Hydrogen Storage Cost Analysis

STRATEGIC ANALYSIS INC

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DOE Hydrogen Program

2021 Annual Merit Review and Peer Evaluation Meeting

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Overview

Timeline

Project Start Date: 9/30/16
Project End Date: 9/29/21
% complete: ~90% (in year 5 of 5)

Barriers

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

Budget

Total Project Budget: $999,946
Total DOE Funds Spent: ~$813,000
(through March 2021 , excluding Labs)

Partners

Pacific Northwest National Laboratory (PNNL)
Argonne National Lab (ANL)

Project Goal

- Conduct rigorous, independent, and transparent, bottoms-up techno-economic analysis of H_2 storage systems using Design for Manufacture and Assembly (DFMA)
- Identify cost drivers and recommend to DOE the technical areas needing improvement for each technology.
- Provide DOE and the research community with referenceable reports on the current status and future projected costs of H2 storage systems

Relevance and 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 to reducing the costs of onboard H_2 storage and to meeting DOE cost targets

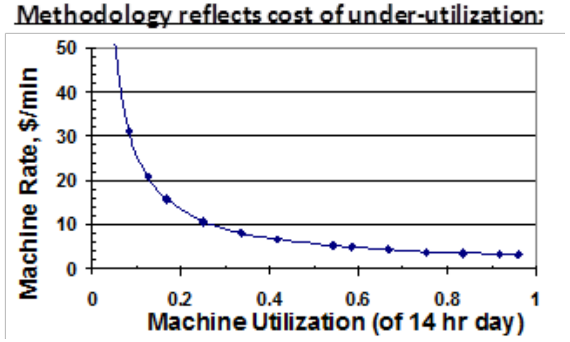
Approach: DFMA® methodology used to track annual cost impact of technology advances

- DFMA® (Design for Manufacture & Assembly) is a process-based, bottoms-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 the actual cost of components or systems based on a hypothesized design and set of manufacturing & 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**

$$\frac{\text{Annual Capital Repayment} + \text{Annual Operating Payments}}{\text{Annual Minutes of Equipment Operation}} = \text{Machine Rate (\$/min)}$$

STRATEGIC ANALYSIS INC

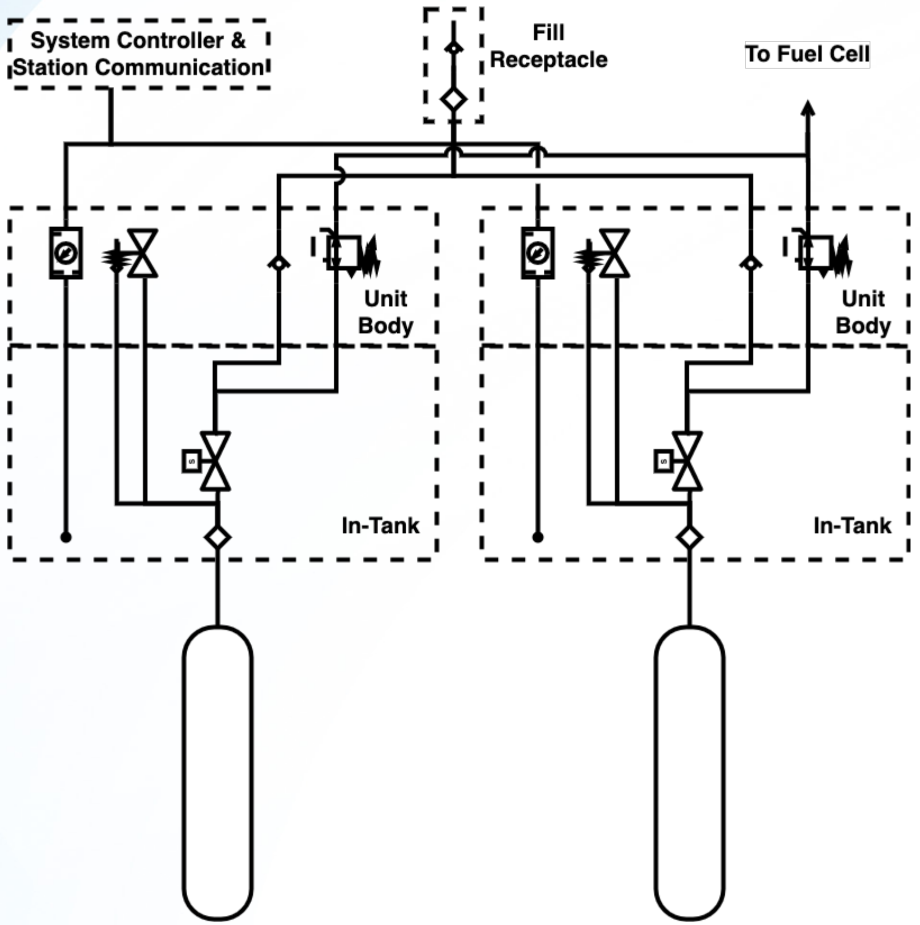
Analyses Conducted Since 2020 AMR

- **Class 8 Long Haul H_2 Storage**
  - Built on previous work evaluating storage system cost for multiple packaging options to develop cost models for Class 8 Long Haul
  - Developed system configuration to compare with DOE Class 8 Long Haul targets
  - Projected costs and path to targets for baseline system assuming 700 bar Type 4 technologies
  - Developed preliminary cost model for LH2 storage

- **LDV H_2 Storage**
  - Completed a low-volume 700 bar Type 4 analysis for annual production between 1,000 – 10,000 systems per year
  - Completed sensitivity analysis of 700 bar Type 4 storage systems in support of HDTT target setting

- **Station Bulk Storage**
  - Scope of analysis includes bulk GH2 and LH2 onsite storage and cascade storage systems at refueling stations
  - Completed cost models for high-capacity gaseous tube trailers in this year
  - Previously reported cascade storage (2020 AMR)
  - Developed preliminary LH2 bulk storage cost model

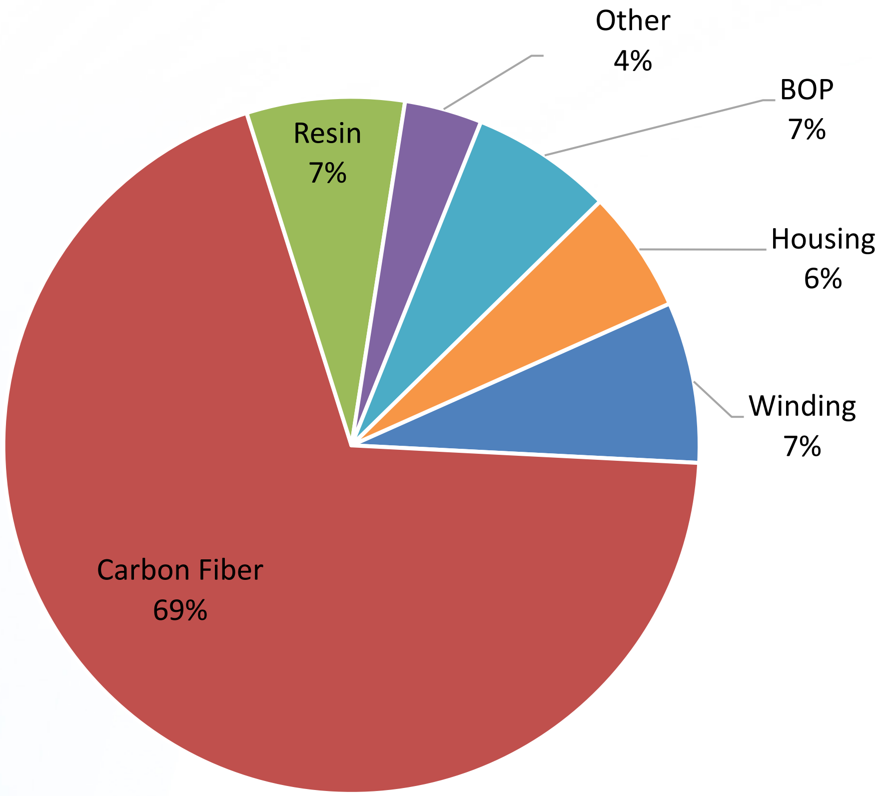
Accomplishment & Progress:
Defined a Baseline Class 8 Long Haul System



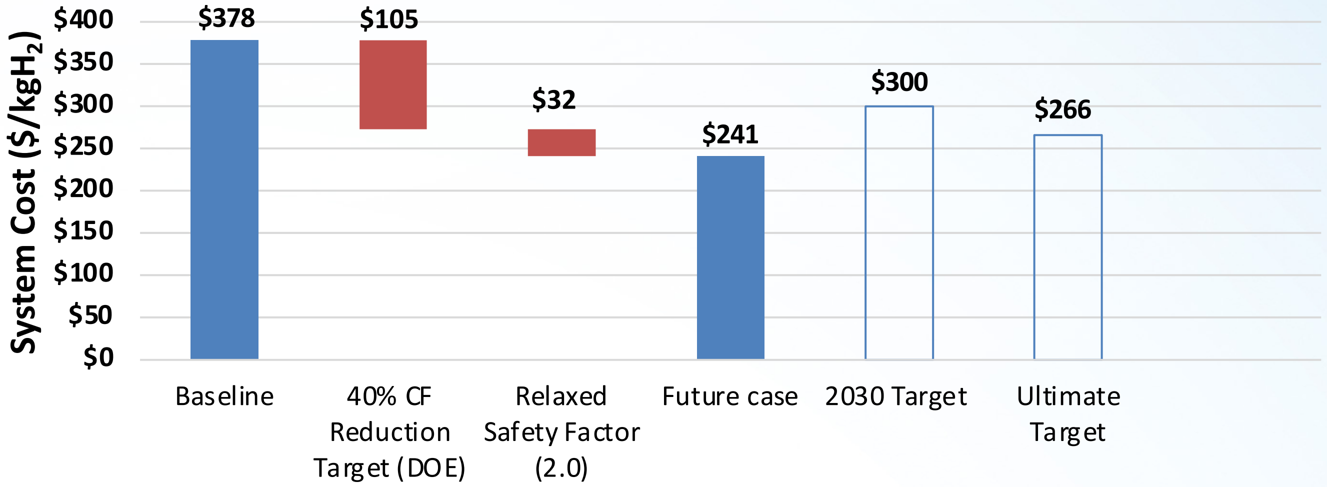
Property	Value	Note
Technology	700 bar Type 4	Highest capacity mature technology
Tank / Total Capacity (kg)	30 / 60	Target definition
Tanks per System	2	Tanks of identical size
External Package Dimensions	250 cm x 64 cm x 64 cm	Assumption. Similar to Quantum Fuel Systems.
Mounting	Strap-Mounting Frame	Assumption. Similar to Quantum Fuel Systems.
BOP	Integrated valve and regulator	Similar to GFI ITVR-70. Redundant minimizes high-pressure line spanning frame
Estimated Composite Mass (kg/tank)	444	Estimated using performance derived from ANL analysis
Estimated Total Mass ($kg_{H2storage}$/truck)	1124	Compared to 750 kg for Quantum 46 DGE CNG System.
Estimated capacity	1.7 kWh/kg; 0.98 kWh/L	
Safety Factor	2.25 (nom)/2.54 (eff)	NGV2, fiber, and mfg. variations

Accomplishment & Progress: HDV Storage Cost Breakdown and Reductions

Projected cost breakdown at 100k systems per year for frame rail mounted 60 kgH_2 (available) 700 bar Type 4 storage system for Class 8 long haul trucks



Potential cost reductions for 60 kgH2 (available) two-tank frame rail mounted 700 bar Type 4 storage system



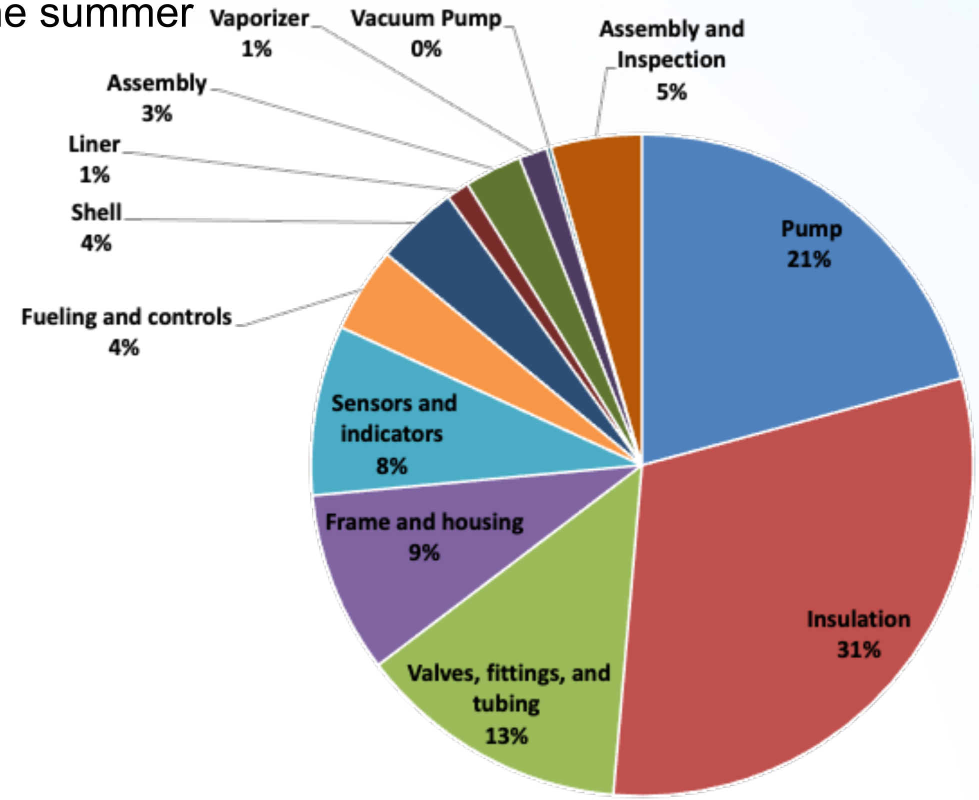
- Carbon fiber is the largest single cost category for 700 bar Type 4 tanks
- The DOE target of reducing carbon fiber* price by 40% would close the gap between the current projected cost ($378/$kgH_2$) and the 2030 target ($300/kgH_2)
- Reducing the current safety factor from 2.25 to 2.0 is projected to exceed the ultimate targe of $266/$kgH_2$
- Long tanks (>2.0m) currently modeled on larger single spindle fiber winder increases winding time per tank compared with smaller LDV tanks on two spindle machines

*carbon fiber price = $26.20/kg
resin price = $4.50/kg

Accomplishment & Progress: Analysis of Advance LH2 Systems for Class 8 Long Haul

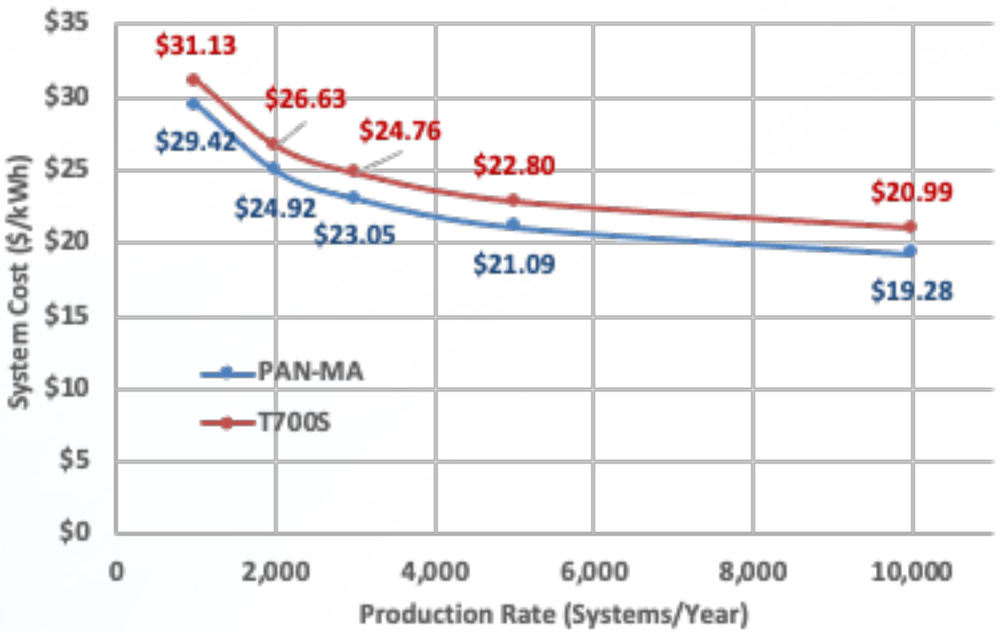
- System design and assumptions were developed under a separate project led by R. Ahluwalia at ANL (ST223)
- Completed a preliminary bottom-up capital cost analysis for the baseline 110.4 kgH_2 frame mounted two-tank LH_2 storage system
- Breakdown and sensitivity analysis are shown for annual production of 100k systems
- Balance of plant components and insulation dominate the system cost and have the greatest impact on cost sensitivity
- Additional work is planned to refine and understand pump costs
- Current preliminary costs are near target and will be finalized over the summer

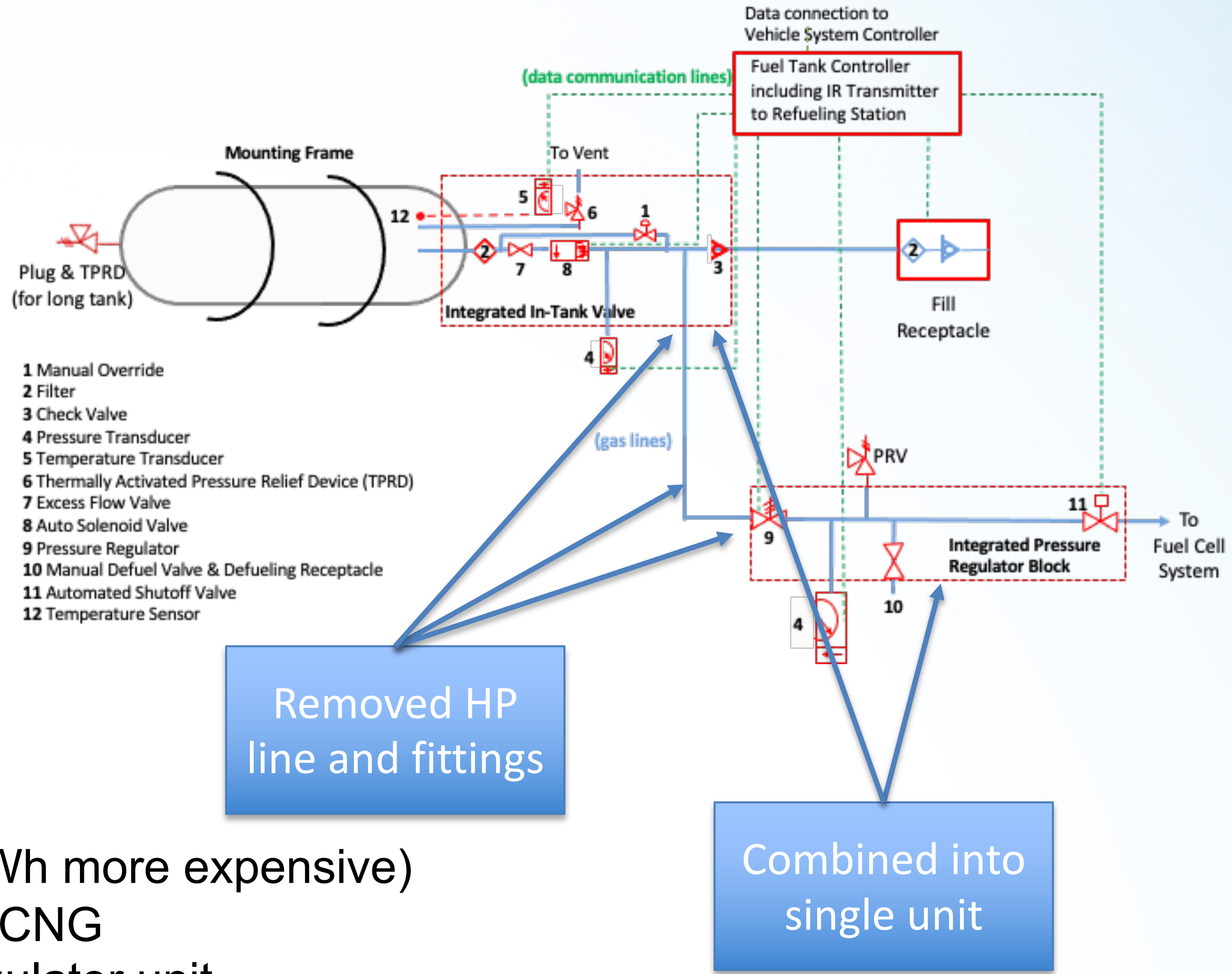
Property	Value
Tank placement	Frame-mounted
Capacity	55.2 kgH_2/tank
Insulation	MLVI
Insulation thickness	21mm
Shell thickness	3.98 mm Al 2219-T78
Liner	1.57mm Al 2219-T78
MAWP	10 bar
Pump	Single on-board pump
Target cost	<$8/kWh



Accomplishments & Progress: Low-Volume LDV System Cost

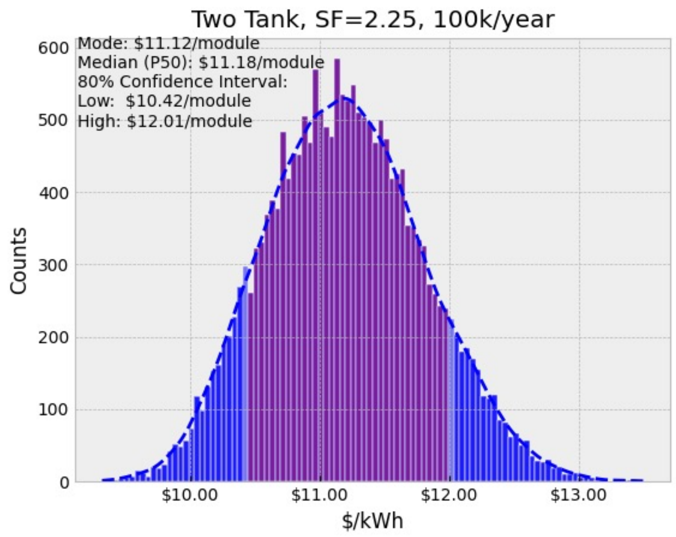
700 bar Type 4 H2 storage system with 5.6 kgH_2 available.

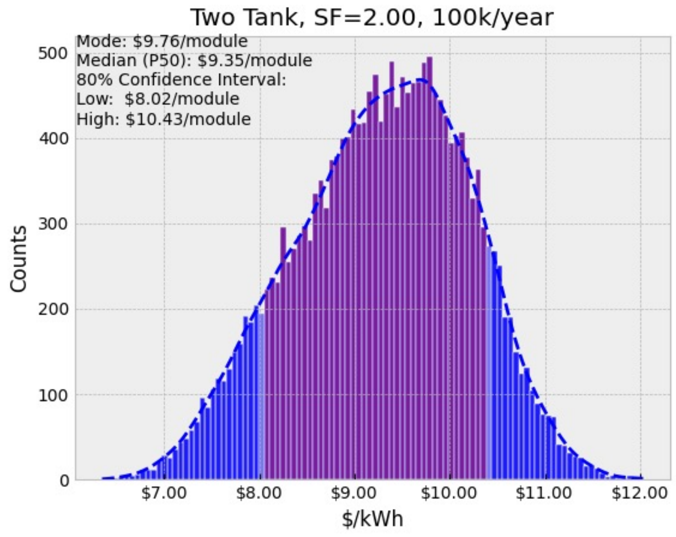




- 700 bar system costs projected to current volumes
- These costs are single tank (two-tank would be ~$2/kWh more expensive)
- Assumed production equipment would be shared with CNG
- BOP is based on a GFI single integrated valve and regulator unit

Accomplishment & Progress: LDV Sensitivity Analysis

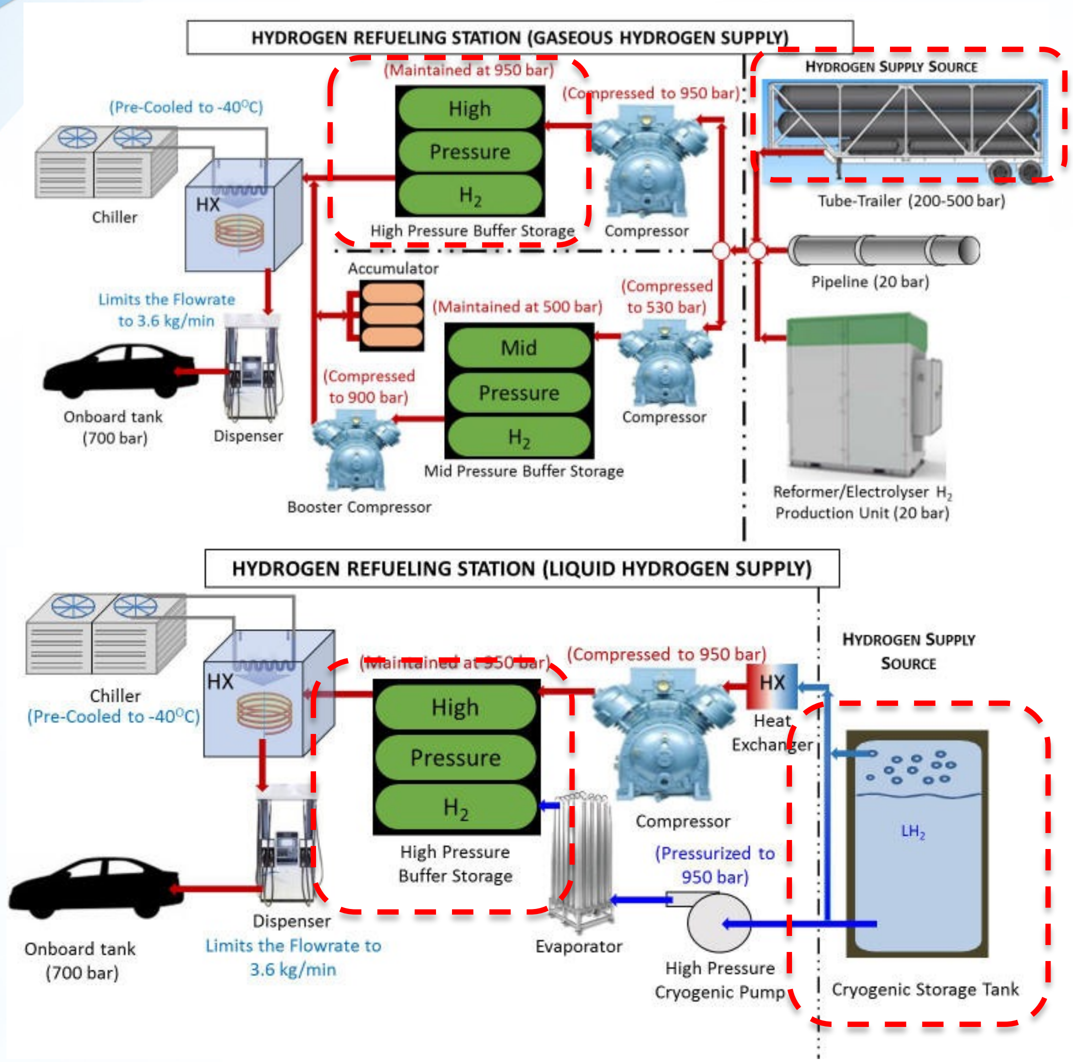




Parameter	2025	2030
Safety Factor	2.25	2.0
Carbon Fiber	Low = $20.80/kg Mid = $22.46/kg High = $25.37/kg	Low = $13.47/kg Mid = $22.46/kg High = $25.37/kg
Projected System Cost (100k/year)	Low = $16/kWh Mid = $18/kWh High = $20/kWh	Low = $14/kWh Mid = $16/kWh High = $18/kWh

- Safety factor alone shifts the distribution but doesn't affect the skew
- The carbon fiber sensitivity range for 2030 tests the effect of achieving DOE targeted price reductions, skews the distribution, which affects the 10% case
- The BOP distribution was treated separately to allow Autonomie simulations that treat cost as a linear function of a fixed BOP($) and variable tanks ($/kg)
- Confidence intervals are reported at 100 vehicles per year but computed for the full range in the model (10k – 500k)
- Other parameters are described in the 2019 Program Record and include capital cost uncertainties, cycle times, and carbon fiber mass

Onsite Refueling Station Storage Analysis Overview



Objective: perform a bottom-up cost analysis onsite storage systems at H_2 refueling station (HRS)

Sub-systems for analysis were selected using the HDSAM model and considered stations with gaseous and liquid H_2 bulk storage.

Three HRS sub-systems were selected for analysis shown in red dashed boxes to the left:

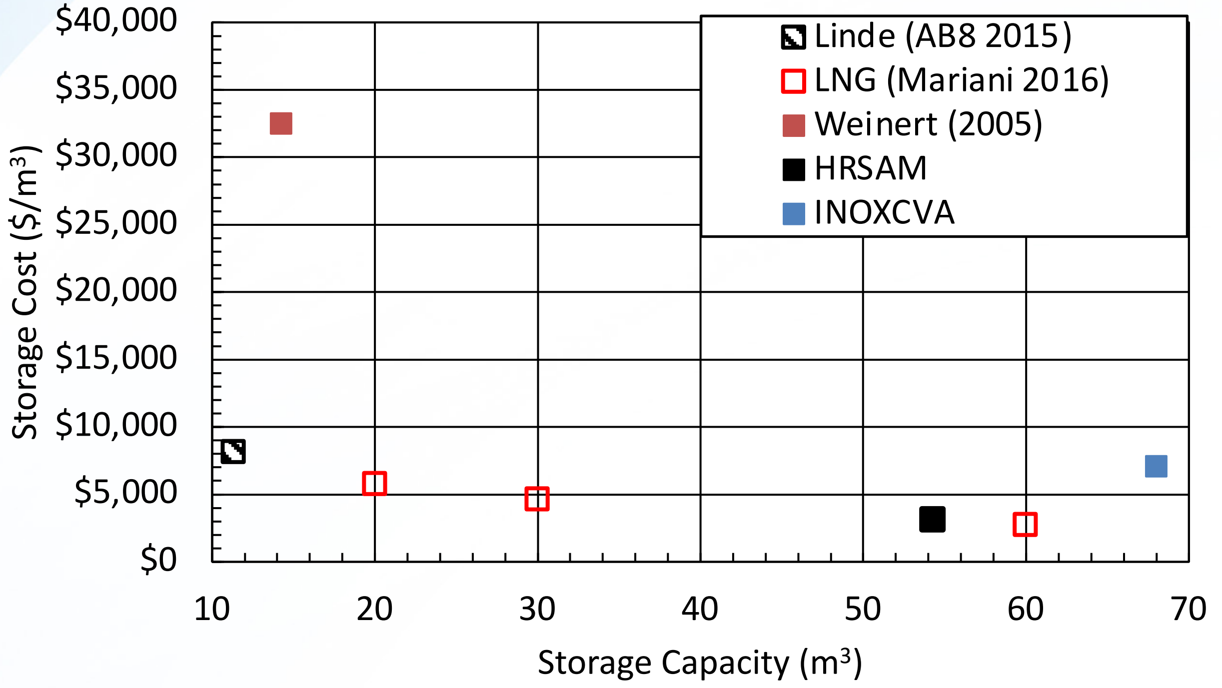
- Cascade storage (reported at 2020 AMR)
  - 950 bar Type 2
  - found at both gH2 and LH2 stations
- Tube trailer (refined analysis and new design added since 2020 AMR)
  - Multiple pressures and configurations of Type 4 tanks
  - gH2 station bulk storage option
- Cryogenic storage tank (new in 2021)
  - LH2 station bulk storage option

Images taken from https://hdsam.es.anl.gov/

Onsite Refueling Station System Parameters

Parameter	GH2	LH2	Notes/Design Basis
Bulk Storage Assumption	Tube Trailer	Dewer	HRSAM
Station Max Daily Dispensing Capacity (kgH_2/day)	1,000	1,000	HRSAM
Number of refueling modules	4	4	ANL/Linde design
Module Dispensing Capacity (kgH_2/day/module)	250	250	ANL assumption based on Linde design
Delivered Pressure (bar)	875	875	1.25 x 700 bar
No. of Tanks in Cascade Storage Bank	5	5	ANL optimization parameter
Cascade Vessel Type	Type 2	Type 2	Based on Linde and FIBA Tech design
Cascade Storage Pressure (bar)	300-950	300-950	ANL optimization parameter
Baseline Tube Trailer Vessel Type	Type 4	Type 4	Titan XL
Baseline Tube Trailer Capacity (kgH_2)	885	NA	Titan XL
Baseline Tube Trailer Pressure (bar)	250	NA	Titan XL
Cascade and Tube Trailer Storage Composite	T700S/ epoxy	T700S/ epoxy	Adams (2019)
Carbon fiber volume fraction	65%	65%	Gotthold (2015 AMR)

Accomplishments & Progress
Surveyed Reported and Quotes Cryogenic Bulk Storage



The figure shows reported cryogenic vessel costs normalized to water volume collected from multiple sources:

[1] Linde reported station cost breakdown for 350 kg/day station in San Ramon, CA

[2] Multiple LNG vessel costs reported in the European Commission DG MOVE Program

[3] Refueling station analysis from UC Davis for 1,000 kg/day capacity and including the vaporizer cost

[4] HRSAM costs for 1,000 kg/day station

[5] INOXCVA costs of a 68m^3 vessel quoted to SA in 2021

[1] Jim McKinney, Elan Bond, Miki Crowell, and Esther Odufuwa, "Joint Agency Staff Report on Assembly Bill 8: Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California," California Energy Commission, CEC-600-2015-016, Dec. 2015. Accessed: Mar. 13, 2018. [Online]. Available: http://www.energy.ca.gov/2015publications/CEC-600-2015-016/CEC-600-2015-016.pdf.

[2]Flavio Mariani, "LNG Blue Corridors: Cost analysis of LNG refuelling stations," CC.SST.2012.2-3 GA No.321592, 2016. Accessed: Feb. 12, 2021. [Online]. Available: https://lngbc.eu/system/files/deliverable_attachments/LNG_BC_D%203%208%20Cost%20analysis%20of%20LNG%20refuelling%20stations.pdf.

[3]Jonathan X. Weinert, "A Near-Term Economic Analysis of Hydrogen Fueling Stations," University of California, Davis, Davis, CA, 2005.

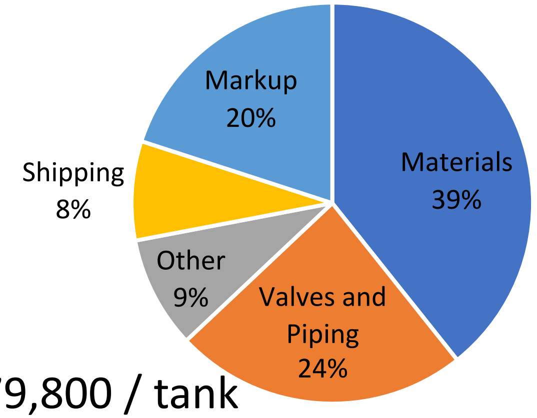
[4] "Hydrogen Refueling Station Analysis Model." https://hdsam.es.anl.gov/index.php?content=hrsam (accessed Mar. 26, 2019).

[5] Private communications between SA and INOXCVA (2021)

Accomplishment & Progress
Preliminary LH2 Storage System Cost Breakdown

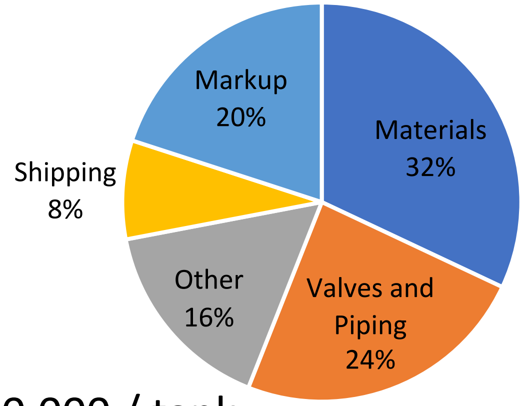
- Bulk Liquid Hydrogen Storage
  - Unlike other cryogenic gases, LH2 requires colder service and better insulation
  - There is exacerbated ice formation on pipes and valves which can cause them to malfunction
  - LH2 imposes material constraints on compatibility and manufacturing constraints to ensure leak tightness
  - Smaller LH2 market and limited cryogenic balance of system suppliers relative to other cryogenic gases leads to higher costs compared with e.g. LNG
- Preliminary system costs are benchmarked against INOXCVA costs shared with SA
  - Assumed shipping from Gujarat, India to Houston, TX
  - SA asserted a 20% markup without comment from INOXCVA.
  - INOXCVA provided high-level cost breakdown and fabrication guidance
    - 304 stainless steel for the liner and carbon steel for the shell account for 50% the cost
    - Valves and piping are 40% for LH2 compared with 15%-20% for LNG
    - Vessels are shipped filled with dry N_2 with the insulation space pumped to 5e-3 mbar
    - Vacuum pump down time is 4-6 weeks
  - The SA cost projections are based on 1,000 systems per year and include all vessel construction steps, insulation, assembly labor, cleaning, and vacuum pump down.
  - The valve and piping category is built up to INOXCVA's reported costs. We have requests for quotes out to suppliers for comparison.

68 m³ LH2 Vessel Cost Breakdown (Current SA Estimate)



$579,800 / tank

68 m³ LH2 Vessel Cost Breakdown (Vendor Estimate: INOXCVA)

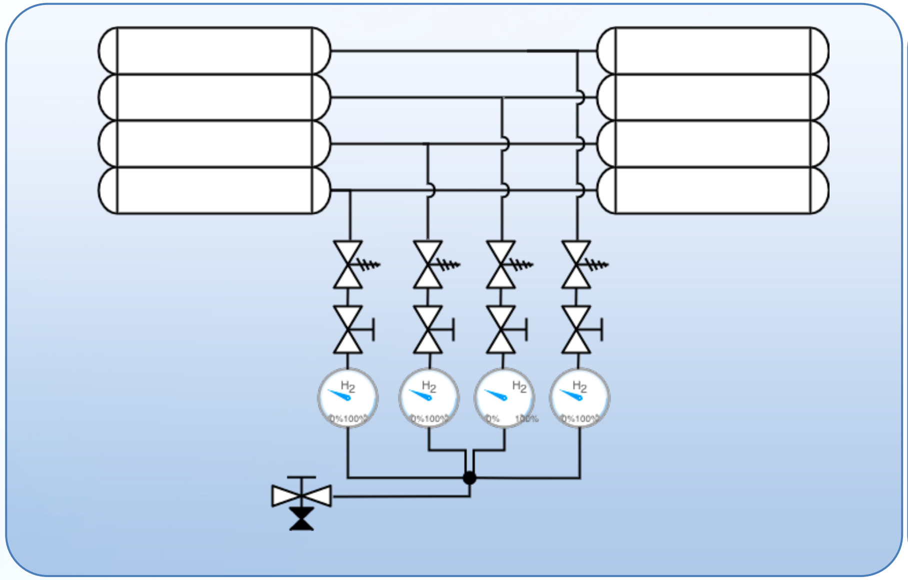


$600,000 / tank

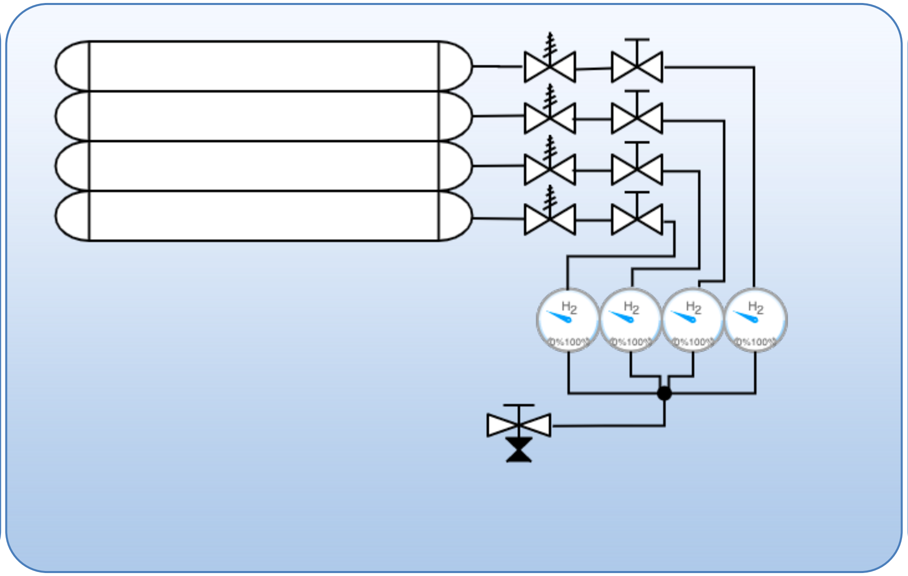
Accomplishments & Progress
Analyzed Multiple Commercial Tube Trailer Designs

- Tank dimensions and number of tanks are estimated from product photos and literature
- Composite mass based on estimated netting analysis (190kg) and performance factor from ANL finite element analysis (198kg)
- CATEC gases has reviewed our work and confirmed the reasonableness of assumptions; however, one HSDTT member recently noted our costs imply a margin of ~100% when compared with a recently received quote.

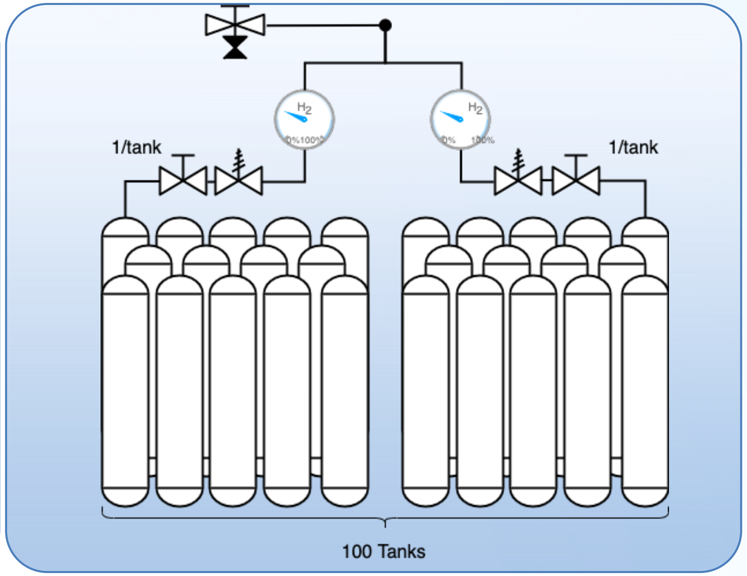
	CATEC	Xperion	Titan XL
Vessels	Type 4	Type 4	Type 4
Pressure (bar)	250	500	250
Number or tanks	8	100	4
Capacity (kg/scf)	1,000/423,300	1,100/465,630	885/374,620



htttps://catecgases.com/



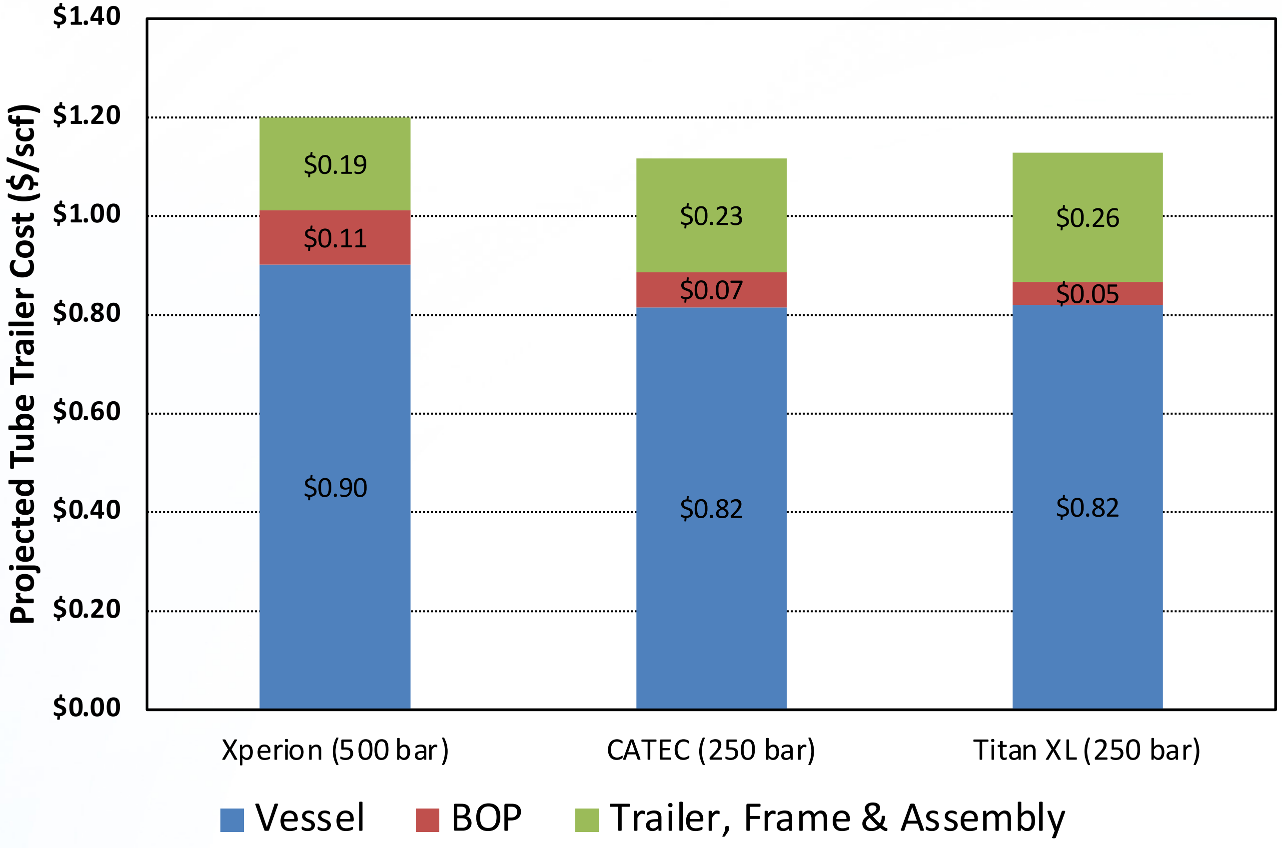
https://www.hexagonraufoss.com/products/gas-transportation/titan



https://hexagongroup.com/solutions/storage-distribution/hydrogen/

Accomplishments & Progress
Tube Trailer Cost Comparison

SA projected cost breakdowns for tube trailers based on three commercially available products



- Cost for industrial gas tube trailers per discussions with CATEC is $1.00/scf – $1.10/scf
- Higher pressure (500 bar) systems appears to trade off higher vessel cost with lower trailer costs on a capacity normalized basis
- Surprisingly, the large number of duplicated valves in the vertical configuration doesn't appear to add significant cost. While the BOP costs is higher in total dollars, it is offset by increased capacity on a $/scf basis
- Vertical tank trailer may benefit from improved capital equipment utilization due to sharing with other standard size (50-250 L) vessels
- Other cost savings such as volume discounts on carbon fiber for large tank producers such as Hexagon and CATEC will reduce total trailer cost in final analysis

Collaborations & Coordination

MDV/HDV	**Argonne**—finite element analysis **PNNL-**–system assumptions Informal discussions, system assumptions, and BOP–**Iljin, Westport Innovations, Worthington, Nikola, Hexagon, Hyzon Motors, Quantum Fuel Systems**
700 bar Type 4 LDV	**ANL**—finite element analysis
Tube trailers	**CATEC Gases**—manufacturing assumptions and costs **Hexagon** (planned)—manufacturing assumptions and costs
Cascade storage	**ANL**—crack propagation analysis **FIBA Tech**—liner assumptions
LH2	**ANL**—System assumptions discussed with Amgad Elgowainy and Rajesh Ahluwalia **Chart Industries**–Dewar and vaporizer costs **INOXCVA**—Dewar costs
Large tank filament winding	**McLean-Anderson**
Frequently consulted	**Mike Veenstra** (Ford) and **Norm Newhouse** (Hexagon ret.)

Accomplishments & Progress
Response to Reviewer Comments

Reviewer Comment	Actions to address/Response to reviewer
In the 2019 AMR, incremental refinements to past analysis focused on compressed hydrogen. The approach would benefit from the inclusion of a cost analysis of other projects within the DOE portfolio.	The analysis presented this year expands the range of systems considered. Per DOE directive, we are focused on high priority storage options around the compressed gas, liquid fuel, and onsite store at refueling stations.
The project team should revisit the models and seek more input from industry.	This comment was specific to the MDV/HDV analysis, but we agree this is broadly true for all the analysis we conduct.
The project team should develop a list of opportunities for DOE and researchers to consider for further reduction in hydrogen tank system costs. The project team could also determine the material cost target by conducting a reverse cost estimation of various material-based systems. In addition, the project team should consider determining the potential cost savings for other project efforts in the DOE portfolio.	Our analysis on system cost of carbon fiber targets suggests additional cost saving approaches are needed to achieve the LDV cost targets. For example, simply halving the carbon fiber cost is not sufficient to reach the ultimate target of $8/kWh. Our analysis suggests additional savings are available from manufacturing improvements and by combining BOP functionality. In contrast, our analysis of Class 8 Long Haul storage system suggests reducing carbon fiber costs would achieve the near-term targets. We plan to investigate whether more aggressive targets can be set for trucks and include suggested pathways in a publication planned for this summer.

Summary

- Class 8 Long Haul
  - Analysis of 700 bar Type 4 storage systems for Class 8 Long Haul show a viable path towards meeting DOE targets if current carbon fiber cost reduction efforts are successful and mandated safety factor can be safely relaxed.
  - Analysis of LH2 storage systems for Class 8 Long Haul trucks are ongoing. Preliminary results suggest that insulation and balance of plant components are the largest cost categories.
- Light Duty Vehicles
  - Monte Carlo analysis suggests that the median cost will be $16/kWh in 2030 for conventional two-tank 700 bar Type 4 systems
  - The 10% probability case suggests that the cost for conventional two-tank 700 bar Type 4 systems could be reduced by 2030 to $14/kWh if carbon fiber is reduced by 40% and the safety factor relaxed to 2.0
- Hydrogen Refueling Stations
  - Comparisons between multiple tube trailer configurations show similar system cost normalized to transported fuel
  - Duplicate balance of system components (e.g. PRDs, valves, etc.) do not appear to contribute significant costs to the refueling module, thus approaches to reduce tank volume and cost appear to be justified to reduce cascade sub-system costs
  - Preliminary cost models completed for cryogenic bulk storage system and show reasonable agreement with manufacturers cost breakdowns

Proposed Future Work*

- Class 8 Long Haul
  - Internal and external vetting of Type 4 results
  - Complete LH2 storage system cost analysis
  - Results will be published in a peer reviewed article comparing multiple storage options: Type 3, Type 4, LH2, and 500 bar cryo-compressed
- LH2 bulk storage
  - Preliminary tank cost models is complete for the tank
  - Multiple manufacturing steps require additional inputs from equipment suppliers to refine capital equipment cost and process time
  - Requests for quotes are out for balance of system components
  - More work may be needed to understand the higher cost of LH2 balance of system components depending on DOE interest.
- Quality control and validation of results
  - We have agreements to review our assumptions and projected costs from suppliers of each of the sub-systems analyzed: cryogenic storage (INOXCVA), tube trailers (CATEC and Hexagon), and cascade storage (FIBA Tech).
  - Each of the analyses will be reviewed and refined again prior to reporting
- Reporting
  - The analyses will be written up in our end of year report and published on www.osti.gov
  - We'll discuss with the program managers other wider distribution

*The project ends in 2021. All proposed work is planned for completion this fiscal year.

Technical Backup and Additional Information

Technology Transfer Activities

Technology transfer does not apply to this analysis-type project

Progress Toward DOE Targets or Milestones

System Investigated	SA Projected Status	SA Projected Future Status	DOE 2025 Target	DOE Ultimate Target
700 bar Type 4 Light-Duty Vehicle Onboard Storage	\$14.20/kWh	\$8.39/kWh	\$10/kWh	\$8/kWh
Class 8 Long Haul Truck Onboard Storage	\$378/kgH_2	\$241/kgH_2	\$300/kgH_2	\$266/kgH_2
Bulk GH2 Delivery Tube Trailer	\$1.13/scfH_2	N/A	N/A	N/A
Bulk LH2 Storage	\$0.33/scfH_2	N/A	N/A	N/A

Class 8 Long Haul Targets and Current Cost Projection Compared with DOE Targets

Property	Units	Status/Assumption	2030 Target	Ultimate Target
Storage capacity	kgH2	60[1]		
Fuel economy	mpgge	17[2]		
Fill rate	kgH_2/hr	--	8	10
Storage system cycle life[a]	cycles	--	5,000	5,000
Pressurized storage system cycle life[b]	cycles	--	11,000	11,000
Storage system cost	$\$/kgH_2$	378[3]	300	266

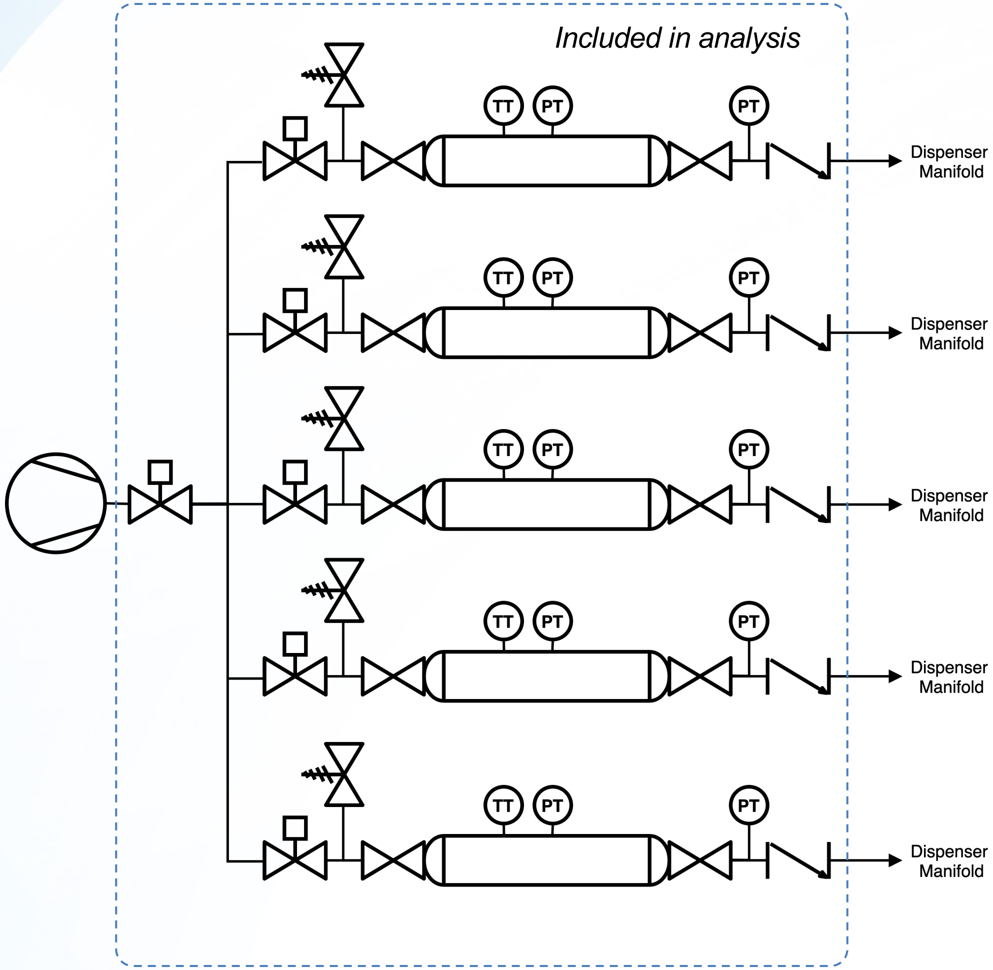
1. Storage capacity depends on range requirement and fuel economy
2. Fuel economy is based on achieving a drive cycle efficiency of 67.2%
3. Based on 700 bar system, two-tank, frame-mounted Type 4 storage system manufactured at 100k

a. The storage system cycle life target is intended to represent the minimum number operational cycles required for the entire useful life of a vehicle used in long-haul operation. This target is technology agnostic.

b. Pressurized storage systems must meet cycle life requirements in applicable codes and standards (i.e., SAE J2579 and United Nations Global Technical Regulation No. 13). These codes and standards cycle life requirements require significantly more cycles than Storage System Cycle Life. For example, the baseline initial pressure cycle life in the United Nations Global Technical Regulation can require 11,000 cycles for a heavy-duty application.

c. 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.

Cascade Storage System Diagrams



- Dispenser modules are based on 250 kg/day with one cascade storage bank per module and four total for a 1,000 kg/day refueling station
- Compressor are not included in analysis per DOE direction
  - Compressors modeled by A. Elgowainy (ANL)
  - Capacity is a parameter in R. Ahluwalia's (ANL) analysis
  - Tank size depends on compressor capacity

Compressor Capacity (100% = 250 kg/day)	Cascade Total Volume (L)	Carbon Fiber Weight (kg)	Liner Material
125%	555	381	SA-372 Grade J
150%	360	227	SA-372 Grade J
175%	241	157	SA-372 Grade J
225%	178	121	SA-372 Grade J

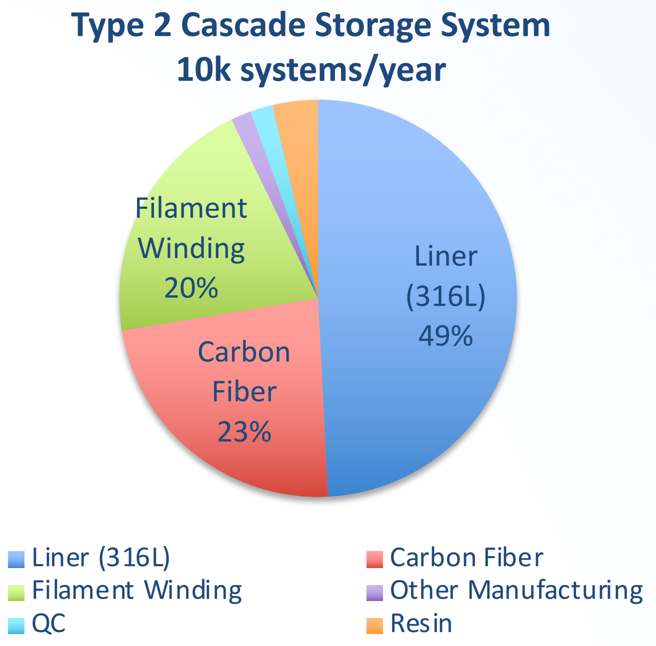
Reported in 2020. Included for completeness

Cascade Storage Sub-System Cost Projections

- DFMA cost breakdowns for Type 2 cascade sub-system tanks are shown in the pie chart
- The shape of the tank cost breakdown (relative %) do not have a strong dependence on cascade capacity
- Liner is modeled assuming seamless tube materials as inputs with a neck forming operation
- Liner materials dominate the cost of the cascade storage sub-system
- We assume the balance of system (valves, PRDs, etc.) is the same regardless of tank size.
- BOS is ~$30k comprises 50% - 20% of the cascade sub-system cost depending on size

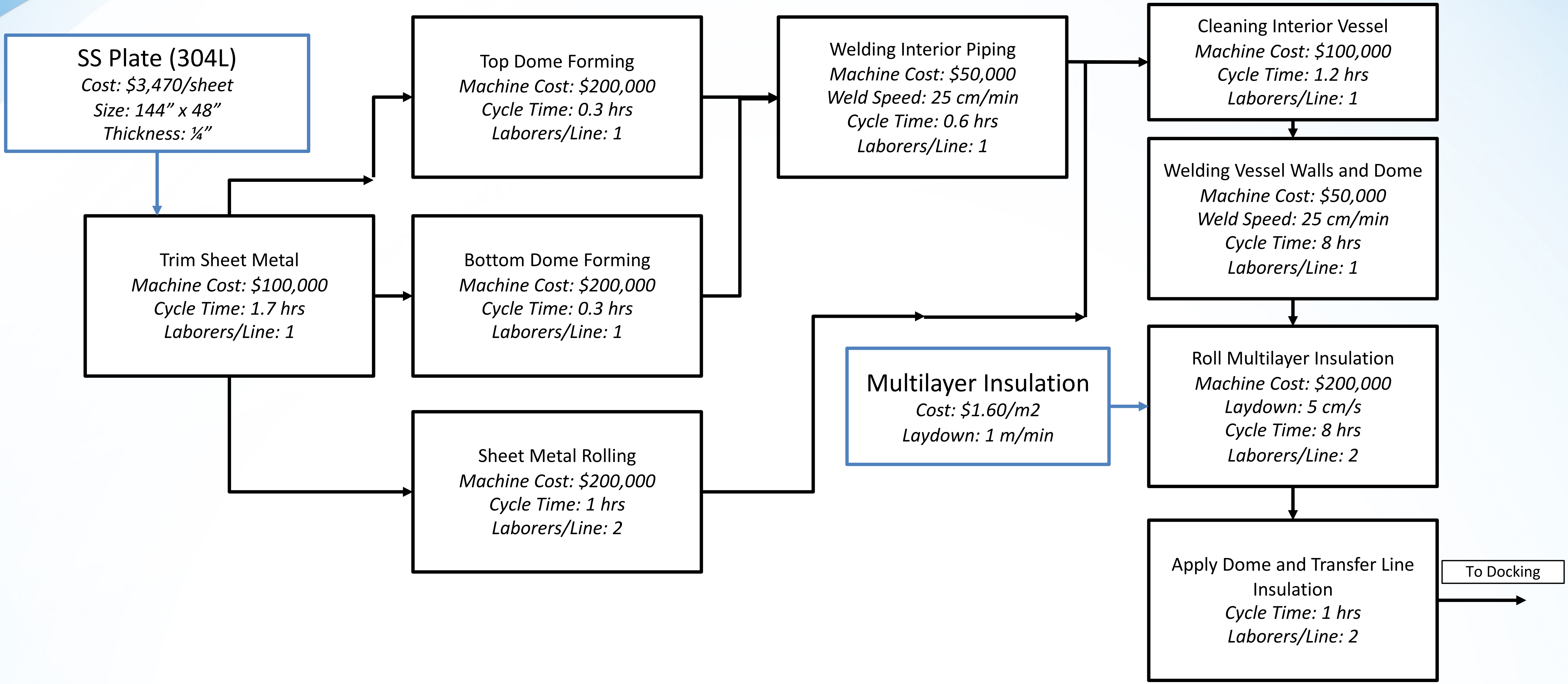
Compressor Capacity	Tanks per Dispenser Module	Tank Cost @ 200 Modules per Year	Tank Cost per Module	BOS*	Cascade Storage Module Cost
225%	5	$ 12,120	$ 60,598	$ 29,692	$ 90,290
175%	5	$ 14,577	$ 72,886	$ 29,692	$ 102,578
150%	5	$ 19,722	$ 98,611	$ 29,692	$ 128,303
125%	5	$ 31,660	$ 158,301	$ 29,692	$ 187,993

Balance of System Component	Number/dispenser	Unit cost	Cost/Dispenser
On-tank valve	10	$ 301	$ 3,010
Pressure relief device	5	$ 601	$ 3,005
Automated valve	5	$ 2,860	$ 14,300
Manual valve	1	$ 292	$ 292
Temperature transmitter	5	$ 650	$ 3,250
Pressure transmitter	5	$ 464	$ 2,320
Check valve	5	$ 703	$ 3,515
Total			**$ 29,692**

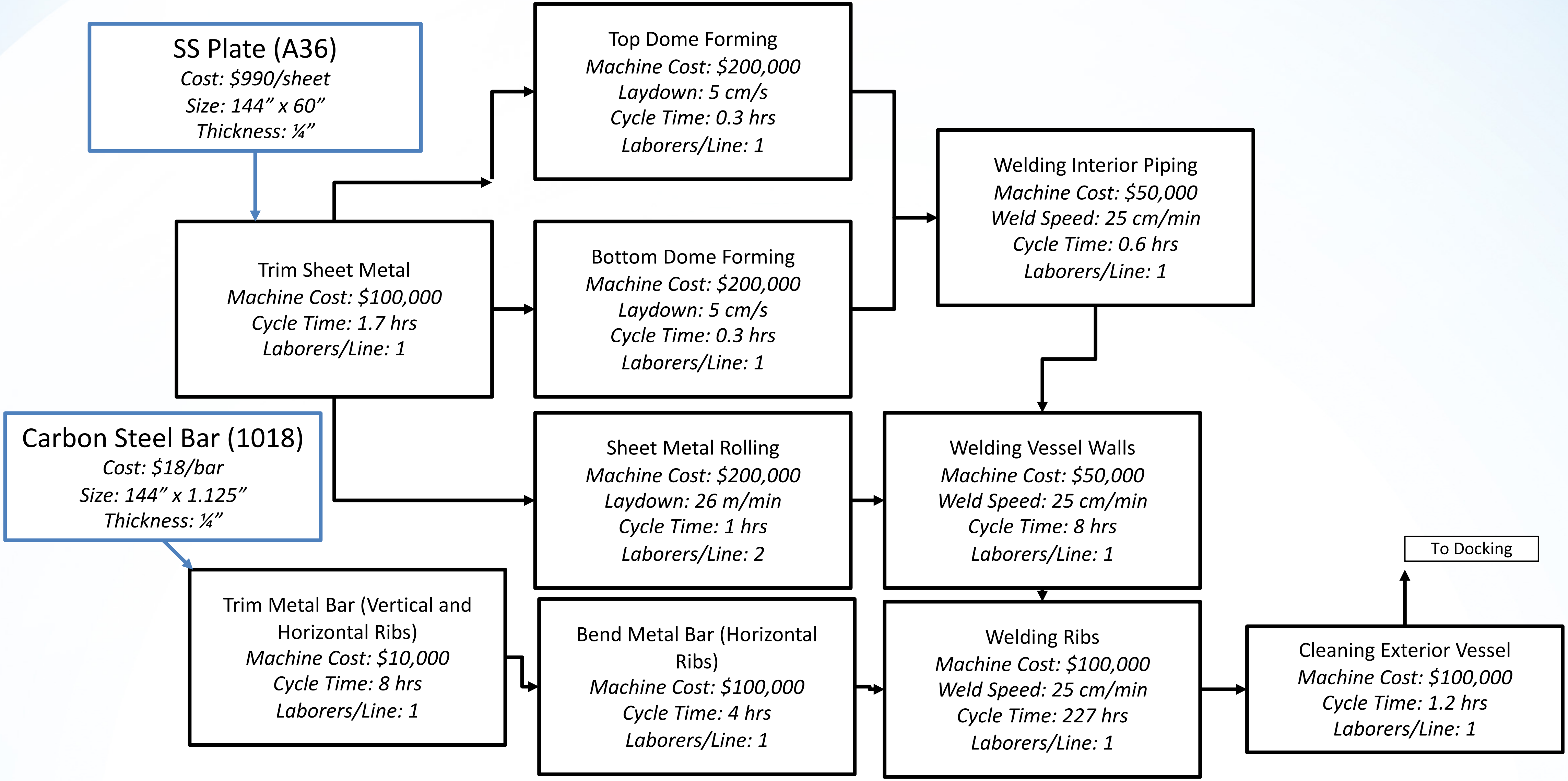


Reported in 2020. Included for completeness

LH2 Manufacturing Process Flow: Inner Vessel



LH2 Manufacturing Process Flow: Outer Vessel



LH2 Manufacturing Process Flow: Finalizing