Hydrogen Storage Cost Analysis

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Award No. DE-EE0009630
DOE Hydrogen Program
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Overview

Timeline

Project Start Date: 9/30/21
Project End Date: 9/29/24
% complete: ~75%

Barriers

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

Budget

Total Project Budget: $699,964
Total DOE Funds Spent: ~$556,000
(through March 2024, excluding Labs)

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 status and future projected costs of H_2 storage systems for onboard, delivery, and stationary applications
- Analyses conducted:
  - Large-Scale LH_2 storage vessels from 5,000 m^3 to 100,000 m^3
  - Helium refrigeration for zero boiloff LH_2 storage
  - Bulk LH_2 transfer terminal
  - 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

Background & Motivation

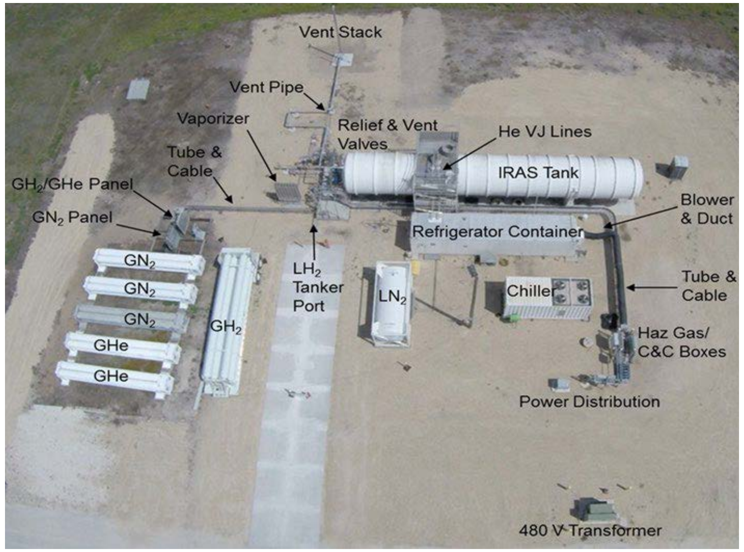
New Insulation Materials

- 2019-2022—construction of 4,732 m^3 LS-LH_2 tank at KSC by McDermott
- Glass bubbles bulk-fill insulation
- Includes internal cooling coil needed for refrigeration upgrade

Fesmire, J. E.; Swanger, A. DOE/NASA Advances in Liquid Hydrogen Storage Workshop: Overview of the New LH2 Sphere at NASA Kennedy Space Center. *Kennedy Space Center, Cryogenics Test Laboratory* **2021**, Presentation. *https://www.energy.gov/sites/default/files/2021-10/new-lh2-sphere.pdf*

Zero Boiloff Loss

- 2012-2016 developed a test/demo system (GODU-LH2) at KSC
- Includes a 125 m^3 LH_2 tank, Linde refrigeration system
- Tested zero-boiloff (ZBO) control, in-situ liquefaction, in-situ solidification/slush H_2



Swanger, A. DOE/NASA Advances in Liquid Hydrogen Storage Workshop: LH_2 Storage and Handling Demonstrations Using Active Refrigeration. *Kennedy Space Center, Cryogenics Test Laboratory* **2021**, Presentation. *https://www.energy.gov/sites/default/files/2021-10/lh2-storage-handling-demonstrations.pdf*

20x Capacity Increase

- Shell led ST241 evaluating LH_2 storage system, new insulation materials, and active refrigeration for trade terminal
- Max vessel capacity is 100,000 m^3 compared with ~5,000 m^3 currently in service

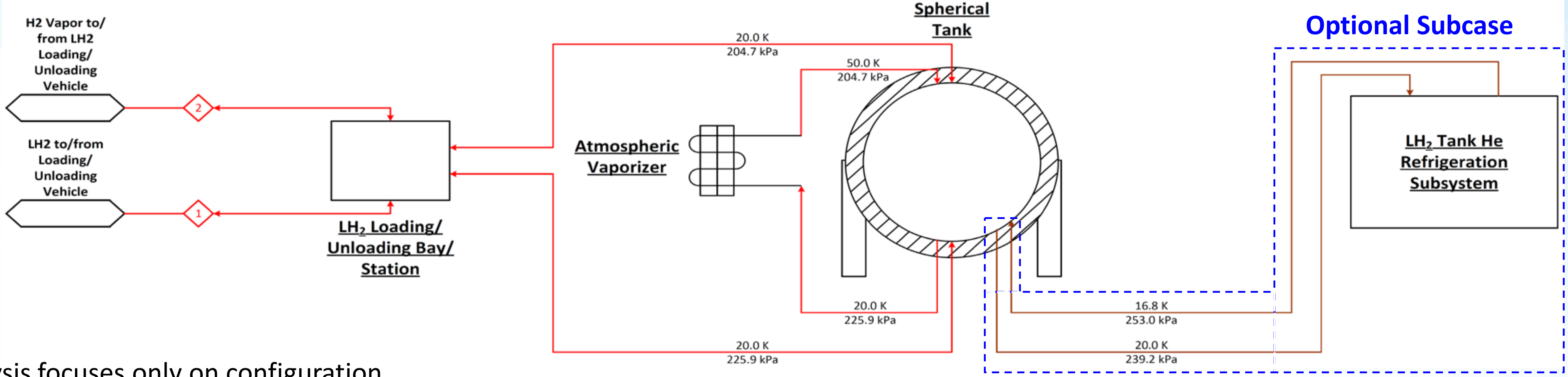
Parameter	Project Target
Boiloff rate	<0.1%/day
CAPEX	<$1,750/$m^3$

- Note that McDermott has a CAPEX assessment task on ST241

https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/st241_holgate_2023_o-pdf.pdf

LH_2 Storage System Overview

Loading/Unloading Subsystem | **Storage Tank Subsystem** | **Helium Refrigeration Subsystem**

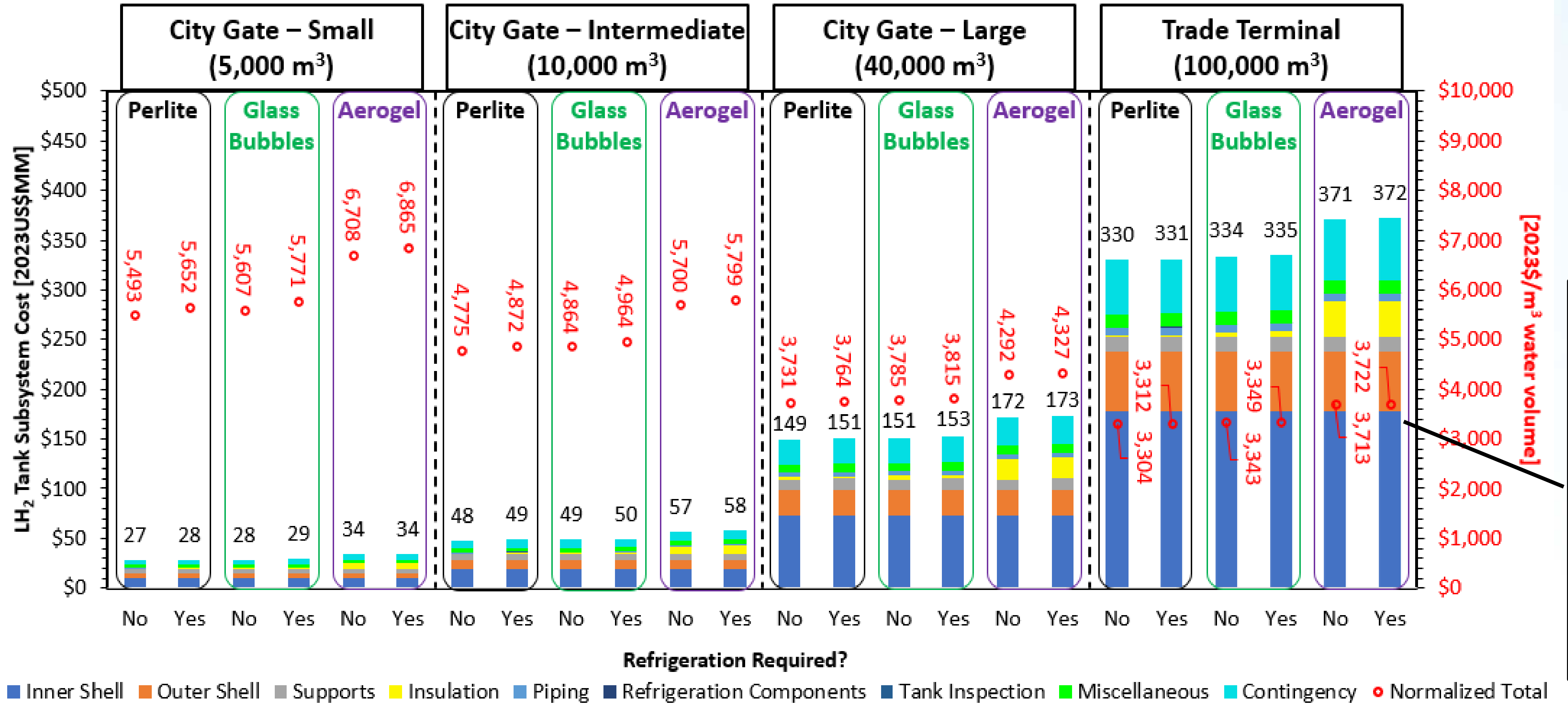


- Analysis focuses only on configuration required for cryogenic tank truck loading
- Identical size parallel lanes for individual vehicles regardless of storage system size
  - Increase number of lanes as storage system capacity increases
- Bottom-up manufacturing estimate (BUME) cost analysis
  - Cost correlations for internal piping, quoted costs for other materials.
  - At this time, includes material costs and a 20% contingency

- BUME uses material quotes, equipment capital costs, labor costs, power costs, and runtime.
- Welding (and associated steps) and roll bending use cost correlations.
- On-site "installation" calculated as a percentage of delivered part cost from Peters, Timmerhaus, and West's (PTW) *Plant Design and Economics for Chemical Engineers*
- BUME costs compared to tank costs estimated using Aspen® cost models

- Cryogenic He refrigeration reverse Brayton cycle simulated in Aspen® as detailed configuration of individual unit operations
- Estimate of refrigeration cycle power demand including key performance metrics for equipment operation & their connected process streams determined in Aspen®
- Installed costs for Aspen® sized equipment (e.g., compressors, expanders, exchangers, etc.) estimated using Aspen® cost models
- Alternative cost build up to estimate miscellaneous components not costed in Aspen® such as cold box, vacuum jacketed piping & valves, adsorbents, refrigerants, lubricants, heat transfer fluids, & insulation

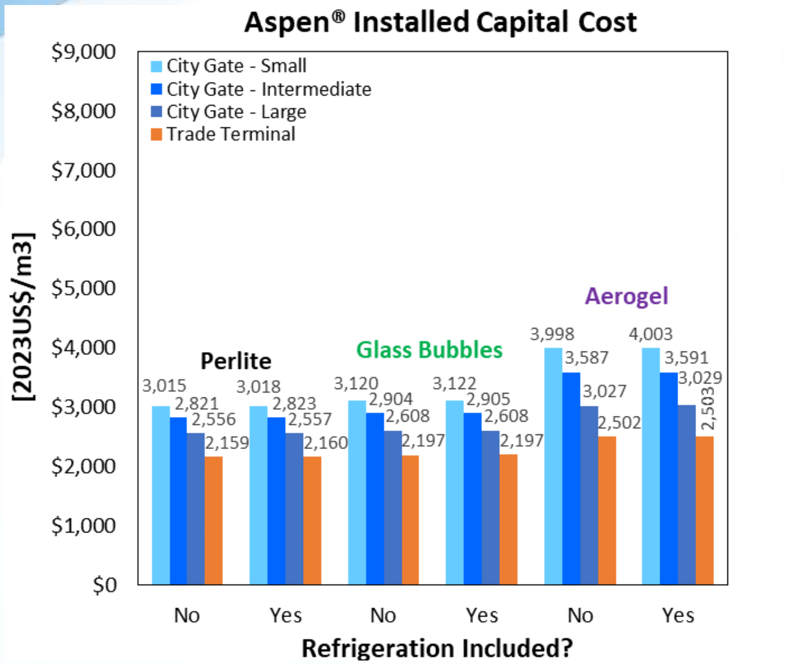
LH_2 Tank Analysis: Capital Cost Results

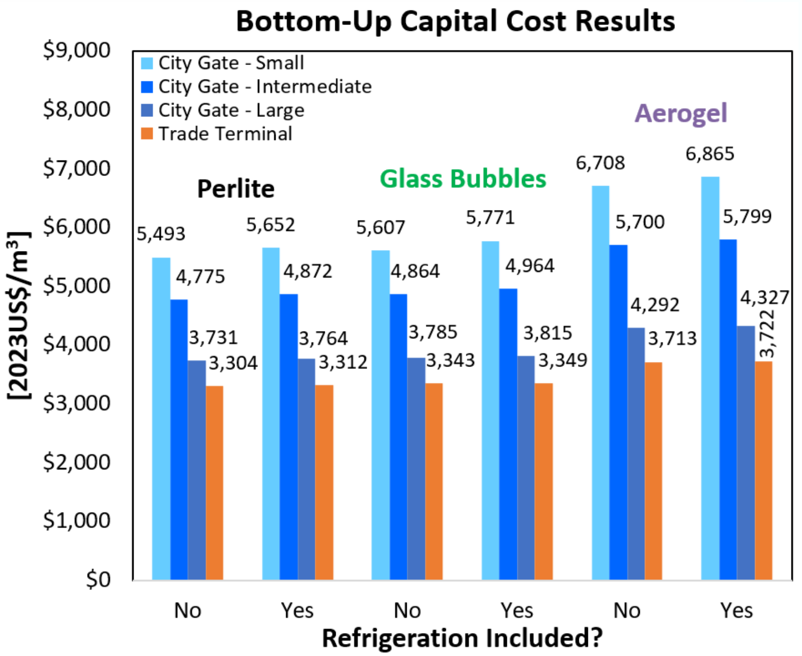


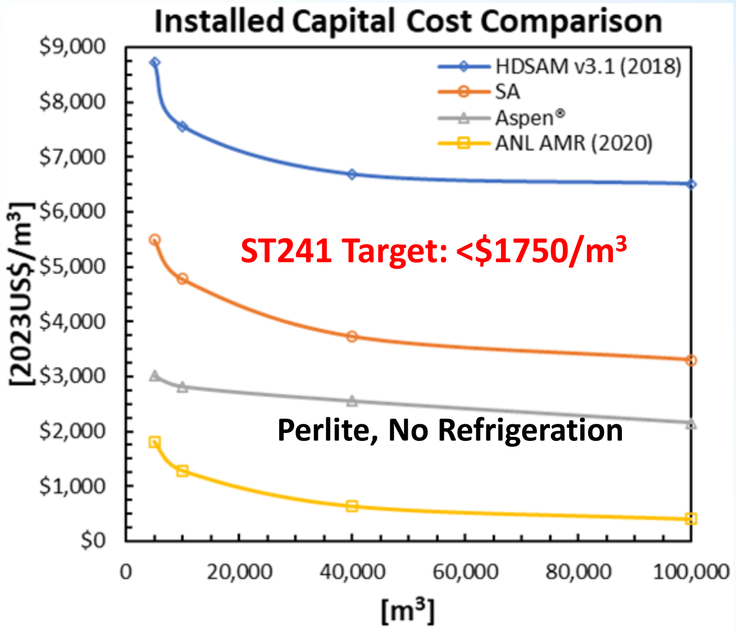
- Inner and outer shells ~60% of total cost
- 50% materials ($2.5-$3/kg; 4-10 cm thick)
- 40% onsite manufacturing includes installation (PTW factor), welding, PWHT, inspection

- "Supports" includes support columns & external struts, internal supports, & the central support tower
- "Insulation" includes insulation loading & vacuum pump down
- "Miscellaneous" includes nozzles/connections, site & foundation, & fire safety system

Storage Tank Analysis: Comparison of Tank Cost Results





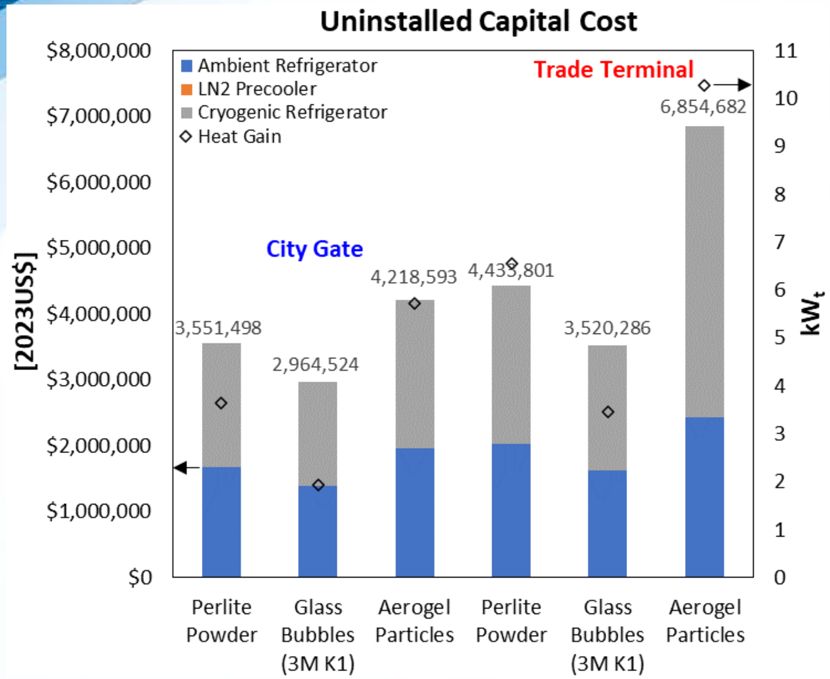


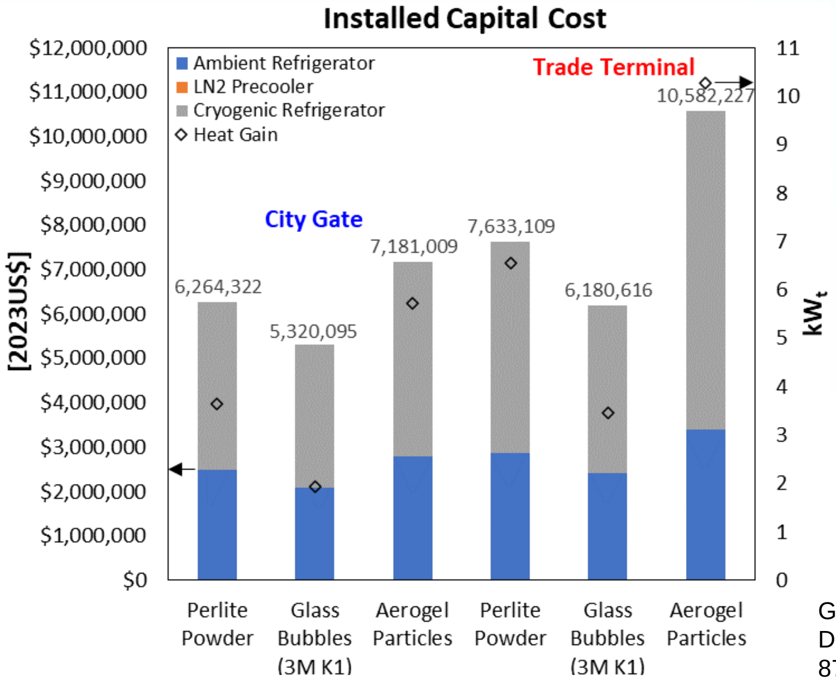
- SA bottom-up and Aspen installed cost models show most agreement (within ~30% for larger systems)
  - Aspen model is a black box, so it is difficult to say what the difference is between models.
- Comparison with ANL, HDSAM, Shell target
  - HDSAM[1] v3.1 LH_2 tank installed capital cost correlation are used around the range of 40,000 m^3 for city gate.
  - ANL[2] reported LH_2 and LNG installed storage cost correlations up to ~8,000m^3. LH2 correlation data up to 3,600m^3. Comparison is likely well outside the range of validity but included here for context and completeness.

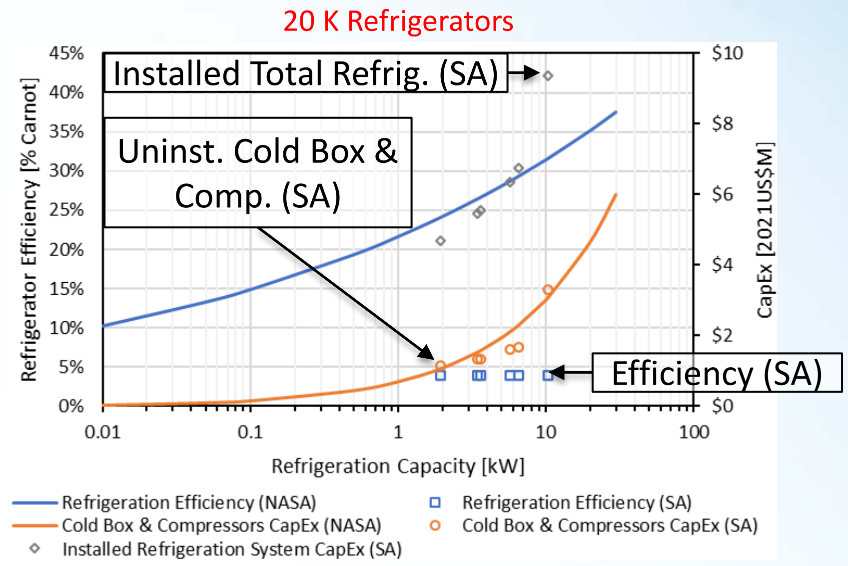
1. 2018, https://hdsam.es.anl.gov/index.php?content=hdsam
2. https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review20/st001_ahluwalia_2020_o-pdf.pdf

†$/$m^3$ refers to storage vessel water volume

Refrigeration Analysis: Capital Cost Results





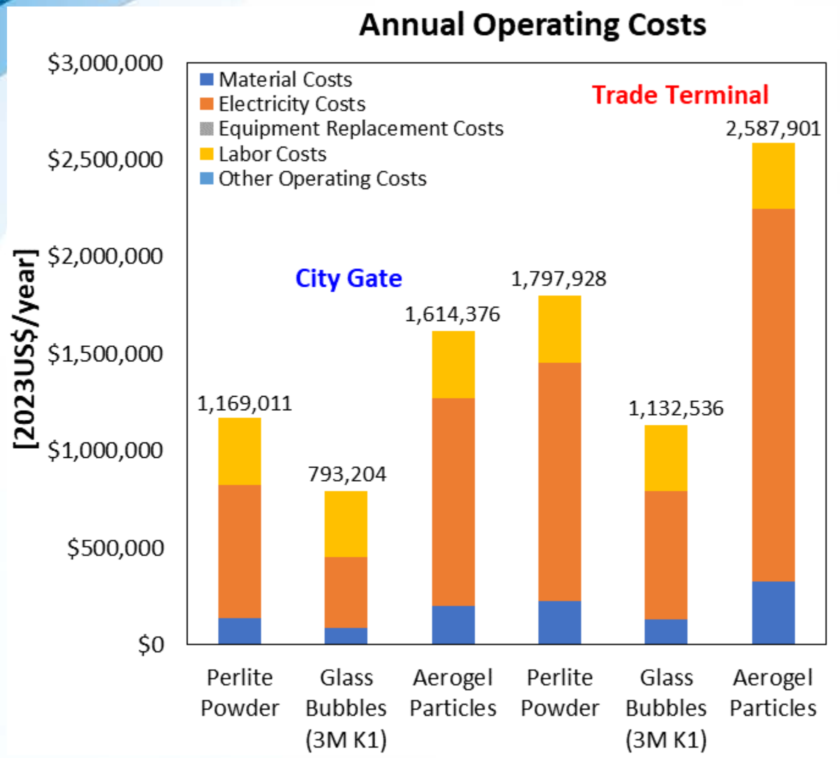


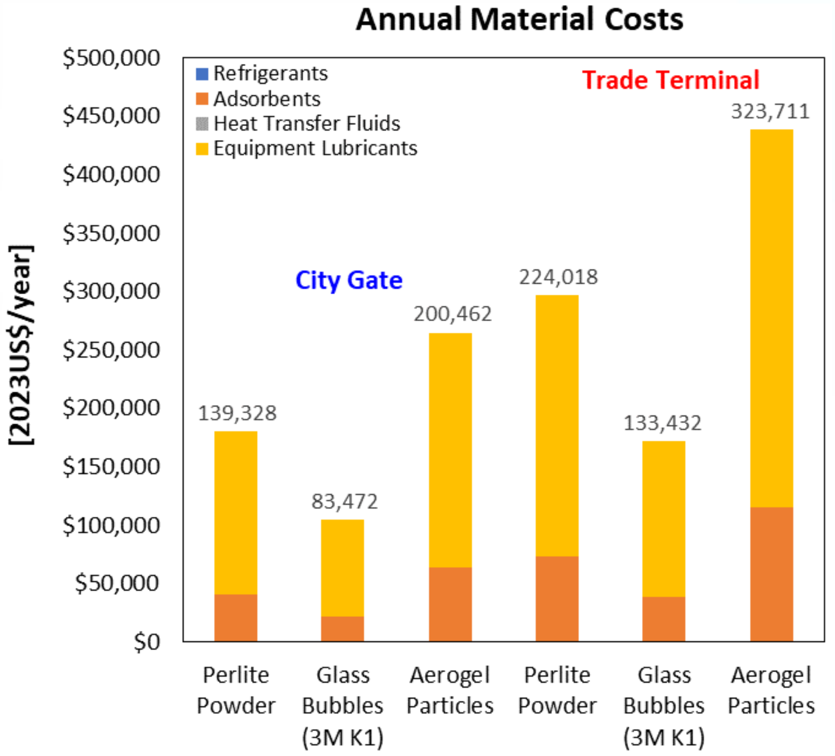
Green, M. A., The Cost of Helium Refrigerators & Coolers for Superconducting Devices as a Function of Cooling at 4 K, *AIP Conference Proceedings* **2008**, 985, 872-878, *https://doi.org/10.1063/1.2908683*

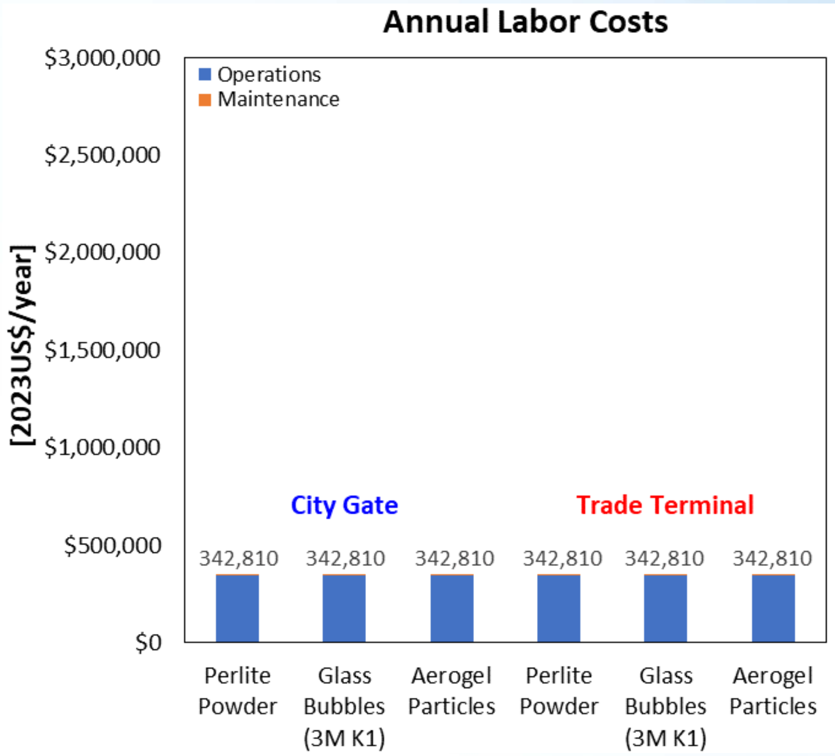
- LN_2 precooling not included in this round of analysis
- Costs scale non-linearly with refrigeration cooling duty in a power-law fashion as Green (2008) & NASA report
- Uninstalled Capital Costs
  - Split almost equally between ambient & cryogenic refrigerator subsystems for both scenarios & all insulation types – cryogenic refrigerator always slightly higher
  - Cryogenic refrigerator cost starts to significantly dominate at cooling loads >10 kW_t
- Installed Capital Costs
  - Cryogenic refrigerator contributes majority with ambient refrigerator remaining nearly constant over range of cooling
- Constant efficiencies used in initial analysis for all rotating equipment
  - Will revise in next pass of analysis to capture efficiency differences with equipment capacity

STRATEGIC ANALYSIS INC

Refrigeration Analysis: Operating Cost Results

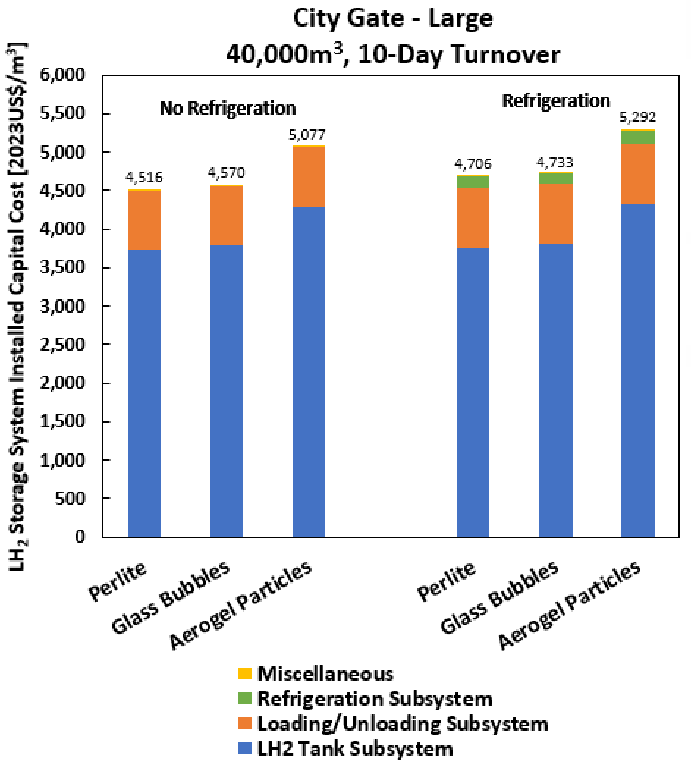


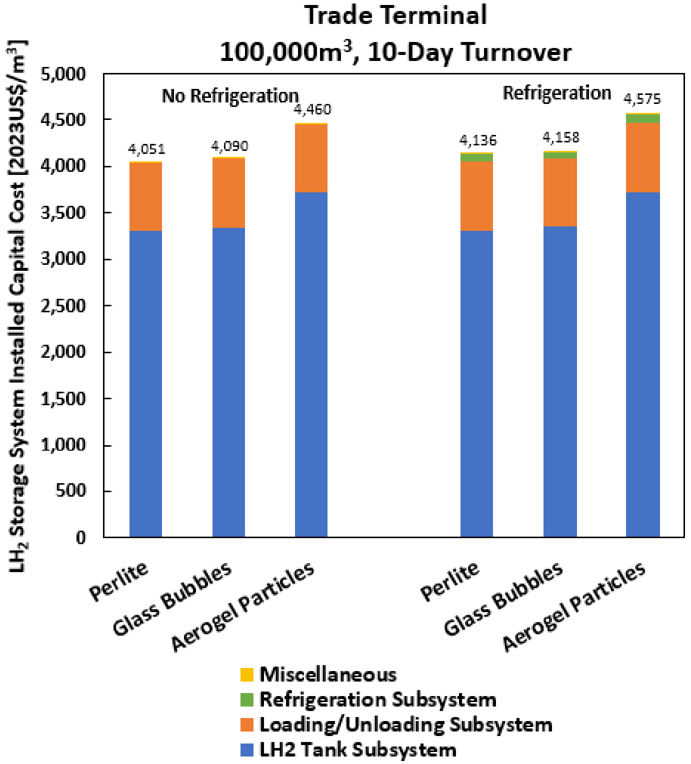


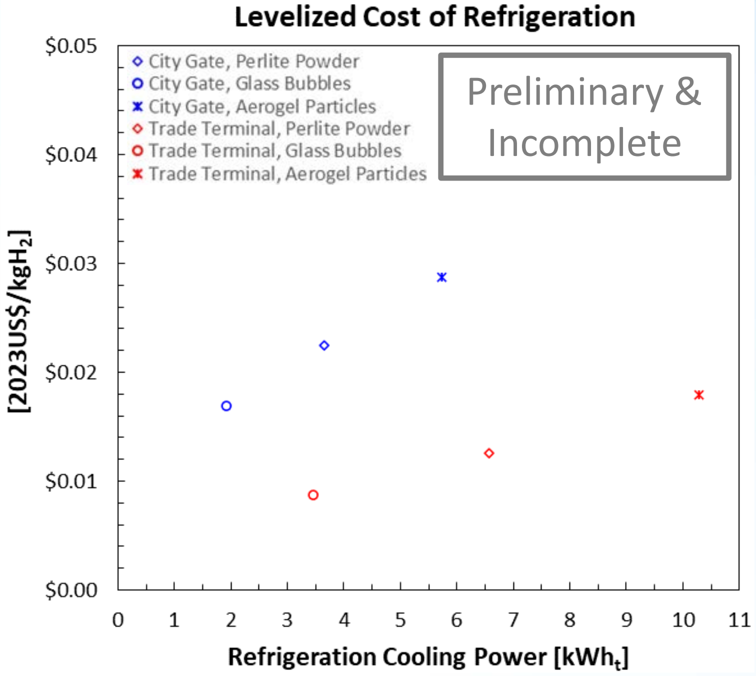


- Operating costs dominated by costs of electricity, followed by labor and materials
- Material costs almost entirely from lubricating oil replacement
- Labor costs are due primarily to operations work force
  - Work force & pay schedules are assumed to be constant across all scenarios studied
  - Equipment quantities & sizes do not change enough across each case to justify adjusting work for and pay schedule

LH_2 Storage System Cost Results



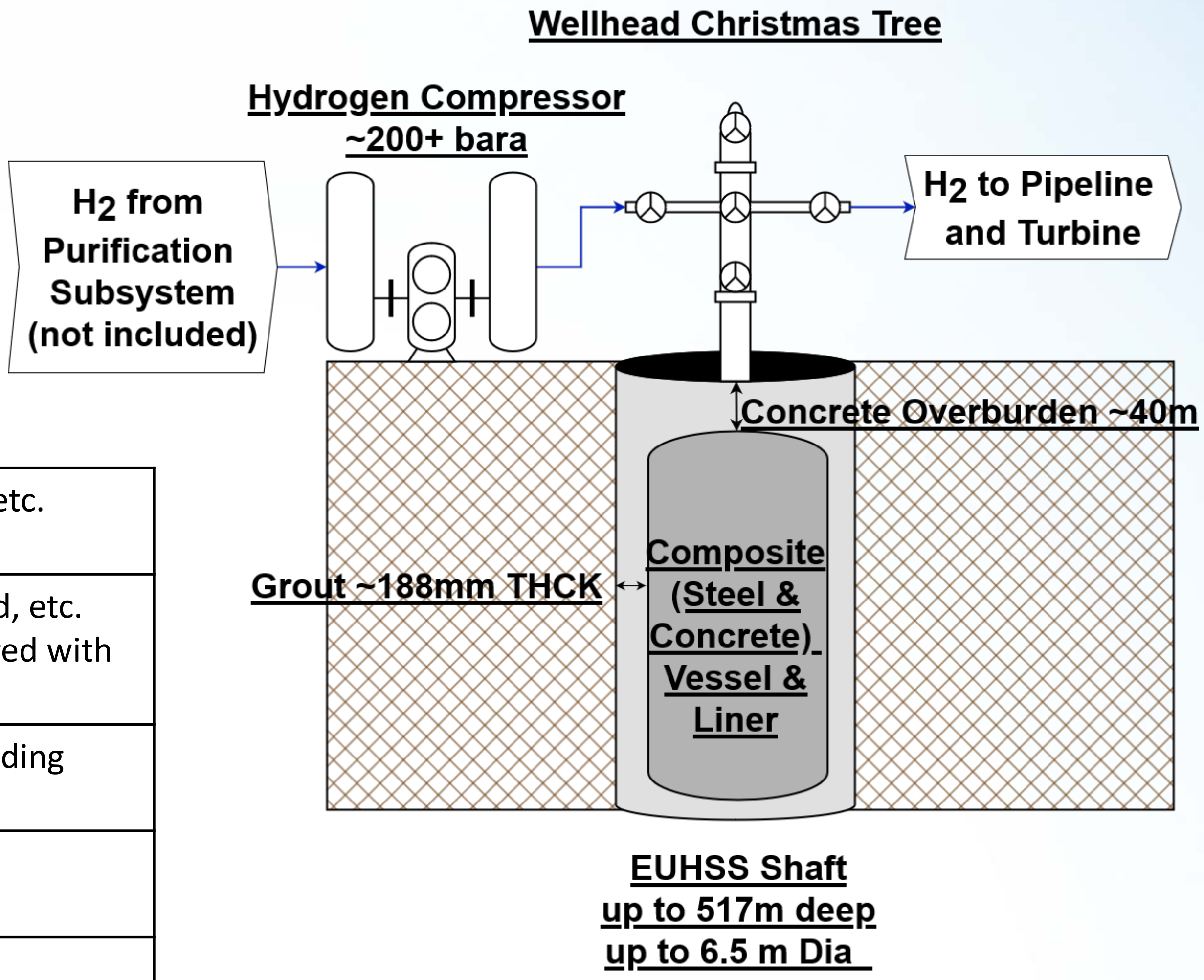




- Miscellaneous includes costs for land, site preparation, & permitting
- Storage system installed capital cost dominated by tank subsystem costs (~80-85%) with loading/unloading (~15-18%) & refrigeration (~1-3%) subsystems contributing much less
- Aerogel particle insulation significantly more expensive than other two insulation types
- LCOR demonstrates pathway to more favorable storage system (20-year, 10-day turnover, 90% capacity)
- Goal is to estimate the LCOS for multiple scenarios
  - Missing/still need to estimate certain elements such as some installation costs & full system operating costs to determine LCOS
  - Analysis will be continued with a shift to estimating LCOS (subsequent slides detail next steps)

Engineered Subsurface Hydrogen Storage Analysis

- Subsurface gaseous storage concept being commercialized by Ardent Underground https://ardentunderground.com/
- Large diameter, blind bore, concrete lined shaft
- Not tied to specific geologies such as those required for lined rock caverns, salt domes, and aquifers
- Small diameter, steel lined subsurface storage concepts are also being modeled



Cost Methodology Approach

Site Prep	Brown field, grading, concrete pad, settling pond, etc. Fixed costs guided by Abergeldie and literature
Drilling	Drill rig Capex, utilization, drill rate, labor, drilling fluid, etc. Cost correlation from Mallants and Abergeldie (compared with 1980s Blind bore report)
Casing Fabrication	Material transport, concrete pouring, steel liner welding DFMA® correlations
Casing Installation	Liner hoisting, welding, PWHT DFMA® correlations
Commissioning	EPC and Contingency SA standard % adders to base cost/CAPEX

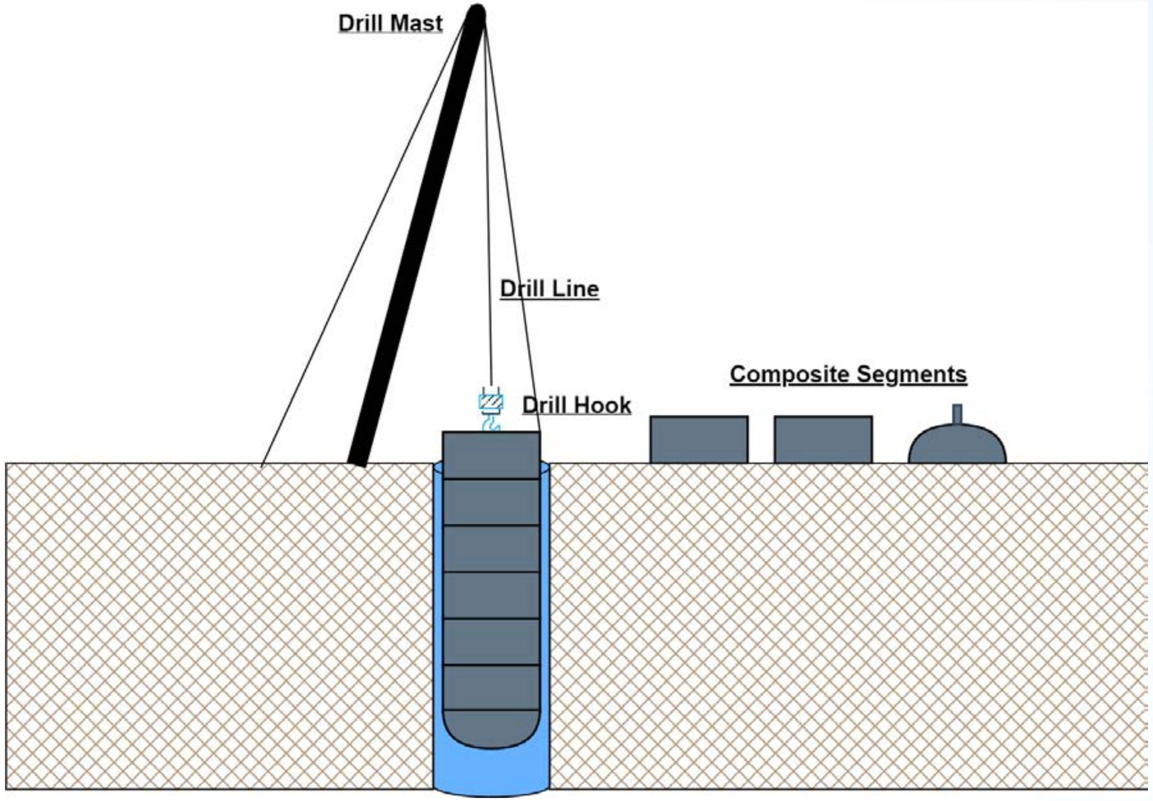
Casing and Pressure Vessel Design and Assembly

- Onsite fabrication, concrete pouring into steel form, steel form fabricated offsite, and cost estimated bottom-up
- Assumed 11mm thick A36 CS exterior liner
- The rebar-reinforced concrete segments were assumed to have a thickness of 269mm
- Interior 316SS liner/pressure vessel thickness of 11mm
- Liner thicknesses based on reviewer feedback and input

Steel / Concrete Casing Sections

https://ardentunderground.com/blind-boring/

- Liner sections are fabricated onsite
- Sections are joined at the surface (weld and grout)
- Bore hole is maintained partially filled with water to act as a float medium to support the liner as it is assembled



Drilling Time

Abergeldie Project Reports (2020s)

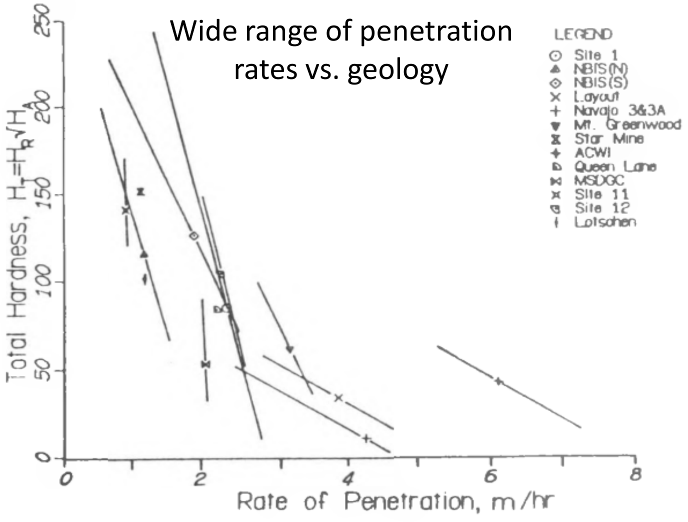
Correlation Data			
Source/ Project Name	Shaft Depth (m)	Shaft Diameter (m)	Drilling (days)
Austar Coal Ventilation Shaft	465	4	579
Dendrobium Ventilation Shafts	270	4	272
Southern Coalfields	517	6.2	753
Assumed Fixed Site Prep Time (days)	$t_{sp} = 235$		
Drilling and Casing Time Correlation (days)	$t_{dc} = 85.48 * (1.028^{Diam\ (m)}) * (1.004^{Depth\ (m)})$		

Average drill rate of 0.7 – 1 m/day

1. Abergeldie Complex Infrastructure, "Design and Construction of a Southern Coalfields." Abergeldie Complex Infrastructure, Jul. 2015.
2. ABERGELDIE MINING PTY LTD, "WHITE PAPER AND CASE STUDY OF DENDROBIUM MINE SHAFTS 2 AND 3." ABERGELDIE MINING PTY LTD.
3. P. Jamieson and C. Pepper, "Austar Coal Mine Proposed Stage 2 Extension Project: Environmental Assessment," Umwelt Pty Limited, New South Wales, Australia, Proposed Stage 2 Extension Project 2274/R56/Final, Jul. 2010.

Schmidt Report (1981)

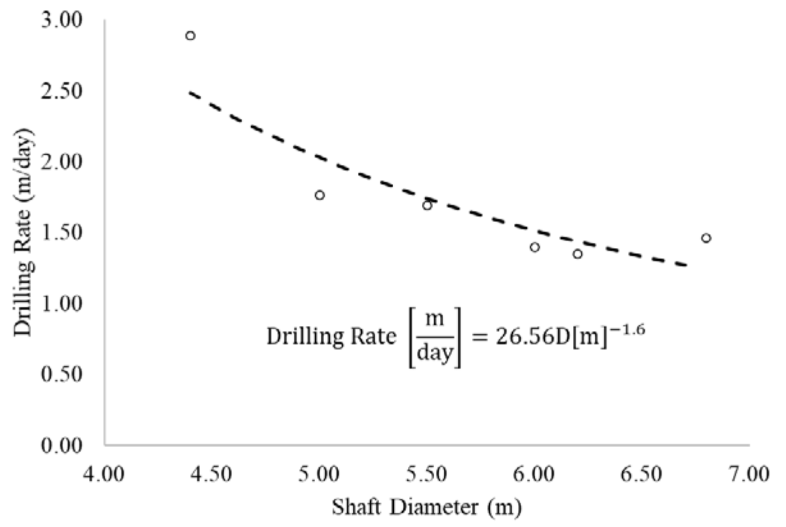
BSB Drill Rates	
Drill Company	Drill Rate (m/hr)
BSB Planned	1.22
BSB Actual	0.65
Fenix and Scisson	753
Hughes Combination Shaft Drill 820	0.19
Hughes Combination Shaft Drill 300	0.14
Robbins 121 BR	1.68
Robbins 80 BR	Not Specified



https://www.osti.gov/biblio/6688301

Drill Penetration Rates Used

- Developed with input from reviewers
- Rate assumes an average geology but is expected to vary widely depending on site-specific properties and complexity
- Primary parameter affecting average rate is assumed to be bore hole diameter
- Drill rate is on the upper end of what is reported by Abergeldie and an order of magnitude slower than Schmidt

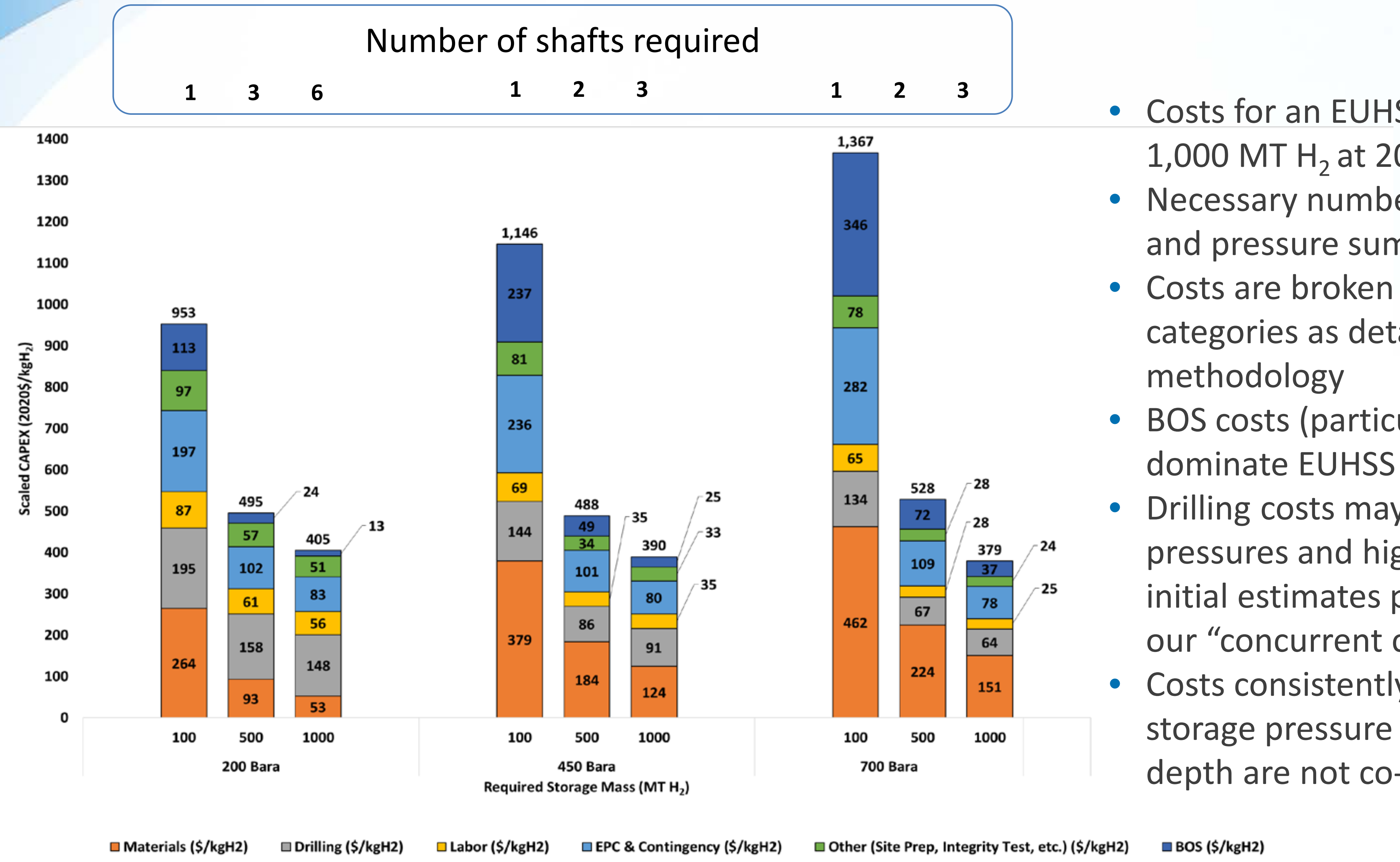


Blind Bore Drilling Literature Comparison

Parameter	UOM	Schmidt	SA
Operating Parameters			
Shaft Depth	[m]	304.8 – 609.6	457.2
Shaft OD	[m]	3.7 – 7.3	6.1
Rate of Advance	[m/hr]	0.1 – 1.7	0.06
Capital Costs			
Rig Utilization*	[%]	30 - 72	27
Rig Rate	[2020US$/day]	7,883 - 16,596	15,000
Drilling Equipment	[2020US$M]	7.6 – 38.4	13.2
Other Equipment	[2020US$M]	1.7 – 9.9	0.2
Total	[2020US$M]	9.3 - 48.3	13.4
Operating Costs (per shaft)			
Materials and Consumables	[2020US$M]	1.7 – 2.9	8.2
Labor	[2020US$M]	0.5 – 2.1	5.5
Other/Indirect Costs	[2020US$M]	0.5 – 0.9	6.8
Overhead, Contingency, & Profit	[2020US$M]	0.9 – 1.7	8.3
Total	[2020US$M]	3.6 – 7.6	28.8

- Completed a detailed comparison with Schmidt report of cost critical operating parameter, capital cost buildup, and operating costs
- Cost escalations from ~1980 are subject to greater uncertainty when comparing individual equipment inflation vs price index reporting average inflation across a sector
- Many parameters used in the current analysis fall within the range of what was reported by Schmidt
- Notable differences
  - Current advance rates are much slower in our model than Schmidt
  - Operating costs are much higher in our model compared with Schmidt
- Sensitivity analyses aren't complete yet but will help us decide what level of scrutiny between the two sets of assumptions is valuable

CAPEX Investigation Major Cost Driver Breakdown



- Costs for an EUHSS that can store 100, 500, and 1,000 MT H_2 at 200, 450, and 700 bara
- Necessary number of shafts for any storage mass and pressure summarized above the chart
- Costs are broken down into the major cost categories as detailed in the cost estimation methodology
- BOS costs (particularly the compressor) begin to dominate EUHSS costs at higher pressures
- Drilling costs may have a larger impact at lower pressures and higher storage masses than these initial estimates predict depending on validity of our “concurrent construction assumption”
- Costs consistently increase with increasing storage pressure when vessel diameter and depth are not co-optimized

Challenges, Barriers, and Proposed Future Work

Challenges & Barriers

LH2 analysis Validation
- Valuable guidance on input parameters and design requirements were provided by system designers and builders
- Feedback on model design and results was provided by people with expertise in bulk hydrogen storage but not direct design and construction experience
- Additional feedback on model results from tank builders would be beneficial

Engineered underground storage analysis
- Current costs are based on a single concept offered by Ardent Underground
- Model inputs are generalized but will vary by site

Comparisons among long-term, bulk hydrogen storage
- Long-term and bulk storage analyses are being conducted by multiple groups, e.g. geologic storage, materials-based storage
- Need to align levelized cost of hydrogen storage methodology with other analysis groups (e.g. LBNL and SHASTA) to allow comparison

Proposed Future Work

LH2 analysis validation
- Limited number of builders globally, so we are actively seeking new contacts
- Compare results and assumptions with published results from ST241 when available

Engineered underground storage analysis
- Expand analysis to include small diameter (6-8”), steel lined storage systems
- Sensitivity studies to capture site variations

Comparisons with other bulk storage
- Working with LBNL and SHASTA to align LCOS methodologies and financial assumptions
- Preparing a critical review of reported storage system costs from kg - ktonnes

**Any proposed future work is subject to change based on funding levels.
This project ends in September 2024.**

Collaboration and Coordination

Bulk liquid hydrogen storage The named individuals provided some or all the following: background information on system design and construction, recommendations on analysis boundaries, data used in the heat load analysis, and review of the preliminary results	**NASA:** Adam Swanger **McDermott:** Brent Rupp, John Jacobson **Matrix:** John Hart, Ken Erdmann, Rama Challa **Shell**: Kun Zhang **Cryomech:** Arifin Budiharjo, Tim Hanrahan, Brian Stoddard, Peter DeCrew **NREL:** Matt Thornton **PNNL** (sub-award): Corey Arhipley, Kevin Simmons, Mark Weimar **ANL** (sub-awardee): Dennis Papadias
Engineered underground hydrogen storage The named individuals provided some or all the following: background information on system design and construction, recommendations on analysis boundaries, data used in the boring operation analysis, commentary on geology, and review of the preliminary results	**Ardent Underground:** David Bentley **Exxon:** Yaofan Yi et al **NREL:** Matt Thornton, Vivek Singh, Xiaofei Pu **SHASTA:** Nicholas Huerta, Gerad Freeman

Summary

Modeled two large-scale bulk hydrogen storage systems

- LH2
  - Built bottom-up capital cost model of vacuum insulated spherical storage vessels with capacities ranging from 5,000 – 100,000 m^3 and with multiple insulation material types
  - Built cost model of helium refrigeration system using Aspen®
  - Built bottom-up cost model of bulk liquid hydrogen storage facility inclusive of storage, refrigeration, loading and unloading, and ancillary buildings
  - Modeled storage and refrigeration system capital costs and refrigeration system operating costs
- Engineered underground storage
  - Built a bottom-up capital cost model for large-diameter bore hole subsurface storage system
  - Built a discounted cash flow storage facility cost model to estimate a levelized cost of storage (results are incomplete and not reported here)
  - Modeled capital cost for multiple size storage facilities

Accomplishments & Progress

Responses to Previous Year Reviewers’ Comments

This project was not reviewed at 2023 AMR