System Level Analysis of Hydrogen Storage Options

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U.S. DOE Hydrogen and Fuel Cells Program
2020 Annual Merit Review and Peer Evaluation Meeting
Washington, D.C.
May 19 - 21, 2020

Project ID: ST001

Overview

Timeline

- Project start date: Oct 2009
- Project end date: N/A
- Project continuation and direction determined annually by DOE

Budget

- FY19 DOE Funding: $500K
- FY20 DOE Funding: $500K

Barriers

- H_2 Storage Barriers Addressed:
  - A: System Weight and Volume
  - B: System Cost
  - C: Efficiency
  - E: Charging/Discharging Rates
  - J: Thermal Management
  - K: Life-Cycle Assessments

Partners/Interactions

- HyMARC: PNNL, NREL, LBNL
- Delivery Team, Hydrogen Interface Taskforce (H2IT), ANL-H2A, ANL-HDSAM
- HMAT, TARDEC, BMW, LLNL
- Ford, ORNL, UM
- Strategic Analysis, PNNL, Ford

Relevance and Impact

Develop and use models to analyze the on-board and off-board performance of physical and material-based automotive hydrogen storage systems

- Conduct independent systems analysis for DOE to gauge the performance of H_2 storage systems
- Provide results to material developers for assessment against system performance targets and goals and help them focus on areas requiring improvements
- Provide inputs for independent analysis of costs of on-board systems.
- Identify interface issues and opportunities, and data needs for technology development
- Perform reverse engineering to define material properties needed to meet the system level targets

Impact of FY2020 work

- Established benchmark costs for H_2 production by SMR, liquefaction, storage, transmission, distribution, and dispensing.
- Developed a model for fracture durability of Type-2 tanks and determined pressure limits for 25-year lifetime.
- Calibrated ABAQUS models for H_2 storage in Type-3 and Type-4 tanks and showed the possibility of lowering the status number for carbon fiber composite requirement.
- Showed that 33–54 kg of usable H_2 can be stored in roof mounted, behind-the-cab and frame-mounted tanks being offered for compressed natural gas trucks.

Approach

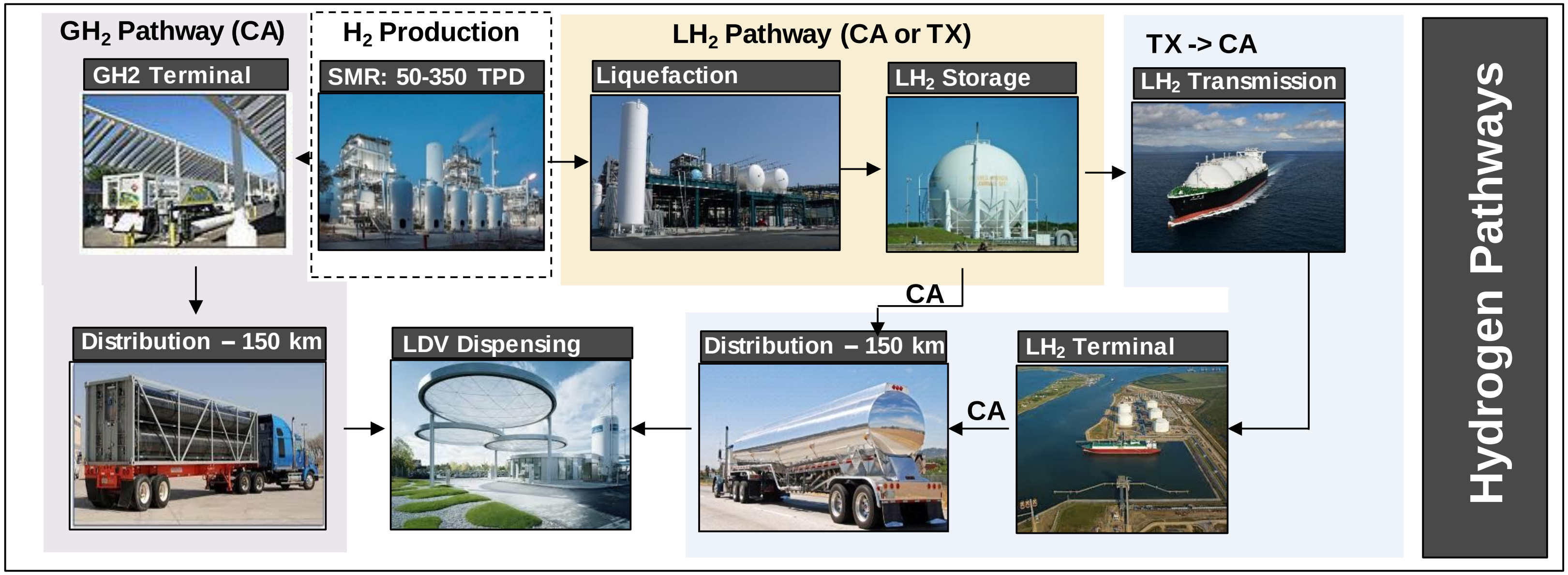
- Develop thermodynamic and kinetic models of processes in physical, complex metal hydride, sorbent, and chemical H_2 storage systems
  - Address all aspects of on-board and off-board storage targets, including capacity, charge/discharge rates, emissions, and efficiencies
  - Perform finite-element analysis of compressed hydrogen storage tanks
  - Assess improvements needed in materials properties and system configurations to achieve storage targets
- Select model fidelity to resolve system-level issues
  - On-board system, off-board spent fuel regeneration, reverse engineering
  - Conduct trade-off analyses, and provide fundamental understanding of system/material behavior
  - Calibrate, validate, and evaluate models
- Work closely with DOE technology developers, national labs and others in obtaining data, and provide feedback
- Participate in meetings and communicate approach and results to foster consistency among DOE-sponsored analysis activities

FY2020 Tasks and Progress

1. Liquid Hydrogen Carrier (FY2020 Q1)
   - Completed initial analysis of liquid hydrogen (LH_2) carrier.
   - Determined costs of liquefaction, and LH_2 storage, ship transmission & distribution.
2. Bulk Storage at Forecourt (FY2020 Q2)
   - Developed models for dynamics of pressure fluctuations and durability of Type-2 tanks.
   - Determined optimum conditions and arrangements for a 250 kg-H_2/day dispenser subject to 25-year lifetime and complete refueling of vehicles.
3. Hydrogen Storage for Medium and Heavy Duty Trucks (FY2020 Q3)
   - Validated ABAQUS models for H_2 storage in Type-3 and Type-4 tanks.
   - Refined analysis of 33-53 kg hydrogen storage for medium and heavy-duty trucks.

		Due Date	Date Completed	% Complete
1	Analyze liquid hydrogen carrier relative to the 2020 targets of \$2/kg hydrogen production and \$2/kg delivery cost.	12/31/2019	12/31/2019	100%
2	Complete analysis of hydrogen storage in Type-2 tanks at forecourt. Determine tank sizes, pressure cycles, and lifetime.	3/31/2020	3/31/2020	100%
3	Validate capacities and carbon fiber requirements for hydrogen storage on-board medium and heavy-duty trucks.	6/30/2020	6/30/2020	75%
4	Prepare a report on liquid hydrogen storage for trains and ships documenting system attributes and costs.	9/30/2020	9/30/2020	25%

Task 1. Comparing GH_2 and LH_2 Pathways



GH_2 Pathway (CA)

GH2 Terminal

Distribution – 150 km

H_2 Production

SMR: 50-350 TPD

LDV Dispensing

LH_2 Pathway (CA or TX)

Liquefaction

LH_2 Storage

TX -> CA

LH_2 Transmission

CA

Distribution – 150 km

CA

LH_2 Terminal

Hydrogen Pathways

ECA=Environmentally Controlled Area (SO_x+NO_x)

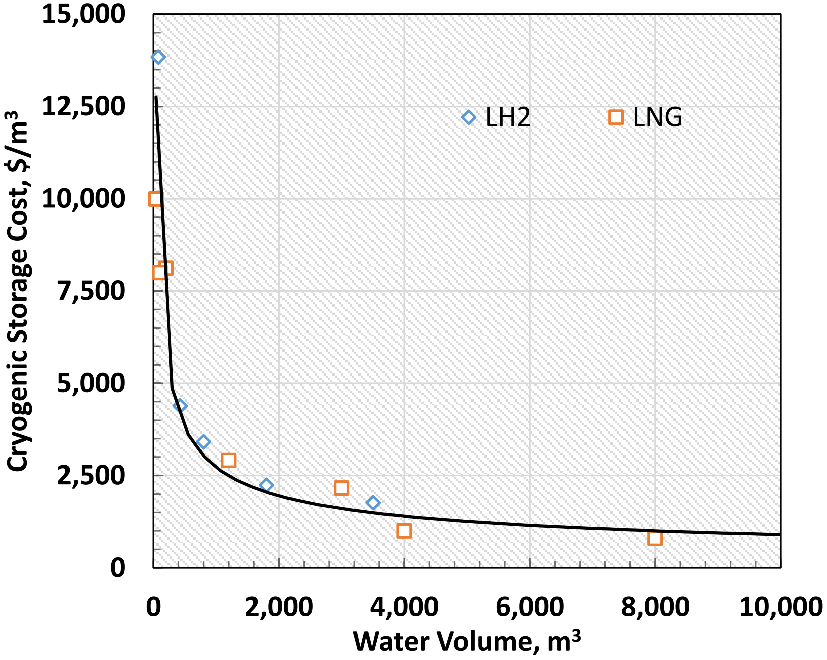
Scenario: GH_2 or LH_2 pathways for LDV refueling

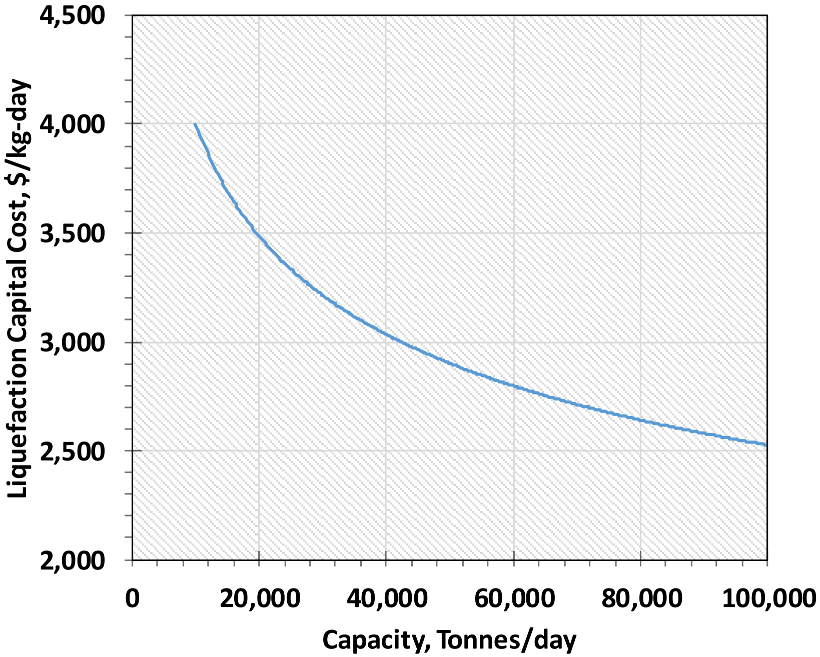
- Hydrogen Production: Central SMR 50-350 TPD in CA, 350 TPD in TX
- LH_2 transmission from Gulf coast to northern CA by cryogenic tankers (up to 180,000 m^3 capacity)
- LH_2 storage at plant site and satellite terminal. Storage requirements depend on number of ships utilized on route
- GH_2 pathway includes 10 days of geological storage (lined rock cavern) for plant outages

Shipping Distance Examples:
Port of LA to Tokyo = 4,853 nm
Geelong (Australia) to Tokyo = 4,910 nm

Baseline GH_2 scenario: Central SMR; GH_2 terminal: H_2 compression & storage; truck distribution;

Liquefaction of Hydrogen – Cost factors





LH_2 Storage Costs

Current Technology

- Storage: Spherical layout, vacuum insulation with glass-bubbles
- Boil-off losses modeled using NASA data for spherical vessels[2]
- H_2 losses during unloading: 0.15%
- Cost of storage dominated by material and welding costs. Cost similar between LNG and LH_2

LH_2 Liquefaction Costs

Current Technology

- LN_2 pre-cooled Claude cycle[1]
- Max liquefier unit: 100,000 kg/day
- Electricity consumption: 10 kWh/kg-H_2
- H_2 losses due to compressor seal: 0.5%
- LH_2 storage: A minimum of 10 days for plant outages at plant gate

[1] *Connelly, E., Penev, M., Elgowainy, A. and Hunter, C. DOE Hydrogen and Fuel Cells Program Record, Record #: 19001, September 9, 2019*

[2] *Majumdar et. al. (2007).* Numerical Modeling of Propellant Boiloff in Cryogenic Storage Tank. NASA/TM—2007–215131

LH_2 Carrier Specifications Adapted from LNG Carriers (Moss type)

Largest Moss Type (Spherical Storage) LNG Carrier: 182,000 m^3

Neopanamax locks limit size of vessel: Length up to 427 m (1,401´), beam up to 52 m (170´), draught up to 18.3 m (60´).

Carrier Specifications/Daily Capacity	50 TPD	100 TPD	350 TPD	500 TPD
Carrier Size (m^3)	23,844	44,009	133,433	178,691
Roundtrips/year	12	13	15	16
LH_2 Delivered/roundtrip (Tonnes)	1,521	2,808	8,517	11,406
LH_2 Boil-off/roundtrip (Tonnes)	12.9	22.4	59.3	77.4
Vessel Length (m)	146.8	176.6	275.0	308.0
Vessel Width (m)	25.4	30.5	45.0	52.0
Draft (m)	6.6	7.7	11.1	11.8
Dead-weight (Tonnes)	12,692	24,122	72,339	96,742
Days of Storage Needed	33	31	27	25

Carrier limited in capacity to ~178,000 m^3 based on Panama Canal size restrictions

- LH_2 carrier specifications and cost structure assumed similar as LNG Moss type carriers (cost of storage between LH_2 or LNG essentially same)
- Round-trip time: 23-31 days depending on carrier size (15-20 kts at sail; 8 h to pass Panama Canal, 24 h to unload and load shipment)
- Ships that operate in Emissions Control Areas (ECA) must limit sulfur content in fuel to <0.1% and use more costly low-sulfur marine gas oil (LSMGO).
- Carrier will spend 27% of its time in ECA zones (sail & at berth). LSMGO as fuel will be used during entire trip
- Panama canal fees vary with ship length, width and laden conditions
- Insulation thickness limited to 1.8 m based on usable[1] storage and width of ship

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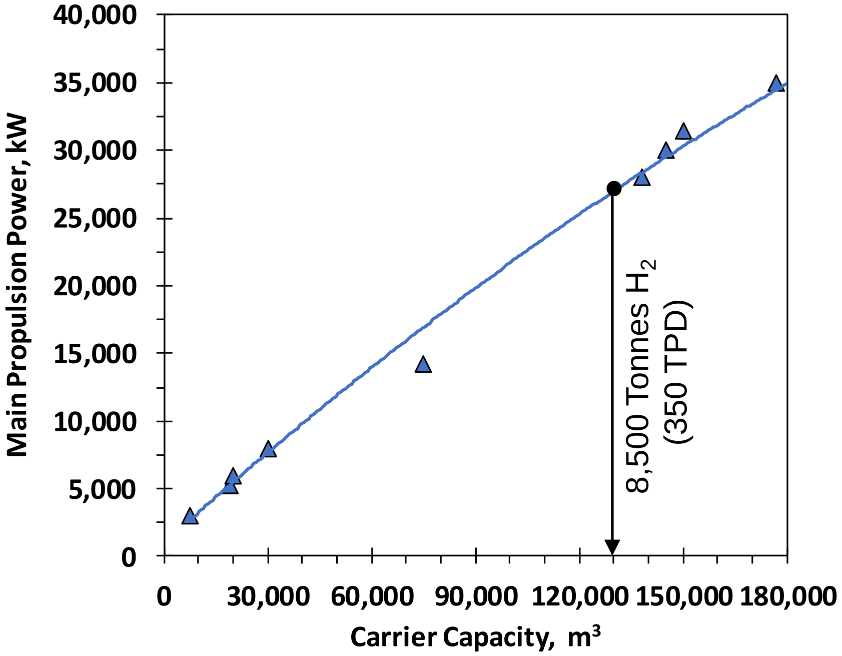
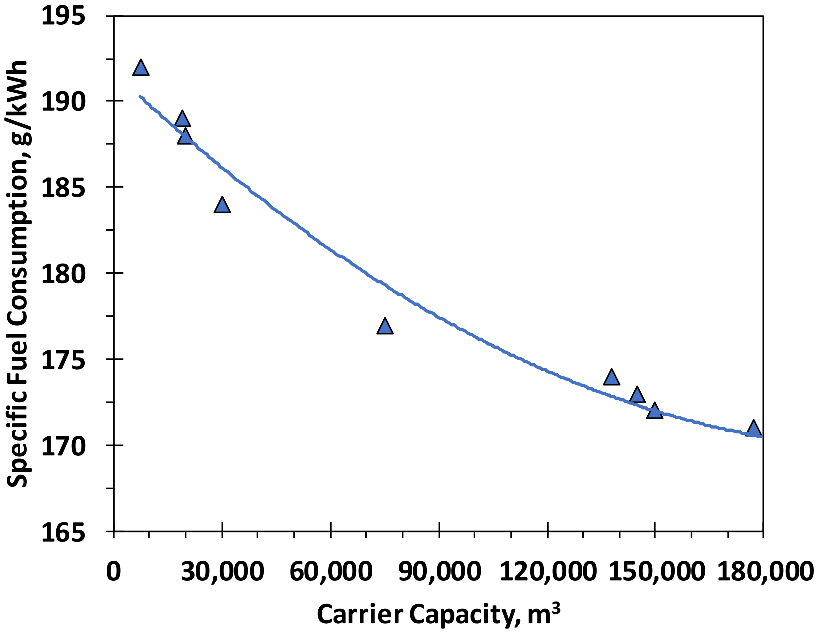
[1] Usable storage: 90% (5% ullage, 5% heel to keep tanks cooled during return trip)

Carrier Cost Factors (Fuel)

We are using LSMGO as the reference fuel for maritime applications considered in this study.

- Small difference in price of MGO and LSMGO. As of end of 2019 cost of LSMGO is \$650/Tonne (LHV = 42.8 MJ/kg, 900 m^3/kg)
- Main fuel consumption occurs at sail. Engine operates at 90% of rated power for maximum fuel efficiency. Auxiliary power needed typically 10% of propulsion power
- Specific fuel consumption decreases with engine size (bigger engines operate at low RPM ~100 with efficiencies approaching 50%)[1]





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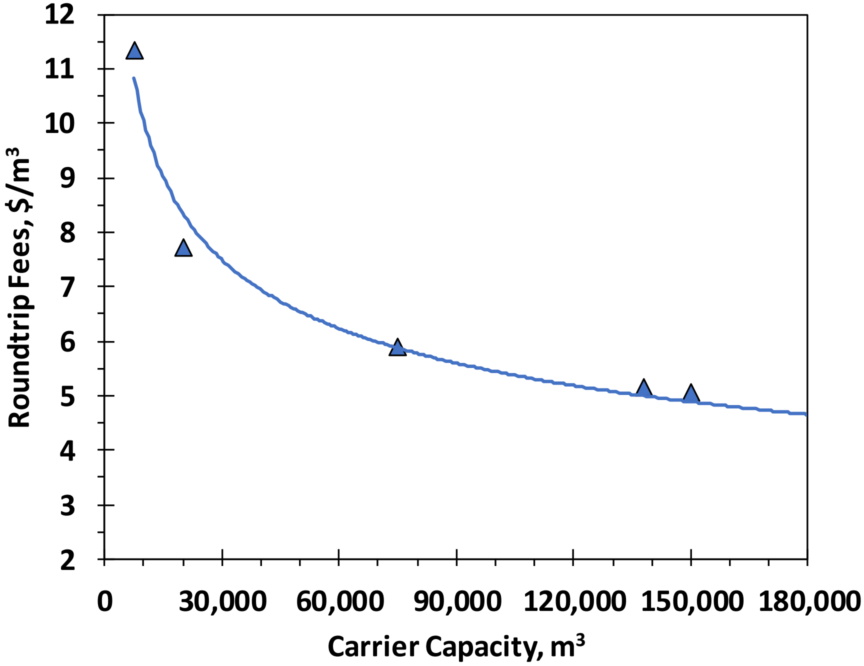
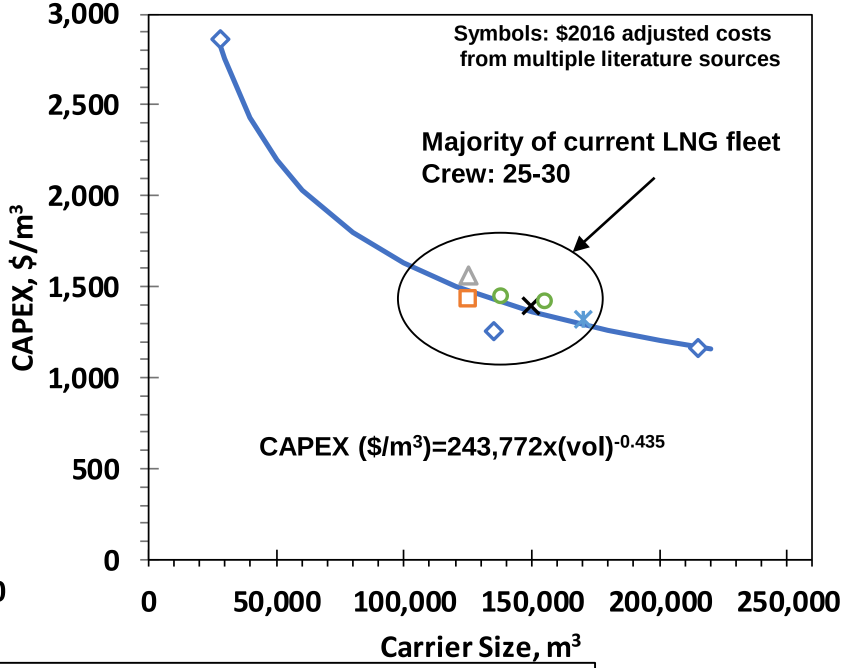
[1] *MAN Diesel & Turbo. (2013). Propulsion Trends in LNG Carriers - Two-stroke Engines. www.mandieselturbo.com*

Carrier Cost Factors (Capex + Opex)

Panama canal fees per roundtrip are based on laden conditions (MCH/Toluene)

- Canal fees decrease (on DWT basis) as ship increases in cargo capacity.
- Additional port fees included at $2/DWT-day.
- Capex of ship as function of size (DWT) based on statistical data around global shipyards. Additional cost of 25% will be included due to maritime commerce between U.S. ports[1]
- Crew size complement: 4 Deck officers, 4 engineers, rest as deckhand





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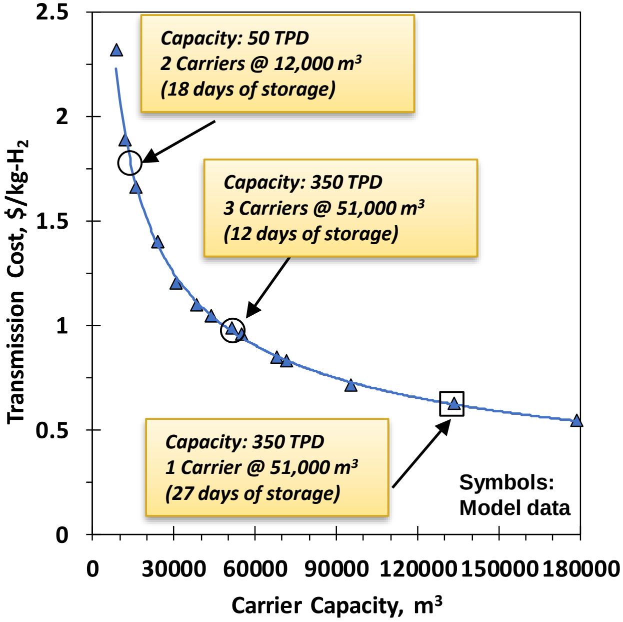
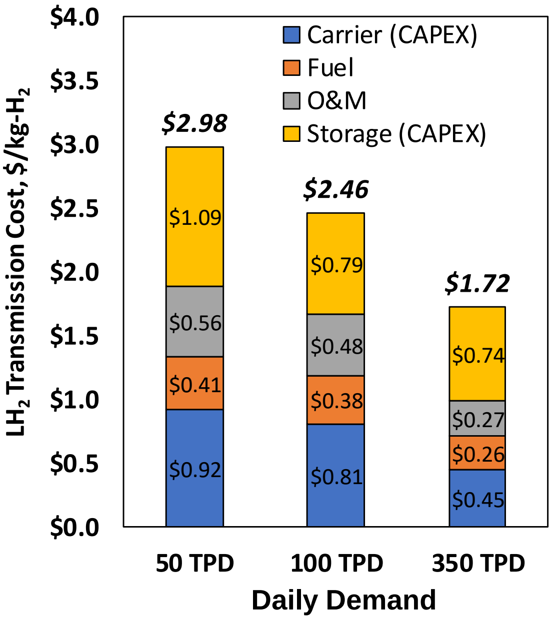
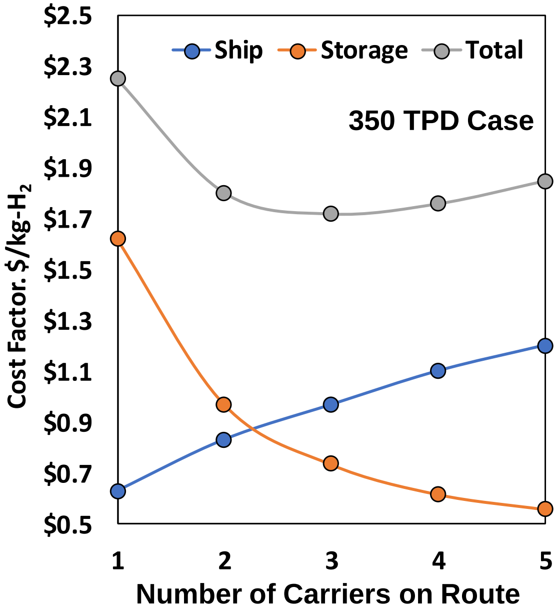
[1] *The **Jones Act** requires goods shipped between U.S. ports to be transported on ships that are built, owned, and operated by United States citizens or permanent residents*

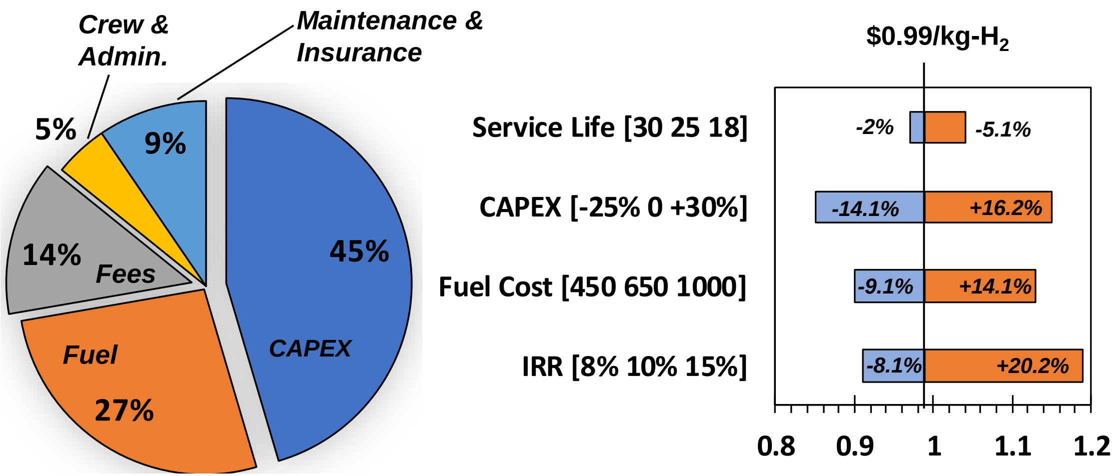
Carrier lifetime 25 years, IRR=10%, Depreciation schedule MACRS 15 years, Inflation=1.9%, Maintenance=1.5% of direct CAPEX, Insurance=1.25% of direct CAPEX, Administrative costs=40% of labor costs

LH_2 Transmission Costs Consider an Optimum of Ship vs. Storage Costs







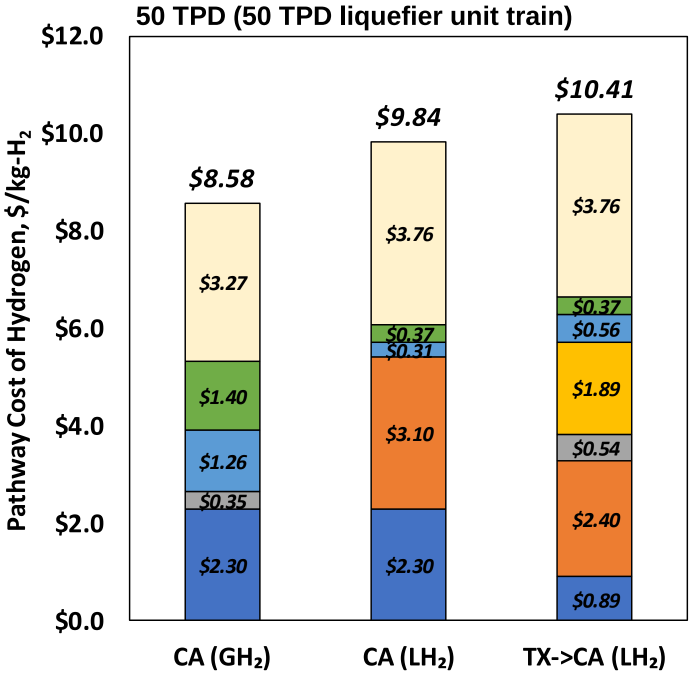


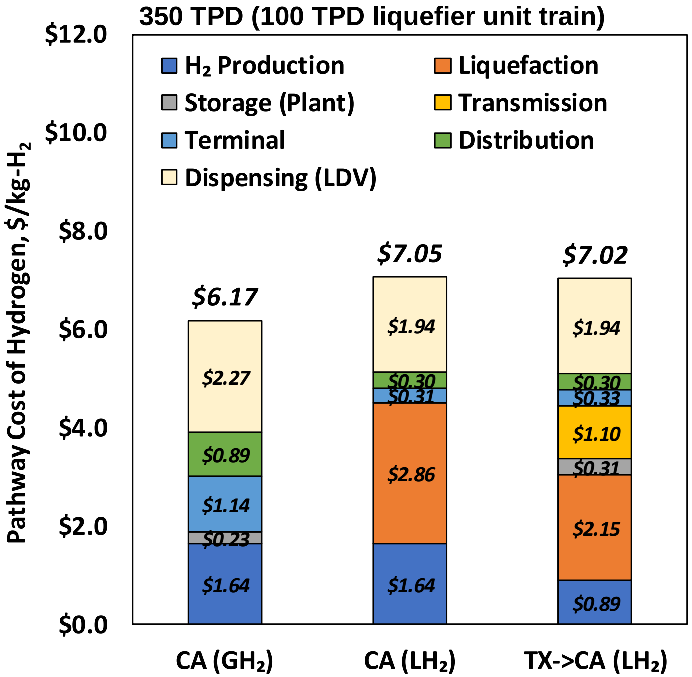
Carrier specific costs 51,000 m³

- Economy of scale favors large tankers (single ship per route)
- Lowest cost is an optimum of more ships per route vs. lower storage costs
- Lowest cost for carriers larger than 50 TPD daily demand is ~3 ships per route

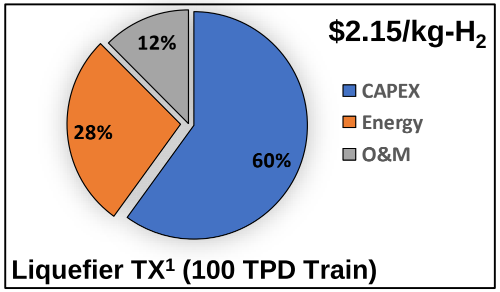
O&M=Fuel, Fees, Maintenance, Insurance, Crew+Administrative fees (Admin.)

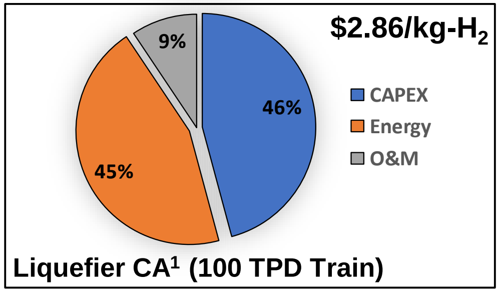
Pathway Cost of Hydrogen





Liquefaction Cost Break-Down





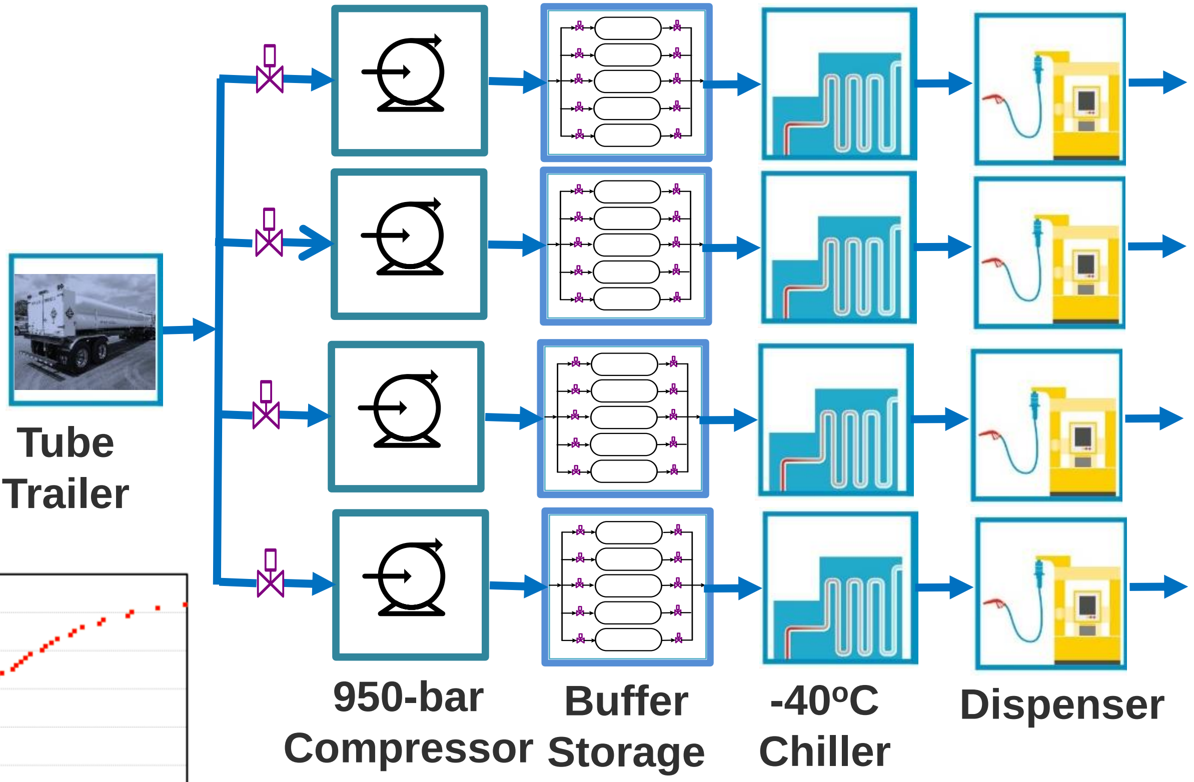
- GH_2 pathway incurs lowest costs for application end-use (LDV fleet) at demands from 50-350 TPD (700 bar on-board storage)
- Dispensing assumptions. 50 TPD (400 kg/day refueling station), 350 TPD (1,000 kg/day refueling station)
- Utilizing a lower H_2 production costs in TX is counteracted by high storage and transmission costs.
- Advantage of lower costs of LH_2 distribution and dispensing vs GH_2 at large capacities (350 TPD) restrained by high liquefaction costs (capital + energy) given incumbent technology

[1] *Price of Electricity (EIA.gov 2019 industrial yearly average): TX = ¢5.79/kWh, CA = ¢12.5/kWh*

Task 2: Modular Refueling Station with Delivered GH$_2$ in Tube Trailers

1000 kg-H$_2$/Day Modular Refueling Station

- 4 x 250 kg-H$_2$/day dispensers
- 250- or 540-bar tube trailer
- Storage tubes valved separately or as high-, medium- and low-pressure cascade



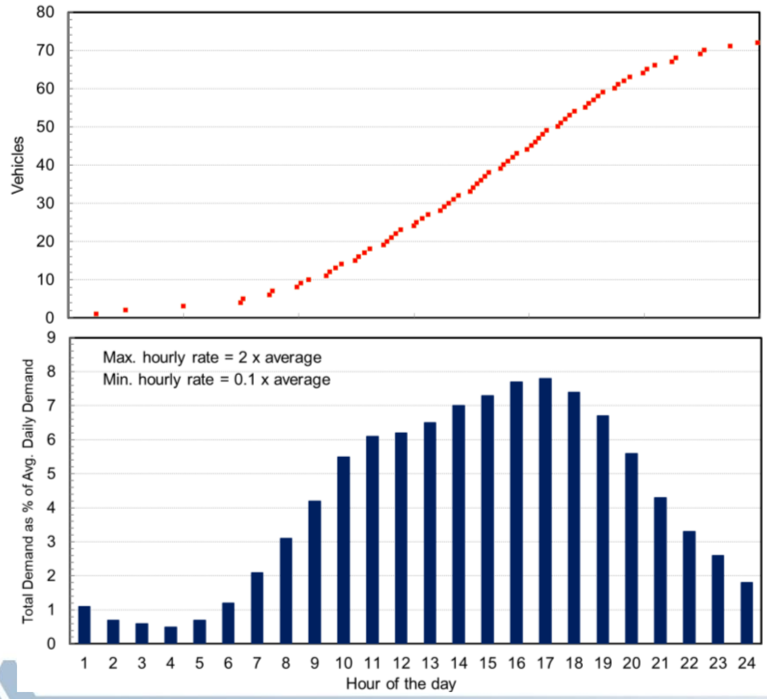
Tube Trailer

950-bar Compressor

Buffer Storage

-40ºC Chiller

Dispenser



Translated Hourly Demand to Charging Schedule

- 72 vehicles charged daily per dispenser
- 3.5-kg H$_2$ charged per vehicle, 1 kg/min H$_2$ refueling rate
- 2-min lingering time prior to post charging

Fracture Durability of Type-II Tanks

C. San Marchi et al, Technical basis for master curve for fatigue crack growth of ferritic steels in high-pressure gaseous hydrogen in ASME section VIII-3 code (PVP2019-93907), SAND2019-8892 C

- Code Case 2938: Design equations for high pressure cH_2 storage vessels
- Fracture mechanics test methods and testing validity
- Formulation of master curve for fatigue crack growth in gaseous hydrogen*

Model Parameters

Design Pressure:
932 atm

Safety Factor: 2.5

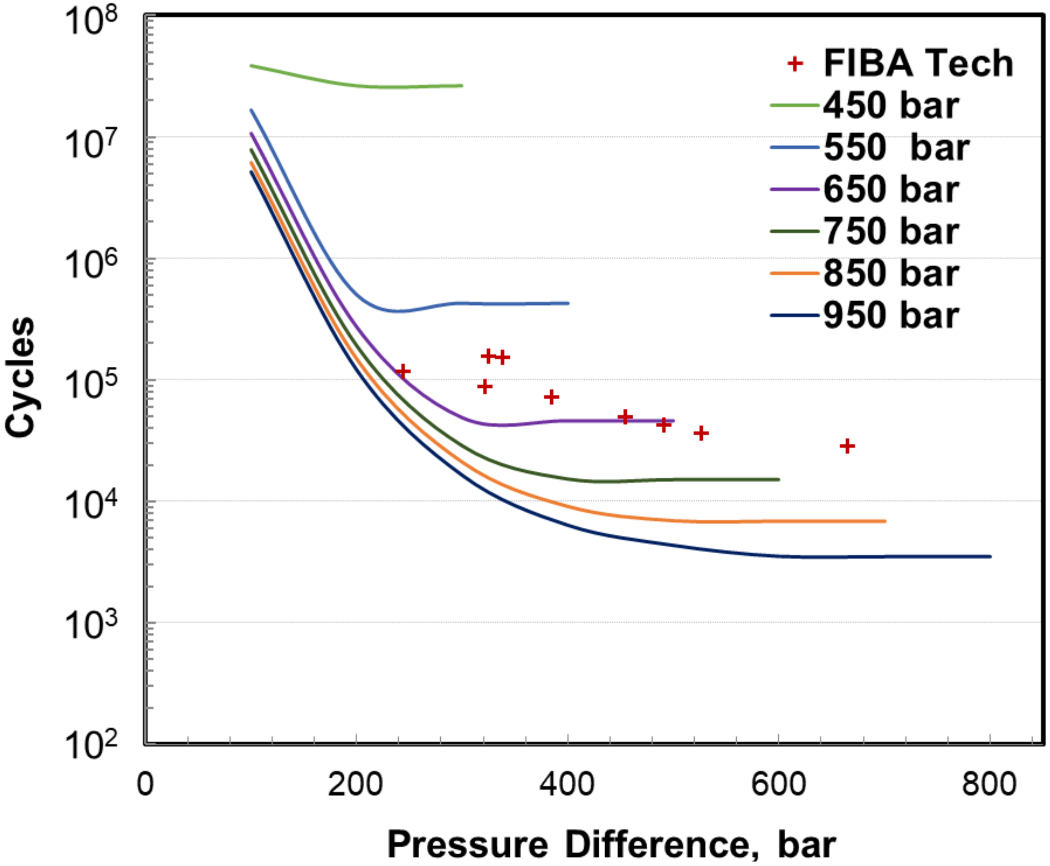
Tank ID: 33.1 cm

Liner Material:
SA-372 Grade J

Liner Thickness:
38.1 mm

CF Thickness:
14 mm

Initial Crack Thickness:
0.84 mm



***Fatigue Design Curves. ASME BPVC VIII.3KD-10.**

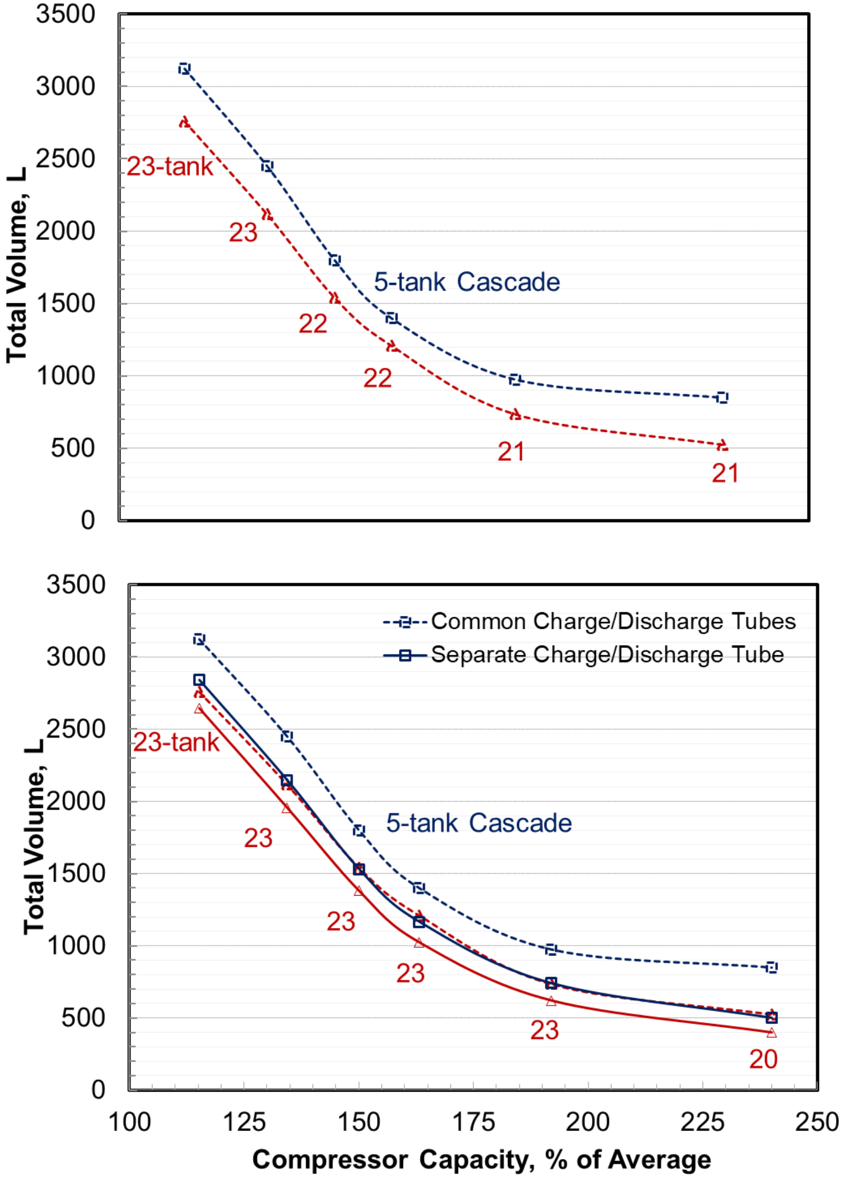
Buffer Storage Requirement

Constrained optimization model

- Variable 1: Tank volume
- Variables 2-N: Upper pressure limits for N tanks
- Constraint 1: Refuel all vehicles on busiest day
- Constraints 2-N: 25-year durability of N tanks

Summary of important results

- Larger compressors → Smaller buffer storage requirement
- Larger compressors → Higher cost, more idle time and on-off cycles
- More number of tanks → Smaller buffer storage requirement
- More number of tanks → More control valves
- Smaller buffer storage requirement with separate charge and discharge tubes



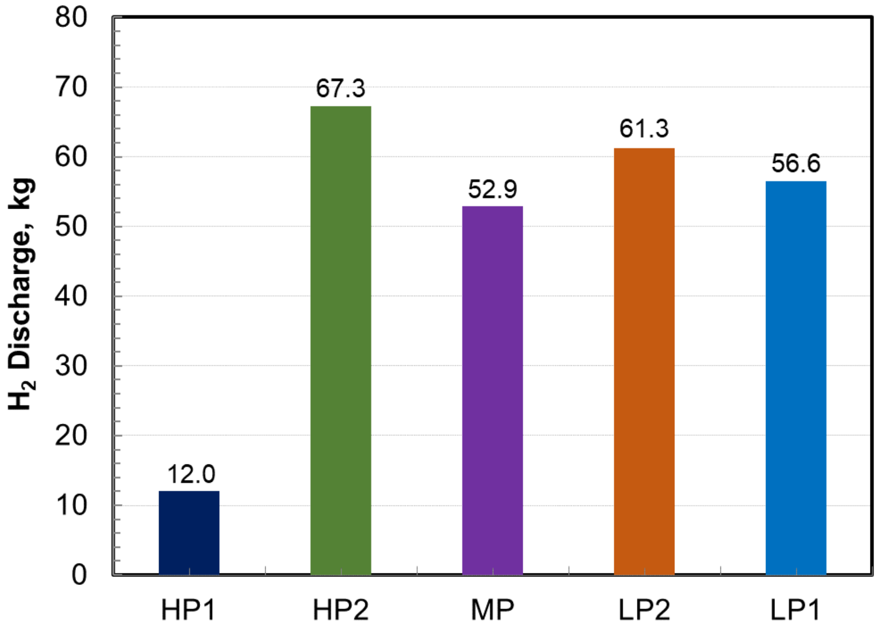
Usable Hydrogen

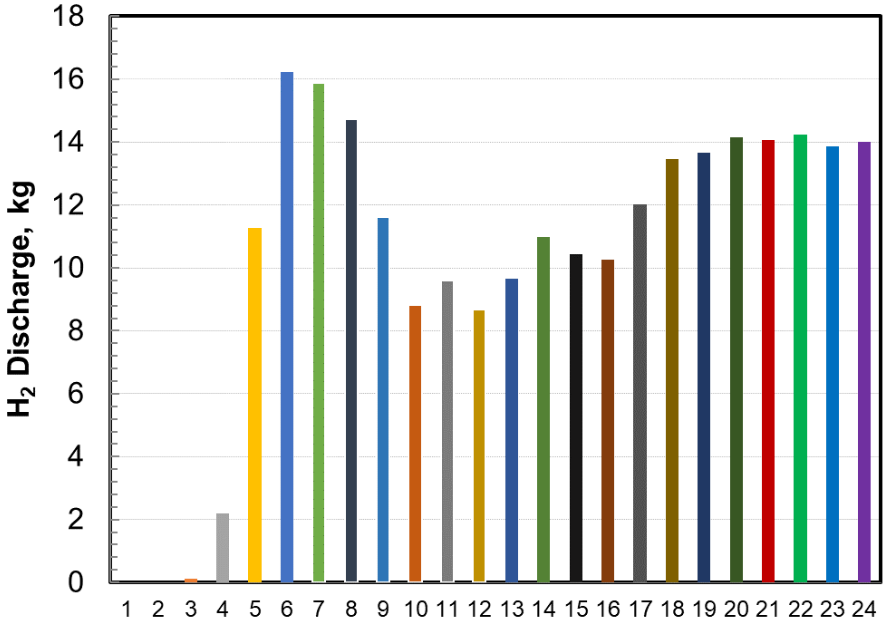
Buffer storage requirement minimized by utilizing lower pressure tanks more than higher pressure tanks

- Refueling priority:
  HP1 > HP2 > MP > LP2 > LP1
- Discharge priority:
  LP1 > LP2 > MP > HP2 > HP1
- H_2 discharge (250 kg/day total):
  Daily H_2 demand met by a tank

Sample results for ccompressor flow rate 150% of average daily demand

- 5-tank cascade: 76 kg-H_2 stored
  360 L tanks storing 17.2, 16.8, 14.4, 14.6, and 13.6 kg-H_2 per tank
- 24-tank cascade: 68 kg-H_2 stored
  70 L storing 2.5 - 3.3 kg-H_2 per tank

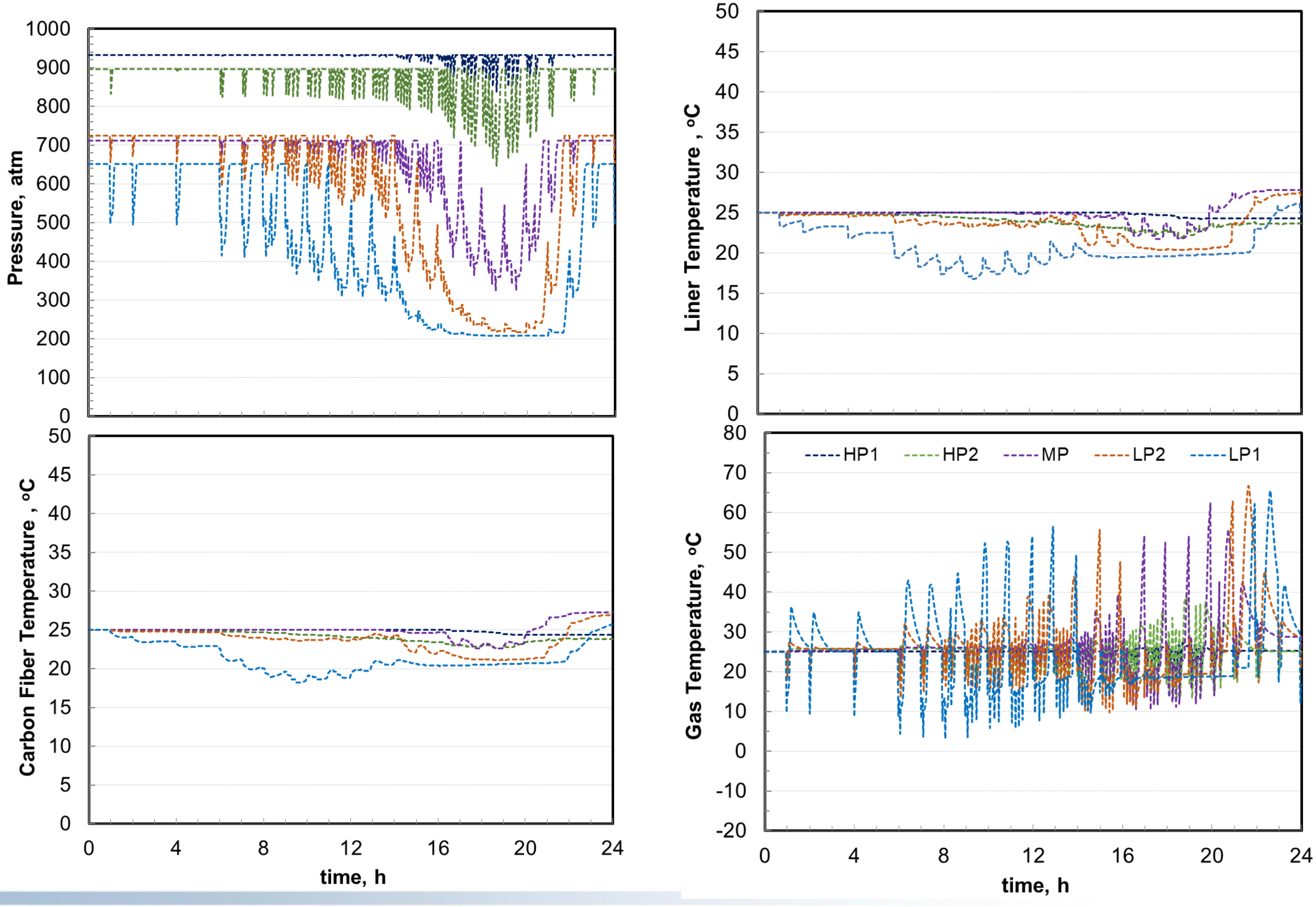




Pressure and Temperature Cycles

5-tank buffer storage system, 150% compressor discharge flow rate, 360 L/tank

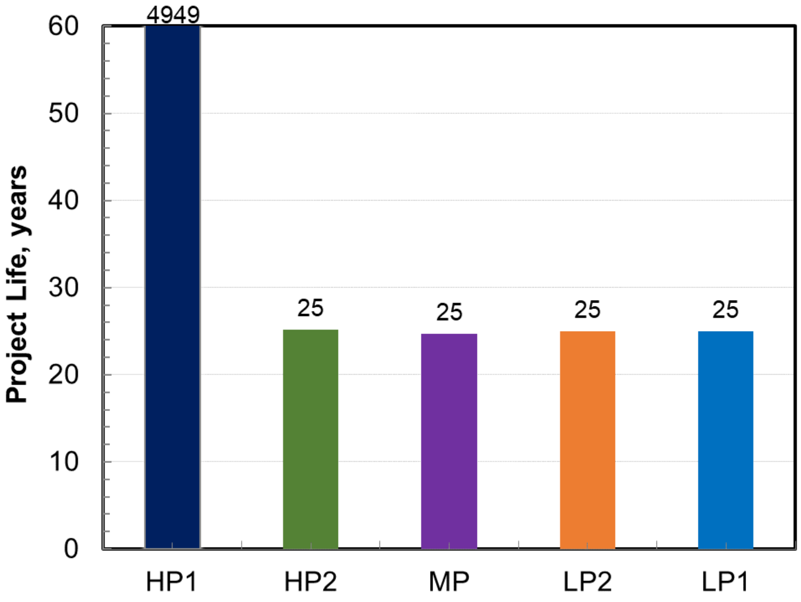
- High pressure limit: 932/896/711/724/652 atm for HP1/HP2/MP/LP2/LP1
- Maximum pressure swing: 94/214/328/168/346 atm for HP1/HP2/MP/LP2/LP1

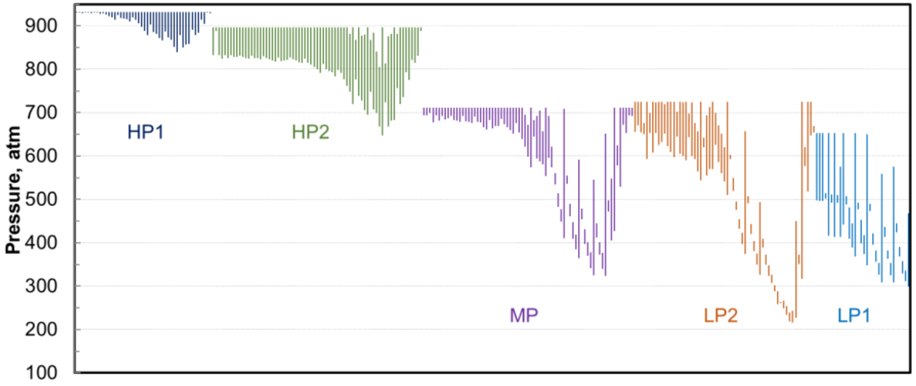


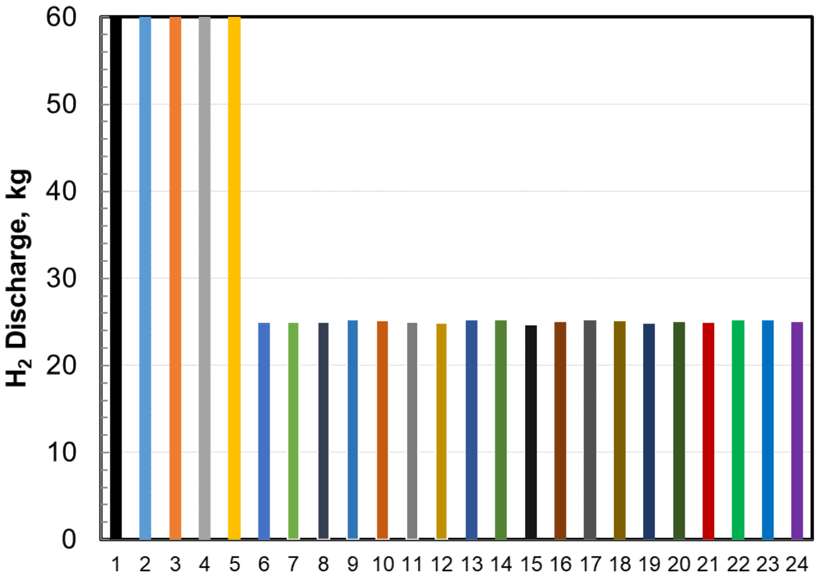
Fracture Life

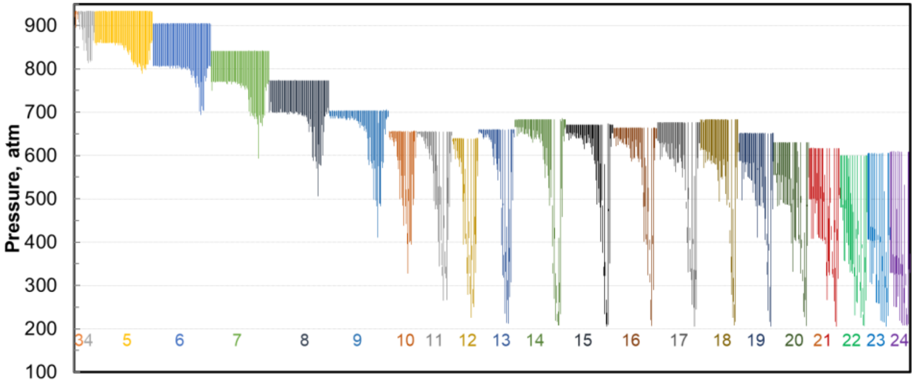
Fracture life depends on pressure swing (ΔP), mean pressure, and actual pressure cycles

- Possible to track residual tank life by recording its pressure history
- Modeled life: 25 years (657,000 vehicles)







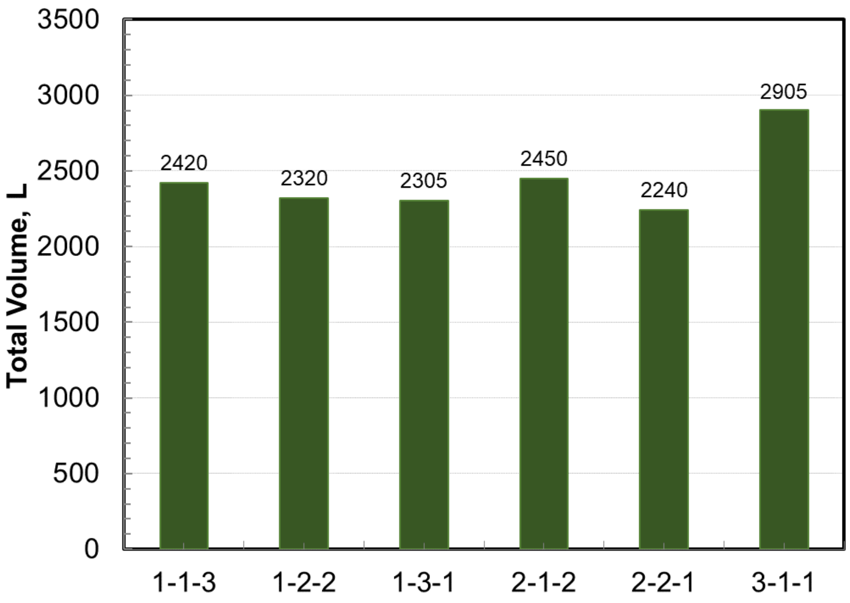


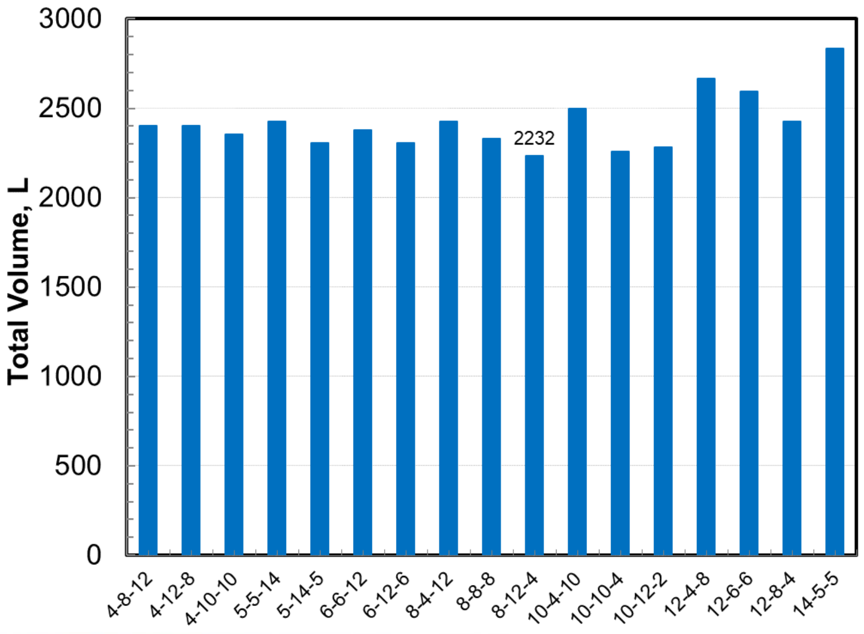
Optimizing as Tube Banks

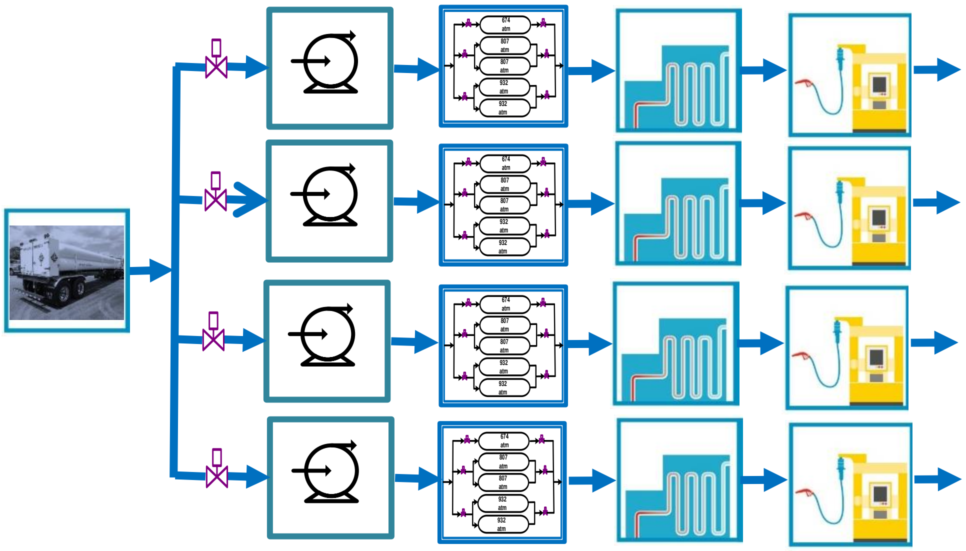
Optimum 3-bank arrangement: sample results for 150% compressor flow rate

- 5-tube cascade: 2 in high-pressure bank, 2 in medium-pressure bank, and 1 in low-pressure bank
  High pressure limit: 932/807/674 atm for HP/MP/LP banks
  Maximum ∆P: 104//260/340 atm for HP/MP/LP banks

- 24-tube cascade: 8 in high-pressure bank, 12 in medium-pressure bank, and 4 in low-pressure bank



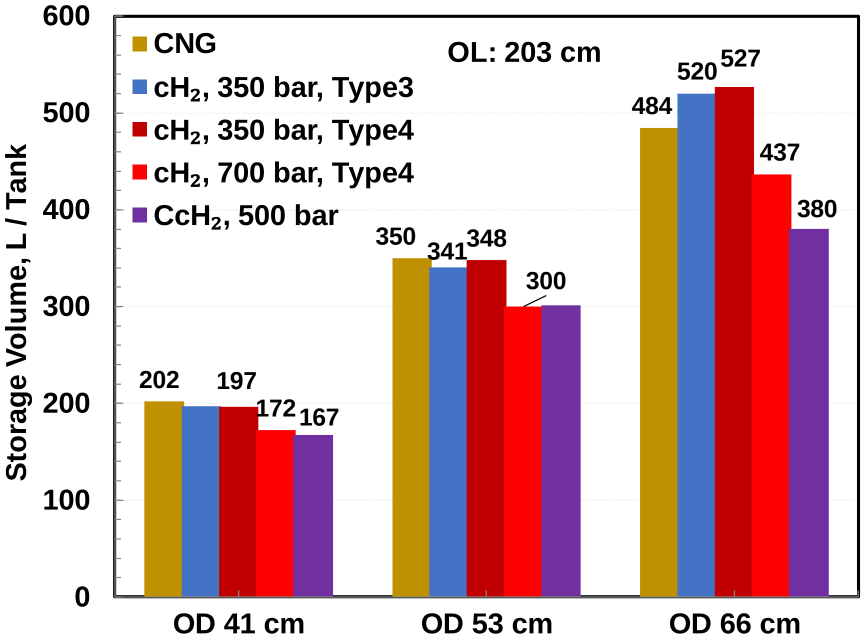


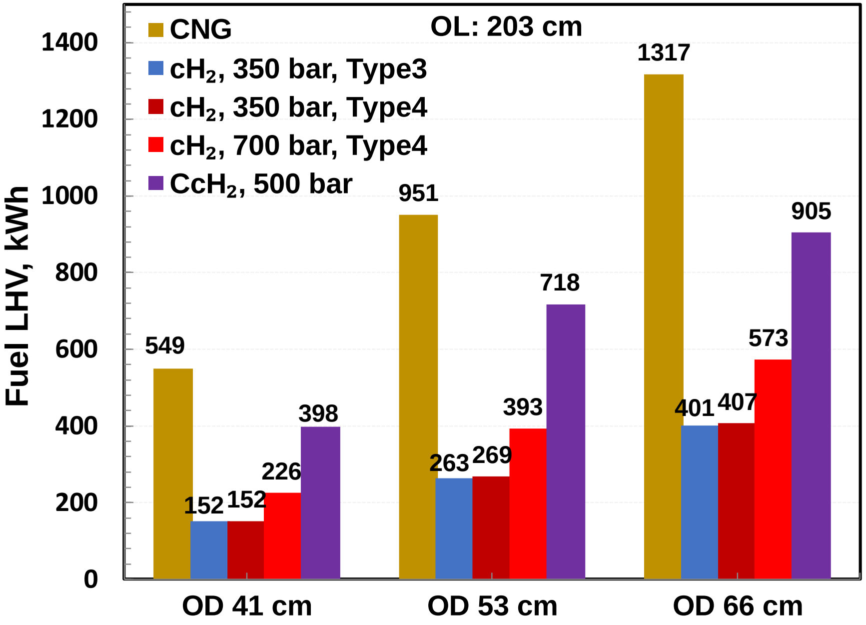


2-2-1 Cascade Storage System

Task 3: Hydrogen Storage for Medium and Heavy-Duty Trucks

Packaging Options[1]





Results for fixed OD and OL tanks: 15/26.5/32-DGE CNG tanks

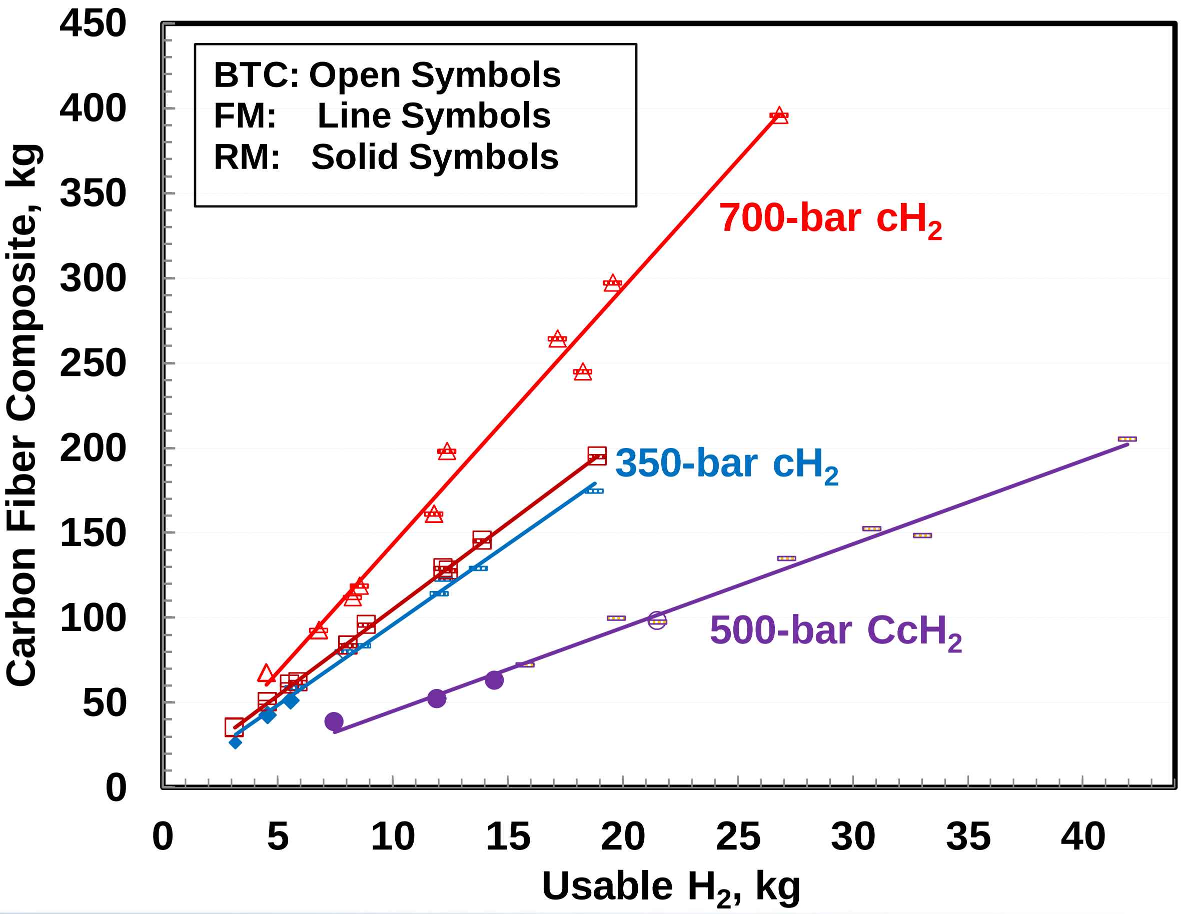
- Storage volume loss compared to CNG tanks: up to 20%, ΔV CcH_2 > 700 bar > 350 bar
- LHV loss compared to CNG tanks: up to 72%, ΔLHV 350 bar > 700 bar > CcH_2

[1] http://www.a1autoelectric.com OD: outer diameter; OL: outer length

H_2 Storage for MD and HD Trucks: Carbon Fiber Requirement

Carbon fiber composite requirements for same usable H_2

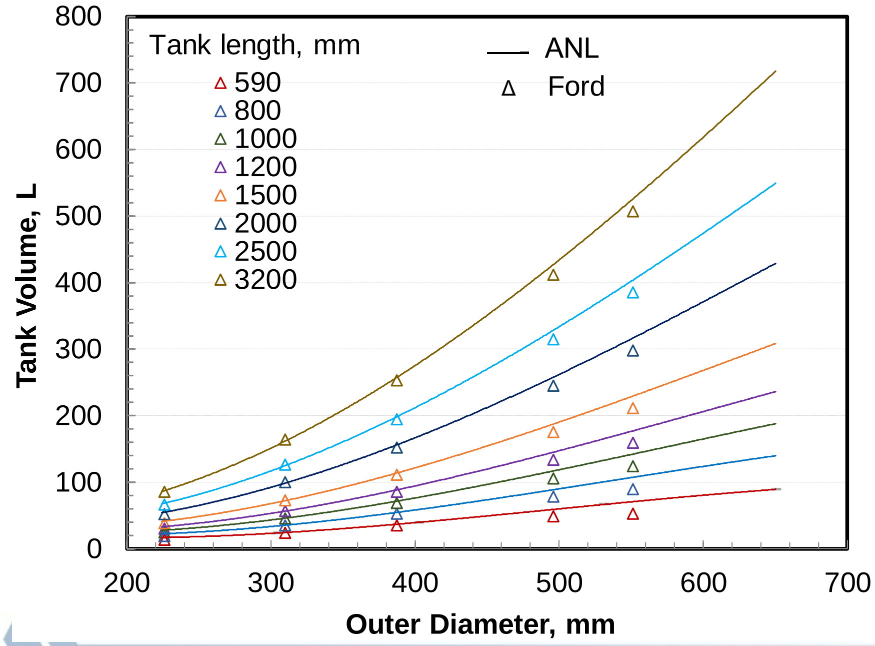
- ABAQUS/WCM FEA and FE-SAFE simulations
- 2.25 burst safety factor
- 15,000 pressure cycles
- CcH_2 << 350 bar Type-3 cH_2 ~ 350 bar Type-4 cH_2 << 700 bar Type-4 cH_2

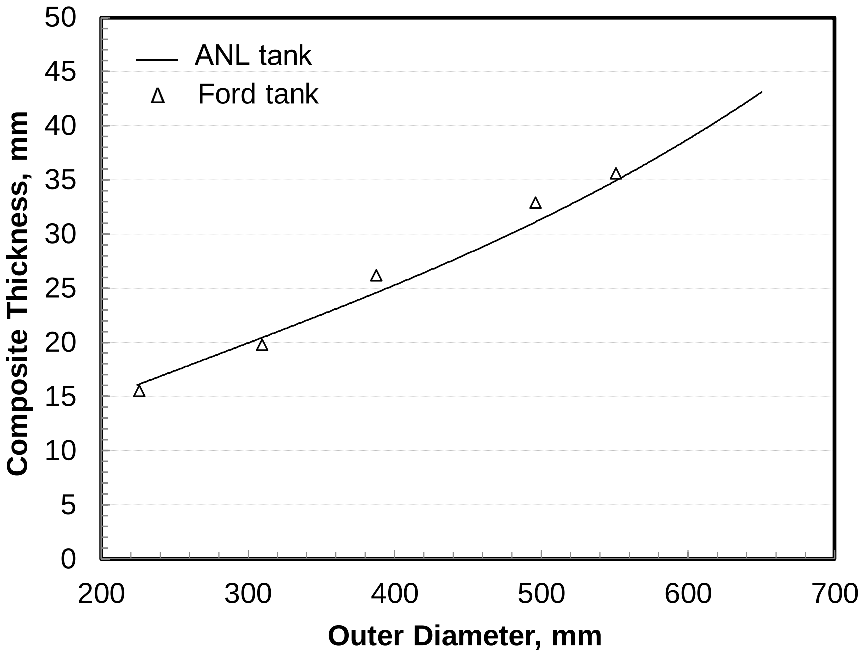


Model Calibration and Validation

- ANL-Ford working group set up to calibrate and validate ANL ABAQUS model with data available at Ford and simulations using their FE model

Material Properties	T700 Fiber	T700 Composite
Tensile Strength	4900 MPa	2550 MPa
Tensile Modulus	230 GPa	135 GPa
Strain at Failure	2.10%	1.70%
Tensile Strength (Failure Strain Basis)		2295 MPa
Density	1.8 g/cc	
Translation Efficiency		78%
Uncertainty		0% for hoop 15% for helical





Performance of 700-bar Compressed Hydrogen Tank

New T700 composite data shows 12% higher tensile strength and 19% higher failure strain

Parameter	Units	Value
Tank type		IV
Tank interior diameter	cm	39.6
Tank interior length	cm	118.9
Usable H_2	kg	5.6
Total H_2 stored	kg	5.8
Nominal working pressure	bar	700
Minimum empty pressure	bar	15
Hydrogen temperature	°C	15
Liner material		HDPE
Liner thickness	cm	0.5
Carbon fiber		T700S
CF tensile strength	MPa	4900
Fiber density	g/cc	1.8
Resin		Vinyl Ester
Resin density	g/cc	1.138
Fiber volume fraction		60%
Translation efficiency		Hoop: 92% Helical: 78%
Composite strength	MPa	2860
Design safety factor		2.25
Manufacturing COV		3.30%
Fiber COV		3.30%
Manufacturing overdesign		14%
Effective safety factor		2.57

Material Properties	T700 Fiber	T700 Composite Data	
		2018 Data	2020 Data
Tensile Strength	4900 MPa	2550 MPa	2860 MPa
Tensile Modulus	230 GPa	135 GPa	134 GPa
Strain at Failure	2.10%	1.70%	2.02%
Tensile Strength based on Failure Strain		2295 MPa	2706 MPa
Density	1.8 g/cc		
Translation Efficiency (Failure Strain Based)		78%	92%
Uncertainty		15% for Hoop 28% for Helical	0% for Hoop 15% for Helical

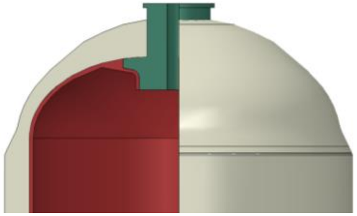
We are projecting that, with the new T700 composite data, the composite mass for a 5.8 kg, 700-bar tank can be reduced to 78 kg

- 2.57 effective safety factor as in 2018 record
- 92% hoop translation efficiency
- 78% helical translation efficiency

	Thickness (mm)			**Weight (kg)**		
	Hoop	Helical	Total	Hoop	Helical	Total
2015 Baseline, Prior T700S Data	16.5	20.9	37.4	36.8	69.8	106.6
2020 Baseline, 2020 T700S Data	11.9	16.5	28.4	26.1	52	78

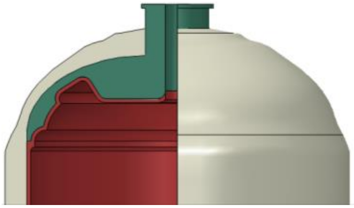
Reinforced Dome and Doilies (90 L Tank)

- Metal-Reinforced Dome Concept
  - Covering the dome section with varying thickness
  - 17% reduction in composite weight: 51 kg to 42.5 kg

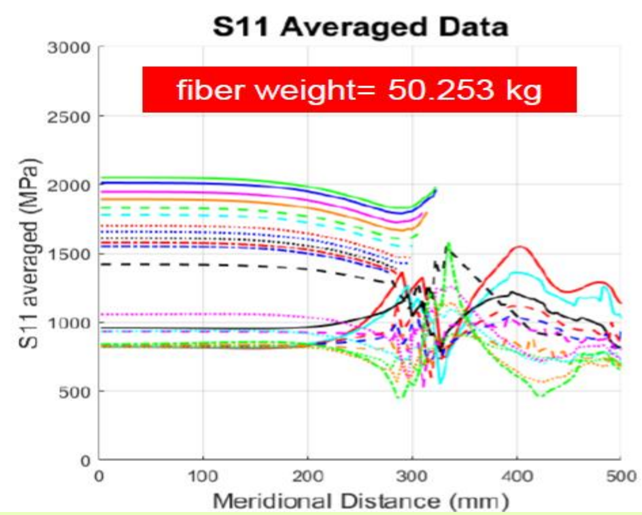


Baseline Boss

- Doily-Reinforced Dome Concept
  - Ford simulations confirm that doilies can reduce the composite weight by 6%.

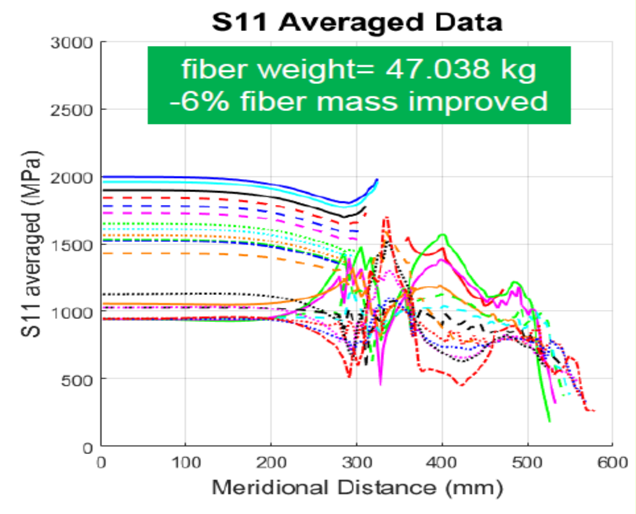


Boss-Reinforced Dome



S11 Averaged Data

fiber weight= 50.253 kg



S11 Averaged Data

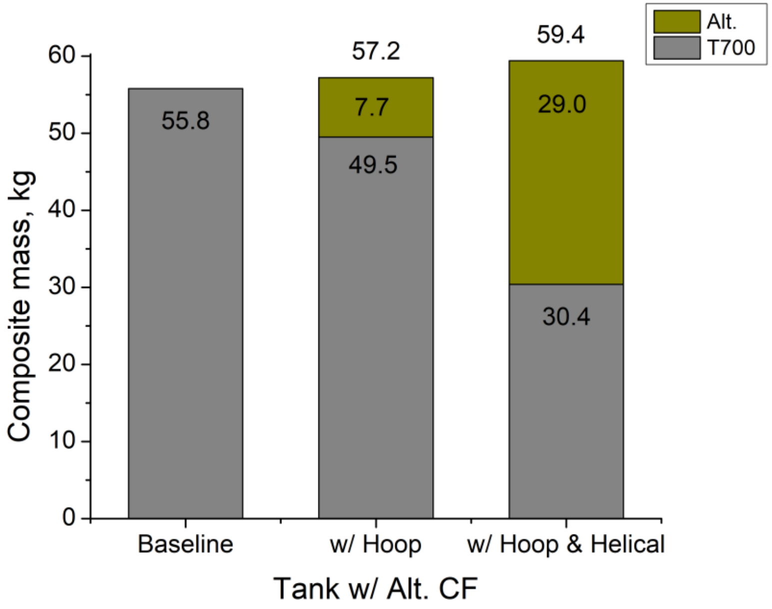
fiber weight= 47.038 kg
-6% fiber mass improved

Presented by Bert (Ford Motor)

Alternate Fiber (90 L)

- Composite properties (failure strain, ε_f)
  - T700/epoxy: 1.7%
  - Alternative fiber: 1.35%
- Alternative fiber in outer hoop layers only
  - Replacing 4.95-mm of outer hoop with alternative fibers reduces T700 composite mass by 10.7%, but the overall composite mass increases 2.5%
- Alternative fiber in outer hoop and helical layers (100%)
  - Low-cost alternative fiber represents ~50% of total composite weight
  - 46% decrease in high-cost T700 composite
  - 6.4% increase in total composite weight

	Fiber	Baseline	Hoop	Hoop & Helical
Hoop	T700	13.2	8.25	8.25
	alt	0	5.78	5.78
	total	13.2	14.03	14.03
Helical	T700	16.5	16.5	9.9
	alt	0	0	7.43
	total	16.5	16.5	17.33
Total	T700	29.7	24.75	18.15
	alt	0	5.78	13.2
	total	29.7	30.53	31.35



FY2020 Collaborations

Hydrogen Carriers	HyMARC: PNNL, NREL, LBNL
Bulk Storage	ANL (H2A Group), ANL (HDSAM), H2IT Taskforce
Compressed Hydrogen (cH_2) Storage for Trucks	SA Team: SA, ANL, PNNL Ford
Cryo-Compressed Hydrogen (CcH_2) Storage for Trucks	HMAT: PNNL, SNL LLNL
Liquid Hydrogen Storage (LH_2) for Locomotives and Marine Applications	Chart Industries
Off-Board Cost	ANL (H2A Group), ANL (HDSAM), H2IT Taskforce
On-Board Cost	Strategic Analysis Inc (SA)

- Argonne develops the storage system configuration, determines performance, identifies and sizes components, and provides this information to SA for manufacturing cost studies

Future Work

1. Hydrogen Carriers
   - Scenarios that favor hydrogen carriers such as by-product H_2
   - Case studies with different demand and supply scenarios
   - Carriers that are particularly suitable for renewable hydrogen production and energy storage
   - Reverse engineering to determine desirable properties of liquid carriers including ease of dehydrogenation and H_2 purification
   - Coordination with HyMARC consortium to analyze emerging materials
   - Investigate H_2 liquefaction cycles to understand limitations in unit train capacity, and possible cost and energy reduction

2. Bulk Storage of Hydrogen
   - Continue to explore different storage methods (geological and non-geological), storage capacities (1-10 days), and storage locations (city gate vs. forecourt)
   - Investigate advanced H_2 liquefaction cycles to understand limitations in unit train capacity, and possible cost and energy reduction
   - Alternate bulk LH_2 storage methods, boil-off recovery and reliquefaction

3. Hydrogen Storage for Heavy-Duty Applications
   - Continue to conduct finite element simulations to verify cycle life and carbon fiber requirements
   - Liquid hydrogen storage for locomotives and maritime applications

Any proposed future work is subject to change based on funding levels

Project Summary

Relevance:	Independent analysis to evaluate on-board and off-board performance of materials and systems
Approach:	Develop and validate physical, thermodynamic and kinetic models of processes in physical and material-based systems Address all aspects of on-board and off-board targets including capacities, rates and efficiencies
Progress:	Established benchmark costs for H_2 production by SMR, liquefaction, storage, transmission, distribution, and dispensing. Developed a model for fracture durability of Type-2 tanks and determined pressure limits for 25-year lifetime. Calibrated ABAQUS models for H_2 storage in Type-3 and Type-4 tanks and showed the possibility of lowering the status number for carbon fiber composite requirement. Showed that 33–54 kg of usable H_2 can be stored in roof mounted, behind-the-cab and frame-mounted tanks being offered for compressed natural gas trucks.
Collaborations:	Ford, HyMARC, LLNL, PNNL, SA, Delivery Team
Proposed Future Work:	Determine desirable material properties and analyze scenarios that favor hydrogen carriers Complete analysis of stationary hydrogen storage for different scales, duration and applications Validate results for hydrogen storage on-board HDVs and MDVs

Reviewer Comments

Generally favorable reviews with the following comments/recommendations

- The approach is straightforward and rational. This project continues to serve a valuable role
- The inclusion of large production plants for the carriers demonstrates notable progress. The bulk storage analysis is a helpful reference for infrastructure and H2@Scale analysis.
- This project is very relevant to DOE’s current focus. The inclusion of MD and HD vehicles to the scope of interest and the prevalence of H2@Scale and its associated projects further enhance the project’s relevance.
- FY20 work scope consistent with recommendations

√ Fostered closer interactions with Ford to calibrate and validate ANL ABAQUS model with data available at Ford and simulations using their FE model

√ The hydrogen carriers were compared to liquid hydrogen as to complete the baseline scenarios.

√ Calibrated ABAQUS models for H_2 storage in Type-3 and Type-4 tanks and showed the possibility of lowering the status number for carbon fiber composite requirement.

√ Developed models for fracture durability of Type-2 tanks and determined pressure limits for 25-year lifetime.