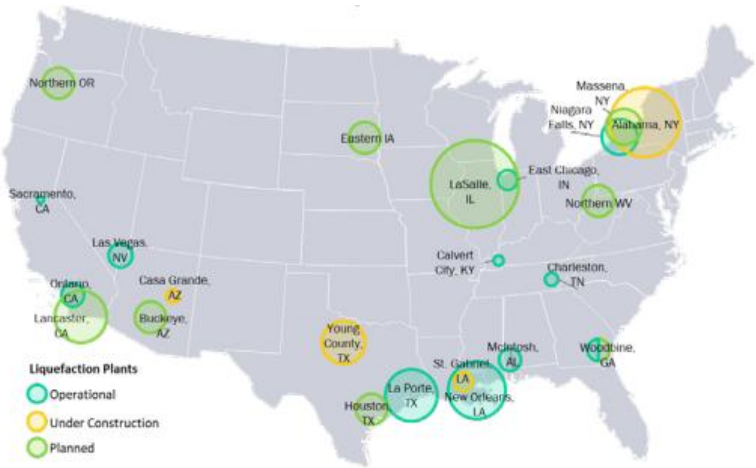
Onboard LH2 storage tanks are expected to have low maintenance costs. LH2 storage tanks are very similar to liquefied natural gas tanks, which have low maintenance needs. Since the tank uses internal pressure transfers, there are few moving parts or single points of failure. The main maintenance tasks would be to inspect and replace relief valves as necessary. Based on previous experience with onboard liquefied natural gas tanks, maintenance for the onboard LH2 storage tank (not including the rest of the vehicle) is expected to be several hundred dollars per year.

4 LH2 Infrastructure

LH2 trucks will require access to a fueling network. There are two aspects of this: LH2 production & supply and LH2 fueling stations. Each of these links in the supply chain is equally important. Disruptions to either part of the supply chain will threaten LH2 supplies to trucking fleets. CALSTART analyzed the state of both ends of the supply chain.

4.1 LH2 Production & Supply

LH2 production & supply is based on a centralized liquefaction network. This network consists of several large liquefaction plants that convert gaseous hydrogen to liquid. The LH2 is then delivered to end users via tanker truck. Since LH2 FCET require LH2, liquefaction capacity is a potential chokepoint for the market.



[1] In some cases, the specific city within a state was not identified or publicly available.
[2] Bubbles are not drawn to scale and are for illustrative purposes only.

Figure 2: Liquefaction Plants in the United States [12]

There is currently 304.2 metric tonnes per day of liquefaction capacity in the United States with an additional 345 metric tonnes per day of capacity either under construction or in the planning stages.

It is very likely that this production capacity is not sufficient to meet the demands of the market for FCETs. If California's Advanced Clean Fleets rule is fully adhered to, hydrogen demand for FCETs in California is expected to be between 6,458 and 8,093 metric tonnes per day [13]. As a result, hydrogen production and liquefaction capacity will need to increase as more FCETs are adopted. Establishing production and liquefaction capacity near end users helps to reduce LH2 distribution costs and makes the supply chain more secure for fleets.

4.1.2 Hydrogen Liquefaction Costs

Gaseous hydrogen must be converted to LH2 before it can be used on an LH2 truck. This conversion occurs through a process called liquefaction. The liquefaction process adds to the cost of the hydrogen. Liquefaction requires specialized equipment, which has high capital costs. The process also requires a large amount of energy. The required energy can vary depending on the type of process used and the scale of liquefaction, with most processes requiring 10 – 13 kWh to liquefy one kg of hydrogen. However, some newer processes have the potential to reduce this to down to 7 kWh per kg of hydrogen [14]. The capital costs, energy costs, and operational costs of the liquefaction plant add to the cost of hydrogen. CALSTART conducted financial analysis of onsite hydrogen liquefaction systems. CALSTART started by producing a baseline for liquefaction costs. This analysis estimated the levelized cost of liquefying hydrogen, on a per kg basis. It is important to note that this analysis only examines the cost of liquefaction and does not represent the total levelized cost of hydrogen. The levelized cost of liquefaction is expressed as $ per kg and is an additional cost beyond that of the gaseous hydrogen feedstock.

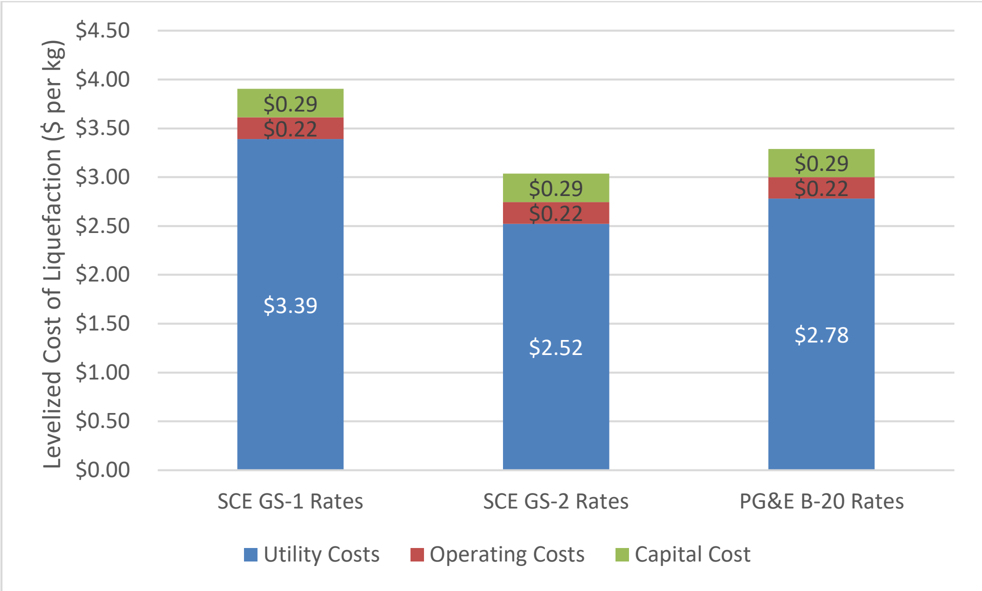


Figure 3: Baseline Levelized Cost of Liquefaction

This analysis assumes that a 30 metric tonnes per day liquefaction system is deployed over a 40-year life cycle. The analysis takes into consideration the capital costs of the plant as well as operational costs which include the gaseous hydrogen feedstock, electricity, labor, insurance, licensing & permits, and maintenance & repairs. These cash flows were then aggregated and divided by expected liquid hydrogen production to calculate the levelized cost of liquefied hydrogen. CALSTART provided baseline cases based on Southern California Edison (SCE) and Pacific Gas & Electric (PG&E) utility rates. These rates were selected because they represent the largest utilities in the California market, which is likely to be an early adopter of LH2 technology in the mobility space. The baseline case also assumes that the liquefaction plant operates at an efficiency of 13 kWh per kg of hydrogen.

The cost of liquefaction is influenced by several factors. The baseline case assumes a liquefaction energy efficiency of 13 kWh per kg of hydrogen, and SCE and PG&E utility rates. However, changes in any of these assumptions can impact the cost of liquefaction. Since liquefaction is energy intensive, utility costs are the largest component of the cost of liquefaction. As a result, changes in liquefaction energy efficiency and electricity costs are also likely to have a large impact on the levelized cost of liquefaction. CALSTART carried out sensitivity analysis to examine the impacts of these variables.

The baseline analysis assumes that the liquefaction plant has an energy efficiency of 13 kWh per kg of hydrogen. Existing liquefaction plant technology has variations in energy efficiency with most plants consuming 10 – 13 kWh per kg. However, as newer liquefaction processes and technologies are developed, the energy efficiency can potentially improve to 7 kWh per kg [15]. Given the potential for significant variation in efficiency, CALSTART analyzed the impact that energy efficiency has on levelized liquefaction cost. This sensitivity analysis examined energy efficiencies between 7 and 13 kWh per kg.

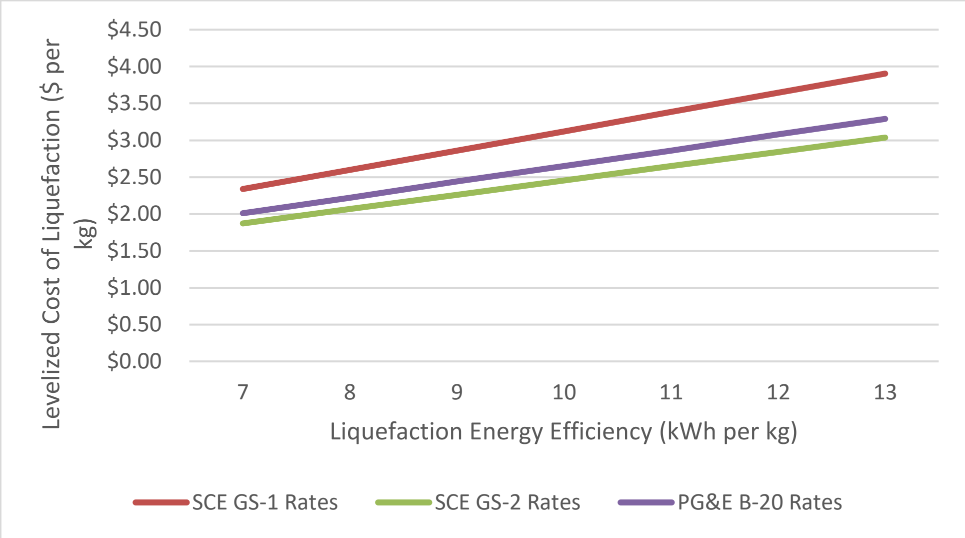


Figure 4: Liquefaction Energy Efficiency Sensitivity Analysis

The baseline analysis examined utility costs for operating a liquefaction plant based on SCE and PG&E utility rates. Based on this analysis, SCE's GS-1 and GS-2 rates have a levelized utility cost of $0.26 per kWh and $0.19 per kWh, respectively. PG&E's B-20 rates have a levelized utility cost of $0.21 per kWh. However, utility rates can vary significantly across the United States. Given the major contribution that utility costs have on the levelized cost of liquefaction, changes in electricity costs will have a major impact on liquefaction costs. CALSTART examined how changes in electricity costs (measured as levelized cost of energy) affects the levelized cost of liquefaction. This sensitivity analysis examined level cost of energy between $0.05 per kWh and $0.30 per kWh. This sensitivity analysis is displayed below:

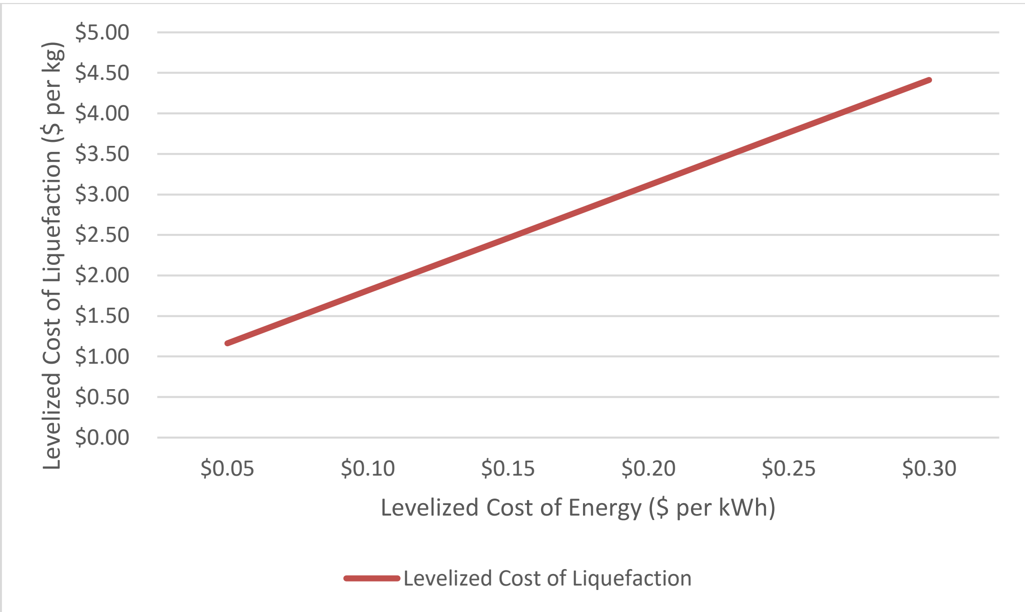


Figure 5: Energy Costs Sensitivity Analysis

4.2 LH2 Fueling Stations

LH2 fueling stations differ from gaseous fueling stations in that they dispense the hydrogen in liquid form. The main components of the system include a LH2 storage tank, a subcooled cryopump, and an LH2 dispenser. A subcooled cryopump cools the LH2 to a temperature below its boiling point. In most systems, the cryopump will be submerged either in the LH2 tank or in a separate sump tank. A cryopump that is not submerged has an approximately 15-minute startup time as LH2 has to enter and create cryogenic conditions in the pump before it can be used. By submerging the cryopump, it will remain in cryogenic conditions and can be used on demand.

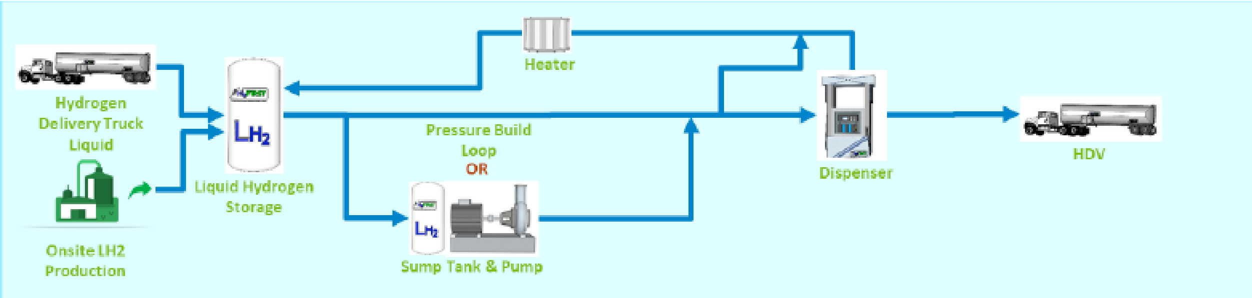


Figure 6: LH2 Fueling Station Process Diagram [16]

LH2 fueling stations also require other minor components. A flow meter is required to measure the amount of hydrogen dispensed and keep track of how much remaining LH2 is in the storage tanks. Piping is required to transport LH2 from the tank to the dispenser. This piping must be vacuum-jacketed to ensure safety. The dispenser also requires specialized equipment. The dispenser will have a vacuum-jacketed hose that is used to facilitate fueling. The hose will also have a coupling that connects the hose to the truck. Industry had to develop specialized couplings that are compatible with LH2. LH2 stations can be deployed as a skid-mounted system or as a permanent station.

When a truck comes to the station, it will need to be connected to the dispenser hose. The system will need to purge the hose to eliminate any impurities. Failure to purge the hose can result in impurities entering the onboard storage tank and eventually poisoning or damaging the fuel cell. The hose can be purged with nitrogen, helium, or boiloff hydrogen. The cryopump is then used to transfer LH2 to the truck's onboard storage tank. LH2 stations operate most efficiently under back-to-back fueling operations. Back-to-back fueling reduces the number of times the cryopump has to start up. Each time the cryopump starts up and circulates LH2, heat is introduced into the system which increases boiloff. As a result, this technology is most efficient with large tenant fleets with back-to-back fueling operations.

There are several companies that are developing a LH2 fueling station or are interested in developing one in the near future. These companies include Linde, Chart Industries, First Element Fuels, Taylor Wharton, and Air Liquide.

4.2.1 Retrofitting Existing Stations

Many gaseous hydrogen stations can be retrofitted to fuel LH2 trucks. Many of the existing and planned hydrogen stations already store LH2, convert it to a gas, and then dispense it using a cryopump. Since these stations already accept LH2, they already have much of the required equipment. These stations can be retrofitted by adding a second outlet to the LH2 storage tank. This second outlet can then be attached to a cryopump and a LH2 dispenser to the system. This architecture will allow the station to dispense both gaseous and LH2. The addition of the additional cryopump and the dispenser does not significantly increase the physical footprint of the station.

Some hydrogen station owners have begun to prepare for LH2 fueling. For example, First Element Fuels developed a MHD station at the Port of Oakland. This station currently dispenses gaseous hydrogen. However, First Element Fuels installed a stub out next to the LH2 storage tank to facilitate a potential future installation of a subcooled LH2 pump and LH2 dispenser.

4.2.2 Mobile LH2 Refuelers

Industry has become increasingly interested in mobile refuelers for FCETs. Mobile refuelers are portable fuelers that can be delivered to a site by truck. Mobile refuelers have small hydrogen tanks and usually only have enough storage to serve a few vehicles. Since they are mobile, they do not need permanent infrastructure and are not required to go through the permitting process. Mobile refuelers are suitable for fleets in the earlier stages of transitioning to FCETs. These fleets are usually engaged in a pilot demonstration and have relatively few FCETs. As a result, they don't have enough hydrogen demand to justify the capital costs of deploying a permanent station. Many fleets use mobile refuelers until their fleet of FCETs grows to the point where a permanent station is economically justifiable.

Industry is interested in deploying mobile refuelers to serve these smaller deployments until fleets adopt FCETs at scale. However, while the market for mobile gaseous hydrogen refuelers is growing, there are regulatory barriers to deploying mobile LH2 refuelers in California. Chapter 58, Section 5809.1 of the California Fire Code explicitly prohibits mobile fueling of LH2. As a result, mobile LH2 refuelers are not a viable fueling option at this time. At the time of writing, CALSTART is not aware of any equivalent regulations in other states.

4.2.3 LH2 Station Costs

LH2 fueling stations have a significantly lower capital cost as compared to regular gaseous hydrogen stations. LH2 fueling stations require fewer components than gaseous hydrogen stations. Since they don't handle gaseous hydrogen, LH2 fueling stations do not require a compressor or cascade storage systems, which represent a significant portion of capital expenditures.

Based on conversations with LH2 fueling station providers, an LH2 fueling station is projected to cost approximately $3 – 4 million. By comparison, a gaseous hydrogen station that uses LH2 storage and fuels at a pressure of 700 bar is expected to cost over $8 million. As a result, the LH2 fueling station is expected to have a much lower capital cost than a gaseous equivalent.

LH2 fueling stations also have implications for operating costs. LH2 fueling stations will have a lower power demand because they do not require compressors. The subcooled LH2 cryopump will also operate at a lower pressure than traditional cryopumps, which also reduces energy costs. The LH2 station providers that CALSTART interviewed stated that the maintenance costs for subcooled LH2 cryopumps should be low. Liquefied natural gas fueling stations have annual maintenance costs equivalent to approximately 2% of the capital costs of the station. LH2 fueling stations should have a comparable maintenance cost.

The maintenance costs for subcooled LH2 cryopumps will likely be lower than the cryopumps used in a traditional liquid-to-gaseous hydrogen station. The subcooled LH2 cryopumps operate at a much lower pressure than the cryopumps that are used in liquid-to-gaseous hydrogen stations. As a result, they experience less mechanical stress. LH2 station providers believe that the subcooled LH2 cryopumps could require less maintenance, which would result in reduced maintenance costs and station downtime. As more LH2 stations are deployed, data should be collected to validate this claim.

5 Conclusion

Onboard LH2 storage for FCETs is a promising technology. LH2 offers numerous benefits over gaseous hydrogen. LH2 has a much higher volumetric density than gaseous hydrogen. This property is important because it allows for more energy to be stored per unit of volume. This is vital to increasing the range of the vehicle, moving FCET technology closer to the range that diesel Class 8 trucks can attain. However, LH2 introduces new technological, supply chain, and safety challenges. Since LH2 is a commonly handled industrial gas, industry has preexisting expertise that can be applied to overcome these challenges.

LH2 onboard storage tanks will need to be integrated onto an FCET. Multiple tanks can be integrated onto the vehicle and it is expected that an FCET can carry more than 100 kg of LH2. This is a large enough quantity of LH2 to facilitate a longer range than gaseous hydrogen storage. Onboard LH2 storage tanks are also expected to weigh less and cost less than an equivalent gaseous hydrogen storage system. This system can be integrated onto the vehicle in a behind the cab or a frame rail-mounted configuration, providing flexibility for the truck design. However, these configurations have tradeoffs and the frame rail-mounted configuration is likely to be both cheaper and weigh less than the behind the cab configuration. This integration can occur without a major redesign of the vehicle. However, the integration process will require collaboration between the FCET manufacturer and the LH2 tank manufacturer. To date, Hyzon Motors and Daimler have carried out demonstrations of this technology.

LH2 infrastructure will also be vital to promoting this technology. The United States has a preexisting network of hydrogen liquefaction plants. Much of this liquefaction infrastructure is located in the American Southwest and can serve the California market. Additional liquefaction capacity is also under construction or in the planning stages. One of the weaknesses of a centralized liquefaction network is that an outage at a single plant can cause major supply disruptions to the market. As a result, the build out of additional liquefaction capacity can help to address these supply chain risks. Alternatively, fleets can mitigate this risk by deploying decentralized, onsite liquefaction systems. Liquefaction also adds to the cost of hydrogen. Since electricity costs are a major component of liquefaction costs, reducing these costs is vital to reducing the cost of liquefaction. Liquefactions plants that have better energy efficiency and those located in areas with lower utility rates will likely have a competitive advantage.

FCETs will also need access to LH2 fueling infrastructure. There are currently no commercially available LH2 fueling stations in the US. However, LH2 fueling station technology has been demonstrated. LH2 fueling stations are most efficient when they dispense large amounts of hydrogen and can engage in back-to-back fueling. Due to hydrogen boiloff, using the LH2 quickly to prevent boiloff loses is important. As a result, this is a highly appropriate technology for larger fleets with high fuel consumption. LH2 fueling stations have fewer components and are therefore expected to have both lower capital costs and lower maintenance costs than a gaseous hydrogen fueling station. This feature can help to reduce at-the-pump hydrogen prices and address some of the challenges that gaseous hydrogen fueling station face. Since many existing fueling stations store hydrogen in liquid form, these stations can be retrofitted to also dispense LH2. As a result, there is an avenue for establishing and expanding an LH2 fueling network.

While LH2 fueling stations have been demonstrated, the technology requires some further technological development, especially for cryopumps, LH2 dispensers, and LH2 connectors. In 2024, the US Department of Energy awarded funding for projects that demonstrate the “Hydrogen Station of the Future” [17]. The US Department of Energy’s support for LH2 will help to advance the development and commercialization of this technology.

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References

[1] Richard, Jacob (2025). CALSTART. “Zeroing in on Zero-Emission Trucks: The State of the U.S. Market.” Available at: https://calstart.org/wp-content/uploads/2025/01/January2025_ZIO-ZET_MarketUpdate_Final.pdf

[2] Pizzutilo, E., Acher, T., Reuter, B., and Will, C. (2023). Subcooled Liquid Hydrogen Technology for Heavy Duty Trucks. Presented at the Electric Vehicle Symposium 36. Available at: http://evs36.com/wp-content/uploads/finalpapers/FinalPaper_Acher_Thomas_Will_Christian.pdf

[3] Hyzon Motors (2023). Hyzon Motors Successfully Completes First Customer Demo of Liquid Hydrogen Fuel Cell Electric Truck. Available at: https://www.prnewswire.com/news-releases/hyzon-motors-successfully-completes-first-customer-demo-of-liquid-hydrogen-fuel-cell-electric-truck-301913272.html.

[4] Lee, Bryan. 2023. The Hydrogen Zero-Emission Tugboat Project. California Energy Commission. Publication Number: CEC-500-2024-051. Available at: https://www.energy.ca.gov/sites/default/files/2024-05/CEC-500-2024-051.pdf

[5] H2Tools. US Department of Energy. Hydrogen Compared With Other Fuels. Retrieved from: https://h2tools.org/bestpractices/hydrogen-compared-other-fuels

[6] *Ibid.*

[7] American Institute of Chemical Engineers. ELA253: CHS’s Introduction to Hydrogen Safety for First Responders (online course). Available at: https://www.aiche.org/ili/academy/courses/ela253/introduction-hydrogen-safety-first-responders

[8] H2Tools. US Department of Energy. Hydrogen Compared with Other Fuels

[9] *Ibid.*

[10] CALSTART (2022). Methods for Assessing Technology and Market Readiness for Clean Commercial Transportation. Retrieved from: https://calstart.org/wp-content/uploads/2022/04/Assessing-Technology-and-Market-Readiness_Final.pdf

[11] Ahluwalia, R.K.; Roh, H.S.; Peng, J-K; and Papadias, D. (2022). Argonne National Laboratory. On-board Liquid Hydrogen Storage for Long Haul Trucks. Liquid Hydrogen Technologies Workshop, hosted by DOE-EERE-HFTO and NASA's Cryogenics Technical Discipline Team. February 22-23, 2022. Retrieved from: https://www.energy.gov/sites/default/files/2022-03/Liquid%20H2%20Workshop-ANL2.pdf

[12] Wieliczko, Marika (2024). US Department of Energy. Hydrogen Liquefaction Capacity in the United States. Available at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24003-hydrogen-liquefaction-capacity-united-states.pdf?sfvrsn=b894666d_1

[13] Lee, Bryan; Gordon, Jon; Sutton, Katrina; and Kushwah, Aditya (2023). Roadmap to Fuel Cell Electric Truck Commercialization California Market Assessment. Available at: https://calstart.org/roadmap-to-fcet-commercialization/

[14] Gardiner, Monterey (2009). Department of Energy. Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs. Retrieved from: https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf

[15] *Ibid.*

[16] Baird, Austin; Hecht, Ethan; Ehrhart, Brian; and Muna, Alice (2022). Sandia National Laboratories. Liquid Hydrogen Heavy-Duty Vehicle Safety Review and Refueling Facility Design. Sandia Report: SAND2022-11745. Retrieved from: https://www.osti.gov/biblio/1885100

[17] Department of Energy (2024). Selections for Hydrogen and Fuel Cell Technologies Office Funding Opportunity Announcement to Advance the National Clean Hydrogen Strategy. Retrieved from: https://www.energy.gov/eere/fuelcells/selections-hydrogen-and-fuel-cell-technologies-office-funding-opportunity-0

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