Title

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Use Of Liquid Hydrogen in Heavy-Duty Vehicle Applications: Station And Vehicle Technology and Cost Considerations

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Sustainable Transportation Energy Pathways Plus (STEPS+) Program

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ITS UCDAVIS
Institute of Transportation Studies

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Executive Summary

In this report, various aspects of the use of liquid hydrogen (LH2) in heavy-duty vehicle applications, especially for fuel-cell transit buses and long-haul trucks, were considered in detail. Special attention was given to the cost of hydrogen refueling stations that receive and store the hydrogen as LH2 and the cost of liquefaction of the hydrogen. Other areas of focus included the physical characteristics and cost of onboard hydrogen storage units being developed that use LH2. Storing hydrogen onboard a long haul truck or bus as a cryogenic liquid (LH2) can increase the range the range (miles per refueling) of the vehicle by a factor of 1.5 to 2 depending on the pressure (350-700 Bar) of the hydrogen gas unit being replaced.

Projections were made of the incremental cost ($/kg) of the hydrogen dispensed at LH2 refueling stations due to the levelized capital and operating costs of the station (see Tables ES-1 and ES-2). The cost of an LH2 refueling station depends on whether the hydrogen will be transferred to the vehicles as a high-pressure gas (350 or 700 bar) or a cryogenic liquid. In one approach, the LH2 is vaporized and then the gas pressure is increased using a compressor. In a second approach, a cryogenic pump is used to increase the pressure of the LH2 and then it is vaporized to a high-pressure gas. Detailed analysis of station costs indicates the second approach results in a significantly lower station cost ($/kgH2/day). The difference in cost is large – at least 50%. A third approach being developed to refuel vehicles at LH2 stations is to transfer the hydrogen as a liquid for storage on the vehicle and vaporizing the liquid to the pressure and temperature needed by the fuel cell. It is anticipated that the cost of this third approach will be even lower than using the previous approach because the hydrogen is always at a relatively low pressure of a few bar. These differences are summarized in Table ES-1.

Table ES-1: Relative LH2 station costs of different refueling approaches

Refueling processes	Energy required to pressurize H2 Mj/kg	Energy required to vaporize the H2 MJ/kg	Cost of the station/fuel $/kgH2/day*	$/kgH2
Gaseous H2 compressed to 700 bar, CH2	8-12	0	1672	1.6
Vaporize LH2, then compress H2 gas to CH2	8-12	.466	2306 (700 bar)** 1205 (350 bar)	2.09 1.24
Cryo-pump LH2 to high pressure and then vaporize to transfer gas to vehicle	.5 (5kg/min)	.466	895 (700 bar) 619 (350 bar)	.74 .53
LH2 directly into a liquid H2 storage tank onboard the vehicle	<.1	<.1	632 (350 bar) 192 (10 bar)	.58 .27

The station results in Table ES-1 indicate that the incremental levelized cost of delivering H2 to vehicles can be lower in LH2 than in CH2 stations. However, the H2 must be liquified at a central liquefaction plant before delivery to the LH2 station. HDSAM calculations show a liquefaction cost of about \$2500/kgH2/da for large central liquefiers and a resultant effect on the cost of hydrogen of \$2-3/kg. This liquefaction cost will result in the dispensed price of hydrogen at stations that receive and store H2 as a liquid being higher than at stations utilizing only gaseous hydrogen. The price difference can be reduced to about \$1/kgH2 if the LH2 stations utilizes a cryogenic pump to pressurize the LH2.

It is important to project the reduction to be expected in the he future cost of the liquefaction of hydrogen as the technology matures and more large plants are built. The end-use energy component of the liquefaction cost is significant, but it is expected to be reduced as systems become more efficient. This reduction combined with the expected reduction in the cost of sustainable electricity from solar and wind will also contribute to reducing the cost of liquefaction. Starting from the liquefaction costs projected from the HDRSAM calculations, it seems likely the liquefaction costs can eventually be less than \$2/kgLH2, probably in the 2030 time frame.

A summary of the contributions of various factors to hydrogen costs is shown in Table ES-2. Costs are shown for both CH2 and LH2 stations. The costs can be expected when the technologies needed are reasonably mature and economies of scale are being realized. This is likely to occur sometime after 2030. The lowest hydrogen price (\$3-4/kgH2) projected is in CH2 stations using H2 produced by SMR. If hydrogen produced using electrolysis is dispensed in the CH2 stations, the projected price is \$4-5/kgH2. The projected hydrogen prices at LH2 stations span a wide range from \$5 to \$7/kgH2. The lowest price (\$4.6/kgH2) is at stations dispensing H2 produced by SMR and transferred into the vehicle storage unit as a cryo-genic liquid. If H2 dispensed in this station were produced using electrolysis, the projected price would be \$5.1/kgH2. The corresponding prices using a high pressure cryo-pump and vaporization are \$4.9 and \$5.4/kgH2, respectively. The highest prices at LH2 stations would be at stations using a low pressure cryo-pump and a compressor after vaporization. The price using SMR hydrogen would be \$6.3/kgH2 and for electrolysis hydrogen, the price would be \$6.6/kgH2. Continued study of these various LH2 station options is needed as more information becomes available.

Table ES-2: Summmary of hydrogen costs from various contributing factors

ES2-a: H2 Production Cost

Production	**SMR**	**Electrolysis**
\$/kg	1.5	2.0

ES2-b: H2 Transportation cost

Transport	**Rail**	**Long distance Pipeline**	**Local Truck**
\$/kg CH2	1.2	.3	.8
\$/kg LH2	0.8	n/a	.3

ES2-c: Liquefaction and total costs ($/kg LH2)

	Compressed H2		**Liquid H2 with cryo-pumps (for liquid on-board storage)**		
	700 bar	**350 bar**	**LH2 with low pressure, vaporize, compressor**	**High pressure LH2, vaporize.**	**Direct cryogenic liquid**
Central plant liquefaction	(No liquefaction needed for gaseous pathways)		1.75	1.75	1.75
H2 refueling stations	1.5	.8	2.0	0.55	.30
Total H2 cost					
SMR	4.1	3.4	6.3	4.9	4.6
Electrolysis	4.6	3.9	6.9	5.4	5.1

Introduction

In this report, various aspects of the use of liquid hydrogen (LH2) in heavy-duty vehicle applications, especially for fuel cell long haul trucks, were considered in detail. Special attention was given to the cost of hydrogen refueling stations that receive and store the hydrogen as LH2 and the cost of liquefaction of the hydrogen. Other areas of special attention were the physical characteristics and cost of onboard hydrogen storage units being developed that use LH2 and the way in which the LH2 is processed before and during transfer to the onboard storage unit. Finally, projections were made of the cost ($/kg) of the hydrogen dispensed at LH2 refueling stations.

Onboard hydrogen storage

Liquid hydrogen (LH2) can be used to distribute and store hydrogen at the refueling stations. Vehicles at the stations can be refueled with the LH2 if they have onboard LH2 storage units. If the vehicles have high pressure gas storage units, the LH2 would have to be vaporized and compressed before being used to refuel the vehicles. The reason that LH2 is attractive for distribution and storage at stations and onboard vehicles is that the density of LH2 is much higher than compressed H2 even at 700 bar (see Table 1). The energy (MJ/kg) needed to compress and liquify hydrogen is also shown in Table 1. In refueling vehicles using compressed gas (CH2) at 350 or 700 bar, a compressor is used to increase the pressure of gaseous hydrogen. For LH2, a cryogenic pump is used to increase the pressure of the LH2 before it is vaporized for delivery as high pressure hydrogen to the vehicle.

Table 1: Densities and energy required for storage onboard vehicles for compressed gas and liquid hydrogen

Hydrogen phase	Temperature deg K	Pressure atm	Density Kg/L	Compressed/liquefied energy MJ/kg
Compressed gas	300	350	.0235	10.2
Compressed gas	300	700	.0387	18.5
Liquid	15-20	.5-2	.071	30-40
Compressed-cryogenic liquid	25-50	300	.08	< 1

The characteristics of various types of onboard vehicle hydrogen storage systems are shown in Table 2. The technologies for the 350 bar and 700 bar gaseous storage units are well developed and mature. Those units are used on vehicles currently being marketed [1]. The storage units that use liquid hydrogen are much less developed and their characteristics are somewhat uncertain. Nevertheless, the onboard storage units using liquid hydrogen will be significantly smaller and lighter than those using a compressed gas even at 700 bar. The hydrogen storage units using compressed cryo-genic liquid hydrogen may be the most attractive in terms of weight and volume, but at the present time they are the least developed. It seems likely that the DOE weight and volume goals for 2025 can be meet by the liquid hydrogen systems, but not by the compressed gas systems. Meeting the DOE cost goal ($/kgH2) of $300/kg is very uncertain.

Table 2: Characteristics of onboard vehicle hydrogen storage systems

Hydrogen phase	kgH2/sys kg	kgH2/L sys	$/kgH2
DOE goal 2025	0.055	0.04	300
DOE Goal ultimate	0.065	0.05	300
Compressed gas 350 bar	0.045	0.016	433 (high volume-2015)
Compressed gas 700 bar	0.042	0.027	566 (high volume 2015)
LH2 Liquid 20-50 deg K 0-20 bar	0.116	0.041	NA
Compressed cryo-genic liquid >300 bar	0.072	0.044	

The LH2 onboard storage unit shown in Figure 1 is a new unit being developed by Chart Industries for use in hydrogen fuel cell long haul trucks [2]. The unit stores the hydrogen as a cryogenic liquid and contains an evaporator to gasify the liquid and deliver the H2 to the fuel cell at the proper inlet pressure and temperature needed for its operation. The inlet pressure and temperature are in the ranges of 1-3 bar and 30-50 deg C, respectively. The evaporator uses waste heat from the cooling system of the fuel cell. Similar units are being developed by Cryomotive in Germany [30] and by Verne [31] in the United States. Cryomotive has recently signed an agreement to work with Chart Industries [32]

Figure 1: The LH2 onboard vehicle storage unit developed by Chart Industries [2]

The hydrogen refueling station would need neither a high pressure cryogenic pump nor a high-pressure compressor to fill the Chart Industries unit because the hydrogen can be transferred into the storage unit as a liquid directly from the large scale LH2 tank at the station. The Chart

Industries unit stores 35 kg of hydrogen and is sized to replace the standard diesel fuel tank placed along the side rails of the tractor of the long haul truck. Two of the H2 storage units can store 70 kg. Each H2 storage unit weighs about 300 kg and has an external volume of 850 L. For a truck that uses .095 kgH2/mi, the daily range for the 70 kg capacity would be over 700 miles, which is comparable to a diesel truck. The Chart Industries LH2 storage unit meets the DOE goals and does not require compression of the hydrogen to high pressure at the refueling station. The unit has been tested successfully with a fuel cell by Ballard [16].

Cryogenic LH2 pumps

LH2 pumps are being developed by a number of organizations for use in vehicle refueling systems. These cryo-genic pumps use as inlet LH2 at low pressure and increase the pressure by varying ratios depending on the application. In [10, 12, 17], the pump is submerged in the LH2 tank as the inlet. The outlet pressure of the pump can be 350-700 bar for systems in which the vehicle refueling is done as gaseous hydrogen after vaporization. For other applications, the output pressure would be much lower. After vaporization, the pressure of the hydrogen would be increased using a compressor. For direct LH2 refueling/transfer of LH2 into a LH2 storage unit onboard the fuel cell vehicle, the pump would increase the pressure of the LH2 to 10-20 bar. Another category of LH2 storage onboard vehicles is termed compressed cryo-genic liquid. This system would use a high-pressure ratio cryo-pump outputting a cryo-genic vapor [4, 5, 25-28].

The thermodynamics of the operation of the cryo-pumps in the various applications is complex and little data for particular cases are available. The only category has been studied in detail is that of compressed cryo-genic liquid at the National Labs (LLNL and ANL) [25, 28]. A short discussion of that testing at LLNL is given below.

LH2 pump takes liquid hydrogen at low pressure (3 bar absolute) and very low temperature (24.6 K) and delivers it as a cryogenic supercritical vapor at pressures as high as 875 bar and temperatures between 30 and 60 K [3]. The basic operation of the pump is illustrated in Figure 2. The pump operates immersed in LH2 (colored in blue) and is filled by gravity. When the piston moves down, a valve opens allowing hydrogen to flood the main cylinder [4, 5]. Upward movement of the piston compresses the hydrogen in the main cylinder to a moderate pressure (6 bar), sufficient to remove the LH2 from near saturation into a thermodynamic state far removed from saturation that is unlikely to cavitate. The piston shaft is hollow, enabling hydrogen to flow from the main cylinder into the second stage of compression, where the piston pressurizes the hydrogen to the vehicle vessel pressure, up to 875 bar. The hydrogen would flow through a check valve into the vehicle vessel after being heated to 50-70 deg K.

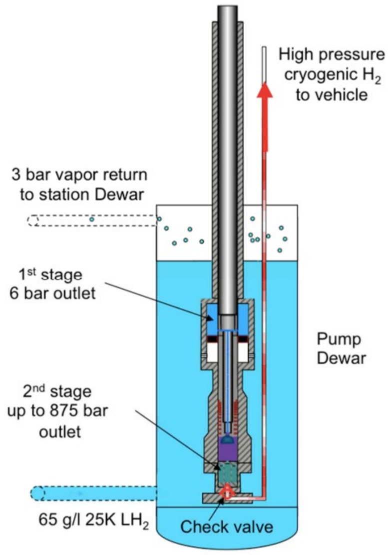


Figure 2: Cryogenic pump for transferring LH2 into onboard storage (5)

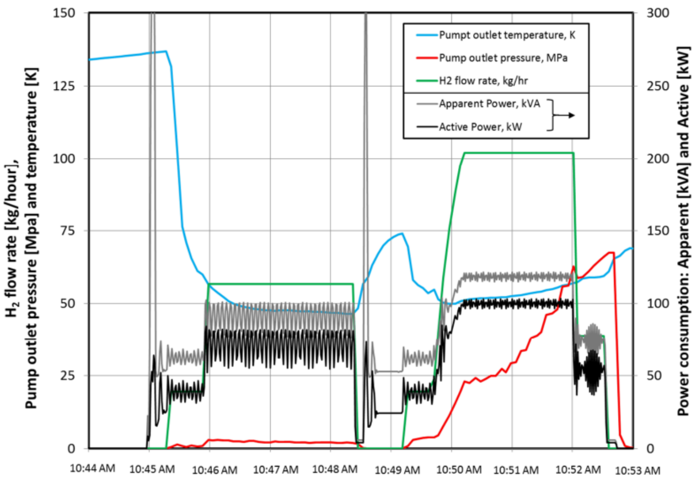


Figure 11. Pump data during first vessel fill to 700 bar on May 13. Left scale: H_2 flow rate (green), and pump outlet temperature (blue) and pressure (red). Right scale: apparent (gray) and active (black) electric power.

Figure 3: LH2 transfer data via pump [5]

Production and transportation of hydrogen including pipeline compatibility

Production of hydrogen

Hydrogen is produced as a low pressure gas by a number of processes and the gas is then compressed to high pressure and/or liquified to a cryogenic liquid for use as the fuel in fuel cell vehicles. The hydrogen gas can be produced in a thermo-chemical process such as steam reforming of methane (SMR) or in an electrolysis process from water using electricity as the energy source. Sustainable hydrogen is produced using solar and wind generated electricity. At the present time, most hydrogen (over 95%) in the United States is produced using the SMR process from natural gas. The GHG from this process is 9.3kg CO_2 /kgH2 compared to less than 1 $kgCO_2$ /kgH2 using electrolysis and solar energy. Hence in the long term, the goal in California is to produce all the hydrogen using electrolysis and solar/wind electricity as shown in Figure 4. Low GHG hydrogen could be produced from fossil fuels if the process is combined with CCS.

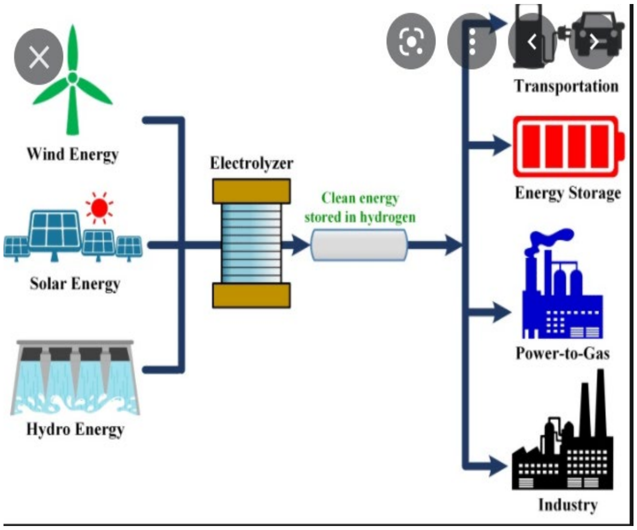
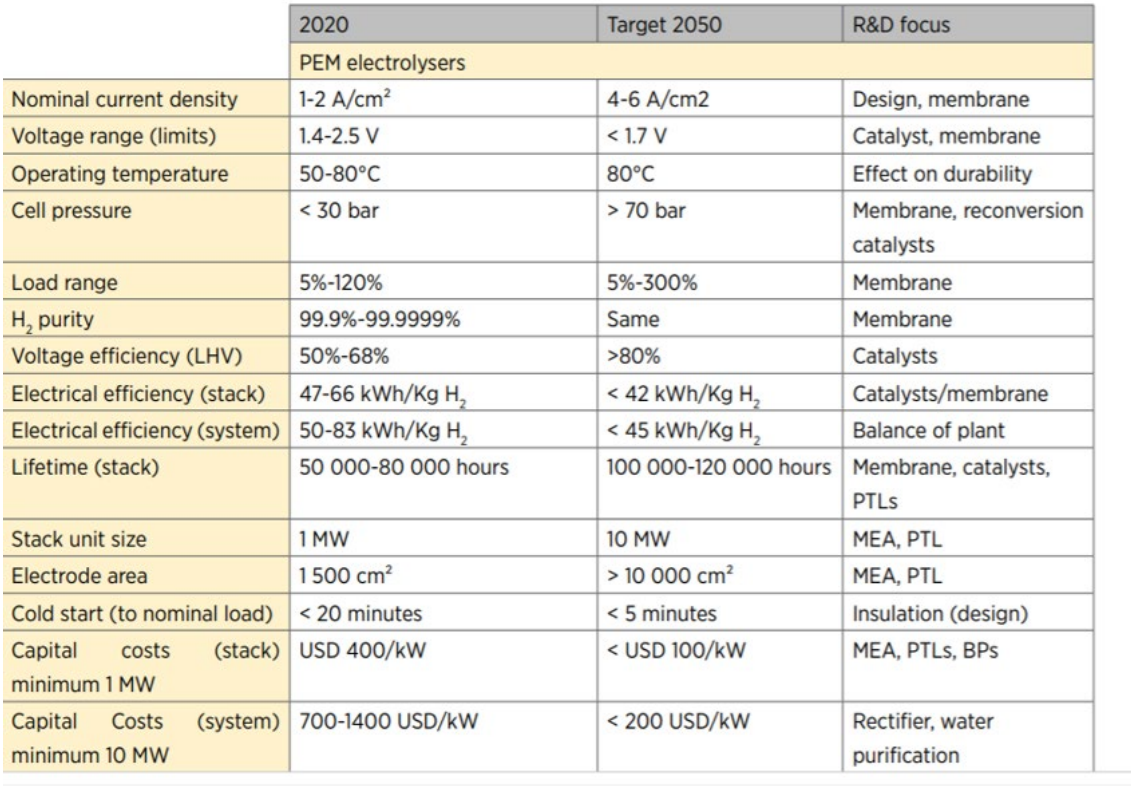


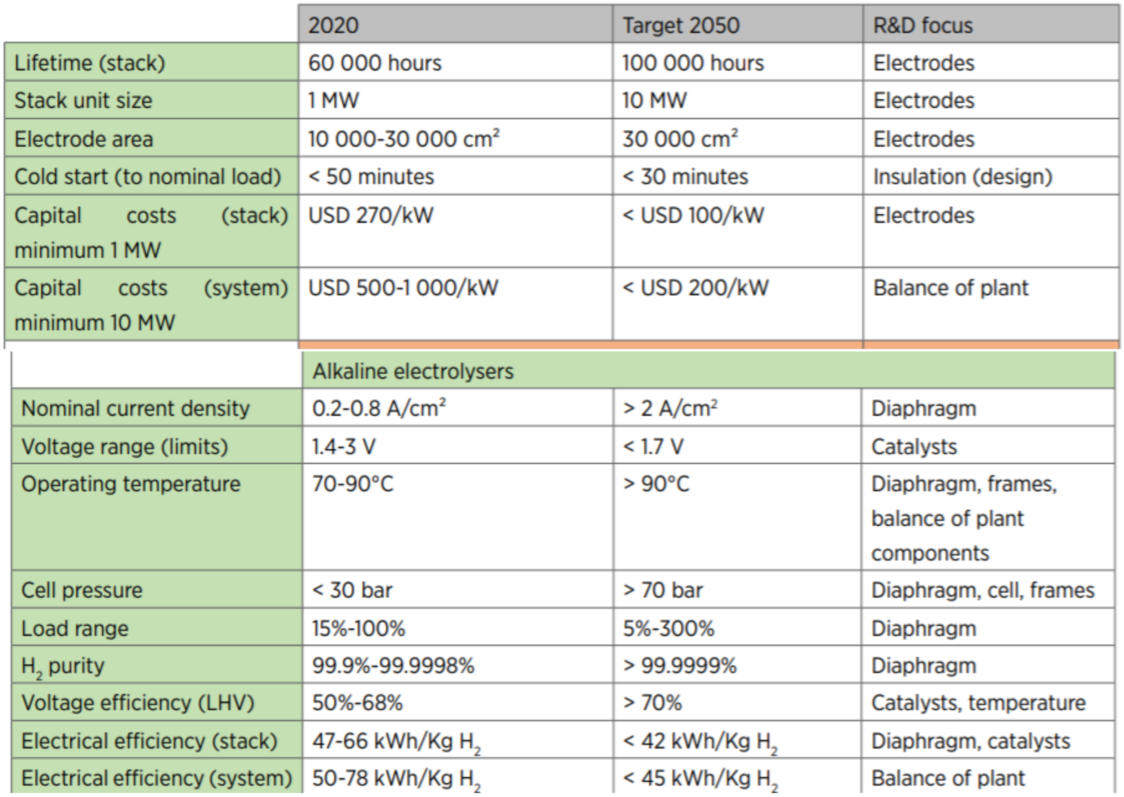
Figure 4: Hydrogen from electrolysis and solar electricity

If the electrolyzer is 75% efficient and is fed 1MW of electricity from the solar panel, it will produce 22.5 kgH2/hr. If it is connected to the grid, the electrolyzer will produce 540 kgH2/day. Hence a 1 MW electrolyzer could provide hydrogen for a 500 kg/day refueling station. The characteristics of PEM and alkaline electrolyzers [6] are given in Table 3. Characteristics for both the present time and long-term in 2050 are given in the table. The PEM electrolyzer technology is closely related to the PEM fuel cell technology being developed for use in vehicles. As a result, the cost of the PEM electrolyzers can be expected to decrease as a result. Hence, there is more interest in using the PEM type rather than the alkaline type at the present time. As shown in Table 4, the cost ($/kg) of producing the hydrogen will depend primarily on the cost ($/kW) of the electrolyzer and the cost ($/kWh) of electricity. The cost of the electricity is the dominant factor in the hydrogen cost.

Table 3: Characteristics of electrolyzers [6]



	2020	Target 2050	R&D focus
	PEM electrolysers		
Nominal current density	1-2 A/cm^2	4-6 A/cm2	Design, membrane
Voltage range (limits)	1.4-2.5 V	< 1.7 V	Catalyst, membrane
Operating temperature	50-80°C	80°C	Effect on durability
Cell pressure	< 30 bar	> 70 bar	Membrane, reconversion catalysts
Load range	5%-120%	5%-300%	Membrane
H_2 purity	99.9%-99.9999%	Same	Membrane
Voltage efficiency (LHV)	50%-68%	>80%	Catalysts
Electrical efficiency (stack)	47-66 kWh/Kg H_2	< 42 kWh/Kg H_2	Catalysts/membrane
Electrical efficiency (system)	50-83 kWh/Kg H_2	< 45 kWh/Kg H_2	Balance of plant
Lifetime (stack)	50 000-80 000 hours	100 000-120 000 hours	Membrane, catalysts, PTLs
Stack unit size	1 MW	10 MW	MEA, PTL
Electrode area	1 500 cm^2	> 10 000 cm^2	MEA, PTL
Cold start (to nominal load)	< 20 minutes	< 5 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	USD 400/kW	< USD 100/kW	MEA, PTLs, BPs
Capital Costs (system) minimum 10 MW	700-1400 USD/kW	< 200 USD/kW	Rectifier, water purification



	2020	Target 2050	R&D focus
Lifetime (stack)	60 000 hours	100 000 hours	Electrodes
Stack unit size	1 MW	10 MW	Electrodes
Electrode area	10 000-30 000 cm^2	30 000 cm^2	Electrodes
Cold start (to nominal load)	< 50 minutes	< 30 minutes	Insulation (design)
Capital costs (stack) minimum 1 MW	USD 270/kW	< USD 100/kW	Electrodes
Capital costs (system) minimum 10 MW	USD 500-1 000/kW	< USD 200/kW	Balance of plant
	Alkaline electrolysers		
Nominal current density	0.2-0.8 A/cm^2	> 2 A/cm^2	Diaphragm
Voltage range (limits)	1.4-3 V	< 1.7 V	Catalysts
Operating temperature	70-90°C	> 90°C	Diaphragm, frames, balance of plant components
Cell pressure	< 30 bar	> 70 bar	Diaphragm, cell, frames
Load range	15%-100%	5%-300%	Diaphragm
H_2 purity	99.9%-99.9998%	> 99.9999%	Diaphragm
Voltage efficiency (LHV)	50%-68%	> 70%	Catalysts, temperature
Electrical efficiency (stack)	47-66 kWh/Kg H_2	< 42 kWh/Kg H_2	Diaphragm, catalysts
Electrical efficiency (system)	50-78 kWh/Kg H_2	< 45 kWh/Kg H_2	Balance of plant

Table 4: Hydrogen cost for various electrolyzer and electricity prices

Electrolyzer cost $/kW	Electricity $/kWh			
	0.2	0.1	0.05	0.02
	Hydrogen $/kg			
1000	9.86	5.41	3.2	1.81
500	9.37	4.93	2.71	1.38
300	9.18	4.73	2.51	1.18
200	9.08	4.64	2.42	1.08

Hydrogen can be produced by a number of pathways in addition to electrolysis [7]. The costs of producing hydrogen from these different pathways are shown in Figure 5 and Table 5. It appears that producing hydrogen for less than $2/kg using any of the sustainable, near zero CO_2 pathways will be difficult. Hydrogen production costs in large production systems [8] are shown in Figure 6 that indicates achieving production cost less than $2/kg will be difficult even in the long term (2040-2050).

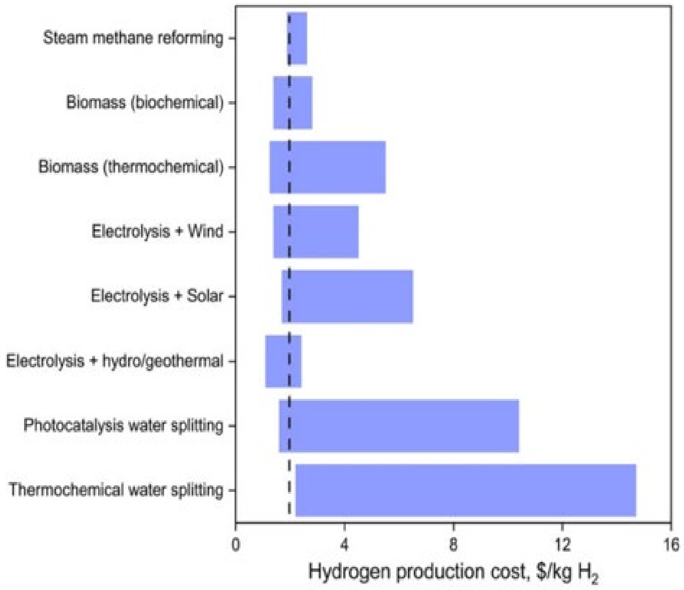


Figure 5: Hydrogen production costs for various pathways [7]

Table 5: Summary of hydrogen production costs [7]

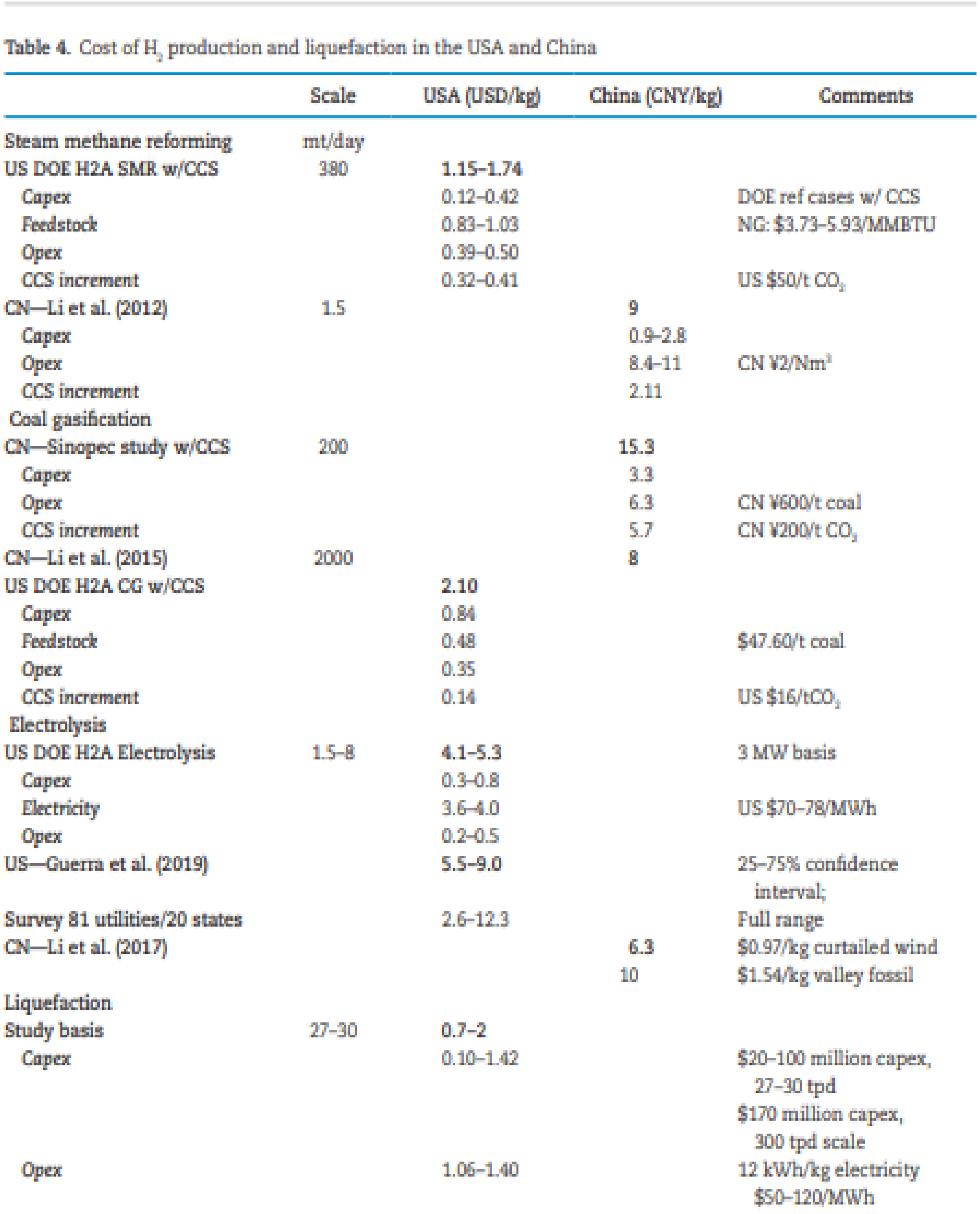
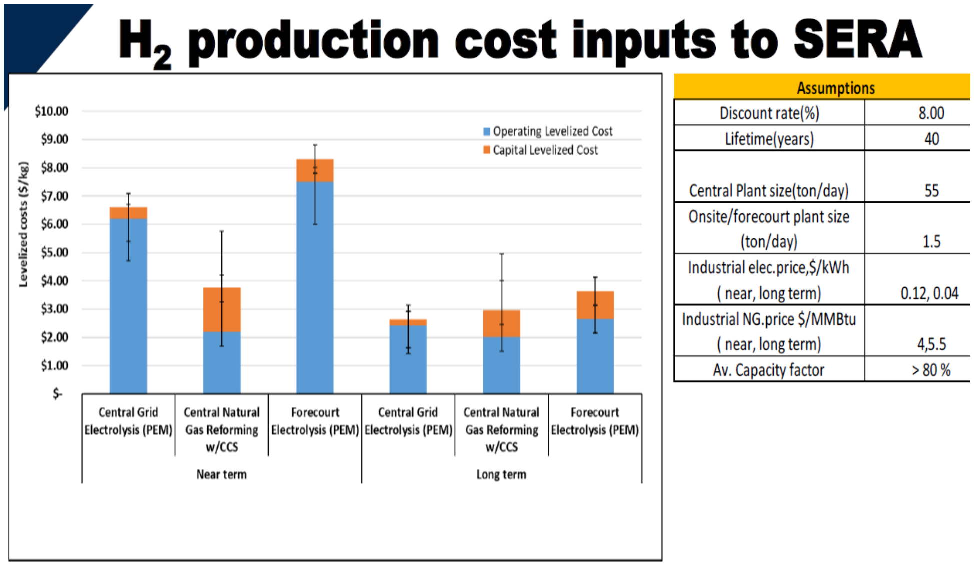


Table 4. Cost of H_2 production and liquefaction in the USA and China

	Scale	USA (USD/kg)	China (CNY/kg)	Comments
Steam methane reforming	mt/day			
US DOE H2A SMR w/CCS	380	**1.15–1.74**		
Capex		0.12–0.42		DOE ref cases w/ CCS
Feedstock		0.83–1.03		NG: $3.73–5.93/MMBTU
Opex		0.39–0.50		
CCS increment		0.32–0.41		US $50/t CO_2
CN—Li et al. (2012)	1.5		**9**	
Capex			0.9–2.8	
Opex			8.4–11	CN ¥2/Nm^3
CCS increment			2.11	
Coal gasification				
CN—Sinopec study w/CCS	200		**15.3**	
Capex			3.3	
Opex			6.3	CN ¥600/t coal
CCS increment			5.7	CN ¥200/t CO_2
CN—Li et al. (2015)	2000		**8**	
US DOE H2A CG w/CCS		**2.10**		
Capex		0.84		
Feedstock		0.48		$47.60/t coal
Opex		0.35		
CCS increment		0.14		US $16/t$CO_2$
Electrolysis				
US DOE H2A Electrolysis	1.5–8	**4.1–5.3**		3 MW basis
Capex		0.3–0.8		
Electricity		3.6–4.0		US $70–78/MWh
Opex		0.2–0.5		
US—Guerra et al. (2019)		**5.5–9.0**		25–75% confidence interval;
Survey 81 utilities/20 states		2.6–12.3		Full range
CN—Li et al. (2017)			**6.3**	$0.97/kg curtailed wind
			10	$1.54/kg valley fossil
Liquefaction				
Study basis	27–30	**0.7–2**		
Capex		0.10–1.42		$20–100 million capex, 27–30 tpd $170 million capex, 300 tpd scale
Opex		1.06–1.40		12 kWh/kg electricity $50–120/MWh



H_2 production cost inputs to SERA

Assumptions	
Discount rate(%)	8.00
Lifetime(years)	40
Central Plant size(ton/day)	55
Onsite/forecourt plant size (ton/day)	1.5
Industrial elec.price,$/kWh (near, long term)	0.12, 0.04
Industrial NG.price $/MMBtu (near, long term)	4,5.5
Av. Capacity factor	> 80 %

Figure 6: Projected production cost of hydrogen from large systems [8]

Transportation of hydrogen

The hydrogen is seldom produced where it is to be used. Hence, the cost effective transportation of the hydrogen is important to the development of a hydrogen distribution network. Hydrogen is produced as a low-pressure gas, but it must be distributed as a high pressure gas and a cryogenic liquid. The hydrogen can be transported in tanks by truck and rail or as a flowing medium in pipes. The high pressure gaseous hydrogen is transported in tube trailers that are driven to refueling stations as needed. The tube trailers can carry 300-600 kgH2 at 228 bar pressure and up to 600 kg at 300 bar. Liquid hydrogen is transported in large tank trailers that hold 4000 to 8000 kg LH2. The LH2 in the insulated tanks is hold at 1.7 bar, 20 deg K. Boil off is a concern with LH2, but the tanks have boil-off of only 0.3-0.6% per day.

Hydrogen is often delivered as LH2 to refueling stations even when the hydrogen is stored at the station as a gas because of the large difference in kgH2 delivered and the cost ($/kg) of the delivery. Hydrogen can be cost effectively distributed by pipelines where an appropriate network is available much like natural gas is presently distributed throughout the United States. The main pipes are 18-36 inches in diameter and transport the gas at 90 bar [9]. Transporting LH2 in pipes is difficult, but some insulated double-wall pipes have constructed for short distances near large central liquefaction plants [15]. The key consideration in transporting hydrogen is the cost ($/kg) added to the pump price for distribution. The cost of distribution is summarized for truck delivery in Table 6 [10]. The cost for compressed gas is about $0.8/kg and for LH2 it is $0.3/kg for reasonably short, urban distances.

Table 6: Cost of transporting H2 in trucks [10]

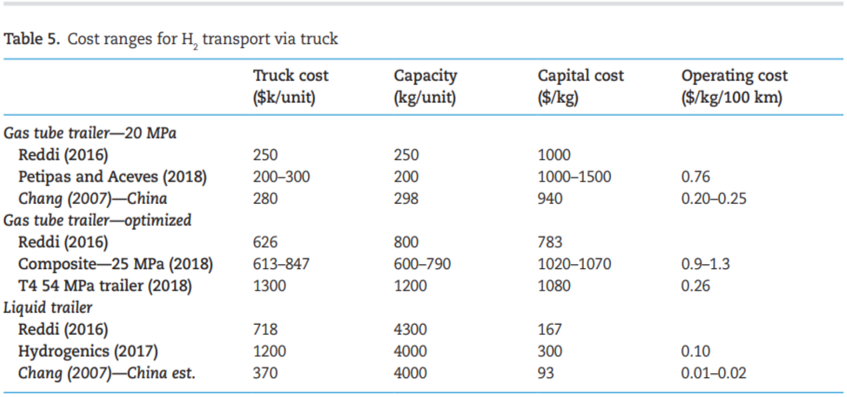


Table 5. Cost ranges for H_2 transport via truck

	Truck cost ($k/unit)	Capacity (kg/unit)	Capital cost ($/kg)	Operating cost ($/kg/100 km)
Gas tube trailer—20 MPa				
Reddi (2016)	250	250	1000	
Petipas and Aceves (2018)	200–300	200	1000–1500	0.76
Chang (2007)—China	280	298	940	0.20–0.25
Gas tube trailer—optimized				
Reddi (2016)	626	800	783	
Composite—25 MPa (2018)	613–847	600–790	1020–1070	0.9–1.3
T4 54 MPa trailer (2018)	1300	1200	1080	0.26
Liquid trailer				
Reddi (2016)	718	4300	167	
Hydrogenics (2017)	1200	4000	300	0.10
Chang (2007)—China est.	370	4000	93	0.01–0.02

Transporting large quantities of hydrogen for long distances is done by pipelines or by rail. Local distribution would be done by truck except to a large, central liquefaction where delivery of gaseous hydrogen would be done by pipeline. Local delivery of the LH2 would done by tanker truck. The cost of long- distance transport is shown in Figures 7 and 8 taken from [9]. For distances less than about 3000 km, transport by pipeline is the lowest cost. For longer distances, it is lower cost to transport the hydrogen as a liquid. In general, the cost of long distance transport will be less than $1/kg. The cost of local distribution will be an additional $0.3-0.8/kg.

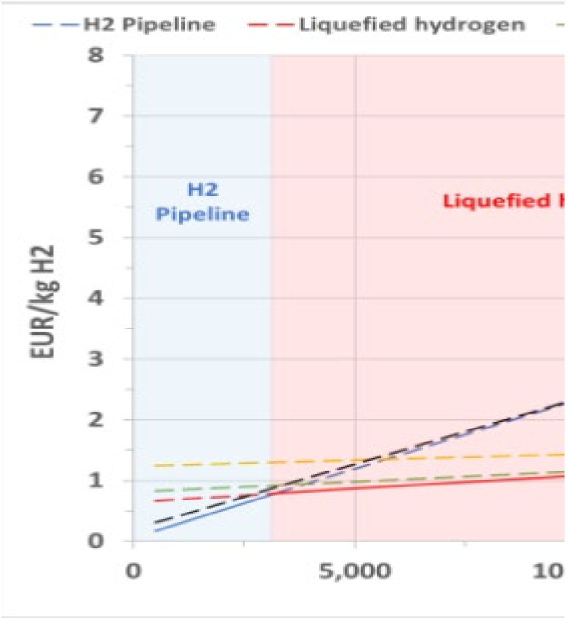


Figure 7: The cost of long distance transport of hydrogen [9]

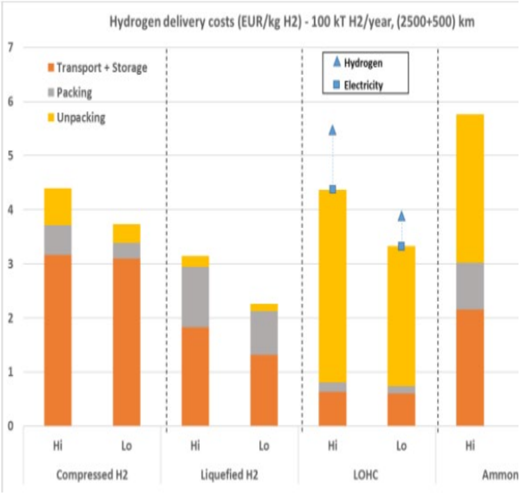
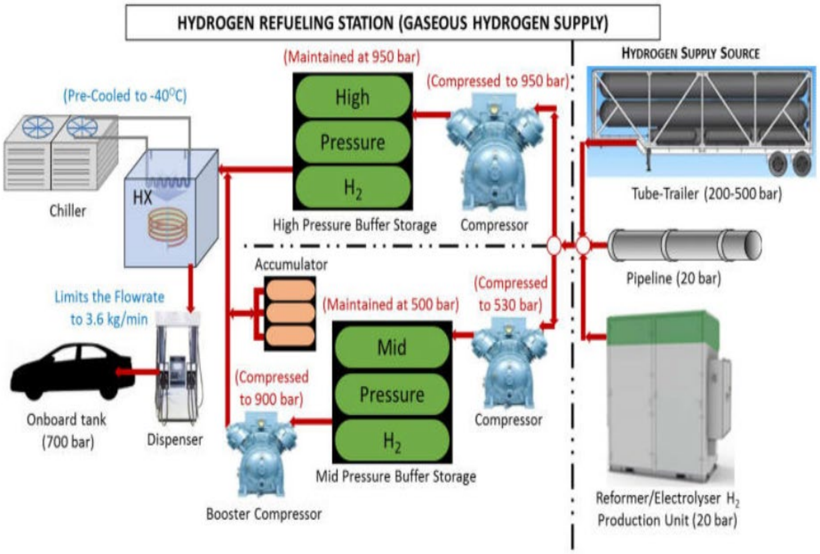


Figure 8: The total delivery cost of hydrogen to a network including for a long distance [9]

Hydrogen refueling stations

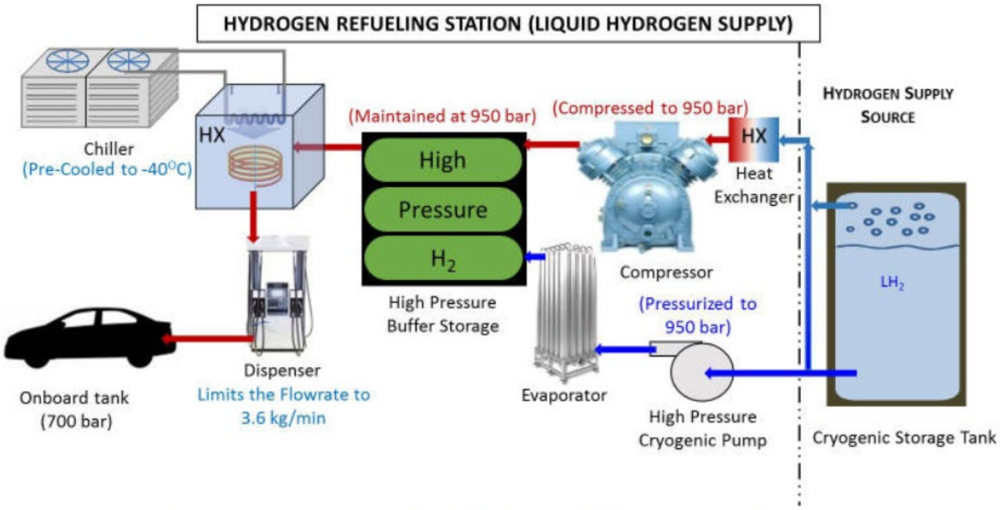
Refueling fuel cell vehicles with compressed gas hydrogen (350 bar or 700 bar) is routine and many stations are in daily operation [11]. Refueling fuel cell vehicles using liquid hydrogen is not routine, but there have been some demonstration projects especially for transit buses [10, 12]. One approach is to store the hydrogen as a liquid at the station and transfer it into the onboard storage unit as a high-pressure gas. In this arrangement, the hydrogen must be vaporized and then compressed to 350 or 700 bar [13, 14]. This is the approach being used at the present time in most LH2 refueling stations (see Fig. 9).



Schematic representation of gaseous hydrogen refueling station configurations

Figure 9: ACH2 refueling station with high pressure gas dispensing [10]

A second approach to refueling a fuel cell vehicle at an LH2 station is to compress the stored LH2 with a cryo-genic pump and then vaporize the hydrogen before transferring it to the vehicle. This approach is illustrated in Figure 10.



Schematic representation of liquid hydrogen refueling station configurations

Figure 10: Schematic of a Liquid H2 refueling station using a cryogenic pump [11]

A third approach to using liquid hydrogen (LH2) in fuel cell vehicles is to store the hydrogen onboard the vehicle as a liquid and to vaporize/pressurize the LH2 as needed by the fuel cell.

This is what is done by the Chart Industries onboard storage unit shown in Fig. 1. Comparisons of the energy requirements and the station and fuel costs of the three approaches are shown in Table 7. These results were obtained using the HDRSAM program. The fuel cost shown is the contribution of the station cost to the pump cost of the hydrogen. The advantages of using the LH2 directly has clear advantages because it avoids the pressurization of the hydrogen which is not needed in the operation of the fuel cell. Table 8 shows the projected advantage of the large LH2 stations in 2050.

All the refueling stations considered in this section of the report are intended to be used by long haul fuel cell trucks having a hydrogen fill requirement of 50-100 kg. Assuming that 100-200 trucks per day use the station, its capacity would need to be 7000-20000 kg/day. Hence the truck refueling stations would be very large stations. Most of the truck refueling stations will likely be built at truck stops resulting in relatively high utilization factors. In order to refuel H2Trucks in times comparable times for diesel trucks, these stations will need high filling flow of 8-10 kg/minute and the ability to perform many back-to-back refills. These requirements can be met using LH2 and cryo-pumps as shown in demonstration projects involving transit buses [24]. Transit bus applications in which a bus fleet must be refueled overnight in 6-8 hours or less are ideal for LH2 because each dispenser can service multiple buses back-to-back at a high fueling rate [11, 12]

Table 7: Relative LH2 station costs of different refueling approaches

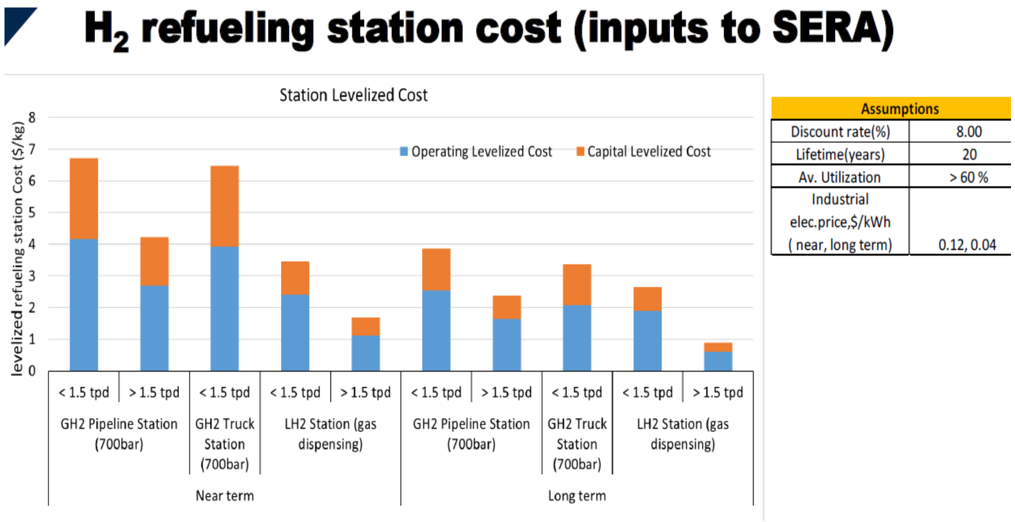
Refueling processes	Energy required to pressurize H2 Mj/kg	Energy required to vaporize the H2 MJ/kg	Cost of the station/fuel $/kgH2/day* $/kgH2
Gaseous H2 compressed to 700 bar, CH2	5	0	1672 1.6
Vaporize LH2, then compress H2 gas to CH2	5	.466	2306 (700 bar) 2.09 1205 (350 bar) 1.24
Cryo-pump LH2 to high pressure and then vaporize to transfer gas to vehicle	1.1 (5kg/min)	.466	895 (700 bar) .74 619 (350 bar) .53
LH2 directly into a liquid H2 storage tank onboard the vehicle	<.1	<.1	632 (350 bar) .58 192 (10 bar) .27

*all stations in the table had a capacity of 7000 kg/day. Calculations with HRDSAM [11, 12] were made for highway hydrogen refueling stations up to 30,000 kgH2/day to get costs for stations for refueling large fuel cell trucks. The results for 700 bar stations are shown in Table 8. These results show the advantages of LH2 for large stations especially those using the cryo-pump, which have station and fuel costs about 30% those of the CH2 station.

Table 8: Comparisons of the costs of large 700 bar gas and liquid H2 stations

Refueling Capacity kgH2/day	700 bar H2 gas station* (CH2 compression) High production-low cost components			700 bar H2 gas station* (LH2 evaporation and compression.) High production-low cost components			700 bar liquid H2 station* (High Press. Cryo-pump + evap) High production-low cost components		
	M$	$/kgH2/da	$/kgH2	M$	$/kgH2/da	$/kgH2	M$	$/kgH2/da	$/kgH2
5000 Vehfleet100	8.3	1672	1.60	7.0	1418	1.48	3.1	618	.58
10000 Vehfleet200	17.4	1461	1.67	14.6	1475	1.52	5.9	586	.52
20000 Vehfleet300	43.1	2154	1.95	37.8	1896	1.80	12.4	620	.52 0
30000 Vehfleet400	78.3	2637	2.27	73.2	2465	2.19	22.4	753	.61

*Station operated 18 hrs/day, minimum number of hoses in each station calculation



H_2 refueling station cost (inputs to SERA)

Assumptions	
Discount rate(%)	8.00
Lifetime(years)	20
Av. Utilization	> 60 %
Industrial elec.price,$/kWh (near, long term)	0.12, 0.04

Figure 11: Projected station costs for H2 refueling stations

Hydrogen can be stored onboard a vehicle as either a high pressure gas or as cryogenic liquid. Refueling fuel cell vehicles that store the hydrogen onboard as a cryogenic liquid is more efficient and lower cost. The hydrogen is stored at 30-50 deg K temperature and 50 bar pressure in an insulated container (Fig 1). The vaporization of the hydrogen occurs onboard the vehicle on delivery to the fuel cell. The hydrogen must be delivered to the fuel cell at the temperature and pressure required for its efficient operation. Control of the flow (gm/sec) of hydrogen on demand is also critical. A detailed description of refueling of the cryo-compressed hydrogen tanks is given in [4, 5]. The hydrogen storage capability of the tanks and refueling with LH2 are compared in Tables 2 and 7. The HDRSAM cost results for a 7000 kgLH2/day station indicate the lowest station and fuel costs using low pressure cryogenic hydrogen. The highest costs are projected for high pressure hydrogen stored onboard the vehicle. The onboard LH2 unit has been demonstrated in a fuel cell test by Ballard and Chart industries [16].

A spreadsheet model using EXCEL was developed to calculate the cost of LH2 refueling stations using the high pressure cryogenic pump in its present and future states [17, 18] of development (see Table 9). Calculations were made with the spreadsheet model for refueling stations for city delivery vans and long haul trucks for the refueling station configurations being compared throughout the paper. The operating conditions of the stations were appropriate for the two vehicle types being studied. The results of the calculations, which are given in Table 10, show the same large cost advantage of LH2 stations using the cryogenic pump for both vehicle types. Further development of the pumps will increase their cost advantage significantly.

Table 9: Characteristics of present and future cryogenic pumps

	Baseline cryo-pump	**Advanced cryo-pump**
LH2 Flow-rate kg/hr	120	280
System energy use kW/kg/hr	0.5	0.25
Cost $/kg/hr		
Mid	2798 (HDRSAM)	2083
Low	2379 (HDRSAM)	1760

Table 10: Spreadsheet results for LH2 refueling stations for delivery vans and long haul trucks using cryogenic pumps

Vehicle	KgH2/day	Cost M$	$/kgH2/day	Sta.$/kgH2
Delivery van 240 20 kg fill 12hrs day	4800			
	CH2 station	9.8	2046	1.55
	LH2 evap+ compressor	7.7	1602	1.21
	LH2 base pump+Evap	3.9	807	0.57
	LH2 adv. Pump =Evap	3.6	743	0.52
Long haul trucks-120 90 kg fill 10 hr day				
	CH2 station	22.7	2104	1.34
	LH2 evap+ compressor	31.6	2927	2.08
	LH2 base pump+Evap	7.7	8714	0.52
	LH2 adv pump+Evap	6.5	601	0.45

Liquefaction technology

The final aspects of using LH2 are concerned with the liquefication of the hydrogen – its cost and energy efficiency. The liquefaction process is complex and energy intensive (see Figure 11). A review of H2 liquefier technology is given [17, 18]. The complexity and size of a relatively small (10t day) unit from Chart Industries are shown in Figure 8. Hydrogen is particularly difficult to liquefy because its critical temperature is very low (20-30 deg K) and Joule-Thomson throttling (rapid reduction in pressure through a valve) cannot be used to reduce the temperature to 20K until the temperature of the hydrogen has been reduced to 200 K (-73 deg C) or lower. As shown in Figure 8, the hydrogen is first compressed to about 100 bar and then cooled using liquid nitrogen to 200K or lower. The initial cooling of the hydrogen is complex and expensive. The energy requirement of the liquefier depends on its size (tH2/day) ranging from 12 kWh/kgH2 for a small unit to 6-8 kWh/kgH2 for very large units. The DOE goal is 6 kWh/kgH2 for a 300t/day liquefier unit, which is an efficiency of 82%. Hence it requires 18-36 % of the energy content (33.3 kWh/kgH2) of the hydrogen to liquefy it.

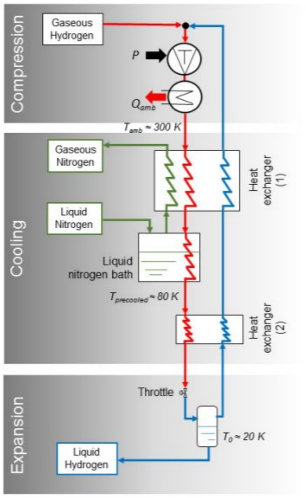
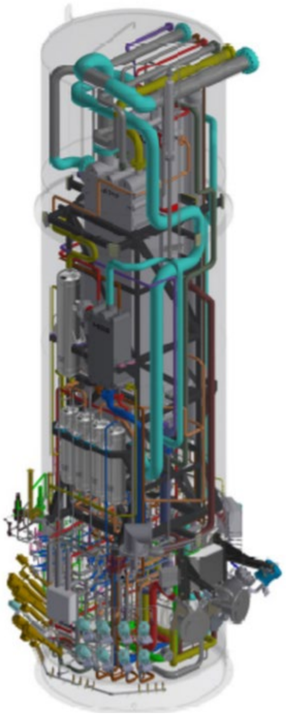
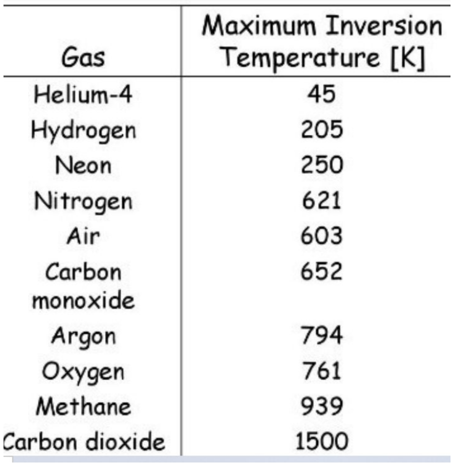


Figure 1. Joule–Thomson process with liquid nitrogen precooling redrawn based on a figure from Alekseev (2016).

Figure 12: Schematic of the hydrogen liquefication process (DOE)





Gas	Maximum Inversion Temperature [K]
Helium-4	45
Hydrogen	205
Neon	250
Nitrogen	621
Air	603
Carbon monoxide	652
Argon	794
Oxygen	761
Methane	939
Carbon dioxide	1500

10 Tons/Day Hydrogen Liquefier Vacuum Cold Box
10 ft Diameter x 40 ft High – 300 K to 20 K

Figure 13: A H2 liquefier from Chart Industries

A recent study (2019) of the cost of hydrogen liquefaction by DOE (Sandia and ANL) and the resultant estimated hydrogen fuel costs are given in [21]. The costs of the liquefier are given in Fig. 14 and 15. DOE used HDSAM in their study and assumed high costs for station components in their calculations. The DOE costs for liquefaction are about $2500/kg/day for large liquefiers and over $4000/kg/day for small liquefiers. The projected effect of liquefaction on the cost of LH2 is $1.3-1.4/kgH2. The DOE paper projected a cost in California (2019) of $14/kg for LH2.

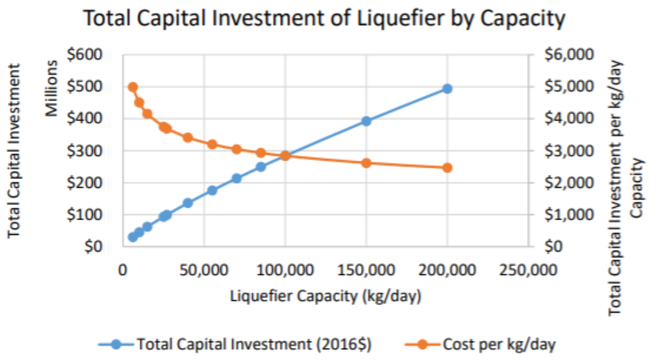


Figure 2. HDSAM results for the total capital investment of hydrogen liquefiers in an early market scenario. Results are presented in 2016$.

Figure 14: Capital costs of H2 liquefiers in early market (low production volume [21]

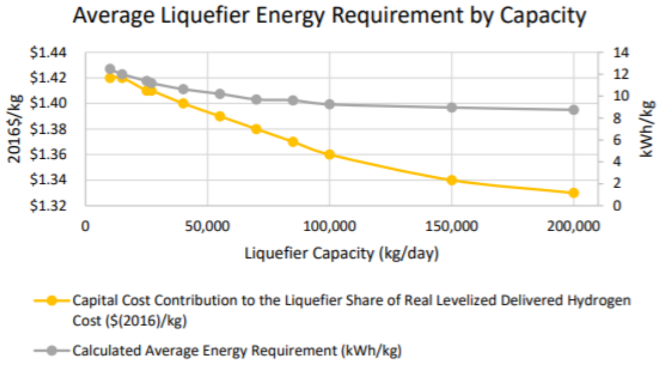


Figure 3. HDSAM results for (i) the liquefier capital cost contribution to levelized cost of hydrogen in an early market scenario (2016$) and (ii) the calculated average liquefier energy requirement (kWh/kg).

Figure 15: Effect of H2 liquefier and electricity costs on hydrogen cost ($/kg) [21]

In the present study, calculations of liquefaction costs were made using HDSAM for several cities of various size (population). The LH2 station results are summarized in the tables below. The population in the Los Angeles area is 12 million while it is 154 thousand in Medford, Oregon. The HDSAM results indicate the differences in the fuel costs in the two cities are relatively small. As indicated in the tables, the cost values used in the HDSAM calculations were for the high production, low cost inputs for the station components. The cost values shown in Table 6 are consistent with the DOE results in Fig. 11. This was not expected because the DOE calculations were made assuming high component costs.

Table 11: Normalized cost of LH2 liquefiers

City area	Liquefier kgH2/da	Liquefier Cost* $	Liquefier $/kgH2/da	Electricity kWh/kgH2
New York	2.9×10^6	7.2×10^9	2480	7.8
Los Angeles	2.18×10^6	5.4×10^9	2550	7.9
Baltimore	400×10^3	987×10^6	2460	
Knoxville	101×10^3	286×10^6	2830	
Medford, OR.	28×10^3	102×10^6	3643	9.59

*High production, low cost option in HDSAM

The HDSAM results for the incremental cost of hydrogen dispensed at LH2 stations in Los Angeles and Medford are summarized in Table 12 for several types of refueling stations. The incremental H2 cost varied between $5.7/kg and $ 3.95/kg in Los Angeles and between $6.5/kg and $3.8/kg in Medford. In both cities, the highest cost was at LH2 stations using compression/vaporization to deliver the hydrogen to the vehicle. The lowest cost was at standard refueling stations delivering 700 bar gaseous H2 to the vehicles. LH2 stations using cryo-pumps had intermediate hydrogen costs. These LH2 costs are consistent with those cited in [21]. The HDSAM calculations indicated LH2 stations are likely to have higher hydrogen prices than CH2 stations due to the cost of liquefaction.

Table 12: Station contributions to the cost of hydrogen at LH2 stations

City	Station type	H2 cost $/kg	Liquefication Cost* $/kg	Station cost* $/kg	Truck deliv*. $/kg
LA area LDV 1600 kg/day	LH2 Compress. 700 bar.	5.74	2.10	3.0	0.30
	LH2 Liquid cryo-pump 700 bar	4.31	2.16	1.54	0.30
	CH2 Compressed 700 bar	3.95	0.96 compression	2.12	0.83
Medford, Oregon LDV 1263 kg/day	LH2 Compress. 700 bar.	6.50	2.90	3.03	0.22
	LH2 Liquid cryo-pump 700 bar	5.04	2.89	1.54	0.22
	CH2 Compressed 700 bar	3.82	1.03 compression	2.12	0.53

*LH2 produced at a central liquefaction plant and delivered to the refueling stations

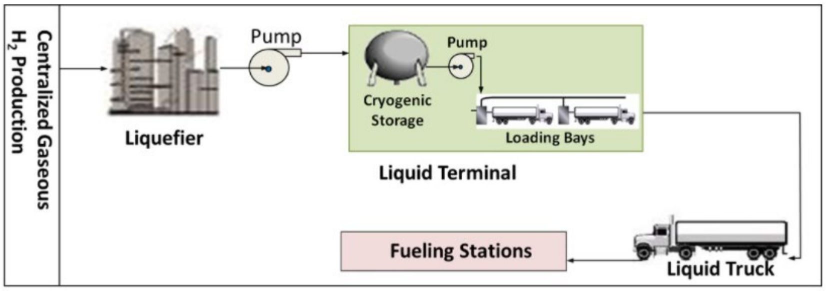
In the hydrogen station cost projections given in Table l2, it was assumed that the liquefaction was done at a large central plant and the LH2 was transported to the refueling station by tanker truck. At large truck refueling stations of capacity 20000 kg/day or larger, onsite liquefaction may be a possibility. That would avoid the transport cost of the LH2 from the central plant and likely reduce the onsite storage of LH2 required. How the cost ($/kgLH2/day) of an onsite plant would compare with that of the larger central plant is not known at present time, but it should be investigated. Further it is important to project the reduction to be expected in the he future cost of the liquefaction of hydrogen as the technology matures and more large plants are built. The energy component of the liquefaction cost is significant, but it is expected to be reduced. This reduction combined with the expected reduction in the cost of sustainable electricity from solar and wind will also contribute to reducing the cost of liquefaction. Starting from the liquefaction costs projected from the HDRSAM calculations, it seems likely the liquefaction costs can be less than $2/kgLH2 in the future.

Electrolysis is clearly the preferred way to produce the gaseous hydrogen because it is “Green”. AS noted in previous discussion, hydrogen can also be produced from natural gas using the SMR process. If the CO_2 produced in the SMR process is captured and stored (CCS, the CH2 could be low in CO2 (blue). The SMR process has the advantage of being co-located with the liquefaction plant because natural gas can be transported/distributed to where ever it is needed. On the other hand, electrolysis require a large area even if it uses grid electricity. Hence SMR has an advantage over electrolysis of both lower cost and of co-location with the liquefaction plant. However, it seems likely that most hydrogen will be transported to large liquefaction plants via pipelines regardless how it is produced.

Liquid hydrogen transportation and storage at Refueling stations

The cost of liquefying the hydrogen and then delivering it by truck and storing it at the refueling station is important in determining the cost of the hydrogen dispensed to vehicles (see Fig. 15). A second option is to liquefy the hydrogen at the refueling station using H2 delivered by pipeline. That may be the best option for the large stations needed to serve long haul HD trucks. As shown in Figure 17, LH2 can be delivered to refueling stations in large (9 ft. diameter-50 ft length) tubular, super insulated containers that hold about 4000 kg of hydrogen. Even larger tanks can be used to transport LH2 by rail. These tanks carry 7700 kgLH2 and have a boil-off of 0.3-0.6 %/day. The LH2 can be off-loaded and stored at the station in horizontal or vertical cylindrical containers as shown in Figure 18. The largest of the LH2 storage tanks from Chart Industries is 10 ft in diameter and 44 ft in length and stores about 2280 kg of LH2 [22]. Larger tanks are available that store up to 5000 kgLH2.

There has not been much consideration of seasonal storage (months) in the literature due at least in part to the difficulty in transporting LH2 [15] to/from large underground storage reservoirs like rock and salt caverns. Seasonal storage of hydrogen is done in the caverns at a relatively low cost of $.5-1/kgH2.



Liquid hydrogen delivery pathways

Figure 16: Hydrogen liquefaction at a central plant and delivery by truck [10]

Figure 17: LH2 tractor-trailer transporter 4000 kgH2

Figure 18: Horizontal and vertical LH2 storage

As discussed previously, the best way to transfer the cryogenic hydrogen to a storage unit onboard the vehicle is using a pump submerged in the station LH2 supply. The pressure in the vehicle's storage unit can vary over a wide range from 10-300 bar using the cryogenic pump [3]. This approach maximizes the density (kgH2/L) in the storage unit and the kg H2 stored. As shown in Table 5, it is also the lowest cost approach to refueling fuel cell vehicles.

Cost of Hydrogen at the pump

The previous sections of the report have discussed in detail the various factors that contribute to the cost of hydrogen at the pump. In this section, the factors will be summarized and the total cost of hydrogen at the pump will be projected for several production pathways and refueling station arrangements. The production pathways considered are SMR and electrolysis.

The refueling station arrangements are 700 bar gaseous (CH2) and several LH2 stations including those using cryo-pumps. The contributors to the total cost ($/kg) of hydrogen dispensed are the following: (1) the cost of production, (2) the cost of transport, both long distance and local, (3) the cost of liquefaction for LH2, (4) Costs associated with the refueling station and dispensing the hydrogen to the fuel cell vehicle. These individual costs are shown in Table 13. The projected total hydrogen costs for each refueling station category are also shown in the table. All the costs shown in Table 13 correspond to the time when considerable progress has been made to reducing the cost of hydrogen and its distribution. That is likely to be sometime after 2030.

Table 13: Summmary of hydrogen costs from various contributing factors

Cost contributor					
Production	**SMR**		**electrolysis**		
$/kg	1.5		2.0		
Transport	**Long distance Pipeline**	**rail**	**Local truck**		
$/kg CH2	.3	1.2	.8		
$/kg LH2		.8	.3		
Central plant liquefaction	Large plants				
$/kg LH2	1.75				
H2 refueling stations	**CH2 700 bar**	**CH2 350 bar**	**700 bar LH2 with compressor Low pressure cryo-pump**	**LH2 with cryo-pumps High pressure/vapor.**	**Direct cryo-genic.**
$/kgLH2	1.5	.8	2.0	.55	.3
Total H2 cost	**CH2 700 bar**	**CH2 350 bar**	**LH2 Low pressure cryo-pump, vaporize, comp.**	**LH2 with high pressure cryo-pump/vaporize**	**Direct cryo-genic**
$/kgH2 SMR	4.1	3.4	6.3	4.9	4.6
$/kgH2 Electrolysis	4.6	3.9	6.9	5.4	5.1

The lowest hydrogen cost ($3-4/kg) at the pump would be for compressed gas produced from SMR, but that H2 is not sustainable and its emissions are not zero. The cost of the hydrogen from electrolysis as a compressed gas is about $1/kg higher from SMR, but it is sustainable and its emissions are zero. In all cases, the cost of the LH2 at the pump is higher than the 700 bar compressed gas due to the cost of liquifying the hydrogen. The price difference depends on how the LH2 is compressed and transferred to the vehicle. If the pressure of the LH2 is increased to 700 bar with a compressor, the price difference is about $2/kg. If the pressure of the LH2 is increased using a cryo-pump, the price difference is less than $1/kg with the lowest LH2 price occurring for the H2 being stored as a cryo-genic liquid onboard the vehicle. All the prices are higher for H2 produced from electrolysis. That difference could be as high as $4-5/kg in 2022, but the difference is expected to decrease to $1-2/kg by 2035. The higher cost of LH2 is due to the cost of liquefaction, which presently could be $4-5/kgH2. It is projected that the cost of liquefaction will decrease to $1.5-2.5/kgH2 by 2030-2035.

The major uncertainty in projecting the cost/price of H2 is not so much the prices attainable, but how soon it can be expected that the low prices will occur in the market. That depends to a large extent on the growth of demand for hydrogen which will depend on the growth of fuel cell vehicle (FCV) sales. That growth itself will depend on the price of hydrogen faced by fuel cell vehicle drivers. At the present time, the high cost of hydrogen is provided to all those that purchase a FCV by the vehicle manufacturers. Without some policies leading to large reductions in the price of hydrogen, it is difficult to see a large growth in fuel cell vehicle sales of either LDVs or MD/HD trucks.

Early applications, constraints, and growth factors for LH2

General considerations

The analyses of the previous sections indicate that LH2 has an advantage over high-pressure gaseous hydrogen (CH2) when handling large quantities of hydrogen are involved whether on the vehicle or at the refueling station. For local transport in tubes and tanks, it is more convenient and lower cost to transport large quantities of hydrogen per day as LH2 than CH2. After delivery to the refueling stations, the dispensing of the hydrogen to the vehicles can be at much lower cost after LH2 delivery than CH2 delivery. This is the case whether the hydrogen is dispensed to the vehicle as CH2 or LH2. Storage of hydrogen onboard the vehicle as a liquid has a large advantage in terms of the kg of hydrogen that can be stored in the available volume. Hence the range of vehicles storing hydrogen onboard as LH2 can be twice or more the range of vehicles storing hydrogen as CH2.

All of these advantages of LH2 are more important for medium-duty and heavy-duty truck applications that involve the need for storing larger quantities (kg) of hydrogen onboard the vehicle and dispensing larger quantities (kg/day) of hydrogen at refueling stations. In addition, the short refueling time possible (10-15 minutes) with hydrogen with either LH2 or CH2 is a more valuable asset compared to battery-electric trucks that require very large and heavy batteries which require much longer to recharge. It seems likely that when the refueling technologies for LH2 are mature that refueling with LH2 will be faster than with CH2. One of the disadvantages with LH2 is boil-off of the hydrogen when it is stored. That disadvantage is less important for commercial truck applications that use fuel on a regular basis.

The primary disadvantages of LH2 are its higher cost due to the cost of liquefaction and the difficulty in transporting LH2 long distances. These difficulties require the development, construction, and operation of large, efficient central liquefaction plants that produce LH2 at relatively low cost. These plants can be supplied with gaseous hydrogens through a pipeline network and the LH2 can be delivered to refueling stations via tanker trucks. Reducing the cost of the liquefaction is important. Present projections based on calculations with the HDSAM DOE program (Table 12) are \$2-3/kgLH2. It seems likely that this cost will be reduced in the future much as has been occurring with battery, fuel cells, and electrolyzers. Another factor in reducing the cost of liquefaction can be the expected lower cost of electricity from solar and wind resources as shown in Table 4. This will also reduce the cost of producing hydrogen from electrolysis. In the hydrogen cost projections shown in Table 13, it was assumed that in the future (post 2030), the cost of liquefaction would be \$1.75/kgLH2 and the cost of hydrogen produced with electrolysis would be \$1.5/kg. The resultant cost of hydrogen is close to \$5/kg.

There seems little doubt as to the advantages of using LH2 for MD/HD fuel cell trucks. The question remains as to possibilities of using LH2 in light-duty applications after or during the development of the hydrogen infrastructure for those vehicles. A key issue here are the characteristics and cost of the LH2 onboard vehicle storage unit being developed for trucks. If these storage unit developments indicate that small 5-10 kg units can be developed at an attractive cost and a strong LH2 infrastructure is developing, it seems reasonable to consider that LH2 is a possibility for light-duty vehicles

Importance of cryo-pump technology for LH2

At the present time, work to develop the technology for LH2 fueling of fuel cell vehicles is focused on heavy duty vehicle (HDV) applications in which large amounts (>50 kg) of hydrogen are stored on the vehicle. As a result, hydrogen refueling stations for HDVs will dispense greater than 5000 kgH2/day. As shown in previous sections of this report, this can be done more effectively with LH2 than CH2. The early applications of LH2 systems have been with transit buses (24). These applications require fast refueling of large quantities of hydrogen at bus terminals. Demonstration bus applications of new cryo-pumps (see Table 5) being developed by NICE [10, 12, 24) have been tested successfully. The tests indicate those technologies will significantly reduce the cost of LH2 refueling stations and of fuel cell HD vehicles. The cryo-pumps being demonstrated appear to be at the TRL 5 level of development or even TRL 6 as some of the new pumps are being to be available for sale.

UCD is performing a detailed study of how the hydrogen economy will evolve in California between 2025 and 2050. One aspect of that study is to project the development of markets for CH2 and LH2 in vehicles. A preliminary result of that study is shown in Fig. 19. The major elements of the market are hydrogen distributed by GH2Truck, LH2Truck, and GH2 pipeline. These results indicate LH2 will be a major player in the hydrogen market with about 40% market share. UCD is also studying the role of both short (days) time and seasonal (months) storage of hydrogen. Most of the storage and distribution will be with CH2, but there will significant storage of LH2 near liquefaction plants and at refueling stations. It is important that the effect of the storage on the dispensed cost of the hydrogen be less than \$1/kg. The cost of liquefaction and storage will be important factors in the development of the LH2 market.

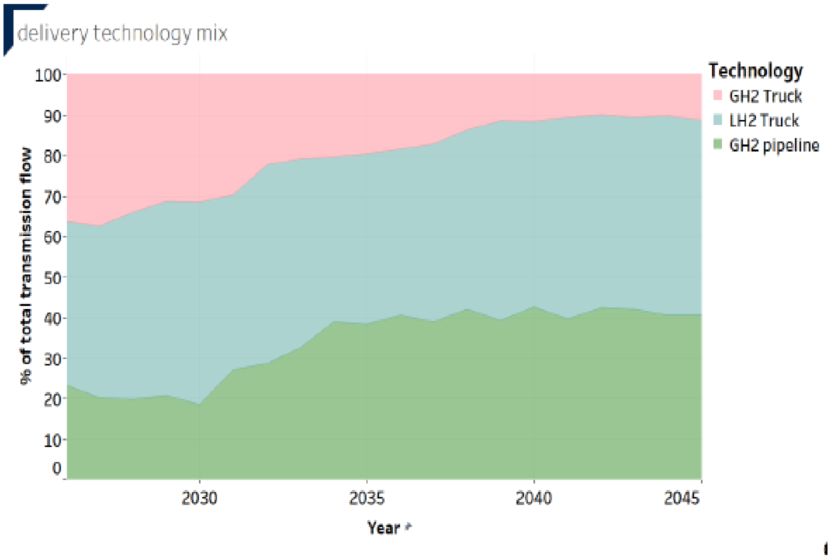


Figure 19: Growth of the use of LH2 in years beyond 2030 [29]

Summary and conclusions

In this report, various aspects of the use of liquid hydrogen (LH2) in heavy-duty vehicle applications, especially for transit buses and fuel cell long haul trucks, were considered in detail. Special attention was given to the cost of hydrogen refueling stations that receive and store the hydrogen as LH2 and the cost of liquefaction of the hydrogen. Other areas of special attention were the physical characteristics of onboard hydrogen storage units being developed that use LH2 and the way in which the LH2 is processed before and during transfer to the onboard storage unit. Finally, projections were made of the cost ($/kg) of the hydrogen dispensed at LH2 refueling stations and the advantages of LH2 for MD/HD truck applications.

The hydrogen can be stored onboard the vehicle as high pressure gas or a cryogenic liquid. Storing the hydrogen as a liquid is advantageous for long haul truck and bus applications because for the same storage volume, the range (miles) of the vehicle can be 2 times greater than using a high pressure gas depending on the gas pressure. The cost of the LH2 units is uncertain as they are still being developed.

The cost of the LH2 refueling station depends on whether the hydrogen will be transferred to the vehicles as a high- pressure gas (350 or 700 bar) or a cryogenic liquid. In addition, the station cost depends on how the high-pressure gas is produced from the LH2. One approach is to vaporize the LH2 and then increase the gas pressure using a compressor. A second approach is to use a cryogenic pump to increase the pressure of the LH2 and then vaporize the high pressure liquid. Detailed analysis of station costs indicates the second approach results in lower cost ($/kgH2/day). The difference in cost is large being at least 50%. The cost of the LH2 station using vaporization and compression to produce the hydrogen gas is close to that of the compressed gas station (700 bar) for all station capacities. All stations dispensing 350 bar H2 are significantly lower cost than those dispensing 700 bar H2. The technology for the stations using a cryogenic pump is presently being demonstrated. A third approach being developed to refuel vehicles at LH2 stations is to transfer the hydrogen as a cryogenic liquid for storage on the vehicle and vaporizing the liquid to the pressure and temperature needed to operate the fuel cell as the vehicle is operated. It is anticipated that the cost of this third approach will be even lower than using the cryo-pump with gaseous hydrogen because the hydrogen is always at a relatively low pressure of a few bar with cry0genic LH2 storage.

The results of this study indicate it is likely that the dispensed price ($/kg) of hydrogen at stations that receive and store H2 as a liquid will be slightly higher than at stations utilizing only gaseous hydrogen. The higher price is due to the cost of liquefying the hydrogen as the LH2 station costs are lower if the stations utilize a cryogenic pump. HDSAM calculations show a liquefaction cost of about $2500/kgH2/da for large central liquefiers and a resultant effect on the cost of hydrogen of $2-3/kg. The use of the cryogenic pump can reduce the dispensed cost of H2 by about $1 kg. Hence, the projected incremental cost of hydrogen at LH2 stations could be $1-2/kg higher than at CH2 stations even in LH2 stations using the cryogenic pump approach.

There seem to be reasonable prospects for reducing the cost of liquefaction on large central plants as more of these plants are constructed and operated. Another factor is the expected lower cost of electricity from solar and wind resources in the future. Liquefaction of hydrogen is energy intensive so a lower electricity cost can have significant effect on the liquefaction cost. In the hydrogen cost projections, a future liquefaction cost of $1.75/kgLH2 was assumed resulting in a dispensed hydrogen cost of close to $5/kgH2 at LH2 stations using cryo-pumps.

The analyses in this report indicate that LH2 has an advantage over high-pressure gaseous hydrogen (CH2) when handling large quantities of hydrogen are involved whether on the vehicle or at the refueling station. After delivery to the refueling stations, the dispensing of the hydrogen to the vehicles can be at much lower cost after LH2 delivery than CH2 delivery. This is the case whether the hydrogen is dispensed to the vehicle as CH2 or LH2. Storage of hydrogen onboard the vehicle as a liquid has a large advantage in terms of the kg of hydrogen that can be stored in the available volume. Hence the range of vehicles storing hydrogen onboard as LH2 can be twice or more the range of vehicles storing hydrogen as CH2. The advantages of LH2 are more important for medium-duty and heavy-duty truck applications that involve the need for storing larger quantities (kg) of hydrogen onboard the vehicle and dispensing larger quantities (kg/day) of hydrogen at refueling stations. In addition, the short refueling time (10-15 minutes) possible with hydrogen with either LH2 or CH2 is a valuable asset compared to battery-electric trucks that require very large and heavy batteries and much longer to recharge. It seems likely that when the refueling technologies for LH2 are mature that refueling with LH2 will be faster than with CH2.

The question remains as to possibilities of using LH2 in light-duty applications after or during the development of the hydrogen infrastructure for those vehicles. The key issues are the characteristics and cost of the LH2 onboard vehicle storage unit being developed for trucks. If these storage unit developments indicate that small 5-10 kg units can be developed at an attractive cost and a strong LH2 infrastructure is developing, it seems reasonable to consider that LH2 is a possibility for light-duty vehicles.

References

1. E. Rivard, M. Trudeau, and K. Zaghib, Hydrogen Storage for Mobility, Materials, 2019,12, 1973
2. P. Murray, Chart Industries, private email on vehicle energy storage, 2021
3. R.K. Ahluwalia, T.Q. Hua, J.K. Peng, et al, Technical Assessment of Cryo-compressed Hydrogen Storage Tank Systems for Automotive Applications, ANL/09/33, December 2009
4. J.M. Blanco, G. Petitpas, F.E. Loza, et al, The fill-density of automotive cryo-compressed hydrogen vessels, Hydrogen Energy, 2018, 10, 227
5. G. Petitpas and S. Aceves, Liquid Hydrogen Pump Performance and Durability Testing through Repeated Cryogenic Vessel Filling to 700 Bar, LLNL-JRNL-746861, Feb 26, 2018
6. Green hydrogen cost reduction scaling up electrolysers to meet the 1.5deg climate goal, IRENA
7. N. Rambhujun, M.S. Salman, T. Wang, et.al., Renewable Hydrogen for the Chemical Industry, MRS Energy and Sustainability, August 2020
8. Vijayakumar, Computer modeling of large H2 networks using SERA, UC Davis Hydrogen Project, Feb. 2022
9. Assessment of hydrogen delivery options, Science for Briefs, European Commission
10. X. J. Li, J. Allen, J.A. Stager, and A.Y. Ku, Paths to low-cost hydrogen energy at scale for transportation applications in the USA and China via liquid-hydrogen distribution networks, Clean Energy, 2020, Vol. 4, No. 1, 26-47
11. Overview-Hydrogen refueling for heavy-duty vehicles, Energy Progress, H2 Mobility, internet
12. A. Ku, J. Li, and J. McRobie, Cracking the chicken-and-egg problem of large-scale hydrogen refueling networks, NICE America Research, Feb. 2022
13. Hydrogen Refueling Station Analysis Model (HRSAM), Energy Systems, available on the internet
14. Hydrogen Refueling Station Analysis Model (HDSAM), Energy Systems, available on the internet
15. C. Zhou, G. Zhu, Y. XU, et.al., Novel methods by using non-vacuum insulated tubing to extend the lifetime of the tubing, Frontier Energy 2015, 9 (20): 142-147
16. Ballard and Chart Industries successfully test a fuel cell powered by liquid hydrogen, Green Car Congress, Feb 4, 2022, internet
17. J. Li, A. Ramteke, E. Youn, et al, Liquid pump-enabled hydrogen refueling system for heavy duty fuel cell vehicles: Pump performance and J2601 compliant fills with precooling, International Journal of Hydrogen Energy, 46 (2021) 22018-22029

18. A.K. Ku, K. Reddi, A. Elgowainy, J. Robie, J. Li, Liquid pump-enabled hydrogen refueling system for medium and heavy duty fuel cell vehicles: Station design and technoeconomic potential, new Ku paper on cryo-pumps, 2022
19. M. Aziz, Liquid Hydrogen: A Review on Liquefaction, Storage, Transportation, and Safety, Energies 2021, 14, 5917
20. L. Yin and Y. Ju, Review on the design and optimization of hydrogen liquefaction processes, Front. Energy 2020, 14(3):530-544,16.
21. E. Connelly, M. Penev, A. Elgowainy, and C. Hunter, Current Status of Hydrogen Liquefaction Costs, DOE Record 19001, September 9, 2019
22. Brochures on hydrogen storage tanks, Chart Industries, 2021
23. A. Elgowainy, K. Reddi, and M. Aly, Hydrogen Refueling Analysis of Fuel cell Heavy-Duty Fleet, Presentation at Fuel Cell Truck Workshop, Argonne National Lab, July 31, 2018
24. J. Li, E. Youn, A. Ramteke, et.al., Liquid pump enabled hydrogen refueling system for heavy duty fuel cell vehicles: Refueling fuel cell demonstration at Stark Area Regional Transit Agency (SARTA)
25. R.K. Ahluwalia, T.Q. Hua, P.J. Peng, et.al., Technical Assessment of cryo-compressed hydrogen energy tank system for automotive applications, International Journal of Hydrogen Energy, 35 (2010), 4171-4184
26. T. Brunner, Cryo-compressed Hydrogen Storage, BMW presentation, Washington, D.C., Feb 11, 2011
27. O. Kircher, G. Greim, et.al., Validation of cryo-compressed Hydrogen Storage (CCH2)- A Probabilistic Approach, BMW report
28. S. Aceves and K. Szoucsek, Hydrogen Storage Tests, Advanced cryo-compressed hydrogen delivery , May 19, 2021and onboard storage, Final report TC02207, LLNL-TR-824154, July 6. 2021
29. Vishnu Vijayakumar, Hydrogen Supply Chain Analysis using SERA for WECE, slides for presentation, March 2022
30. German Startup Cryomotive launches hydrogen storage, internet, Jan 31, 2022
31. Verne-hydrogen storage for trucks- Sustainable transport, internet, 2022
32. Chart Industries invests in and signs commercial agreement with Cryomotive, internet, May 19, 2021