Hydrogen Storage Cost Analysis

Cassidy Houchins (PI)
Jacob H. Prosser
Max Graham
Zachary Watts
Brian D. James

June 2023

Project ID: ST235
Award No. DE-EE0009630
DOE Hydrogen Program
2023 Annual Merit Review and Peer Evaluation Meeting

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Overview

Timeline

Project Start Date: 9/30/21
Project End Date: 9/29/24
% complete: ~50%

Budget

Total Project Budget: $699,964
Total DOE Funds Spent: ~$262,000
(through March 2023, excluding Labs)

Barriers

A: System Weight and Volume
B: System Cost
K: System Life-Cycle Assessment

Partners

Kevin Simmons, *Pacific Northwest National Laboratory*
Rajesh Ahluwalia, *Argonne National Lab*

Project Goal

- Conduct rigorous, independent, and transparent, bottom-up techno-economic analysis of H_2 storage systems using Design for Manufacture and Assembly® (DFMA®)

- Identify cost drivers and identify which performance parameters can be improved to have the greatest impact on cost

- Provide DOE and the research community with referenceable reports on the current status and future projected costs of H_2 storage systems in various forms including a levelized cost of storage (LCOS)

- Analyses conducted:
  - Onboard cryogenic (CcH_2, LH_2) and compressed (350 and 700 bar) H_2 storage systems for Class 8 Long Haul trucks
  - Large-Scale LH_2 storage systems at city gate and trade terminals
  - Utility-scale engineered underground storage

Relevance & Potential Impact

- DFMA® analysis is used to predict costs based on both mature and nascent components and manufacturing processes depending on what manufacturing processes and materials are hypothesized

- Identify the cost impact of material and manufacturing advances and to identify areas of R&D with the greatest potential to achieve cost targets

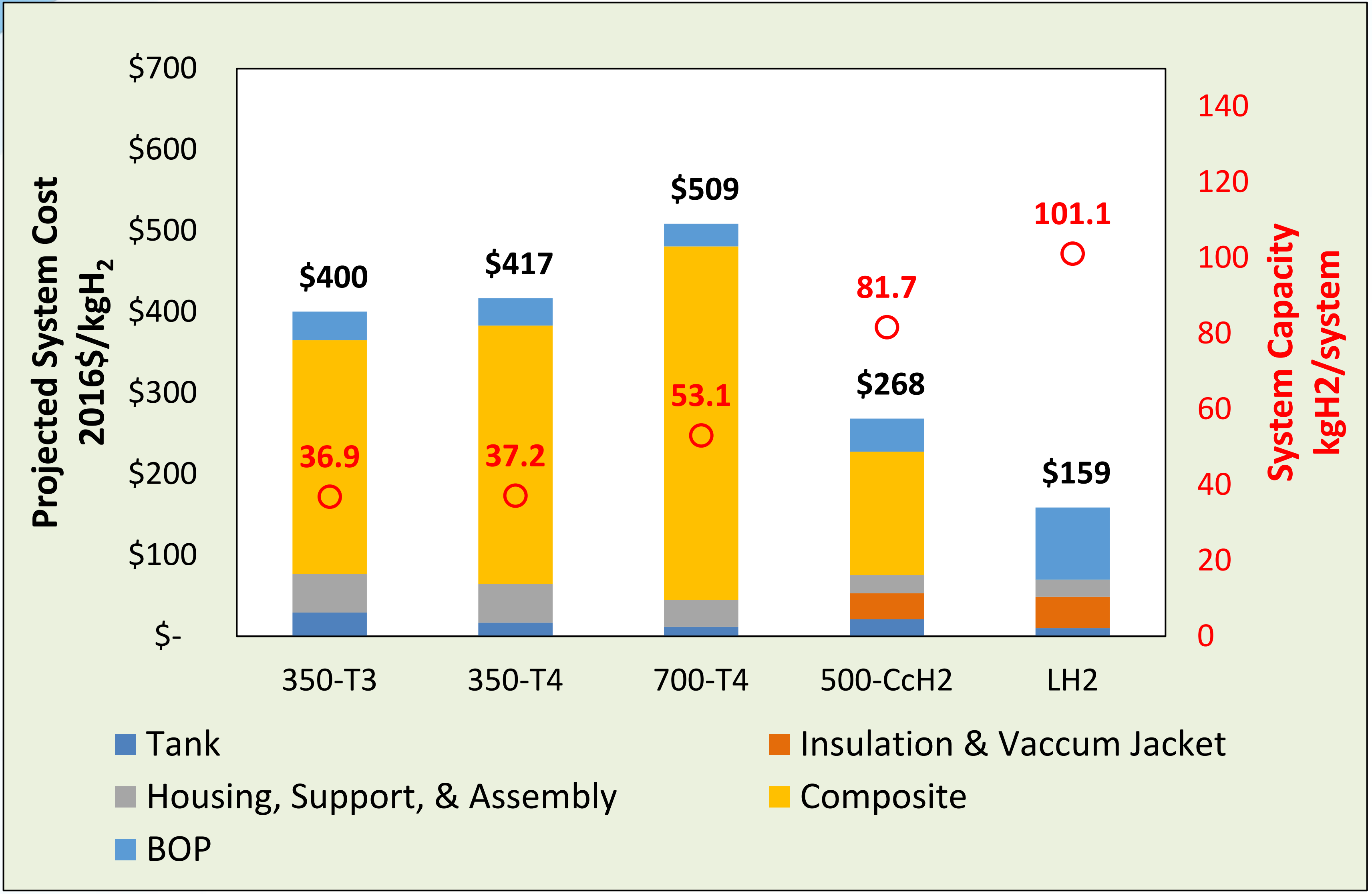
- Provide insight into which components are critical for reducing costs of H_2 storage and for meeting DOE cost targets

Class 8 Long Haul Targets and Current Cost Projection

Property	Units	Status/Assumption	2030 Target[1]	Ultimate Target[1]
Storage capacity	kgH2	60[2]	None	None
LH2		90.5-101.1[4]		
350 bar Type 3		35.3-36.9		
350 bar Type 4		35.5-37.2		
700 bar Type 4		49.9-53.1		
500 bar CcH2		69.8-81.7		
Storage system cost projections	2016$/kg$H_2$		300	266
LH2		$159-238		
350 bar Type 3		$400-487		
350 bar Type 4		$417-506		
700 bar Type 4		$509-633		
500 bar CcH2		$268-347		
Refueling cost[3]	2016$/kg$H_2$		4	2
10 bar LH2		~8-10		
350 bar		~6		
700 bar		~6		
500 bar cryocompressed		~~8-10		

[1]See Marcinkoski et al for full list of targets and assumptions. Marcinkoski, Jason. "Hydrogen Class 8 Long Haul Truck Targets." Washington D.C.: U.S. Department of Energy, December 12, 2019. https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf.
[2]DOE hasn't established capacity targets but assumes 60kgH2 is needed to achieve 750 mile range
[3]Estimated from HRS cost contribution projections in https://www.hydrogen.energy.gov/pdfs/review20/sa170_elgowainy_2020_o.pdf and delivered fuel cost projections in https://www.hydrogen.energy.gov/pdfs/review20/sa170_elgowainy_2019_o.pdf. Note that CcH2 dispensed cost is for 350 bar, so costs are expected to be higher.
[4]Range includes the confidence interval from sensitivity analysis and the basis point from our analysis. See Slide 8 for further information

Projected Cost and Storage Capacity for Class 8 Trucks



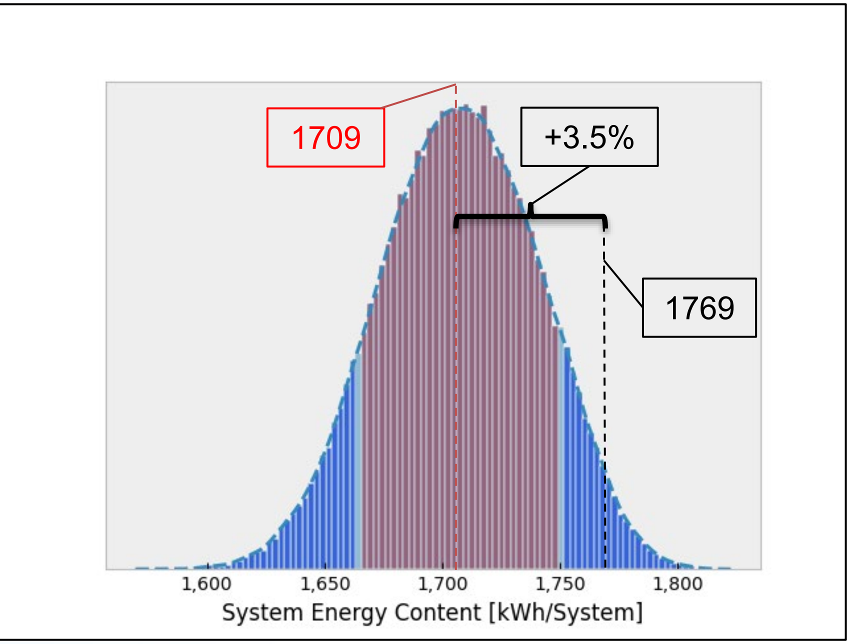
- Cost are projected to 100,000 systems manufactured annually
- Storage capacity is based on the largest available package with external dimensions of 66 cm x 305 cm*
- Two frame-mounted tanks

See slide 26 for available configurations.
https://www.hydrogen.energy.gov/pdfs/review22/st235_houchins_2022_p.pdf

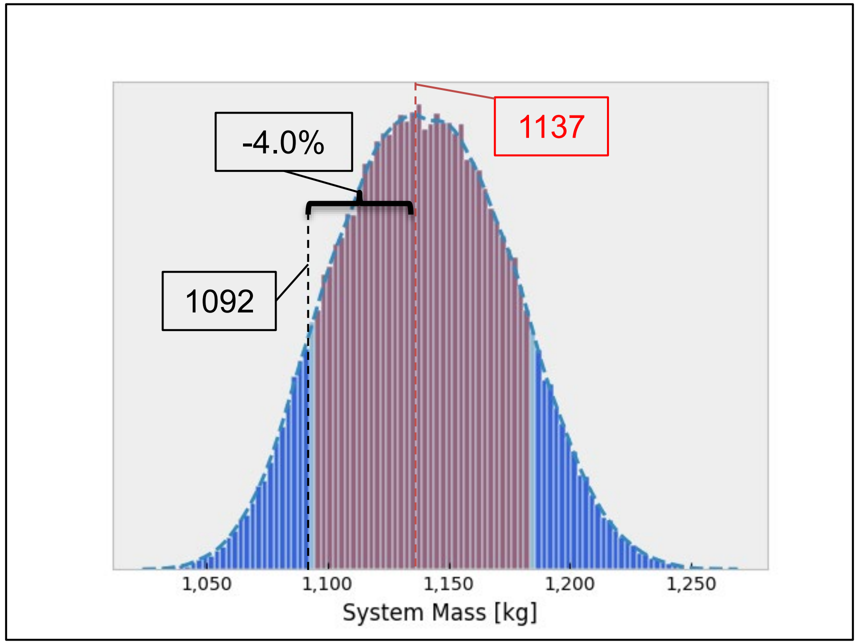
Uncertainty Analysis Completed

- Monte Carlo uncertainty analysis was completed for all systems investigated
- Results for 700 bar Type 4 systems show that baseline projections (represented by the black, dashed line and data label) reflect best case scenario for all parameters studied.
- The most statistically probable case is demonstrated by the mode of the data (represented by the red, dashed line and data label).
- See backup slides for complete results of all storage system types investigated

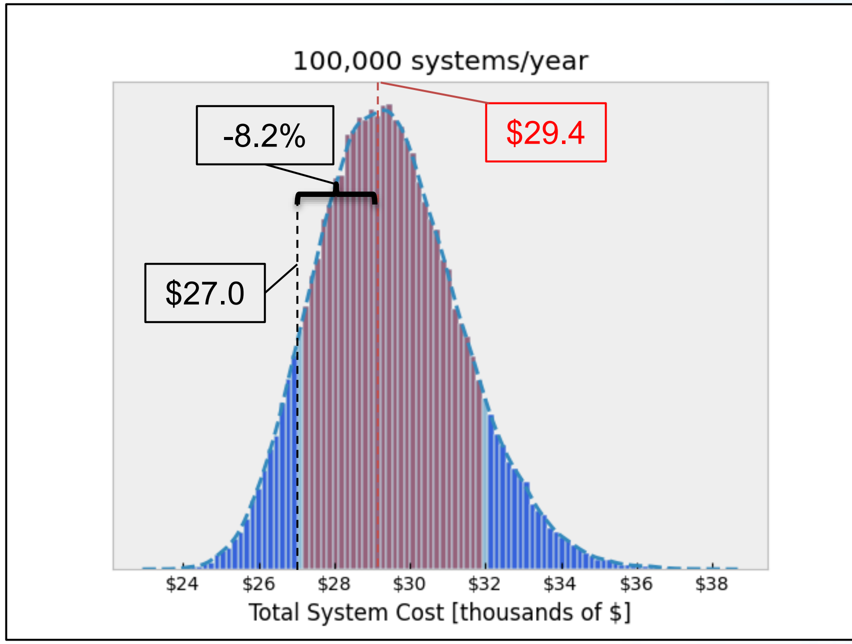
Storage Capacity (kWh)



System Mass (kg)



System Cost (2016$)



Approach

Correlative Model for Large-Scale LH_2 IRAS Cost Analysis

- Simplified cost correlations for primary system components separately reported by different groups (i.e., NASA, ANL)
  - Use tank Total Capital Investment correlation from HDSAM v3.1 (2018) developed by ANL[5]
  - Use refrigeration capital cost estimates & efficiencies from NASA 2016-2021 IRAS analysis[6]
  - Assume approximate top-level percentages for other miscellaneous components (e.g., piping, valves, instrumentation & controls, other structural, etc.) & missing installation & site preparation costs
- Perform system simplified heat transfer analysis
  - Calculate heat flux into tank using effective thermal conductivities measured & reported by NASA for various bulk-fill tank insulation materials & heat transfer relationships
  - Apply approximate top-level percentages for heat addition into other miscellaneous components
  - Estimate equivalent LH_2 boiloff for no refrigeration or refrigeration requirements in the IRAS system
- Estimate operating costs
  - Assign LH_2 from typical cost value reported in current LH_2 delivery cost analysis literature & compute costs associated with LH_2 boiloff loss
  - Assign electricity price from typical cost values currently reported for industrial-scale applications & compute electricity utility costs
  - Postulate operations & maintenance personnel work force, total wages, system service life & operating efficiency, & calculate labor costs
- Combine amortized total capital & operating costs to produce a total system LCOS

5. UChicago ANL. HDSAM © v3.1 **2018**, https://hdsam.es.anl.gov/index.php?content=hdsam
6. A. Swanger & J. Fesmire. Economics of Energy Efficient, Large-Scale LH2 Storage Using IRAS & Glass Bubble Insulation. *NASA KSC-CTL* **2021**

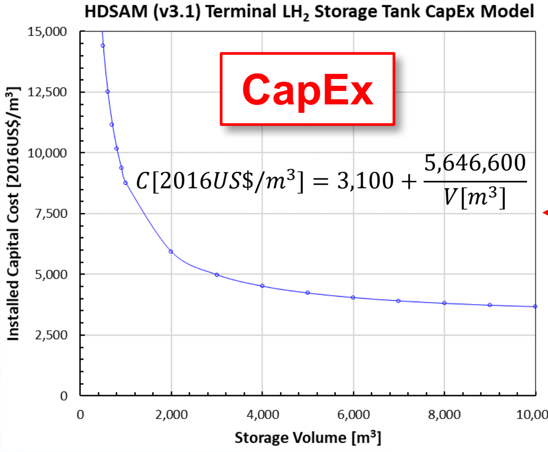
Accomplishments & Progress

Correlative Model Basis for Large-Scale LH_2 IRAS Cost Analysis

Main Assumptions

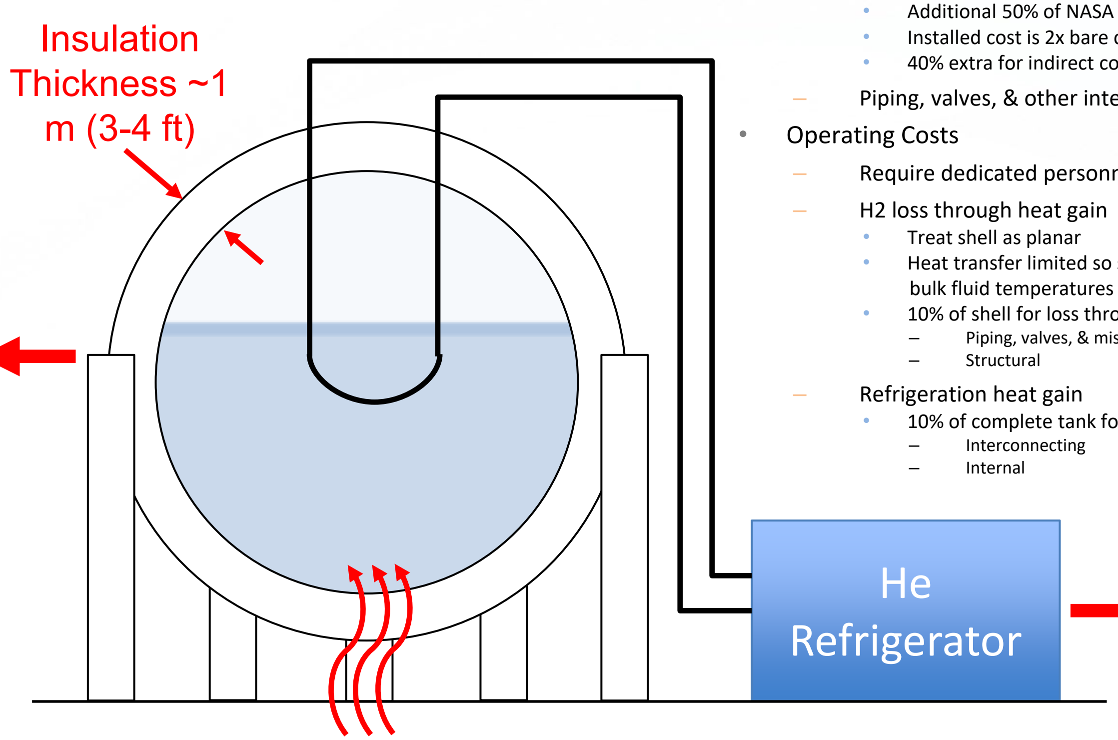
- Capital Costs
  - Refrigeration Subsystem
    - Additional 50% of NASA CapEx estimate to account for other equipment
    - Installed cost is 2x bare capital cost
    - 40% extra for indirect costs (i.e., site prep, E&D, licensing, etc.)
  - Piping, valves, & other interconnecting equipment is 2% of tank & refrigeration installed costs
- Operating Costs
  - Require dedicated personnel for operations & maintenance
  - H2 loss through heat gain
    - Treat shell as planar
    - Heat transfer limited so surface temperatures are at bulk fluid temperatures
    - 10% of shell for loss through:
      - Piping, valves, & miscellaneous equipment
      - Structural
  - Refrigeration heat gain
    - 10% of complete tank for:
      - Interconnecting
      - Internal

ANL HDSAM (v3.1)



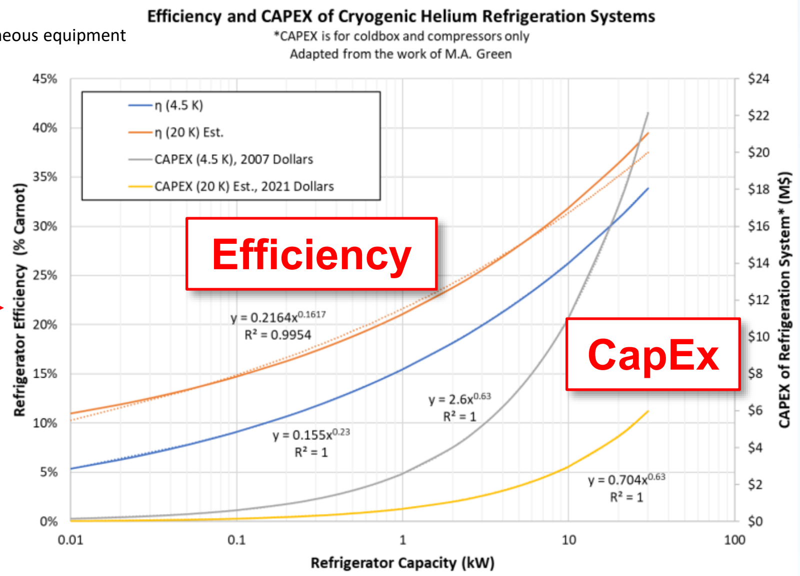
5. UChicago ANL. HDSAM © v3.1 **2018**, https://hdsam.es.anl.gov/index.php?content=hdsam

HDSAM = "Hydrogen Delivery Scenario Analysis Model"



Heat load calculated as a function of tank design, storage conditions, exposed area, shell evacuation, & insulation type

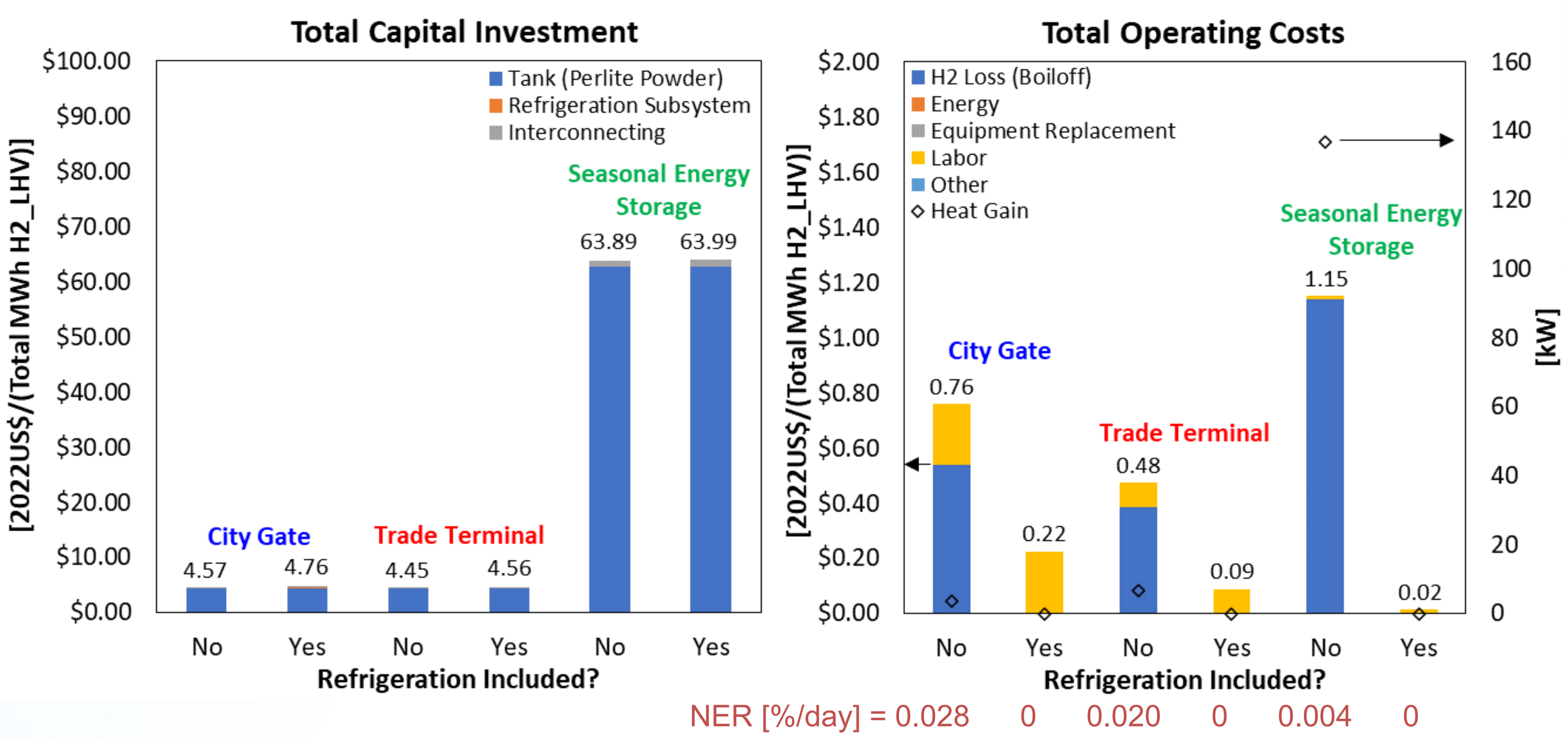
NASA's IRAS



6. A. Swanger & J. Fesmire. Economics of Energy Efficient, Large-Scale LH2 Storage Using IRAS & Glass Bubble Insulation. *NASA KSC-CTL* **2021**

Accomplishments & Progress

Preliminary Results for Correlative Large-Scale LH_2 IRAS Cost Analysis



	City Gate	Trade Terminal	Seasonal Energy Storage
Nominal Capacity [m3]	40,000	100,000	~10,000,000
Turnover Period [days]	10	10	146[7]

Assumptions/Other Parameters:

- Ambient Conditions: T = 28 °C, P = 1 Atm
- Inventory Conditions: T = 20 K, P = -1.6 PSIG
- Insulation Shell Pressure: 20 mtorr (average of typical Nasa operating range)
- Insulation Packing: Loose (132 kg/m3), 1 m of thickness
- Ullage: 10%
- System Operating Efficiency: 98% (8,568 hrs/yr)
- H2 Price: $6.50/kg
- Electricity Price: $0.06/kWh
- 24-hour operation@$60/hr base pay, maintenance as needed@~$65/hr base pay (average)

7. Estimated from: Mitsubishi Power Americas, Inc. Why the Western US Needs Energy Storage. White Paper **2020**, https://aces-delta.com/wp-content/uploads/2022/03/Mitsubishi-Power-White-Paper-Why-the-Western-U.S.-Needs-Energy-Storage.pdf

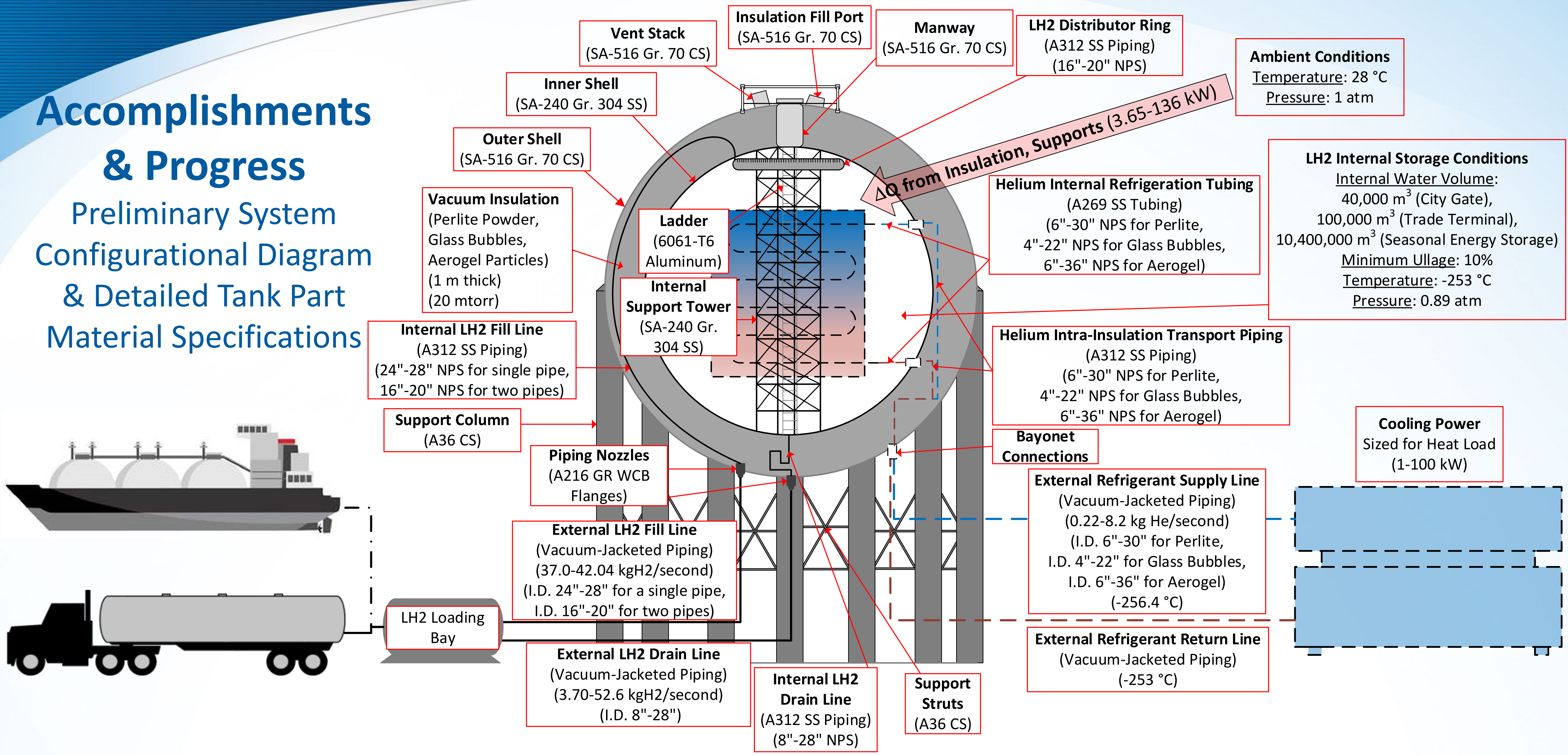
Approach

Detailed, Bottom-Up Model for Large-Scale LH_2 IRAS Cost Analysis

- Initial correlative IRAS model developed in FY2023 Q1 limited due to inability to scale tank costs
  - Basis for HDSAM v3.1 (2018) trade terminal storage tank total capital investment correlation could not be determined
    - Tank design & insulation type & amounts unknown
  - Not possible to accurately apply scaling rules to determine cost variation/difference with insulation type & amount, & tank design aspects
- Identified 4 large-scale LH_2 storage industry experts & held consultation meetings with each
  - NASA KSC-CTL, McDermott (CB&I), Shell, & Matrix Services
  - Purpose was to:
    - Confirm validity of correlative cost models & system components
    - Acquire any insights for how to improve these correlative cost models
    - Obtain feedback & confirmation on model parameters & proposed storage scenarios
  - Main discussion outcomes were determining the need to develop detailed, bottom-up cost models for the system
- Development of detailed, bottom-up cost models & total system LCOS
  - Compile detailed parts list & bill of materials (BOM) for all system components
    - Complete tank including internal piping, fittings, and valving
    - Loading/Unloading station/bay
    - Refrigeration subsystem
    - Interconnecting piping, fittings, & valves, & other miscellaneous components for site development, installation, & construction
  - Estimate full material costs for all system BOM parts
    - Raw material costs
    - Manufacturing/Fabrication & other commercial product costs
  - Combine with on-site construction cost estimates & updated amortized operating costs to yield a total system LCOS

Accomplishments & Progress

Preliminary System Configurational Diagram & Detailed Tank Part Material Specifications

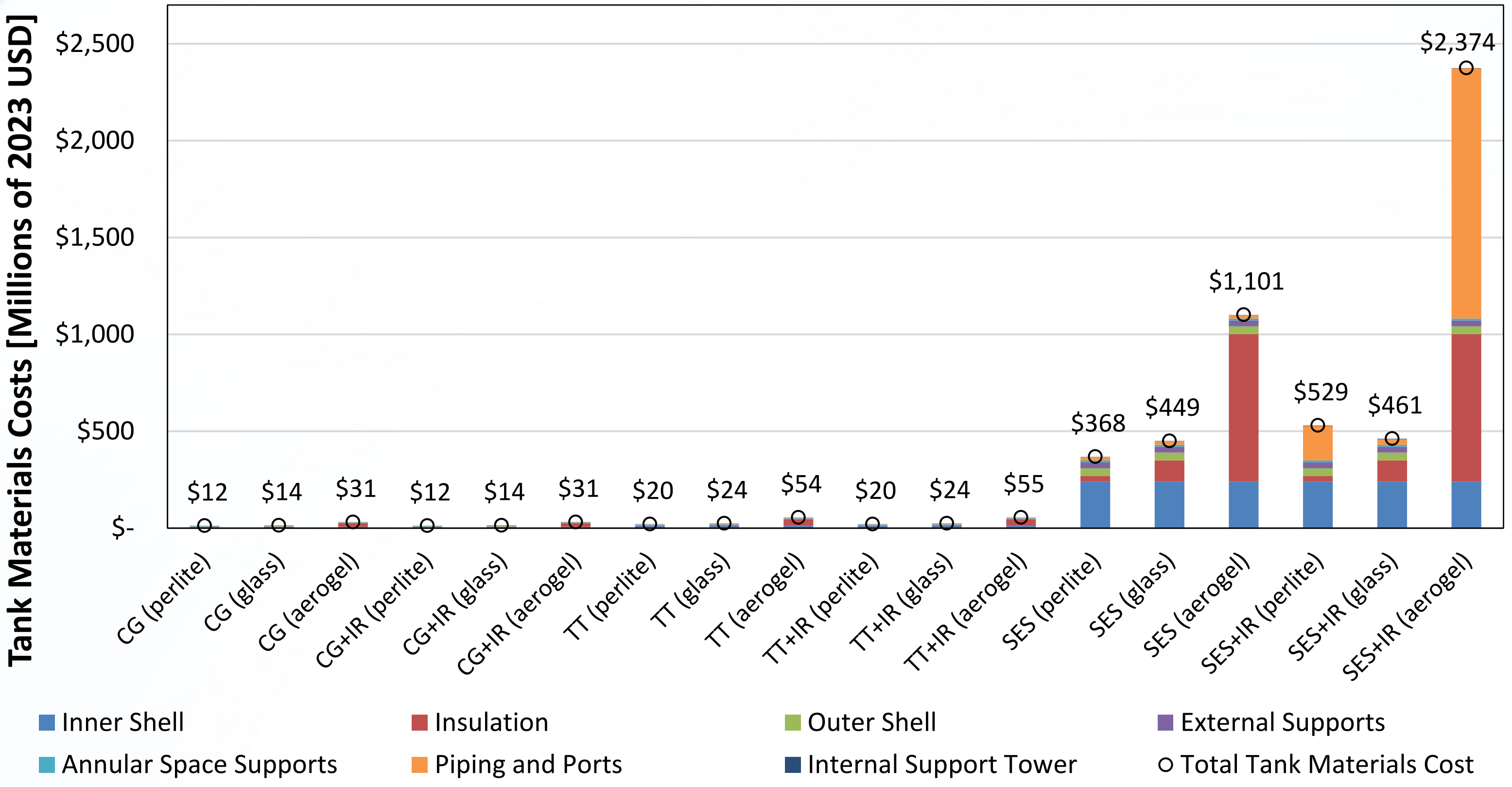


Dashed lines (– – –) denote additional components required for the zero-boiloff case

Dashed-Dotted lines (– • –) indicate the possibility for marine handling and transport

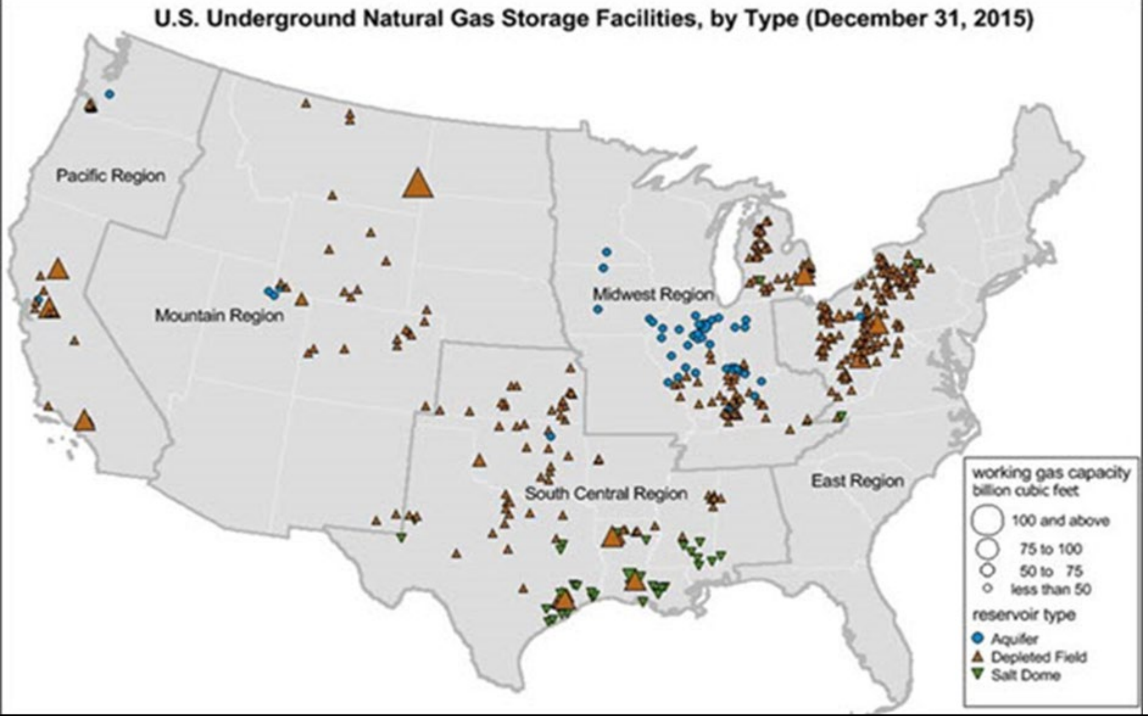
Accomplishments & Progress

Preliminary Results for Detailed, Bottom-Up Model for Large-Scale LH_2 IRAS Cost Analysis



- 3 Storage Scenarios Evaluated
  - CG = City Gate (40,000 m^3, 10-Day Turnover Period)
  - TT = Trade Terminal (100,000 m^3, 10-Day Turnover Period)
  - SES = Seasonal Energy Storage (10,000,000 m^3, 6-Month Turnover Period)
- Inclusion of Integrated Refrigeration (IR) as a configuration option (passive vs. active boiloff control)
- Perlite vs. glass bubbles vs. aerogel particles bulk-fill insulation (1 m thick)

- Most material costs do not include manufacturing & other commercial fabrication costs
  - Costs for bulk-fill insulation, piping, tubing, and some structural components are based on commercially available products



Underground Storage Background

- Underground fossil gas storage is mature, with an average of 60 billion cubic meters of capacity in the US
- Most capacity is stored in depleted oil/gas reservoirs and salt caverns
- <10 underground H_2 facilities exist worldwide

https://www.phmsa.dot.gov/pipeline/underground-natural-gas-storage/locations

Underground Storage Facility Types and Properties

	unit	Engineered	Salt Cavern	Depleted Gas Reservoir	Lined Rock Cavern
Capacity	tH_2	Up to 500	2,000-6,000	4700+	1,000-2,000
Pressure	Bar	200-700	50-150	50-100	150-300
Volume Energy	m3 GWh	6,700 16.5	500,000 133[8]	1,000,000 + 155	40,000 50
Cushion Gas Requirements	% of Volume	0	25	50	10
Construction Process	N/A	Blind Bore Drilling	Solution Mining	None	Drill and Blast
Concerns	N/A	Casing and Seal Leak/Damage	H_2S generation by Micro-organisms, leakage	H_2S generation by Micro-organisms, leakage	Hydrogen Embrittlement and Sliding Layer, leakage

Underground H_2 Storage

	Unit	Teeside	Clemens Dome	Spindletop	Moss Bluff
Location	--	UK	TX	TX	TX
Operator	--	BP	ConocoPhillips	Air Liquide	Praxair
Market	--	North England	Gulf Coast	Gulf Coast	Gulf Coast
Commissioned	--	1970s	1983	1983	2007
Depth	m	370	850	850-1400	850-1400
Capacity	m3	210,000	580,000	600,000	580,000

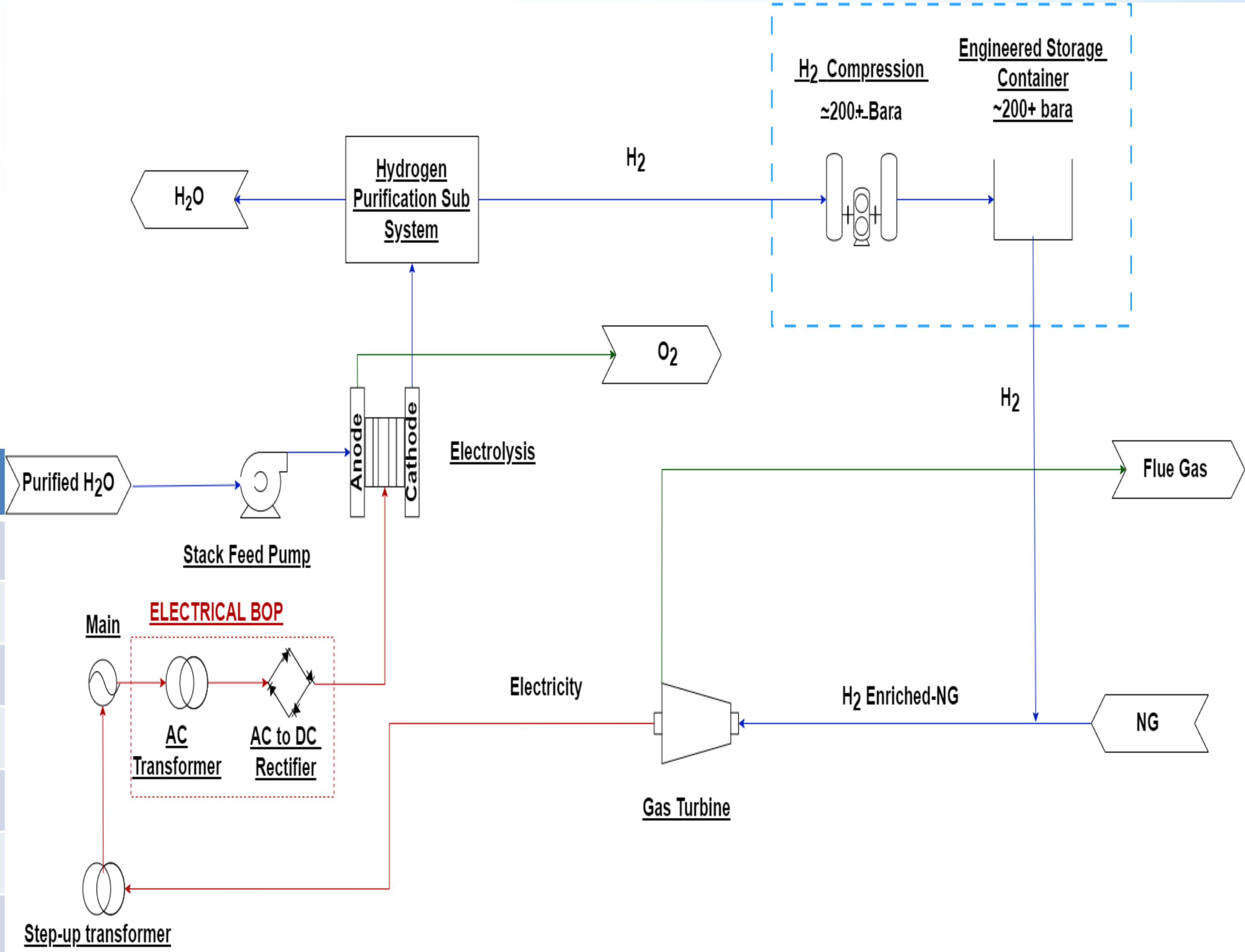
8. D. G. Caglayan et al., "Technical potential of salt caverns for hydrogen storage in Europe," International Journal of Hydrogen Energy, vol. 45, no. 11, pp. 6793–6805, Feb. 2020, doi: 10.1016/j.ijhydene.2019.12.161

Accomplishments & Progress

Hydrogen Energy Storage System Definition

- Analysis includes full capital cost build up for underground GH_2 storage facility plus all units for H_2 energy conversion system (e.g., electrolyzer, turbine or fuel cell, etc.)
- LCOS will be calculated for facility
- System design inspired by Ardent Underground (https://ardentunderground.com/) and Gravitricity (https://gravitricity.com/)

Parameter	Units	Storage Vessel
Peak Pressure	bara	250-700
Average Temperature	°C	29
Vessel OD	m	5.69
Vessel Height	m	201.2
Shaft Diameter	m	6.5
Shaft Depth	m	318.4
Storage Capacity	MT H_2	92.5-208.0



Accomplishments & Progress

Responses to Previous Year Reviewers' Comments

- Project was not reviewed at 2022 AMR

Collaborations & Coordination

MDV/HDV	**Argonne**—finite element analysis, system performance analysis **PNNL**–system assumptions
Onboard H_2 storage	**ANL**—finite element analysis and performance analysis **LLNL**—System and manufacturing requirements
LH_2	**ANL**—System assumptions discussed with Amgad Elgowainy and Rajesh Ahluwalia **Demaco**—Cryogenic piping, tubing, & connection (vacuum jacketed) costs, LH2 loading bays/station costs **Cabot**—Aerogel bulk-fill insulation costs **Cryomech**—Cryo-Refrigeration technical design, costs **Imerys**—Perlite bulk-fill insulation costs **NASA**—System design assumptions, costs, use cases **Matrix Services**—System design assumptions, costs, use cases **McDermott (CB&I)**—System design assumptions, costs, use cases **Palmer Holland**—Glass bubbles bulk-fill insulation costs **Shell**—System design assumptions, costs, use cases **Technifab**—Cryogenic piping, tubing, & connection (vacuum jacketed) costs

Remaining Challenges & Barriers

- Onboard H_2 Storage
  - System validation is needed for cryogenic storage
    - Completed preliminary discussions with cryo-compressed and LH_2 system developers and have agreements to review and comment on assumptions and results
    - LNG reference study is planned
    - LNG tear-down at PNNL will provide system design parameters
- Large-Scale LH_2 Storage
  - Refrigeration system costs are too granular
- Underground GH_2 Storage
  - Excavation costs for 6m bore holes are currently scaled from drilling studies with largest bore hole diameters of 2m
  - Vessel dimensions and overburden are currently estimated from system images
    - Rigorous calculations are needed

Summary and Conclusions

- Onboard storage for long haul trucks
  - Baseline total system costs, mass and storage capacity fall outside the confidence bound.
  - COV_{fiber} and $COV_{manufacturing}$ assumptions are likely too aggressive
- LH_2
  - From correlative cost model
    - Refrigeration requirements are small & so capital & operating costs for the refrigeration subsystem do not contribute a significant portion to the overall storage system capital cost
    - Cost savings from H_2 zero boiloff payback cost of refrigeration subsystem & only small percentage of remaining system costs
      - Proportion of system payback:
        - » Decreases with increasing system size/capacity for the same turnover period
        - » Increases with increasing turnover period for the same system size/capacity
  - From detailed cost model
    - Material costs dominated by:
      - First
        - » Tank shell materials (mostly inner SS shell) for use of perlite & glass bubbles bulk-fill insulation
        - » Bulk-fill insulation for use of aerogel particle insulation
      - Second
        - » Piping/Tubing & tank nozzles/connections & tank inner structural supports for use of perlite insulation
        - » Bulk-fill insulation materials for use of glass bubbles
        - » Tank shell materials (mostly inner SS shell) for use of aerogel particle bulk-fill insulation
    - Piping/Tubing costs estimated to become significant portion of capital costs for larger systems with refrigeration due to estimated cost increases of large-diameter refrigeration piping & tubing, particularly for aerogel particles since this insulation material is not as effective
- GH_2
  - Initial cost results and system capacities are in good agreement with published results
  - Extrapolated drilling costs from small bore operations appears to give reasonable cost results, but this approach needs to be refined to give greater confidence in the analysis

Proposed Future Work

- Class 8 Long Haul
  - Validate LH_2 system cost with LNG teardown and quotes
  - Finalize and publish comparative cost paper
    - Refueling costs need to be accounted for in total storage system cost evaluation, so publication will be coordinated with members of the ANL systems analysis group
- Large-Scale LH_2 storage
  - Complete detailed, bottom-up cost analysis
  - Investigate LCOS as a function of storage size, choice of insulation materials, and cost impact of active refrigeration to achieve zero boiloff
- Underground GH_2 storage
  - Complete detailed, bottom-up cost analysis
  - Investigate LCOS as a function of storage size
  - Compute LCOS for use-cases such as seasonal energy storage and load balancing

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

Technical Backup and Additional Information

Technology Transfer Activities

Technology transfer does not apply to this analysis-type project

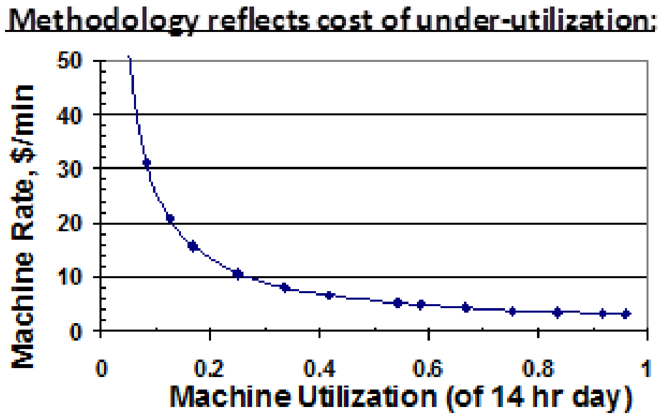
Approach: DFMA® methodology used to track annual cost impact of technology advances

- DFMA® (Design for Manufacture & Assembly®) is a process-based, bottom-up cost analysis methodology which projects material and manufacturing cost of the complete system by modeling specific manufacturing steps
- Registered trademark of Boothroyd-Dewhurst, Inc.
- Basis of Ford Motor Company (Ford) design/costing method for the past 20+ years
- Predicts actual cost of components or systems based on a hypothesized design and set of manufacturing and assembly steps
- Determines the lowest cost design and manufacturing processes through repeated application of the DFMA® methodology on multiple design/manufacturing potential pathways

Estimated Cost = (Material Cost + Processing Cost + Assembly Cost) x Markup Factor

Manufacturing Cost Factors:

1. Material Costs
2. Manufacturing Method
3. Machine Rate
4. Tooling Amortization



Methodology Reflects Cost of Under-utilization:

Capital Cost
Installation
} **Initial Expenses** → **Used to calculate annual capital recovery factor based on:**
- Equipment Life
- Interest Rate
- Corporate Tax Rate

Maintenance/Spare Parts Utilities
Miscellaneous
} **Operating Expenses**

(Annual Capital Repayment + Annual Operating Payments) / Annual Minutes of Equipment Operation = Machine Rate ($/min)

Class 8 Long Haul Truck Storage Status (Reported 2022)

The baseline storage system is frame mounted 700 bar Type 4

Property	Value	Note
Storage System	Type IV	T700S/epoxy, PA6 liner, aluminum boss
Tank / Total Capacity (kg)	30 / 60	Target definition*
Tanks per System	2	Tanks of identical size
External Package Dimensions	250 cm x 64 cm	Assumption. Similar to Quantum Fuel Systems.
Mounting	Strap-Mounting Frame	Assumption. Similar to Quantum Fuel Systems.
BOP	Integrated valve and regulator	Similar to GFI ITVR-70. Cost is assumed to be 120% of LDV unit cost per guidance from GFI.
Estimated Composite Mass (kg/tank)	444	Estimated using performance derived from ANL analysis
Estimated Total Mass ($kg_{H2storage}$/truck)	1100	Compared to 750 kg for Quantum 46 DGE CNG System.
Safety Factor	2.25 (nom)/2.54 (eff)	NGV2, fiber, and mfg. variations
Projected Cost ($/kg$H_2$)	383	Projected to 100k systems per year. Compared with 2030 target of $300/kg$H_2$*

- Baseline system is currently projected to able to meet DOE targets
- Pathways to 2030 ($300/kg$H_2$) and the ultimate target ($266/kg$H_2$) requires 40% carbon fiber cost and weight reduction from relaxed safety factor
- Alternatives to compressed gaseous H_2 are described in the following slides and compared with the baseline

* https://www.hydrogen.energy.gov/pdfs/19006_hydrogen_class8_long_haul_truck_targets.pdf

System Design Assumptions

System Design Assumptions

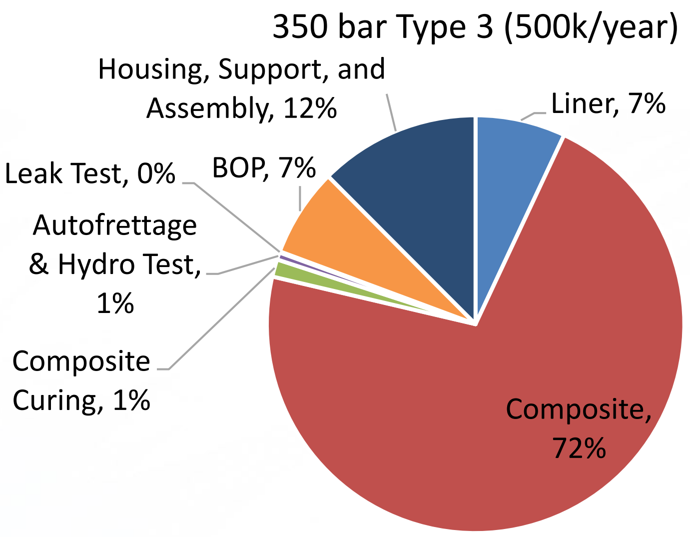
Parameter	Units	Value				Notes
Tank type		Type 3, 350 bar	Type 4, 350 bar	Type 4, 700 bar	Type 3, 500 bar	Type 3 tanks utilize metal liners, Type 4 tanks utilize polymer liners
Liner material		Aluminum	HDPE	HDPE	316L	HDPE = High density polyethylene, 316L = 316L grade stainless steel
Hydrogen storage method		cH2			CcH2	cH2 = compressed hydrogen; CcH2 = cryo-compressed hydrogen
Nominal operating temperature	°C	14.85			-201.15	
Tank interior diameter	cm	60.4	60.2	55.4	51.0	
Tank interior length	cm	287	291	286	291	
Usable H2	kg	18.5	18.6	26.5	20.4	Based on hydrogen densities from Cool Prop[9]
Minimum empty pressure	bar	15				Based on parameters for ANL calculations[10]
Liner thickness	cm	0.6	0.5	0.5	0.2	
Shell material		-			6061 Aluminum	
Shell thickness	cm	-			0.3175	
Shell diameter	cm	-			53.0	
Shell length	cm	-			245	
Vacuum insulation material		-			MLI	MLI = multilayer insulation
Vacuum insulation pressure	mtorr	-			1	
Vacuum insulation thickness	mm	-			10	
Vacuum insulation mass	kg	-			0.5	
Carbon fiber		T700S				
Fiber tensile strength	MPa	4900				Based on Toray T700S performance[11]
Resin		Vinyl Ester				
Fiber volume fraction		0.6				
Fiber mass	kg	119	133	271	140	Estimated from ANL total composite mass
Resin mass	kg	50.3	56.2	114	59.1	Estimated from ANL total composite mass
Composite mass	kg	170	189	385	199	ANL model calculation

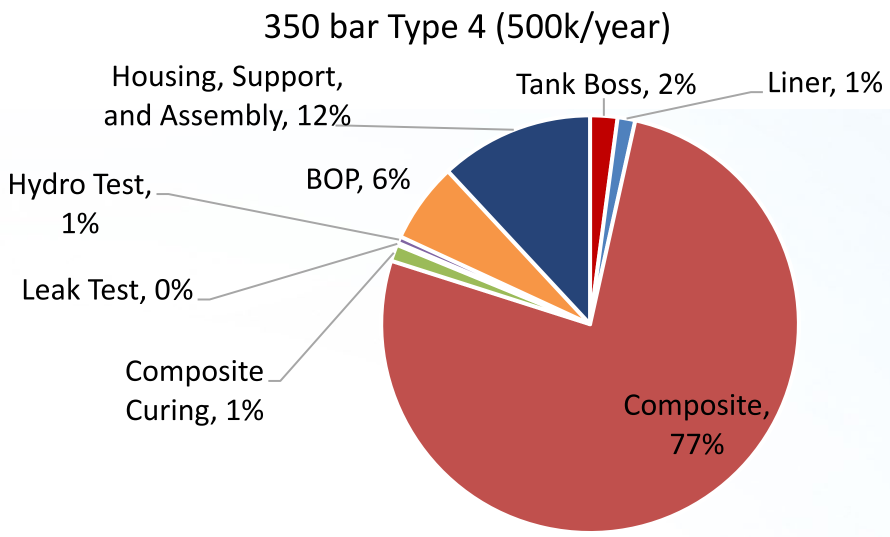
9. Bell, I. H.; Wronski, J.; Quoilin, S.; Lemort, V. Pure and Pseudo-Pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp. *Ind. Eng. Chem. Res.* **2014**, *53* (6), 2498–2508. https://doi.org/10.1021/ie4033999.
10. Ahluwalia, R. K.; Peng, J. K.; Roh, H. S.; Hua, T. Q.; Houchins, C.; James, B. D. Supercritical Cryo-Compressed Hydrogen Storage for Fuel Cell Electric Buses. *International Journal of Hydrogen Energy* **2018**, *43* (22), 10215–10231. https://doi.org/10.1016/j.ijhydene.2018.04.113.
11. https://www.toraycma.com/wp-content/uploads/T700S-Technical-Data-Sheet-1.pdf

Cost Breakdown for all Tank Types at High Production

Total system cost: $14,145

System energy cost: $11/kWh



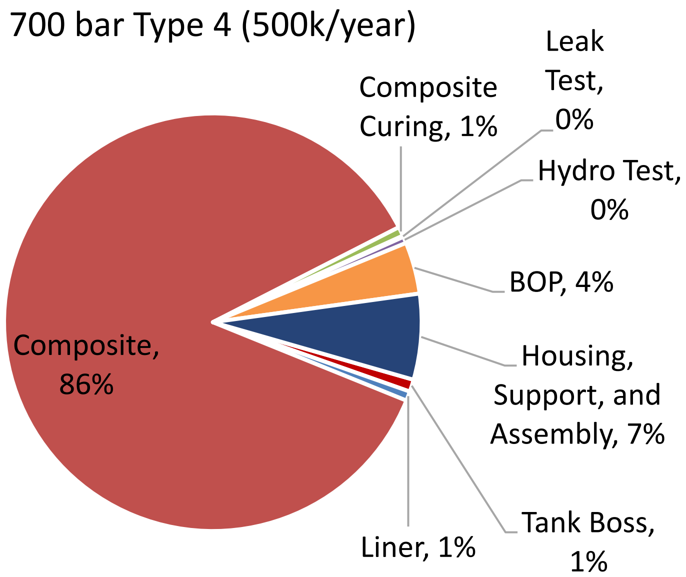


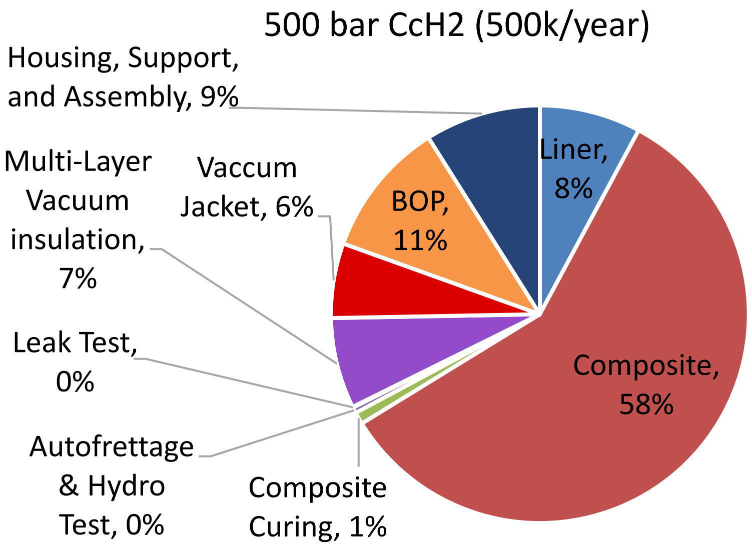
Total system cost: $14,812

System energy cost: $12/kWh

Total system cost: $26,574

System energy cost: $15/kWh

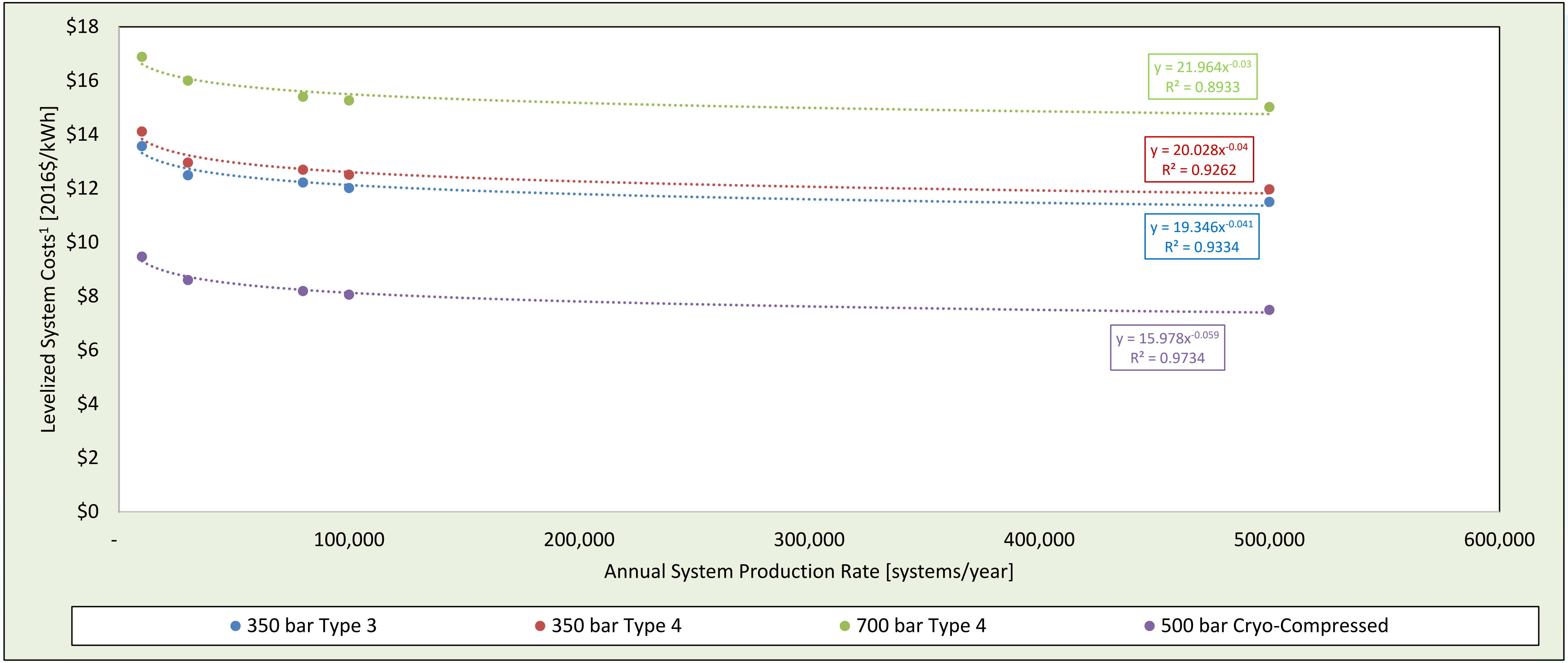




Total system cost: $20,390

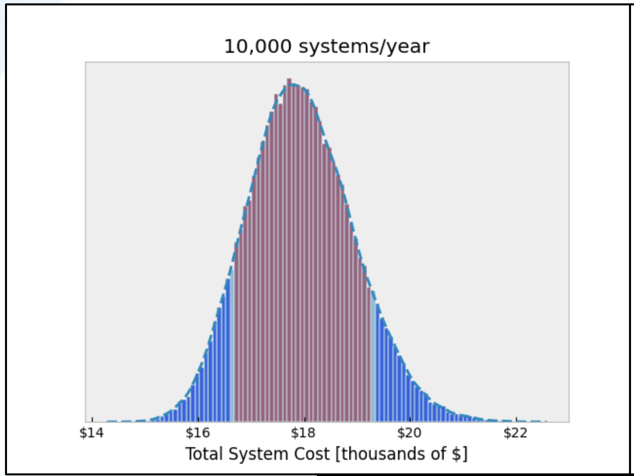
System energy cost: $7/kWh

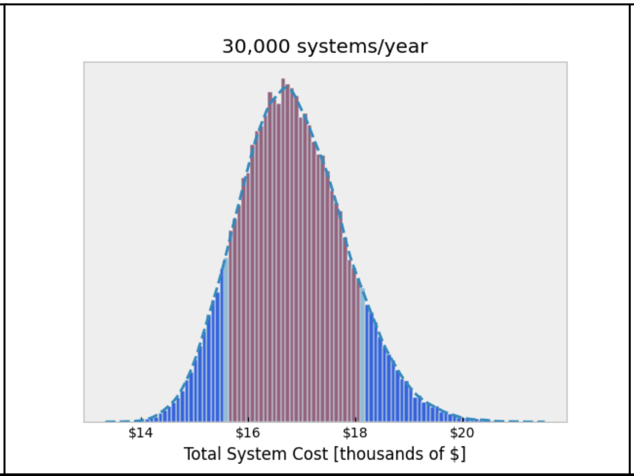
System Cost vs. Annual Production Rate

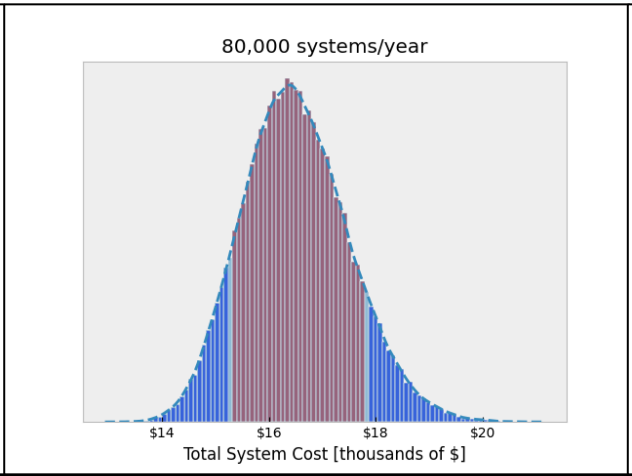


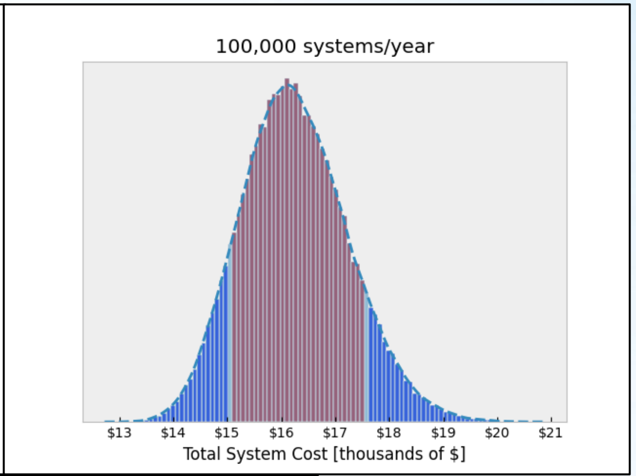
[1]The levelized system cost is the total storage system cost divided by the usable hydrogen energy stored in the tank.

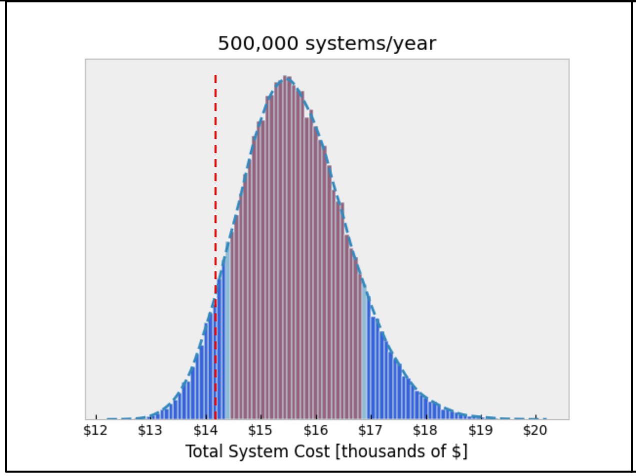
Sensitivity Analysis Results for T3 Tanks Storing cH_2 at 350 bar

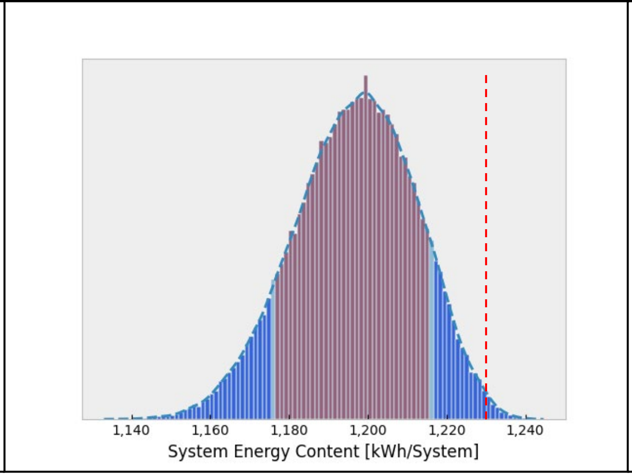


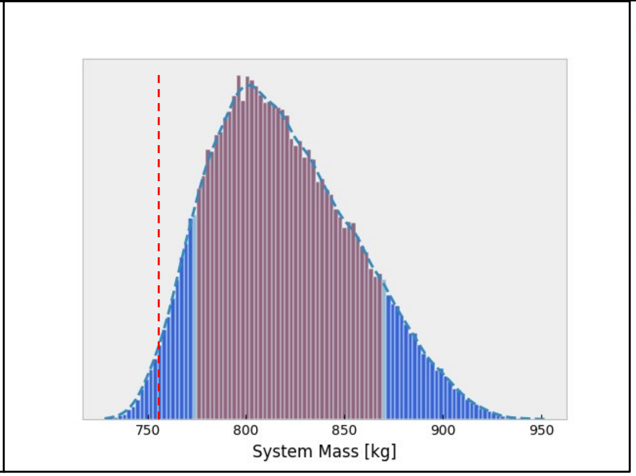






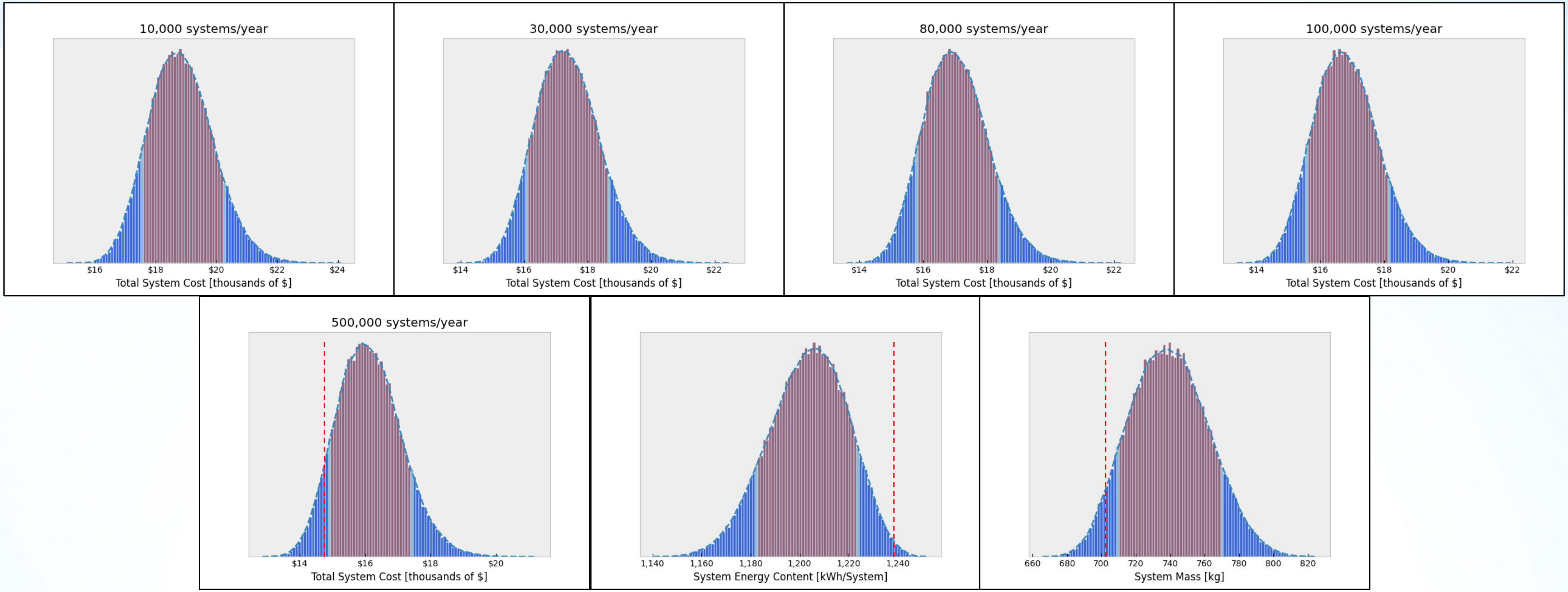






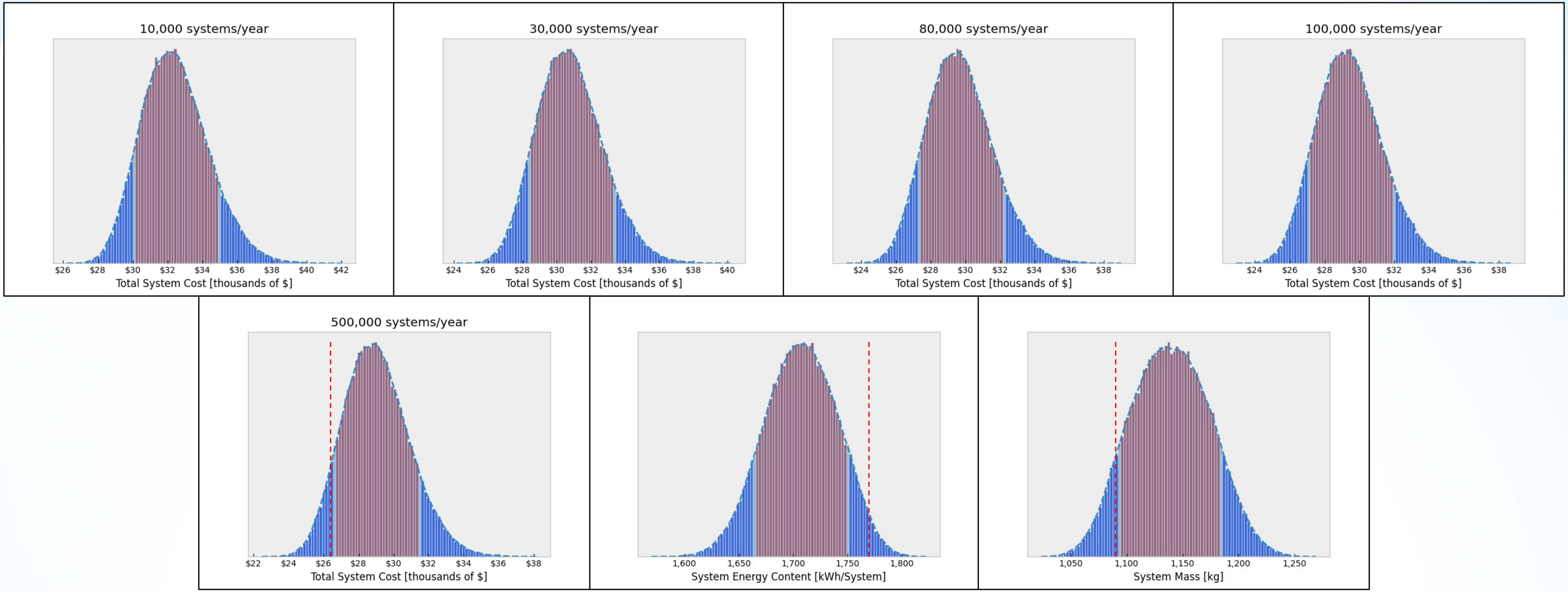
The base case used in our analysis is indicated by the dotted, red line. Dollar amounts are 2016$.

Sensitivity Analysis Results for T4 Tanks Storing cH_2 at 350 bar



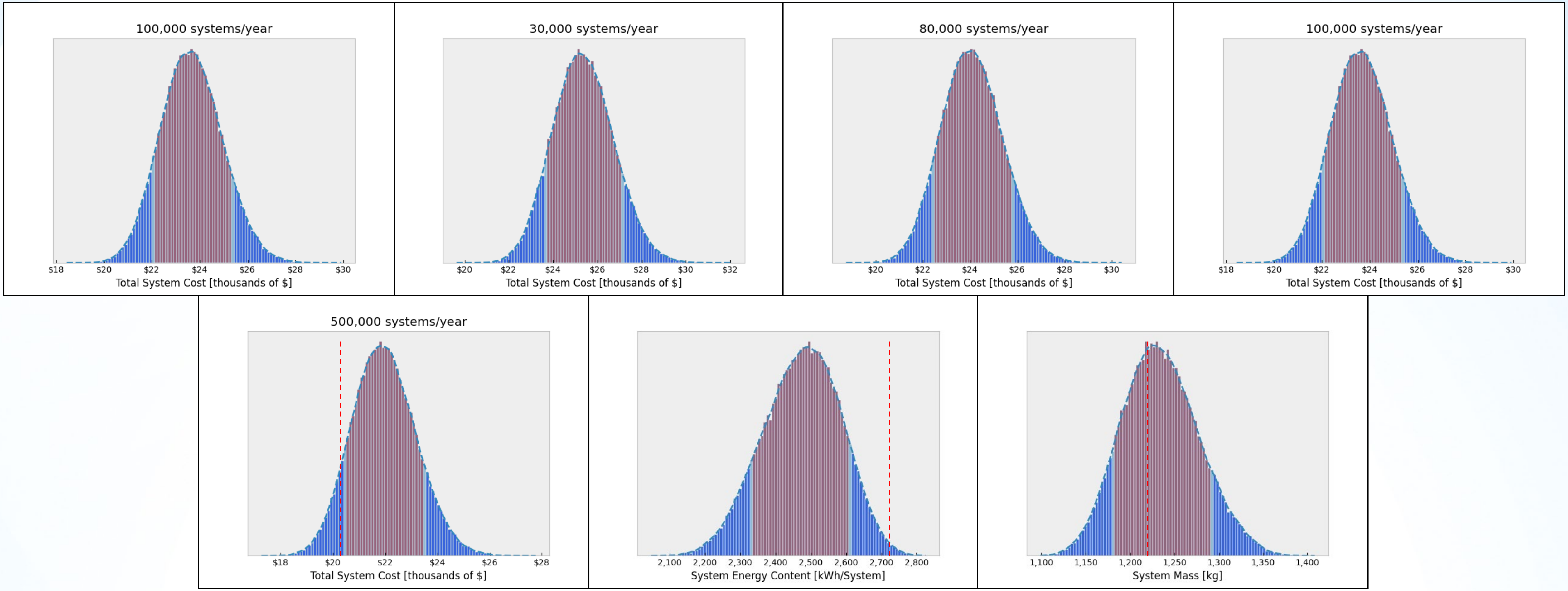
The base case used in our analysis is indicated by the dotted, red line. Dollar amounts are 2016$.

Sensitivity Analysis Results for T4 Tanks Storing cH_2 at 700 bar



The base case used in our analysis is indicated by the dotted, red line. Dollar amounts are 2016$.

Sensitivity Analysis Results for T3 Tanks Storing CcH_2 at 500 bar



The base case used in our analysis is indicated by the dotted, red line. Dollar amounts are 2016$.

Storage Scenarios/H_2 Use-Cases

Storage Scenario	Description	Use/Purpose	Nominal Capacity	Storage/Hold Period	Comparisons
City Gate	Holding Terminal for Short-Range Distribution	Energy or Chemical	40,000 m^3 2,800 t 93 GWh	10 days	
Trade Terminal	Holding Point at Port (International or Domestic)	Energy or Chemical	100,000 m^3 7,000 t 233 GWh	10 days	LNG, LPG, or NH3 Terminals
Seasonal Energy Storage*	Energy Storage for Long-Term Load Leveling	Energy	10,000,000 m^3 700,000 t 23,300 GWh	6 months upper bound (further defined by expected runtime)	Pumped Hydro Storage, Underground gH2, Electric Batteries, Flow Batteries
Load Shifting/ Shedding Mitigation*	Energy Storage for Short-Term Load Leveling	Energy	130,000 m^3 9,000 t 300 GWh	4 - 16 hours (typical)	Pumped Hydro Storage, Underground GH2, Electric Batteries, Flow Batteries

*The full extent of the difference between seasonal and load shifting isn't clear yet

Accomplishments & Progress

Preliminary Detailed, Bottom-Up Large-Scale LH_2 IRAS Tank Insulation Cost & Performance Comparison

Parameter	Units	CG+IR (perlite)	CG+IR (glass bubbles)	CG+IR (aerogel)	TT+IR (perlite)	TT+IR (glass bubbles)	TT+IR (aerogel)	SES+IR (perlite)	SES+IR (glass bubbles)	SES+IR (aerogel)
Estimated Heat Load	[kW]	3.65	1.93	5.72	6.56	3.46	10.3	137	72.2	215
Piping & Ports Material Cost	[$M/tank]	1.54	1.53	1.54	2.18	2.18	2.18	178.55	29.11	1290
Insulation Material Cost	[$M/tank]	0.74	2.83	19.70	1.34	5.13	35.60	28.68	109.98	761
Total Material Cost (Piping/Ports & Insulation Only)	**[$M/tank]**	**2.28**	**4.36**	**21.20**	**3.52**	**7.31**	**37.80**	**207.23**	**139.08**	**2,050**

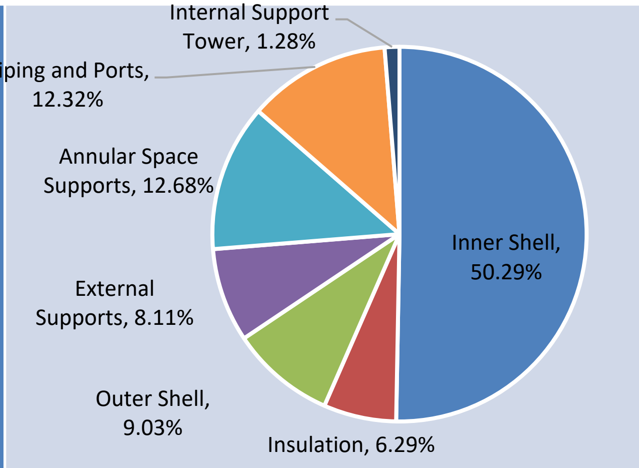
Note: these are preliminary results with cost values given in millions of 2023 US$ ($M) accounting for the cost of raw materials, not a completely manufactured tank. These results assume that there is a 1-meter-thick layer of insulation used for each tank configuration.

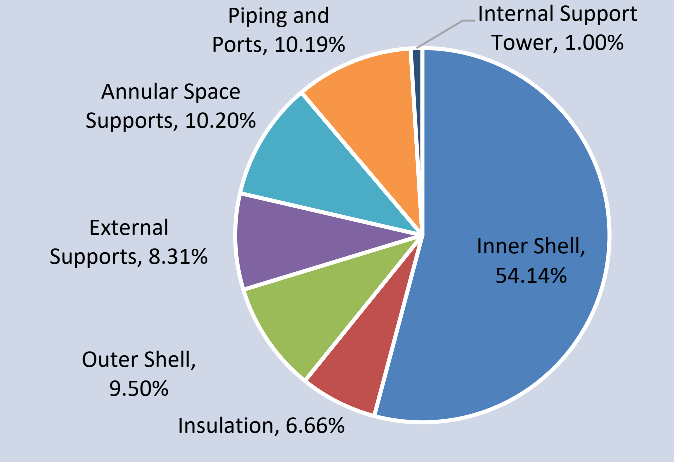
Accomplishments & Progress

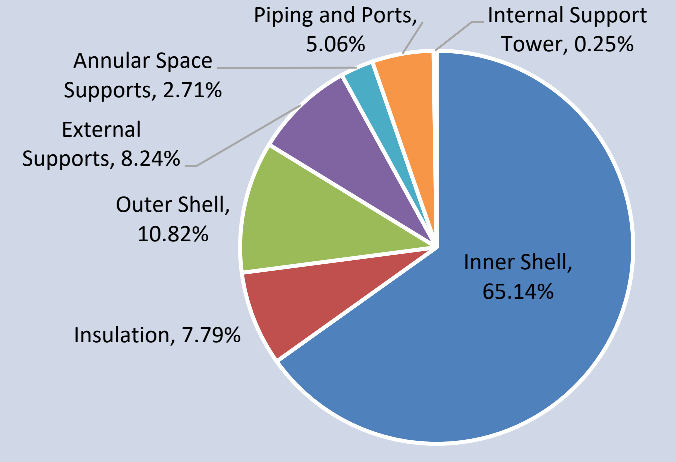
Preliminary Detailed, Bottom-Up Large-Scale LH_2 IRAS Tank Material Cost Breakdowns (Perlite)

City Gate	Trade Terminal	Seasonal Energy Storage

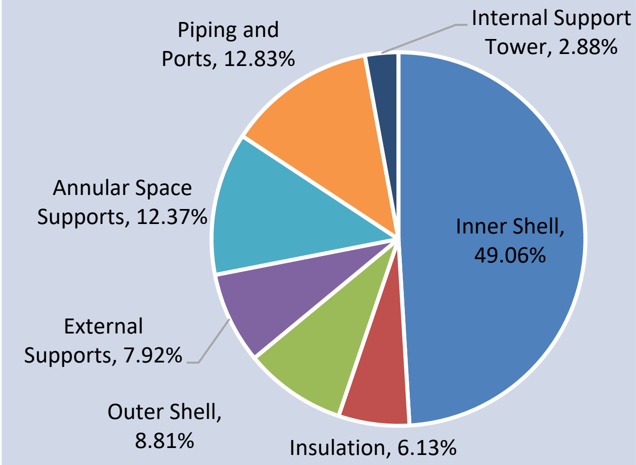
Without Refrigeration

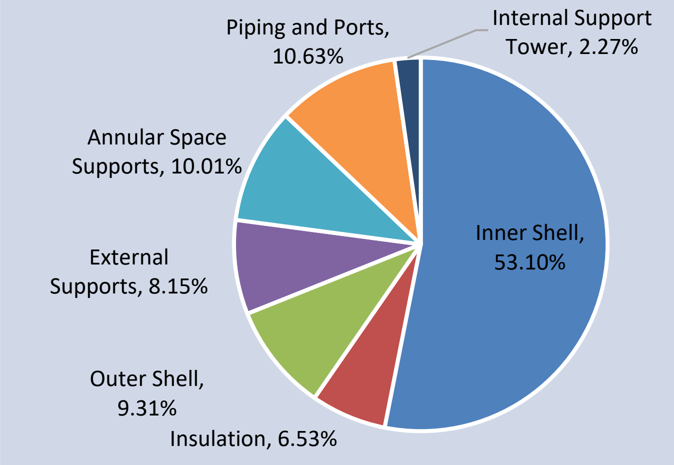


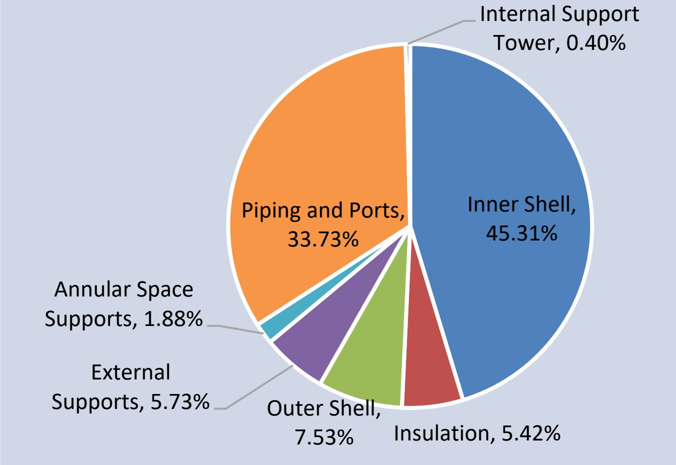




With Refrigeration

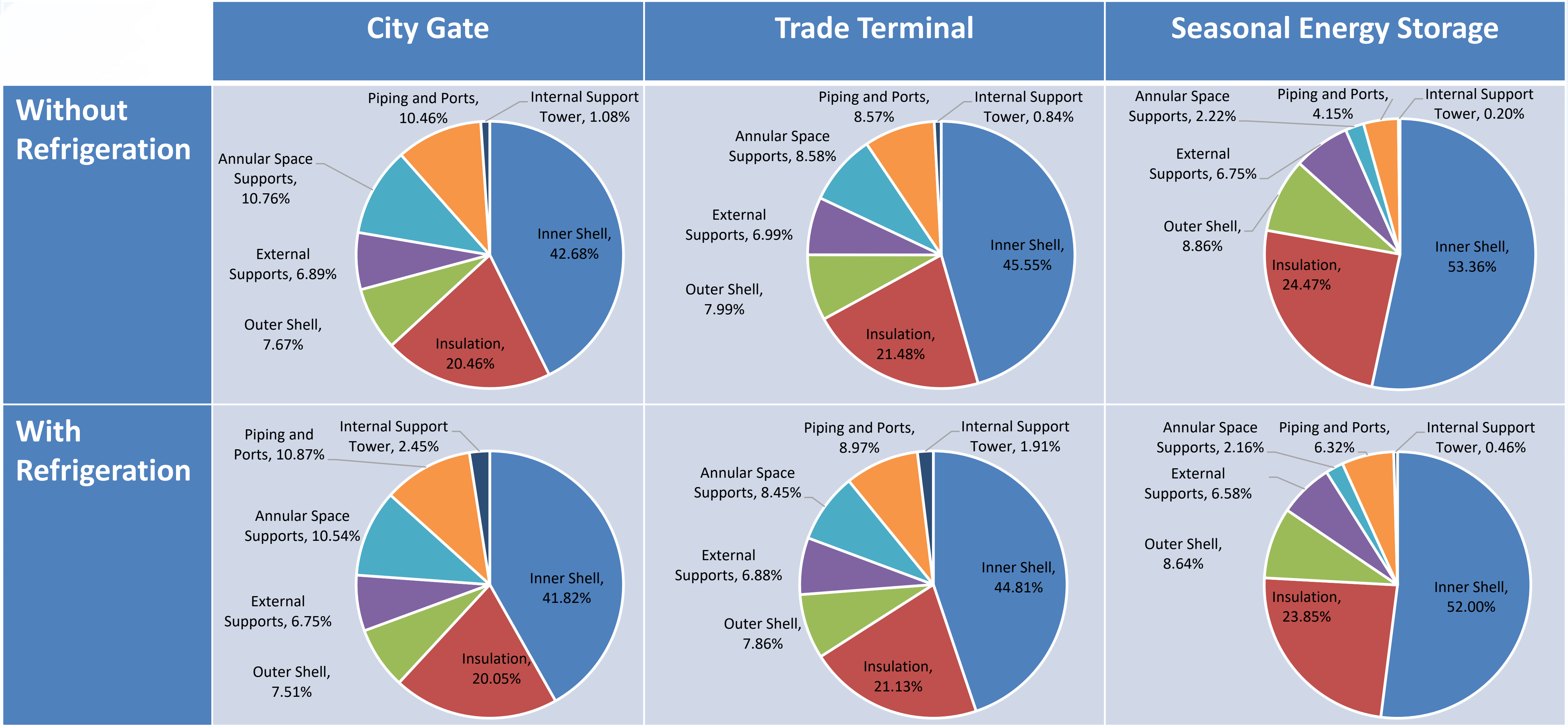






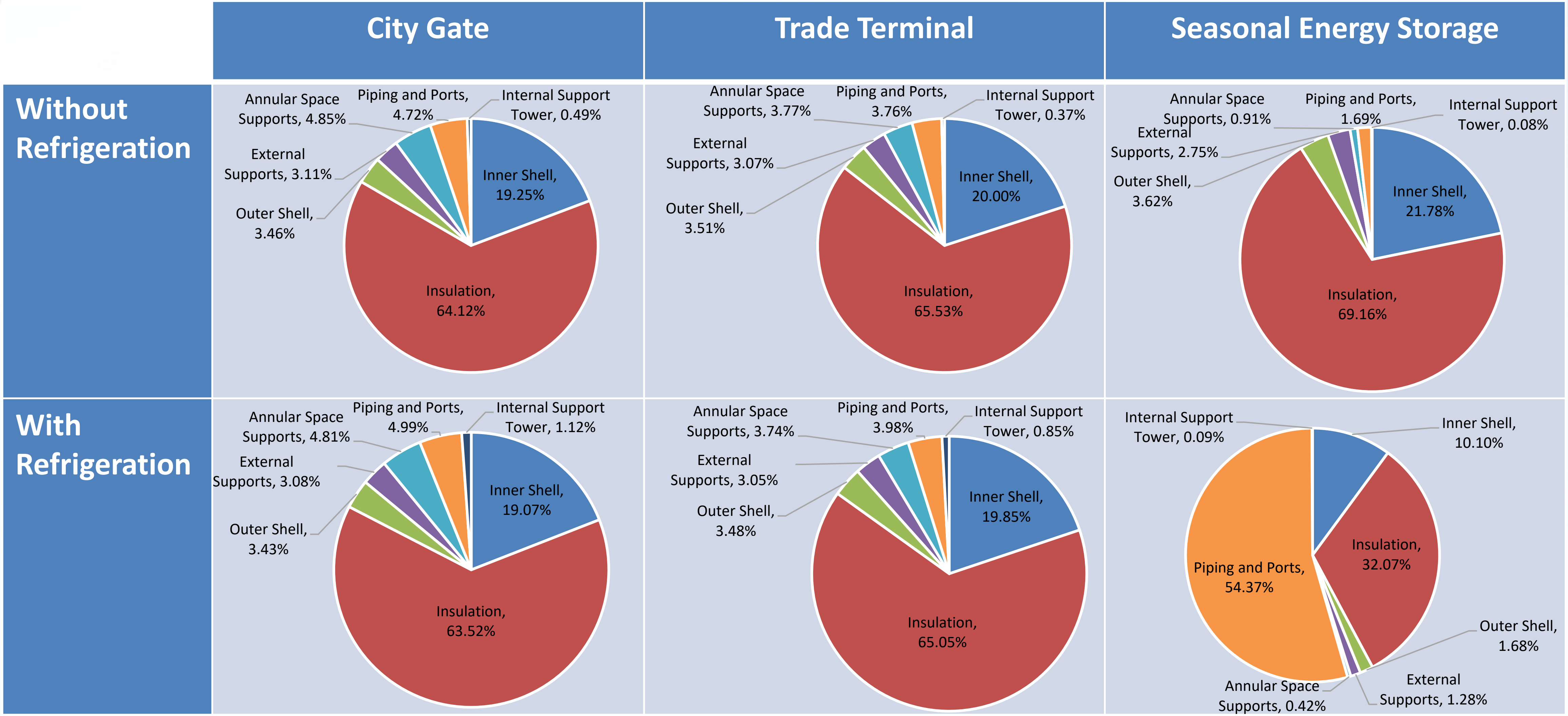
Accomplishments & Progress

Preliminary Detailed, Bottom-Up Large-Scale LH_2 IRAS Tank Material Cost Breakdowns (Glass Bubbles)



Accomplishments & Progress

Preliminary Detailed, Bottom-Up Large-Scale LH_2 IRAS Tank Material Cost Breakdowns (Aerogel)



Accomplishments & Progress

Preliminary Detailed, Bottom-Up Large-Scale LH_2 IRAS Tank Bill of Materials

Tank Component	Component Material
Inner Shell	A240 TP304 SS
Insulation	Perlite Powder, 3M K1 Glass Bubbles, or Aerogel Particles
Outer Shell	A516 GR70 CS
External Supports	
Support Columns	A36 CS
Support Struts	A36 CS
Support Foundation	
Concrete	C150 TP II
Concrete Reinforcement Bars	A615 GR60 CS Rebar
Anchor Plates	A36 CS
Support Fasteners	
Anchor Bolts	4.5" Diameter F1554 Grade 55 Galvanized Double End Threaded Straight Anchor Bolt
Hex Nuts	4.5" A563 Grade A Heavy Hex Nut Plain Finish
Washers	4.5" USS Flatwasher Plain Finish
Annular Space Supports	
Vertical Support Rods	304 SS
Sway Rods	304 SS
Horizontal Support Girder	304 SS
Equator Girder	304 SS

Tank Component	Component Material
Piping and Ports	
LH_2 Load/Unload Internal and External Piping	
Internal	A312 TP304 SS
External	304 SS Vacuum Jacketed
He Refrigeration Internal & External Piping & Tubing	
Internal Coil Tubing	A269 TP316 SS
Intra-Insulation Piping	A312 TP304 SS
External Piping	304 SS Vacuum Jacketed
Miscellaneous Internal Piping	A312 TP304 SS
LH2 Distributor Ring Apparatus	
Piping	A312 TP304 SS
Supports	304 SS
External Ports	
Ports	A516 GR70 CS
Pipe Jacketing	A240 TP304 SS
Pipe Nozzles	A216 GR WCB Flanges
Bayonett Connections	Bayonett Connections
Fire Safety System	A106 CS
Internal Support Tower	
Central Structure	304 SS
Internal Refrigeration Manifold Supports	304 SS
Ladder	6061-T6 Aluminum

Accomplishments & Progress

Preliminary Detailed, Bottom-Up Large-Scale LH_2 IRAS Tank Bill of Materials

Analysis Case		CG+IR (PP)	CG+IR (GB)	CG+IR (AP)	TT+IR (PP)	TT+IR (GB)	TT+IR (AP)	SES+IR (PP)	SES+IR (GB)	SES+IR (AP)
Tank Component	**Units**									
Inner Shell	**[$M/tank]**	**$5.90**	**$5.90**	**$5.90**	**$10.87**	**$10.87**	**$10.87**	**$239.83**	**$239.83**	**$239.83**
Insulation	**[$M/tank]**	**$0.74**	**$2.83**	**$19.67**	**$1.34**	**$5.13**	**$35.63**	**$28.68**	**$109.98**	**$761.49**
Outer Shell	**[$M/tank]**	**$1.06**	**$1.06**	**$1.06**	**$1.91**	**$1.91**	**$1.91**	**$39.83**	**$39.83**	**$39.83**
External Supports	**[$M/tank]**	**$0.95**	**$0.95**	**$0.95**	**$1.67**	**$1.67**	**$1.67**	**$30.32**	**$30.32**	**$30.32**
Support Columns	[$M/tank]	$0.62	$0.62	$0.62	$1.13	$1.13	$1.13	$23.10	$23.10	$23.10
Support Struts	[$M/tank]	$0.02	$0.02	$0.02	$0.03	$0.03	$0.03	$0.13	$0.13	$0.13
Support Foundation	[$M/tank]	$0.29	$0.29	$0.29	$0.48	$0.48	$0.48	$6.95	$6.95	$6.95
Support Fasteners	[$M/tank]	$0.03	$0.03	$0.03	$0.03	$0.03	$0.03	$0.14	$0.14	$0.14
Annular Space Supports	**[$M/tank]**	**$1.49**	**$1.49**	**$1.49**	**$2.05**	**$2.05**	**$2.05**	**$9.97**	**$9.97**	**$9.97**
Vertical Support Rods	[$M/tank]	$0.24	$0.24	$0.24	$0.36	$0.36	$0.36	$2.11	$2.11	$2.11
Sway Rods	[$M/tank]	$0.41	$0.41	$0.41	$0.54	$0.54	$0.54	$2.45	$2.45	$2.45
Horizontal Support Girder	[$M/tank]	$0.28	$0.28	$0.28	$0.38	$0.38	$0.38	$1.80	$1.80	$1.80
Equator Girder	[$M/tank]	$0.56	$0.56	$0.56	$0.77	$0.77	$0.77	$3.61	$3.61	$3.61
Piping and Ports	**[$M/tank]**	**$1.54**	**$1.53**	**$1.54**	**$2.18**	**$2.18**	**$2.18**	**$178.56**	**$29.12**	**$1,290.87**
LH2 Load/Unload Piping	[$M/tank]	$0.75	$0.75	$0.75	$1.11	$1.11	$1.11	$12.38	$12.38	$12.38
He Refrigeration Piping & Tubing	[$M/tank]	$0.10	$0.09	$0.10	$0.13	$0.13	$0.14	$159.93	$10.49	$1,272.24
Miscellaneous Internal Piping	[$M/tank]	$0.003	$0.003	$0.003	$0.004	$0.004	$0.004	$0.01	$0.01	$0.01
LH2 Distributor Ring Apparatus	[$M/tank]	$0.45	$0.45	$0.45	$0.58	$0.58	$0.58	$4.51	$4.51	$4.51
External Ports	[$M/tank]	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.04	$0.04	$0.04
Fire Safety System	[$M/tank]	$0.23	$0.23	$0.23	$0.32	$0.32	$0.32	$1.69	$1.69	$1.69
Internal Support Tower	**[$M/tank]**	**$0.35**	**$0.35**	**$0.35**	**$0.46**	**$0.46**	**$0.46**	**$2.12**	**$2.12**	**$2.12**
Central Structure	[$M/tank]	$0.14	$0.14	$0.14	$0.19	$0.19	$0.19	$0.87	$0.87	$0.87
Internal Refrigeration Manifold Supports	[$M/tank]	$0.20	$0.20	$0.20	$0.26	$0.26	$0.26	$1.20	$1.20	$1.20
Ladder	[$M/tank]	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.05	$0.05	$0.05
Tank Material Cost	**[$M/tank]**	**$12.04**	**$14.12**	**$30.97**	**$20.47**	**$24.26**	**$54.78**	**$529.31**	**$461.17**	**$2,374.43**
Tank Material Cost, Energy Basis	**[$/kWh]**	**$0.14**	**$0.17**	**$0.36**	**$0.10**	**$0.11**	**$0.26**	**$0.02**	**$0.02**	**$0.11**
Tank Material Cost, Volume Basis	**[$/m³]**	**$300.89**	**$352.97**	**$774.13**	**$204.74**	**$242.65**	**$547.76**	**$51.04**	**$44.47**	**$228.98**

All costs given in 2023 US$ & in millions ($M) where indicated

Approach

Detailed, Bottom-Up Model for Large-Scale Underground Storage Cost Analysis

- Scope
  - Survey underground hydrogen storage costs for multiple natural and engineered systems
  - Prepare detailed cost analyses of engineered underground storage systems
- Goals
  - Develop capital cost models that account for a range of multi-tonne storage system capacities
  - Develop cost models that account for different range of storage time (days to months)
  - Report capital cost (total $ per plant), cost per unit hydrogen ($/tH2), and LCOS ($/MWh)
- Identified 2 large-scale engineered storage system concepts to base conceptual designs on: Ardent Underground (Australia) and Gravitricity (UK)
- Develop detailed, bottom-up cost models & total system LCOS
  - Compile detailed parts list & bill of materials (BOM) for all system components
    - Completed storage system lining, cap, and plug
    - Completed piping, fittings, valving, and compression
    - Additional facility sub-units such as electrolysis, power conditioning, and H2 combustion specified for single use-case
  - Preliminary cost analysis completed
    - Raw material costs
    - Excavation
  - Combine with on-site construction cost estimates & updated amortized operating costs to yield a total system LCOS