On-board Cryogenic Hydrogen Storage Performance and Cost Analysis

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Hydrogen Infrastructure Priorities to Enable Deployment in High-Impact Sectors

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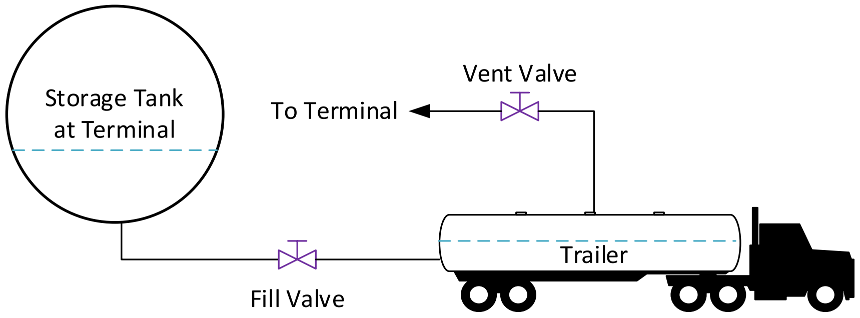
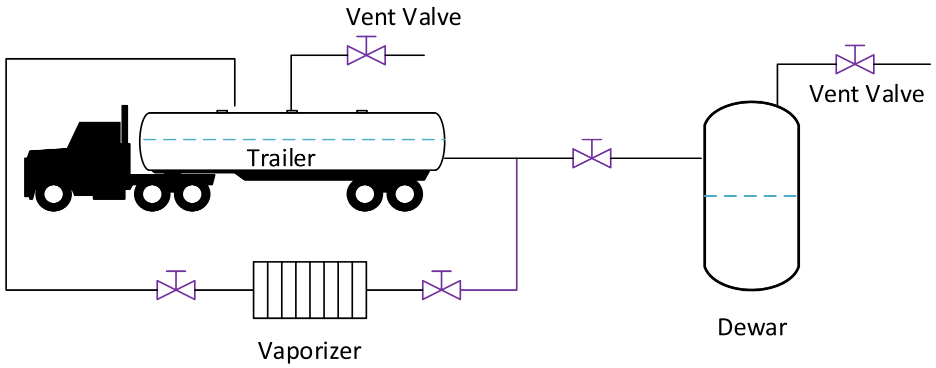
NATIONAL LABORATORY

LH_2 Scenario

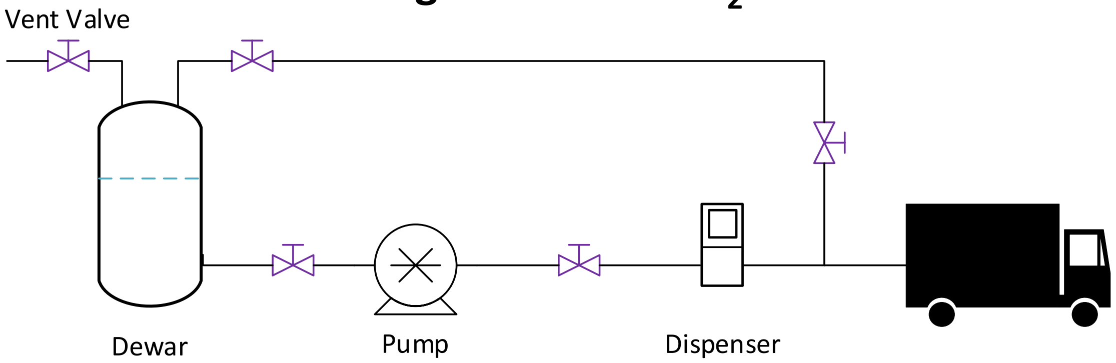
Trailer Loading at Terminal



Dewar Loading at Refueling Station



Refueling of FC Truck LH_2 Tank



Loading 64,350-L Trailer at Terminal (Liquefaction Plant)*

- Pressure transfer from terminal at 24 psia to trailer at 20-22 psia, ~600 kg/h LH_2 transfer rate
- 3.3% total boil-off during loading and initial trailer depressurization

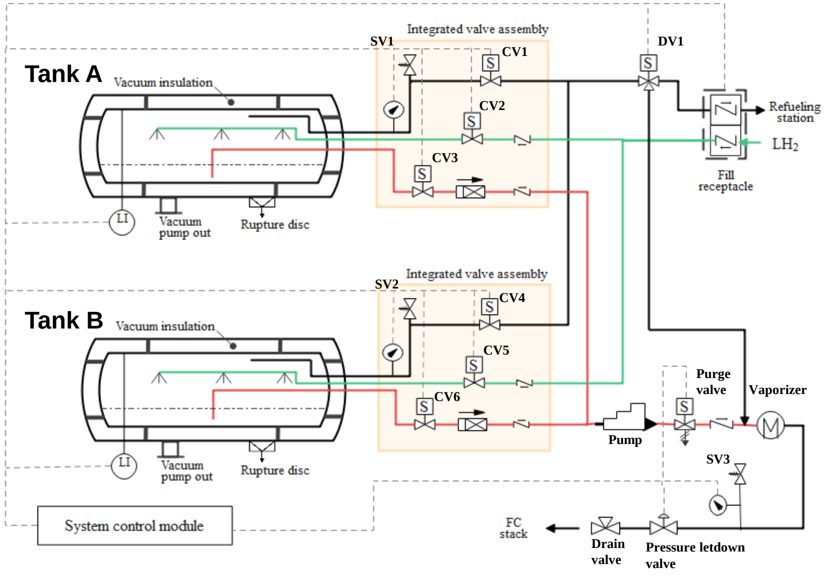
Loading 12,500-L Dewar at Refueling Station*

- Pressure transfer from trailer pressurized to 60 psia to Dewar maintained at 45 psia, ~1100 kg/h average LH_2 transfer rate
  - ➢ 16% total boil-off loss including 3% from Dewar during loading and 12% from final depressurization of trailer to 20 psia
- Pump transfer can greatly reduce the H_2 loss rate
  - ➢ 3.4% from Dewar, 0% from trailer

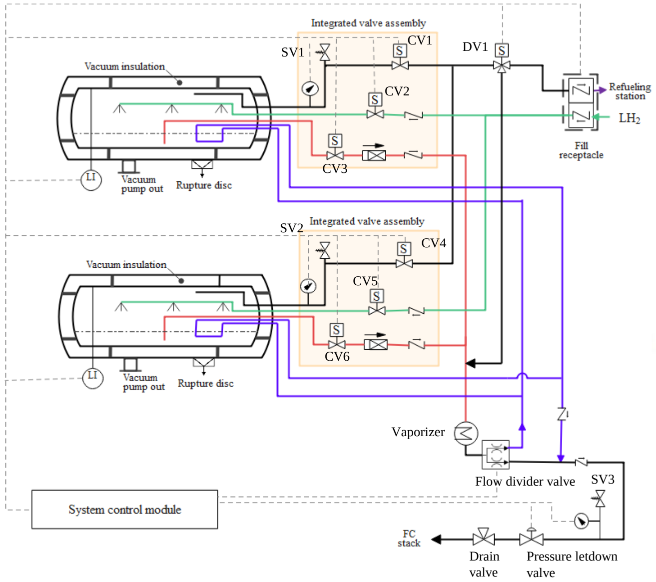
- *Guillaume Petitpas, "Simulation of boil-off losses during transfer at a LH_2 based hydrogen refueling station," IJHE, 43 (2018) 21451-21463

LH_2 Storage for Heavy Duty Trucks

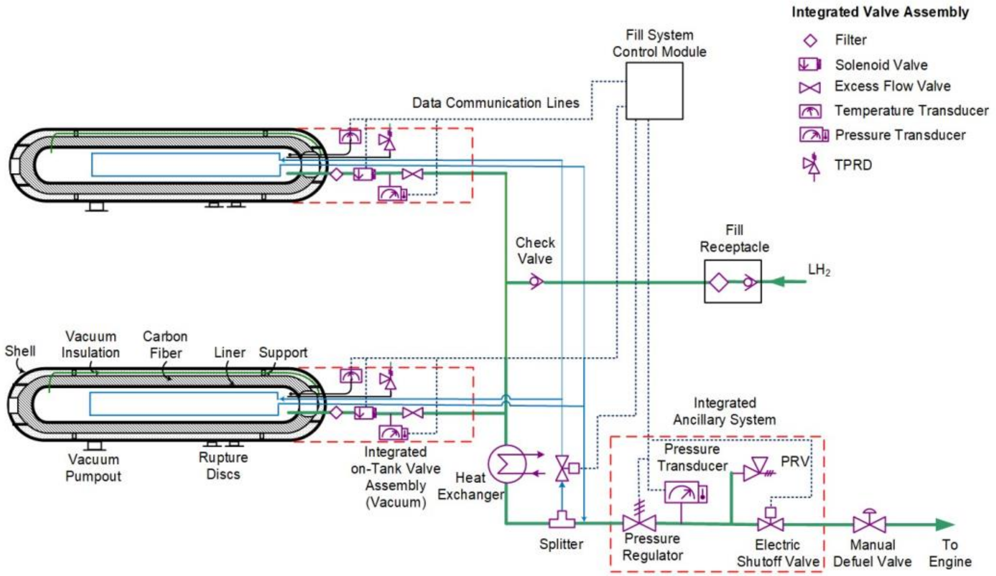
LH_2-1 (with On-Board Pump)



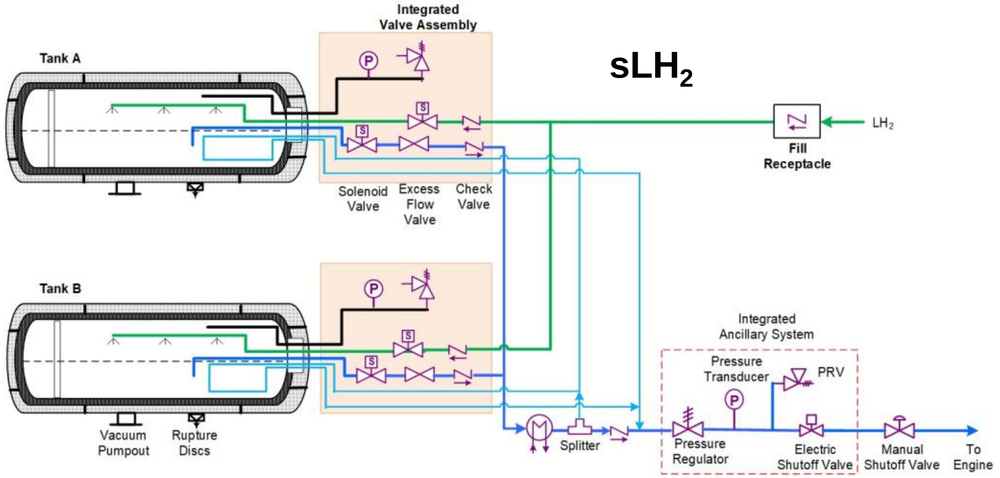
LH_2-2 (without On-Board Pump)



CcH_2



sLH_2



	LH_2-1	LH_2-2	CcH_2	sLH_2
On-board Pump	Yes	No	No	No
In-Tank HX	No	Yes	Yes	Yes
MAWP (bar)	10	10	400	20
Operating Pressure (bar)	3-5	6-8	6-400	6-13
Allowable Heat Gain (W/m^2)	2	1	2	2
Minimum Dormancy (h)	24	24	>24	24

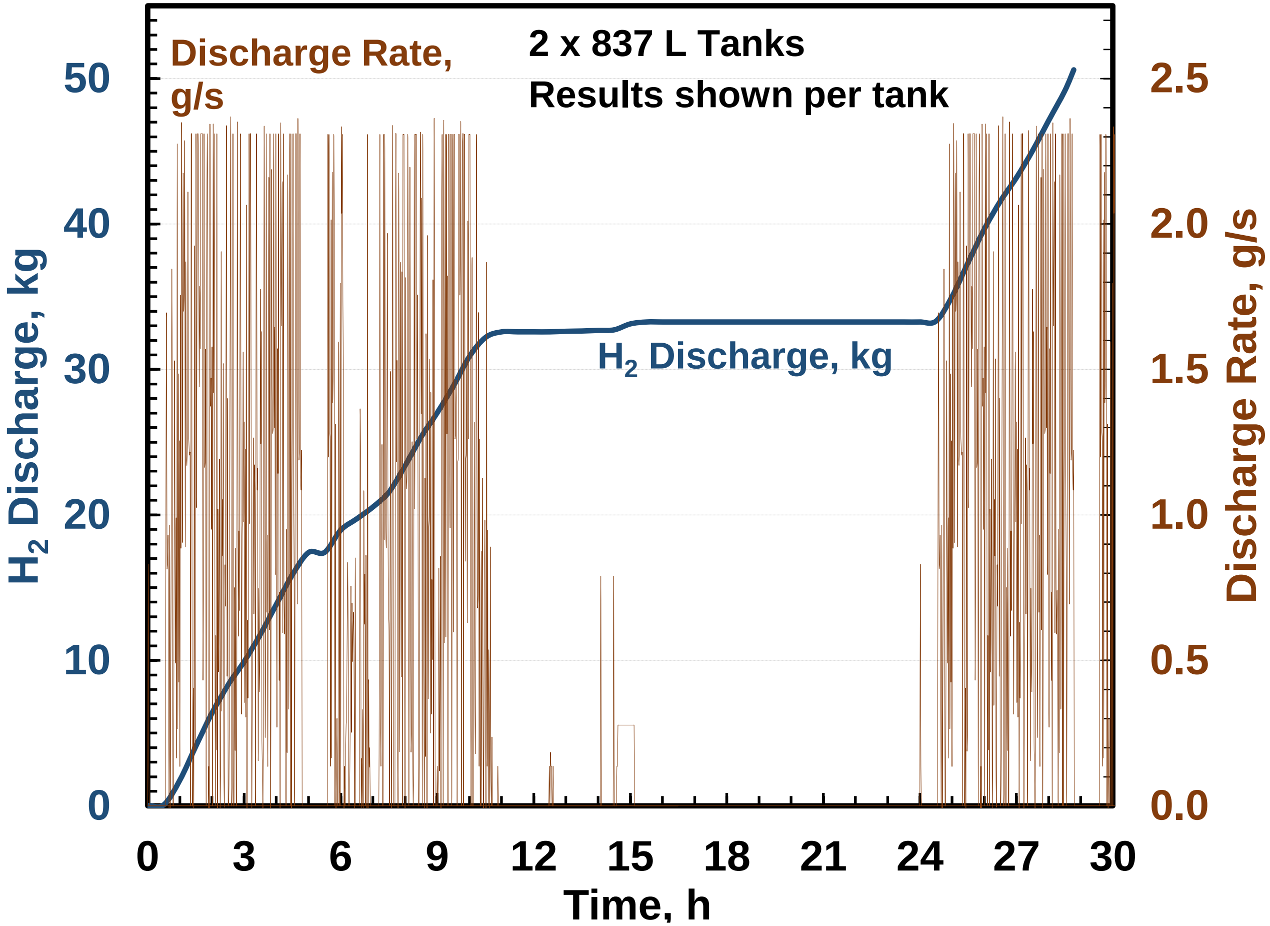
1. R K Ahluwalia, et al, “Liquid hydrogen storage system for heavy duty trucks: Configuration, performance, cost, and safety,” IJHE, 48 (2023) 13308-13323
2. R K Ahluwalia, et al, “Liquid hydrogen storage system for heavy duty trucks: Capacity, dormancy, refueling, and discharge,” IJHE, 48 (2023) 34120-34131
3. R K Ahluwalia, et al, “Supercritical cryo-compressed hydrogen storage for fuel cell electric buses,” IJHE, 43 (2018) 10215-10231
4. S Schäfer and S. Maus, “Technology Pitch: Subcooled Liquid Hydrogen (sLH_2),” NOW & CEP Heavy Duty Event, April 21st , 2021

On-Board Storage System Metrics

Task	Metric	AnalysisTarget	Analysis Approach
1	**Storage System Range**	750 miles	Assemble and analyze duty cycles Harmonize with 21st Century Truck Partnership
2	**Storage System Capacity**	>60 kg	Consider packaging and sizes of CNG tanks for MD and HD trucks Frame Mounted, Roof Mounted and Behind the Cab Configurations
3	**Refueling Rate**	8-10 kg/min	Develop specifications for off-board refueling pump Develop model for refueling dynamics
4	**Discharge Rate**	4.6 g-H_2/s (16.6 kg/h) 6-bar discharge pressure	Consider 275-kW fuel cell system with 46-kWh battery storage system Develop thermal management requirement Simulate tank discharge dynamics with and without on-board pump Develop pump requirements: 1-stage or 2-stage
5	**Hydrogen Loss**		Determine H_2 loss during refueling
6	**Insulation and Dormancy**	>1-2 W/m^2 heat gain <2 mbar vacuum	Consider multi-layer vacuum insulation for minimum 1-d dormancy Conduct heat transfer analysis to determine number of layers and vacuum pressure
7	**Structural Analysis**	5,000 refueling cycles 11,000 cycles	Liner: ABAQUS FE analysis of hoop stress and safety factor, ASME BPVC Div-1 code for liner thickness; Shell: ABAQUS FE buckling analysis for maximum stress and safety factor, ASME BPVC Div-1 code for liner thickness
8	**Strucural Materials**		Aluminum 2219 -T87 preferred for cryogenic applications Aluminum 5083 and SS 304 also considered as candidates
9	**Gravimetric Capacity**	15 wt.% (study goal)	Conceptualize system with all BOP components Estimate component weights
10	**Volumetric Capacity**	>35 g/L (study goal)	Conduct system analysis and estimate componet volumes
11	**System Cost**	8-9 $/kWh	Bottom-up cost analysis
12	**Safety Codes and Standards**	Applicable SAE and and GTR standards	Failure modes and effects (FMEA) and safety codes and standards (SCA) analyses Review codes: SAE J2343, SAE2578, SAE2579, NFPA-52
13	**LH_2 Refueling Interface**		Conceptual design of LH_2 refueling station

LH_2 Storage for Heavy Duty Trucks: Packaging Options and Capacity

- Autonomie simulation of power demand by Vincent Freyermuth (ANL): 21st Century Partnership platform for long-haul class 8 HD truck
- Fuel cell simulation of Hydrogen Consumption: 275 kW FCS hybridized with 70 kWh battery
- Peak H_2 flow rate: 4.6 g/s (16.6 kg/h)
- 16 packaging options in frame mounted (FM), roof mounted (RM) and behind-the-cab (BTC) configurations for medium- and heavy-duty vehicles[1]



Packaging Options[1]

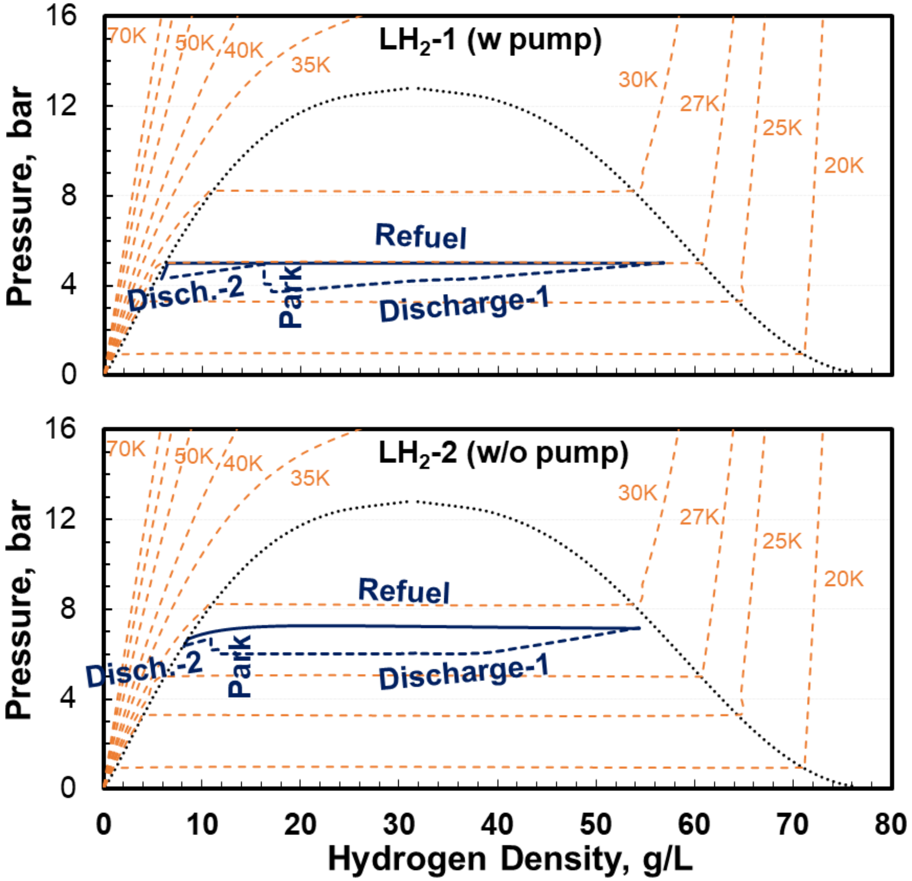
Baseline Packaging Options		
Outer Diameter (cm) X Outer Length (cm)		
Frame Mounted, FM	**Roof Mounted, RM**	**Behind the Cab, BTC**
2 Tanks	4 Tanks	2, 3 or 4 Tanks
53 X 120	41 X 203	41 X 203
53 X 152	41 X 246	53 X 203
53 X 203	30 X 246	
66 X 152		
66 X 203		
66 X 229		
66 X 305		

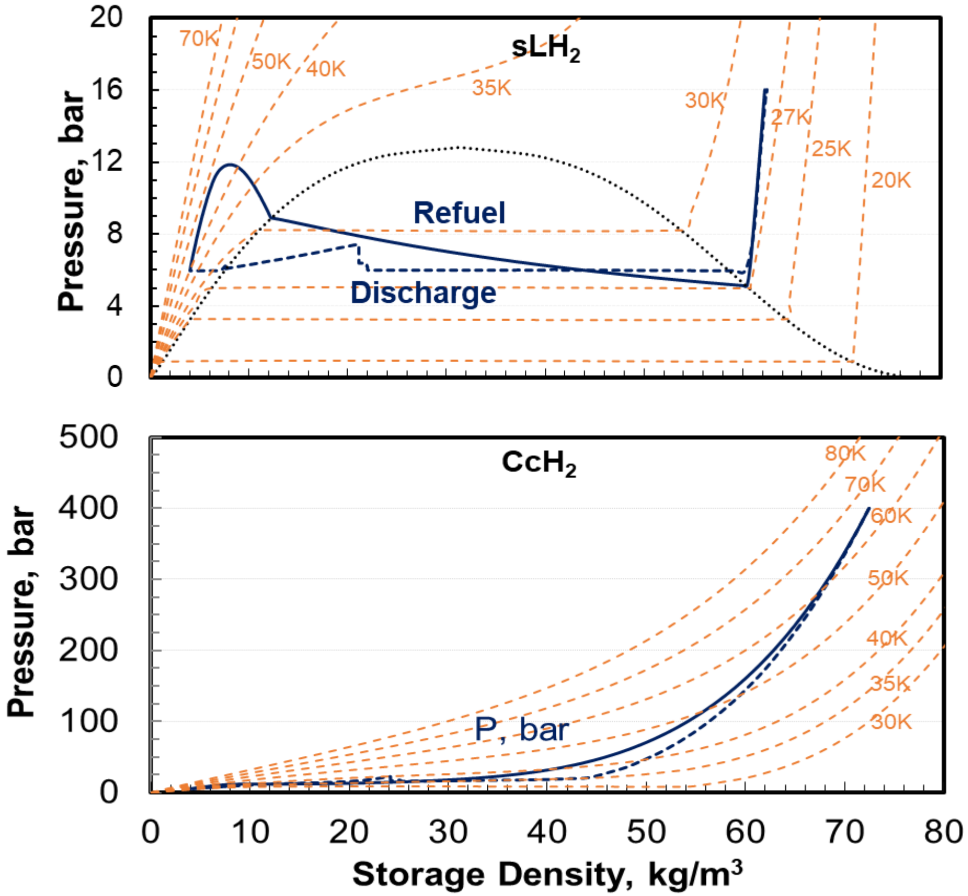
[1] http://www.a1autoelectric.com

Tank Refueling and Discharge

1. LH_2-1 system uses feed and bleed protocol (FBP) during the constant pressure refueling phase.
   - FBP requires dual nozzle refueling
   - H_2 return to the station can be avoided by raising the pressure head of the refueling pump above 8 bar but the storage capacity decreases
2. LH_2-2 system w/o on-board pump supplies heat during discharge to maintain tank pressure above 6 bar.

1. sLH_2 system relies on the refueling pump to pressurize LH_2 to 16 bar.
   - It operates in subcooled, 2-phase and superheated regions
2. CcH_2 system relies on the in-tank HX to operate in supercritical region.
   - Depending on the pump delivery pressure, it can reach storage density higher than 70 kg/m^3.





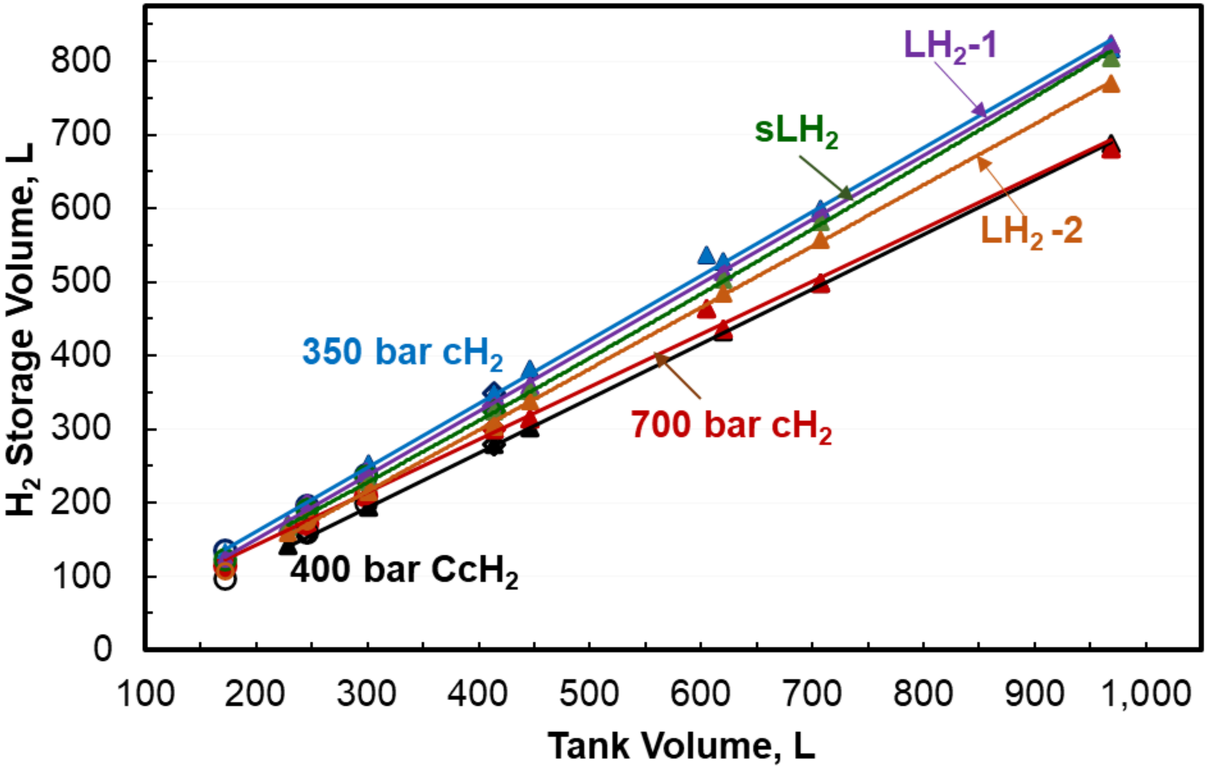
H_2 Storage Volume

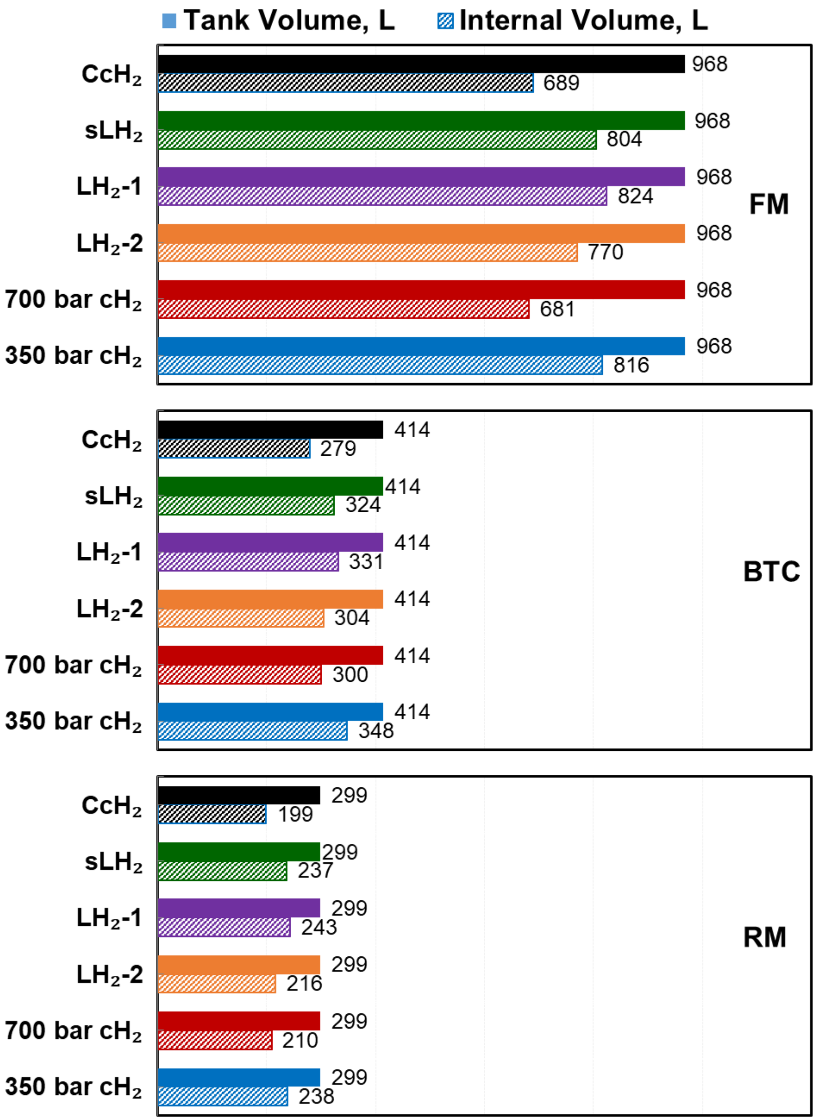
- FM: 66 x 305 Tank (968 L)
- BTC: 53 x 203 Tank (414 L)
- RM: 30 x 246 Tank (299 L)

LH_2 -1 has the largest available internal volume for H_2 storage.

Volume distribution in 968 L tank

System Configuration	**LH_2 - 1**	**cH_2 350 bar**	**sLH_2**	**LH_2-2**	**CcH_2**	**cH_2 700 bar**
H_2 Storage Volume [%]	85.1	84.3	83.1	79.5	71.1	70.4
Liner (%)	1.8	3.2	3.7	1.7	3.2	2.9
Carbon Fiber Composite (%)		12.5			13.2	26.7
Vacuum Insulation (%)	9.3		9.5	15.0	8.6	
Outer Shell (%)	3.8		3.8	3.8	3.8	



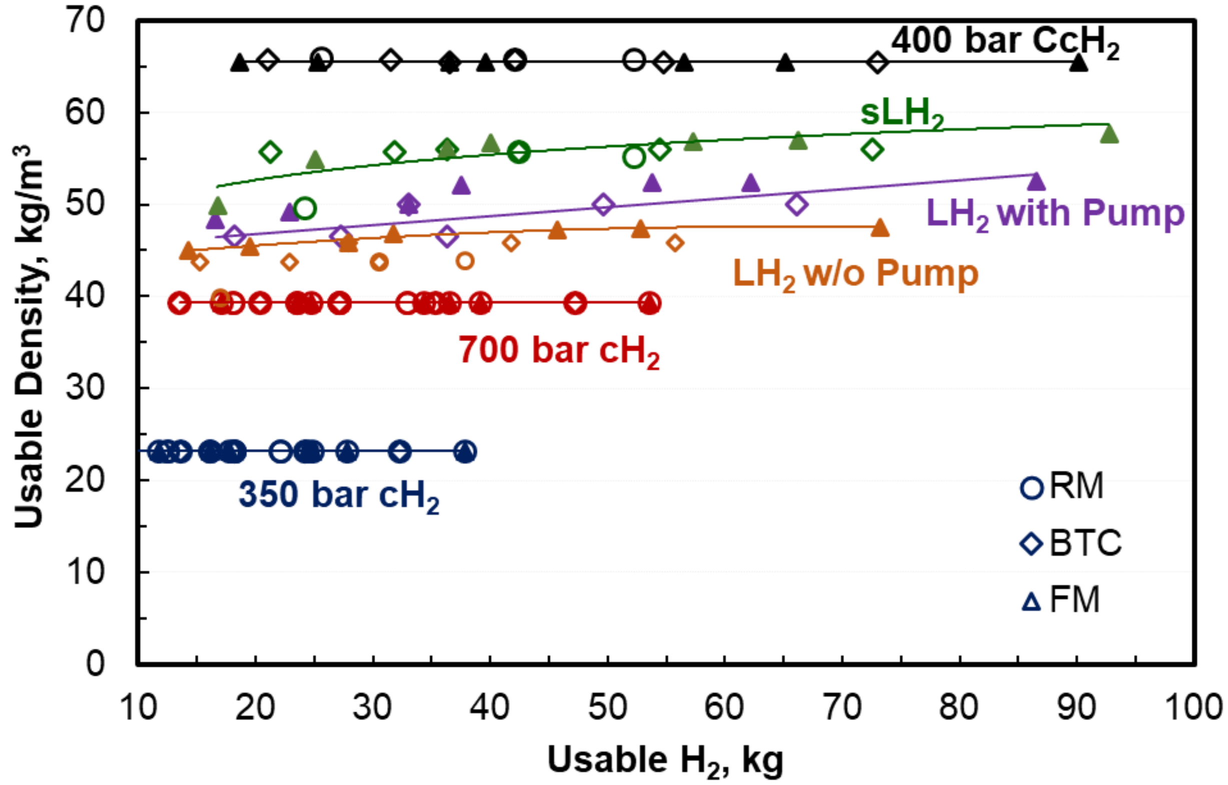


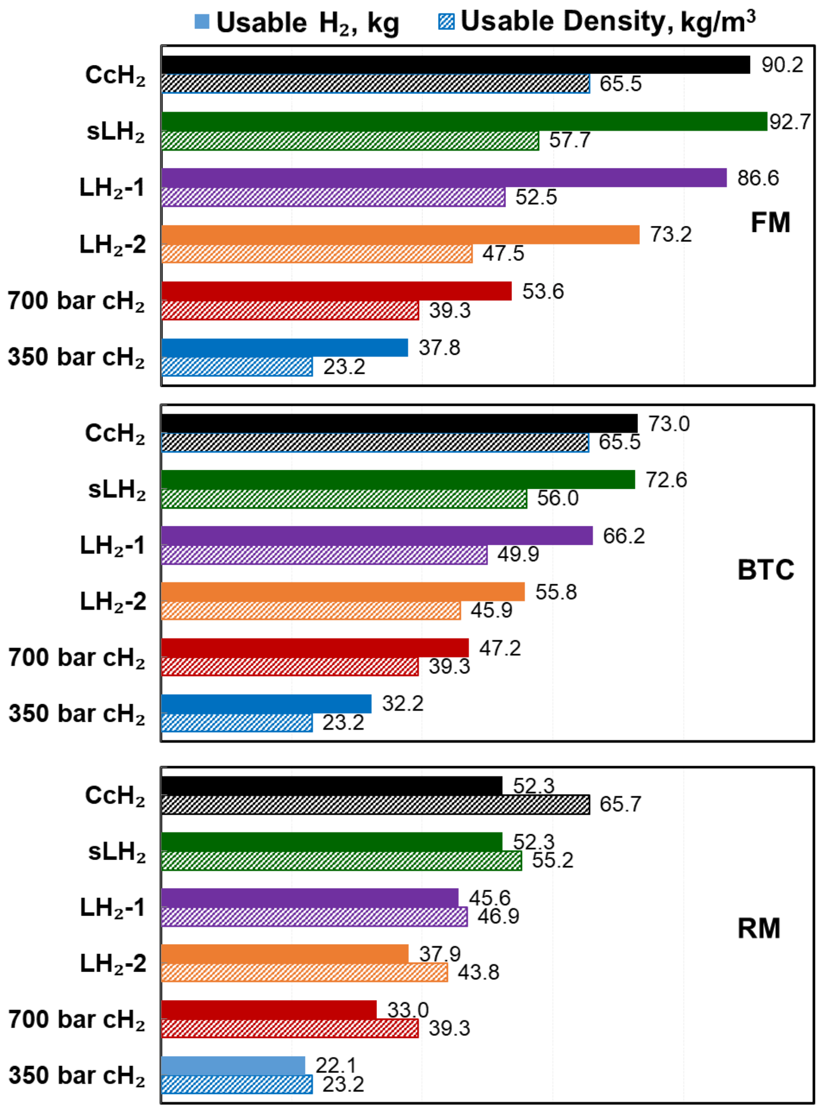
Usable H_2 Storage Density

CcH_2 has the highest usable H_2 storage density in the 2 x 66 x 305 FM tank system

▪ CcH_2	65.5 kg/m³
▪ sLH_2	57.7 kg/m³
▪ LH_2-1	52.5 kg/m³
▪ LH_2-2	47.5 kg/m³
▪ cH_2-700 bar	39.3 kg/m³
▪ cH_2-350 bar	23.2 kg/m³

- FM: 2 x 66 x 305 Tanks
- BTC: 4 x 53 x 203 Tanks
- RM: 4 x 30 x 246 Tanks



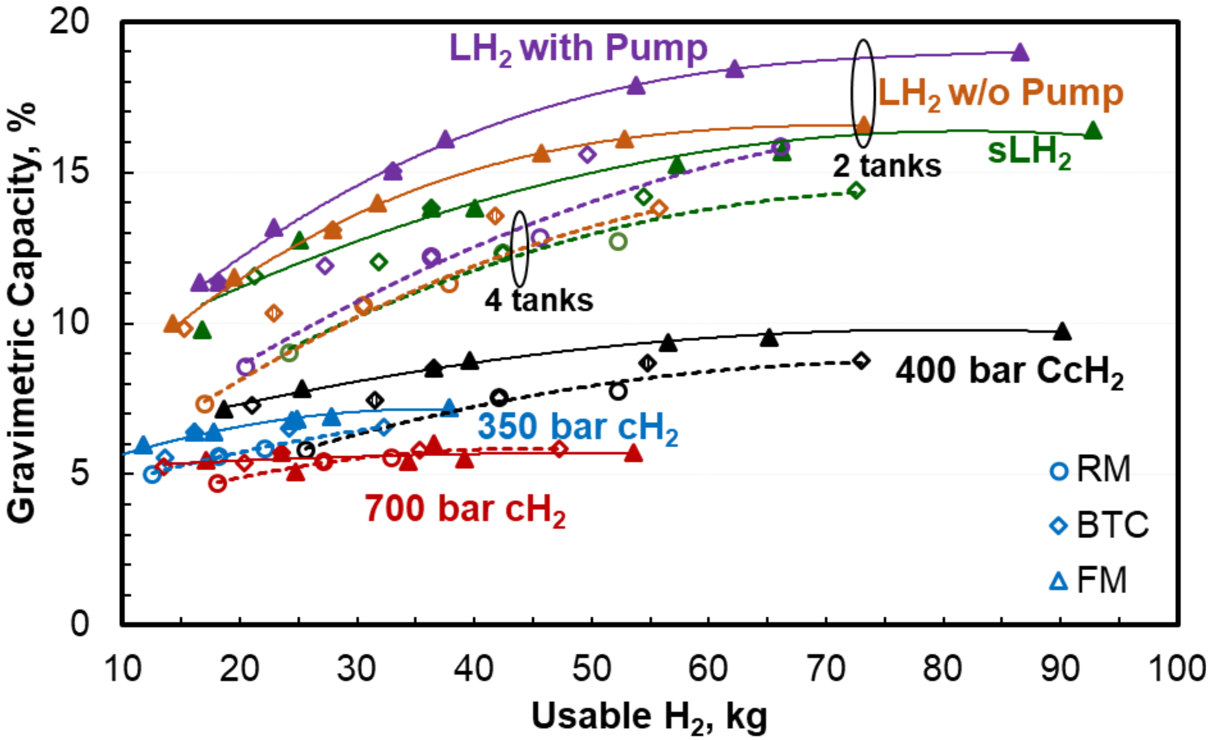


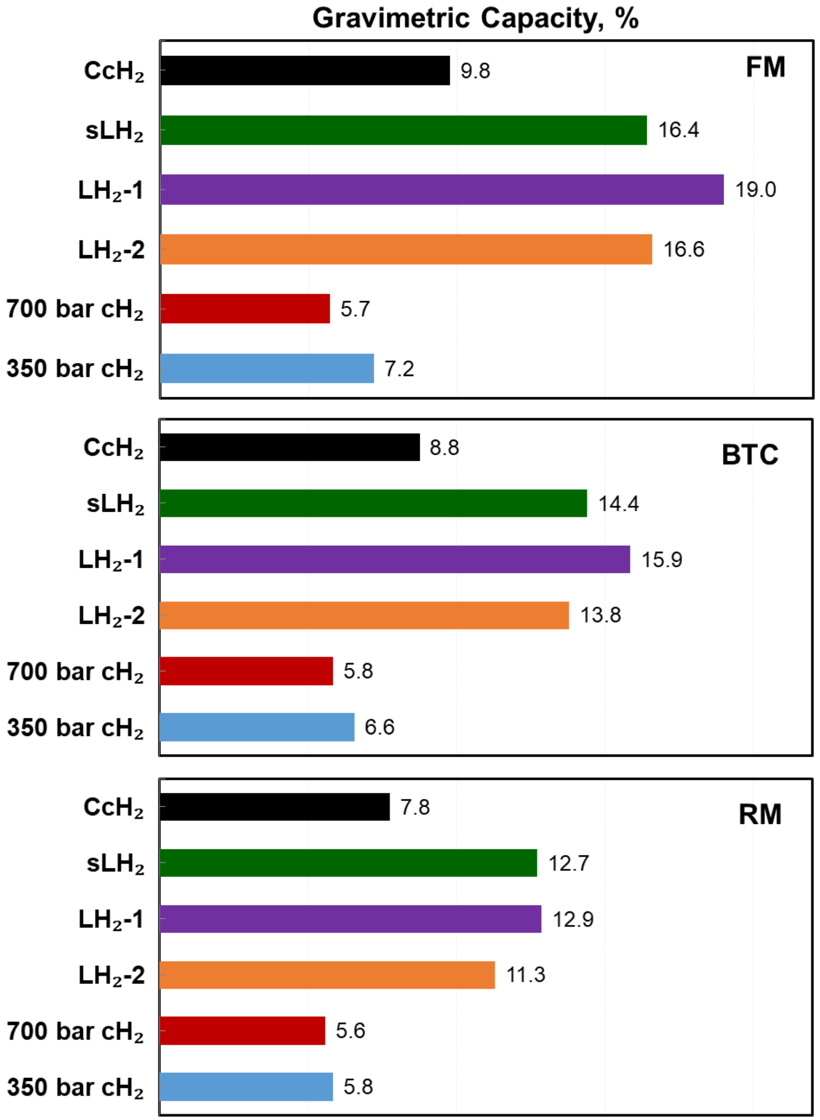
Gravimetric Capacity

LH_2 -1 has the highest gravimetric capacity in the 2 x 66 x 305 FM tank system

LH_2-1	19%
LH_2-2	16.6%
sLH_2	16.4%
CcH_2	9.8%
cH_2-350 bar	7.2%
cH_2-700 bar	5.7%

- FM: 2 x 66 x 305 Tanks
- BTC: 4 x 53 x 203 Tanks
- RM: 4 x 30 x 246 Tanks



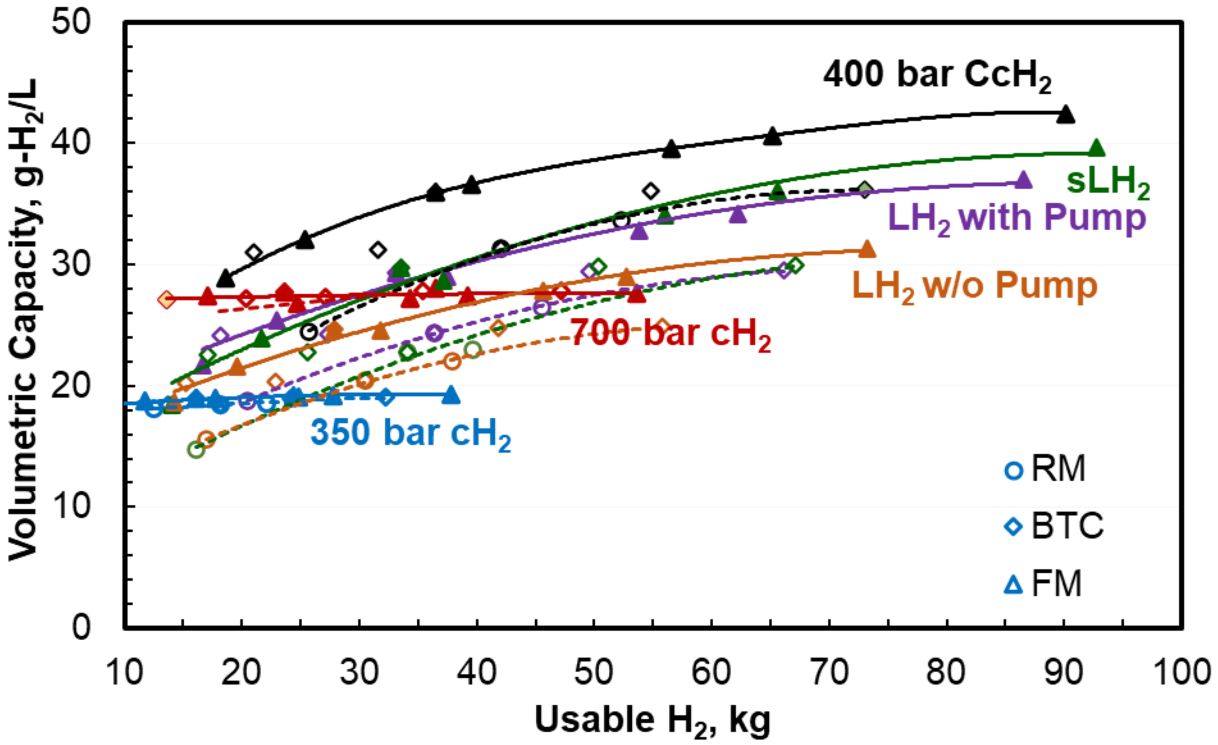


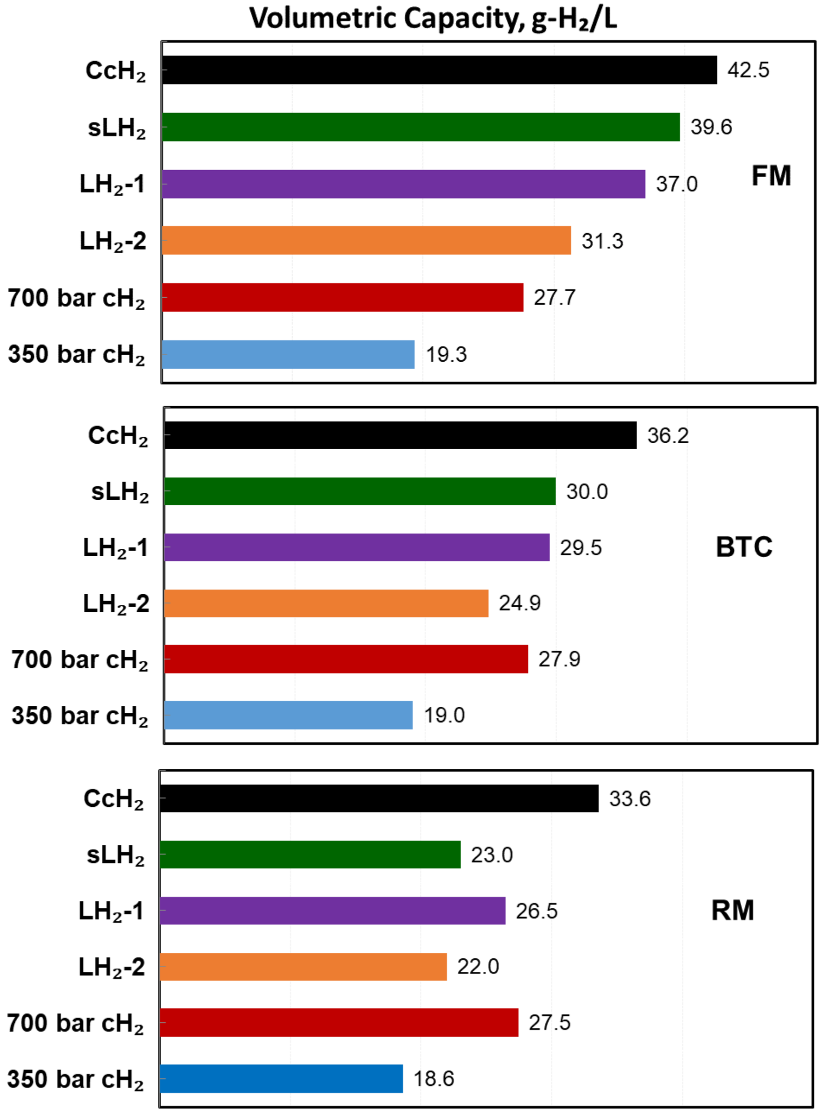
Volumetric Capacity

- FM: 2 x 66 x 305 Tanks
- BTC: 4 x 53 x 203 Tanks
- RM: 4 x 30 x 246 Tanks

CcH_2 has the highest volumetric capacity in the 2 x 66 x 305 FM tank system

▪ CcH_2	42.5 g-H_2/L
▪ sLH_2	39.6 g-H_2/L
▪ LH_2-1	37 g-H_2/L
▪ LH_2-2	31.3 g-H_2/L
▪ cH_2-700 bar	27.7 g-H_2/L
▪ cH_2-350 bar	19.3 g-H_2/L



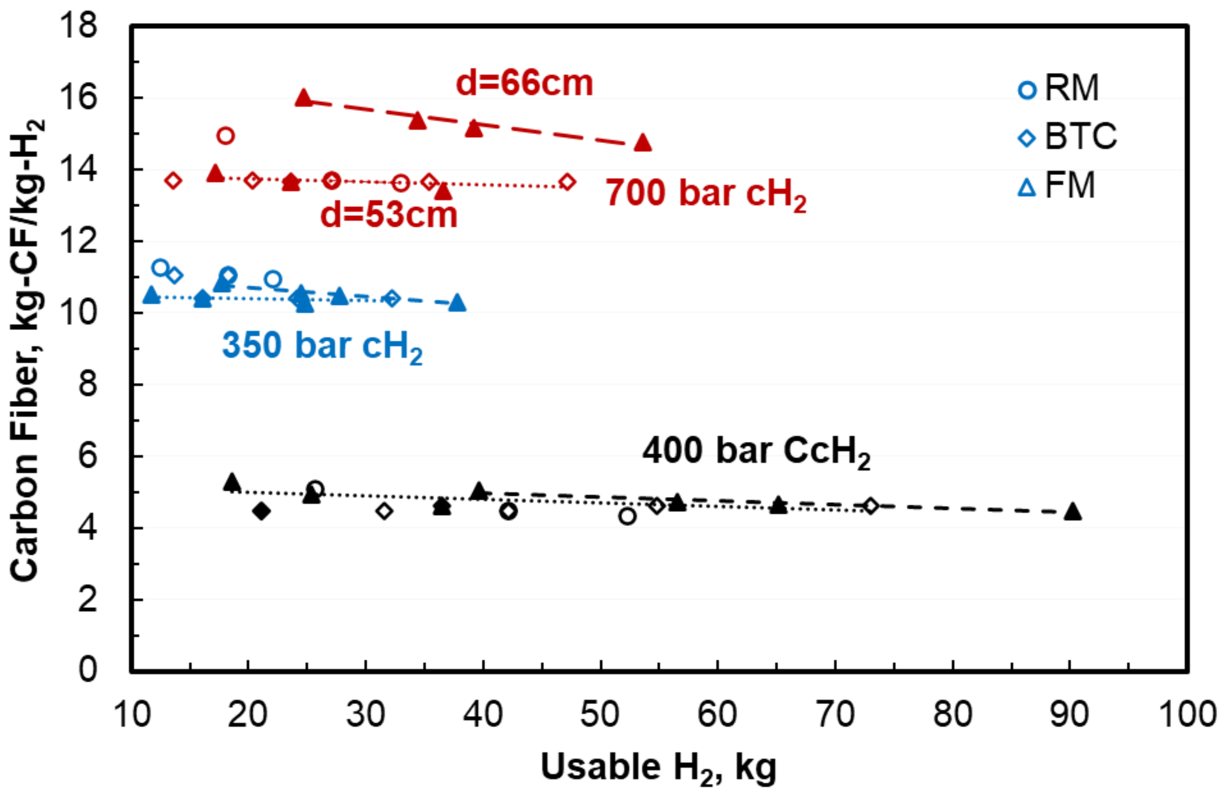


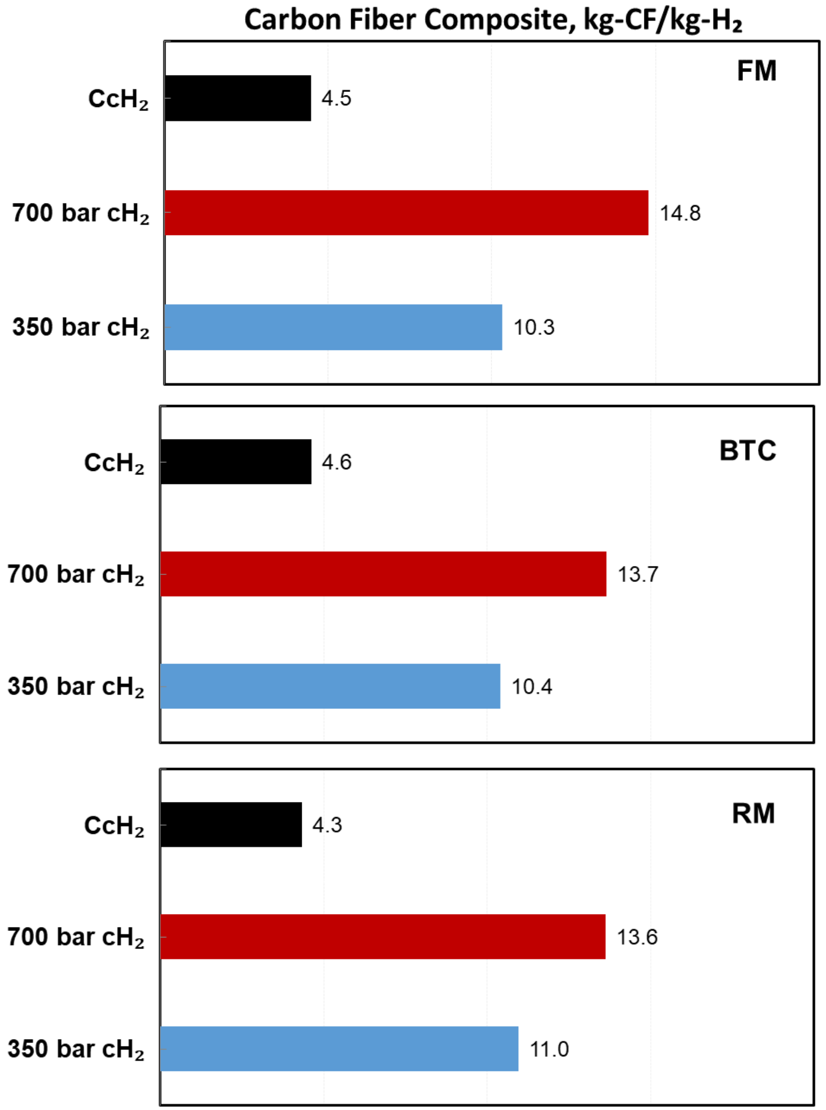
Carbon Fiber Usage

- FM: 2 x 66 x 305 Tanks
- BTC: 4 x 53 x 203 Tanks
- RM: 4 x 30 x 246 Tanks

CcH_2 uses the least amount of carbon fiber composite in the 2 x 66 x 305 FM tank system

CcH_2	4.5 kg-CF/kg-H_2
cH_2-700 bar	10.3 kg-CF/kg-H_2
cH_2-350 bar	14.8 kg-CF/kg-H_2





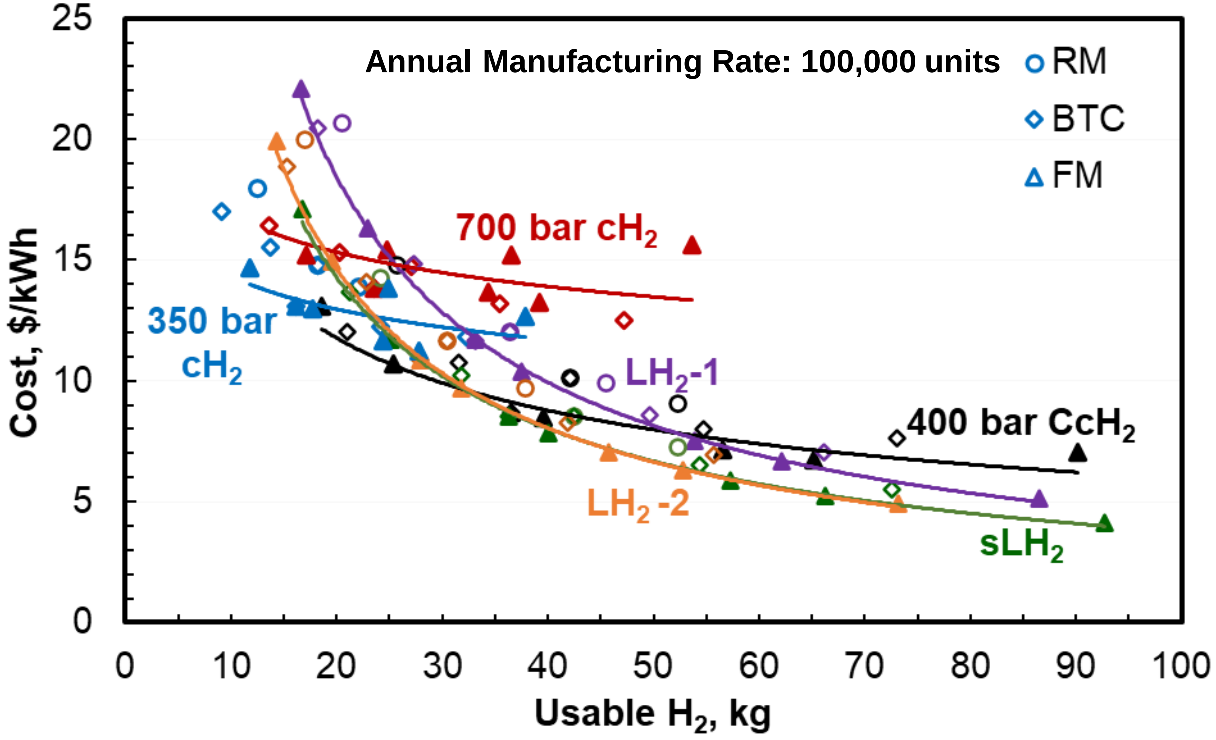
Cost*

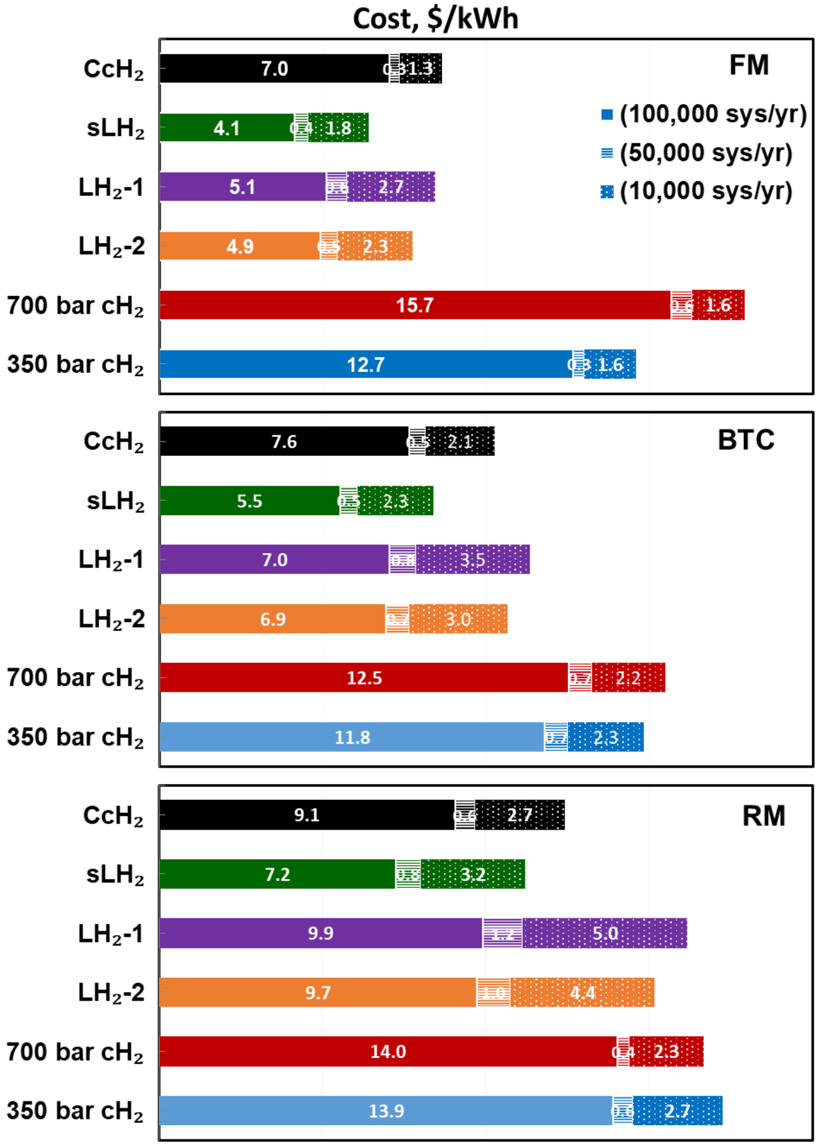
- FM: 2 x 66 x 305 Tanks
- BTC: 4 x 53 x 203 Tanks
- RM: 4 x 30 x 246 Tanks

sLH_2 is the lowest cost option for heavy-duty applications

- Cost breakdown in 2 x 66 x 305 FM tank systems, 100K units/year

System Configuration	cH_2 350 bar	cH_2 700 bar	LH_2 - 1	LH_2-2	CcH_2	sLH_2
Total Cost [$/kWh]	$12.66	$15.65	5.11	$4.91	$7.03	$4.13
Liner (%)	3.4	1.7	6.9	8.0	5.2	15.6
Carbon Fiber Composite (%)	77.0	86.1			60.0	
System Testing (%)	0.7	0.6	0.3	0.4	0.5	0.4
Vacuum Insulation (%)			4.0	6.7	3.5	4.5
Outer Shell (%)			14.0	17.2	6.4	16.1
BOP (%)	7.9	5.3	60.7	50.3	15.7	47.0
Housing, Support, and Assembly (%)	11.1	6.3	14.1	17.3	8.6	16.2





*Cost analysis results from Zachary Watts and Cassidy Houchins, Strategic Analysis, September 2023

Future Outlook

1. Model results indicate that CcH_2 and sLH_2 are attractive on-board H_2 storage options for heavy duty trucks if the fuel cell system accepts H_2 delivered at 5 bar.

Representative results for 2 x 66 x 305 FM tank systems manufactured at 100K units/year

System Configuration	Usable H_2	Usable H_2 Density	System Gravimetric Capacity	System Volumetric Capacity	Specific Carbon Fiber Requirement	Specific System Cost
	kg	kg/m^3	%	kg-H_2/L	kg-CF/kg-H_2	\$/kWh
CcH_2	90.2	65.5	9.8	42.5	4.5	7.03
sLH_2	92.7	57.7	16.4	39.6		4.13
LH_2-1 (w Pump)	86.6	52.5	19.0	37.0		5.11
LH_2-2 (w/o Pump)	73.2	47.5	16.6	31.3		4.91
cH_2 - 700 bar	53.6	39.3	7.2	27.7	14.8	15.65
cH_2 - 350 bar	37.8	23.2	5.7	19.3	10.3	12.66

2. CcH_2 is the only viable liquid storage option if the fuel cell system requires H_2 to be delivered above 15 bar.
3. Low pressure LH_2 storage becomes competitive if on-board boost pumps capable of delivering 16 kg/h H_2 at 5-15 bar pressure are developed.
4. Stationary pumps capable of transferring LH_2 from trailer truck at 1100 kg/h and providing 5 bar pressure head can greatly reduce H_2 loss during Dewar loading.
5. Future study to assess the potential of eliminating H_2 loss from the Dewar with a cryo-cooler