Analysis of Advanced H_2 Production & Delivery Pathways

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Overview

Timeline

- Project start date: 10/1/2016
- Project end date: 9/30/2020
- Percent complete: 38% of project

Budget

- Total Funding Spent
  - ~$494k cumulative through March 2018
- Total DOE Project Value
  - ~$1.2M (over 4 years, including Lab funding)
- Cost Share Percentage: 0%
  (not required for analysis projects)

Barriers

- **Wire-Wrapping of Steel Vessels for H_2 Forecourt Storage**
  - A: System Weight and Volume
  - B: System Cost
- **Transmission Methods for Energy Carriers**
  - A: Lack of Hydrogen/Carrier and Infrastructure Options Analysis
  - D: High As-Installed Cost of Pipelines

Partners

- National Renewable Energy Laboratory (NREL)
- Argonne National Laboratory (ANL)

Collaborators (unpaid)

- WireTough Cylinders, LLC

Relevance and Impact

- Investigates production and delivery pathways selected/suggested by DOE that are relevant, timely, and of value to FCTO.
- Supports selection of portfolio priorities through evaluations of technical progress and hydrogen cost status.
- Provides complete pathway definition, performance, and economic analysis not elsewhere available.
- Provides analysis that is transparent, detailed, and made publicly available to the technical community.
- Results of analysis:
  - Identifies cost drivers
  - Assesses technology status
  - Provides information to DOE that may be used to help guide R&D direction

Selection of H_2 Production & Delivery Cases

- DOE selects cases that support the FCTO development mission
  - Advanced Water Splitting
  - Biomass-based processes
  - Waste recovery to H_2 processes
- Cases selected based on:
  - Highest priority cases with direct application to FCTO mission
  - Data availability
  - Ability to assist studies in providing relevant cost estimates
    - Beneficial for cases without cost estimates
    - Provide assistance for proper development of H2A cases

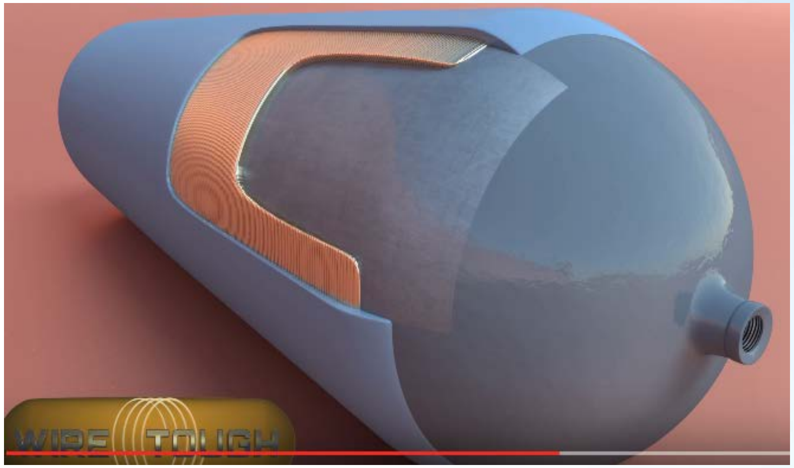
- Recently Completed Cases
  - WireTough
    - High-pressure H_2 Storage at forecourt
  - The Cost of Transmitting Energy
  - More cases will be analyzed as assigned

WireTough's Wire-Wound H_2 Storage Pressure Vessel

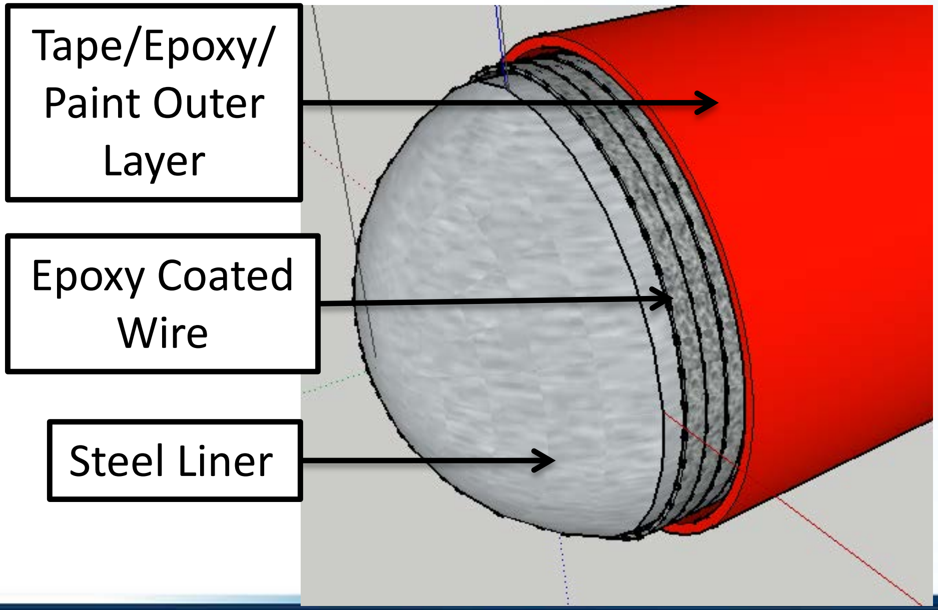
All cost/price results for WireTough Pressure Vessels in 2016$

WireTough LLC H_2 Storage System

- 13kpsi-rated H_2 storage vessel for use at forecourt facilities
  - Steel liner wrapped with steel wire
  - 6,600 psi pressure vessel acts as Liner
  - Steel wire is layered around cylindrical section of liner, coated in epoxy, and taped to hold in place
    - After wire wrapping, vessel is rated for greater than 13,000 psi
  - Holds approximately 35 kg of H_2
- Vessel fabrication modeled by SA
  - DFMA® analysis methodology
  - Sensitivity analysis identifies the most cost impactful parameters
  - Monte Carlo (uncertainty) analysis projects the range of vessel costs for 90% confidence

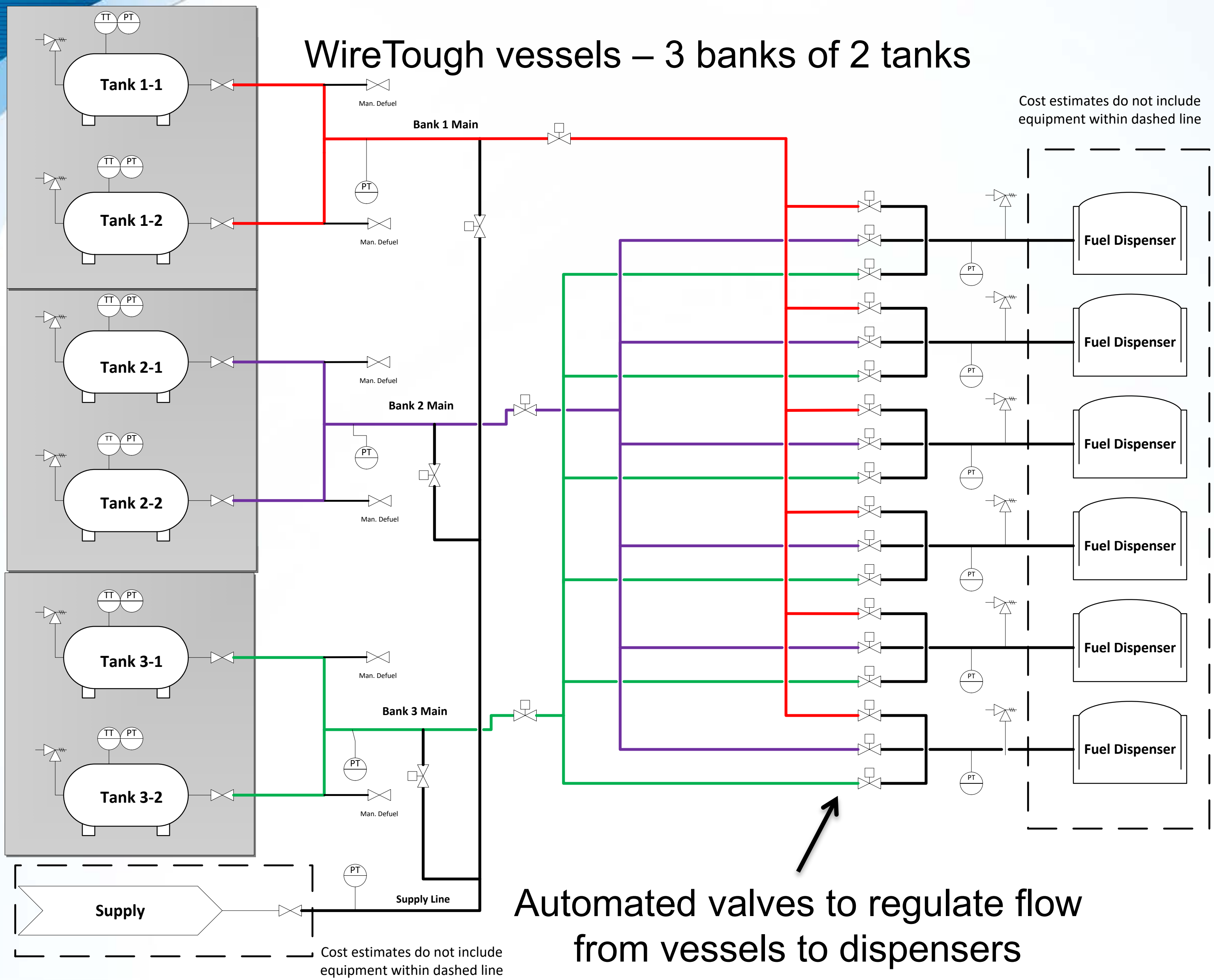


Courtesy of WireTough Cylinders, LLC
http://wiretough.com/innovative/



WireTough Vessels in Forecourt Station

WireTough vessels – 3 banks of 2 tanks



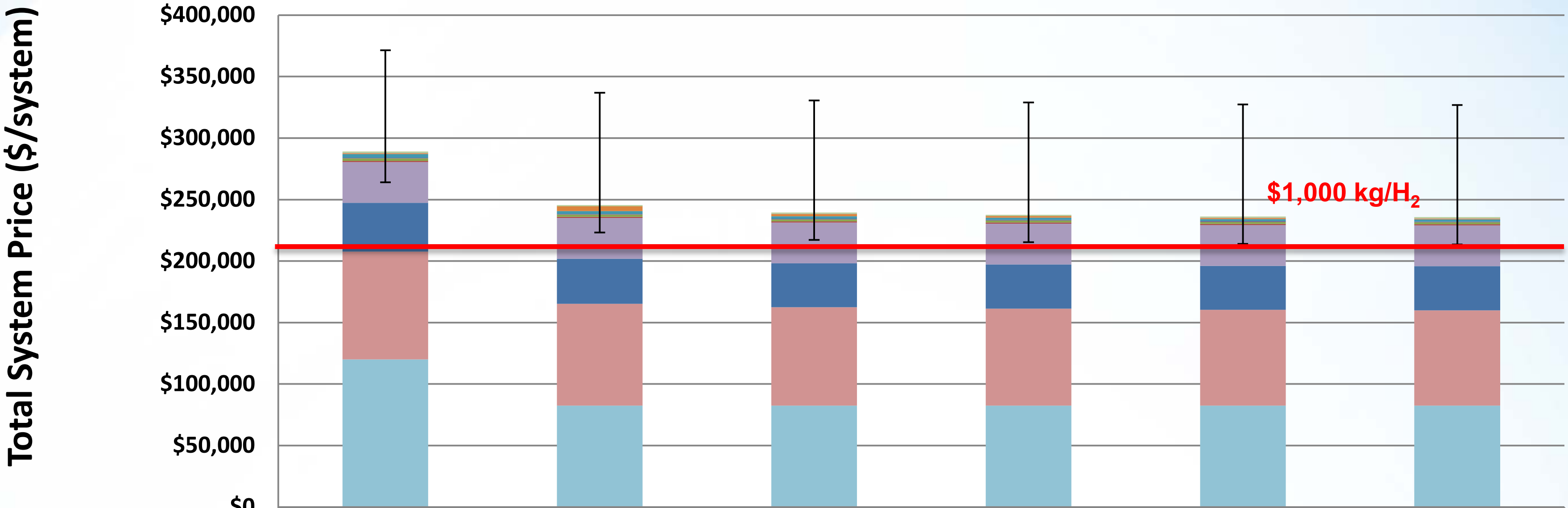
Automated valves to regulate flow from vessels to dispensers

Six Dispensers for nominal 1,000 kgH_2/day H2A Dispensing Station

Pressure Vessel Analysis Results

Accomplishments and Progress

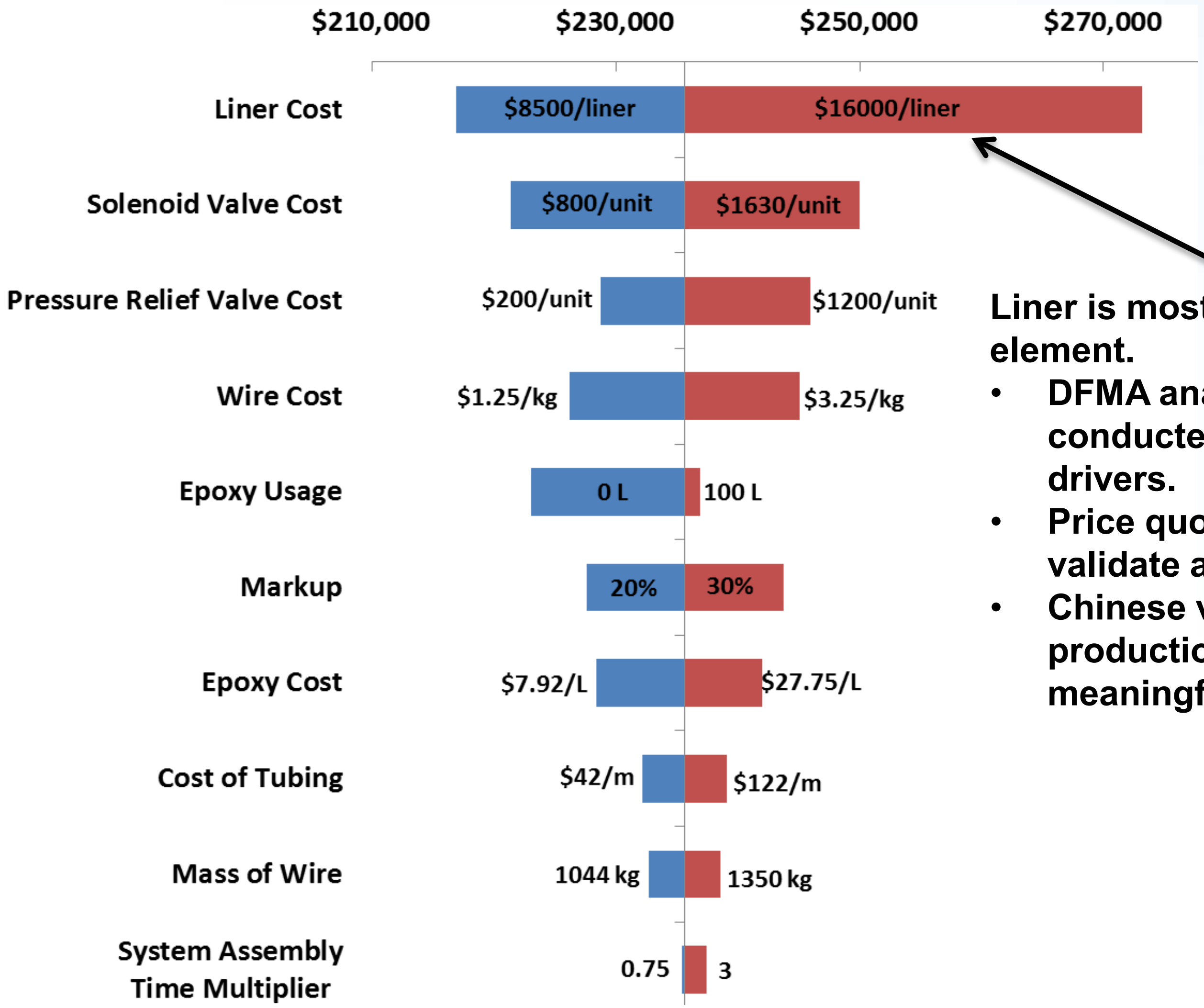
Production Rate vs System Price



	40 Sys/Yr	100 Sys/Yr	200 Sys/Yr	300 Sys/Yr	400 Sys/Yr	500 Sys/Yr
System Assembly	$1,330	$1,019	$915	$881	$915	$895
Inspection	$79	$79	$79	$79	$79	$79
Paint Booth	$825	$3,919	$1,983	$1,338	$1,015	$822
Hydro Test	$3,028	$2,176	$1,892	$1,797	$1,749	$1,835
Final Cure	$496	$496	$496	$496	$496	$496
Oven Cure	$1,983	$1,812	$1,640	$1,583	$1,640	$1,606
Tape Winding	$976	$975	$975	$975	$975	$975
System Installation	$33,128	$33,128	$33,128	$33,128	$33,128	$33,128
Wire Winding	$39,566	$36,689	$35,671	$36,010	$35,671	$35,875
Balance of System (BOS) Items	$87,741	$82,787	$80,059	$78,778	$77,982	$77,453
Liner Price	$120,000	$82,500	$82,500	$82,500	$82,500	$82,500
System Cost ($/kg H_2)	$1,359	$1,154	$1,125	$1,116	$1,110	$1,107

6 Vessels, approximately 35 kg H_2/each

Single Parameter Sensitivity Study for 3,000 vessels per year

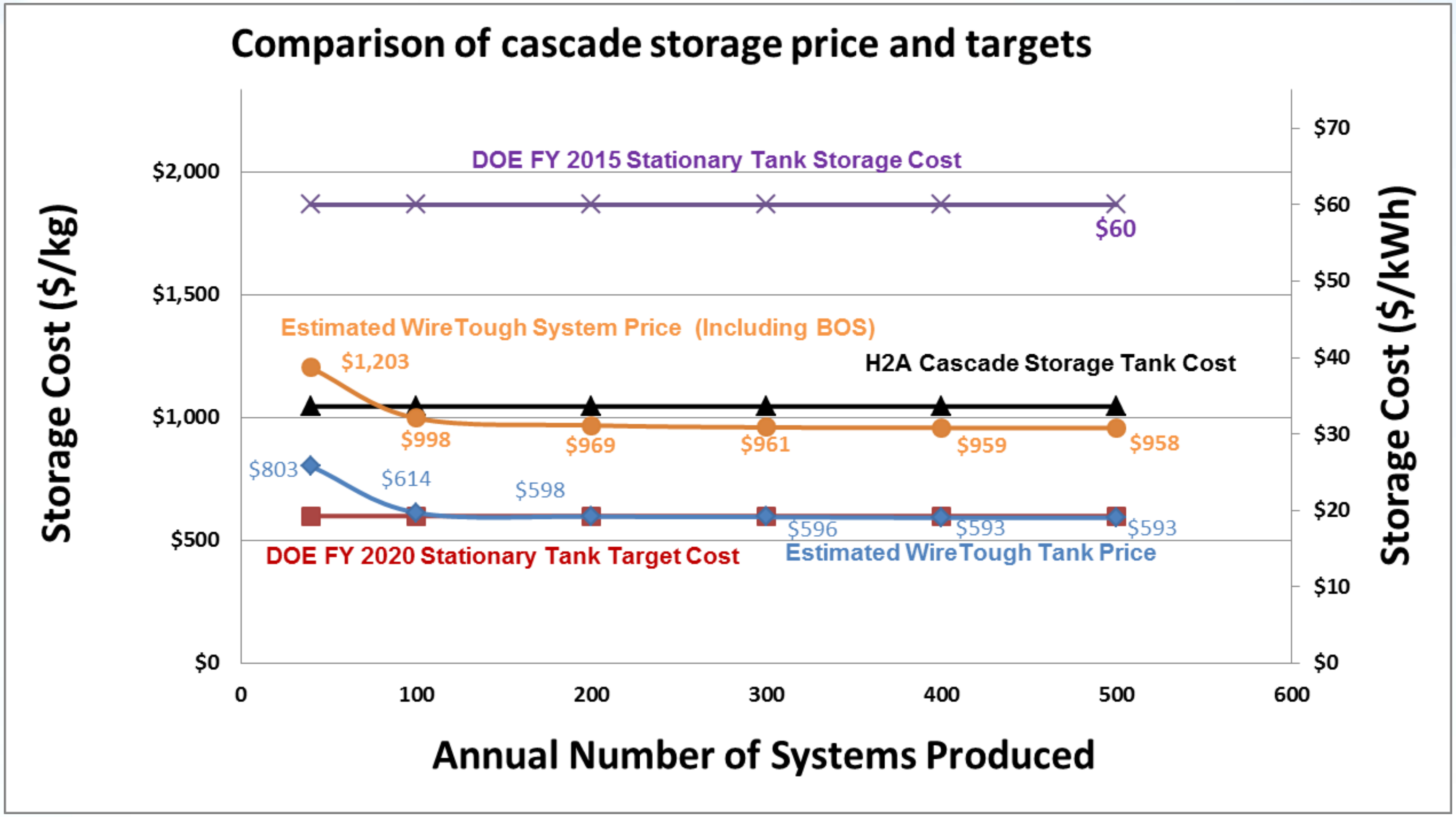


Liner is most uncertain cost element.

- **DFMA analysis was conducted to explore cost drivers.**
- **Price quotes obtained to validate analysis.**
- **Chinese vs. US production has meaningful price impact.**

Conducted a sensitivity study using generous percentages for each variable. The liner cost, solenoid valve cost, and pressure relief valve are the largest cost drivers.

Comparison of WireTough Estimates to DOE Targets



- Past DOE/H2A definition of tank has included tank, support frame, painting, cleaning & testing.
  - By this definition, WireTough system is slightly below DOE 2020 targets
- New, more comprehensive definition of system includes additional BOP components
  - By new definition, system cost is ~$1,000/kg H_2, right at previous assumption.
  - Future analysis will make sure all components are specified (and not double counted)

*Estimated WireTough System Price (including BOS) does not include system installation here

Long-Distance Energy Transmission

Project objective:

Compare the cost of long-distance, bulk transport of electrical or chemical energy independent of production method or end-use.

Analysis Outline

- **Energy Transmission Methods Analyzed:**
  - Electrical Transmission Lines, Liquid Pipelines, Gas Pipelines
- **Estimate capital cost based on existing cost models but normalized to our specs**
  - Compare costs for 1,000 miles of transmission
  - Compare all costs on an even basis
    - Present data as $/mile (traditional) as well as $/mile-MW and $/MWh
  - Models include CapEx for materials, labor, Right of Way (ROW), pumping/compression stations, and miscellaneous expenses
- **Develop total costs for transmitting energy**
  - Some sources report capital cost as the total cost of transmission
    - A few studies suggest that a set percentage of the total transmission cost is the capital cost
    - Transmission cost should include capital cost and operating cost
  - Include costs of pumping and compressor stations for pipelines
  - Include transmission line losses for electrical lines
- **Costs for electricity production, fuel production, and fuel conversion are not included**

Cost Metrics

- Most studies compare electrical & pipeline cost on $/mile basis
  - Does not account for capacity
  - Only represents capital cost
  - Usually shows electrical and pipeline capital cost on a similar order of magnitude
- By comparing the transmission cost on a $/mile-MW basis, the capacity of the transmission method is included
- Amortizing the capital cost to derive an annual capital repayment amount allows for a comparison of total transmission cost in $ Operating/MWh

Thus we compare transmission methods on three bases:

- **$Capital Cost/mile, $Capital Cost/mile-MW, and $Operating/MWh**

Electrical Transmission Lines

- Modeled parameters:
  - Aluminum Core Steel Reinforced (ACSR) lines on a new lattice structure
  - 500 kV HVDC lines modeled with 2 substation locations
  - Terrain estimates are broken up evenly between 8 types, ranging from flat ground to wetland & mountain terrain
  - Similarly, Right-Of-Way (ROW) costs are broken up into 12 zones, evenly distributed among each zone for a representative model
- Capital costs and resistive losses are based on *Capital Costs for Transmission and Substations*. (2014)
  - Electrical line losses based on line resistance ($P=I^2*R$) at maximum current per circuit

Representative transmission tower. Courtesy of wikicommons.com

Assumptions consistent with large-scale transmission.

Gas & Liquid Pipelines

- Pipeline cost models taken from literature (Rui *et al*)
  - Pipeline models are derived from *Oil and Gas Journal* data.
  - Data is for on-shore, natural gas pipelines from 1992-2008.
  - No reliable cost data was found for liquid pipelines. Following common practice, the same cost models used for gas pipelines were also used for liquid pipelines.
- Pipeline cost models predict materials, labor, ROW, and miscellaneous expenses.
- Pumping/Compression models were further incorporated for a complete model
  - Models were optimized for lowest cost (by selecting optimal pumping station spacing)
  - Capital costs and operating power requirements were assessed
  - Power (purchase) requirements were costed at 5 cents/kWh

Transmission Method	Liquid Pipeline			Gas Pipeline	
Energy Carrier	Crude Oil	Methanol	Ethanol	Nat Gas	Hydrogen
Pipe diameter (in)	36	36	36	36	36
Flow velocity (m/s)	3.7	3.9	3.9	18	18
Pressure Drop (bar/mile)	2.5	2.5	2.5	0.67	0.19
Pump / compressor load (MW/station)	29	30	30	39	18
Pipeline Operating Power (MW/1000mi)	715	757	758	464	162

Assumptions consistent with large-scale transmission.

Pipelines – Special Cases

Whereas, natural gas and oil pipelines are common, other gases/liquids require special consideration:

- **Ethanol and Methanol**
  - Proof of existence case: Kinder-Morgan modified a 106-mile pipeline to carry ethanol.
    - Cost of these modifications were linearly scaled with length and surface area and added to pipeline capital cost models for ethanol and methanol.
  - No methanol analogue has been reported. Ethanol cost modifications were assumed to be suitable for methanol.
- **Hydrogen**
  - Recent paper by Fekete *et al* describes material and labor cost adders to account for steel thickness and welding differences between natural gas and hydrogen pipelines.
  - Proposes that, under upcoming ASME changes, the material and labor costs of hydrogen pipelines will be approximately 8% higher than natural gas lines.

Results

(Relatively) Low-Capacity drives electrical transmission costs up.

Liquids have high energy densities and low pumping costs

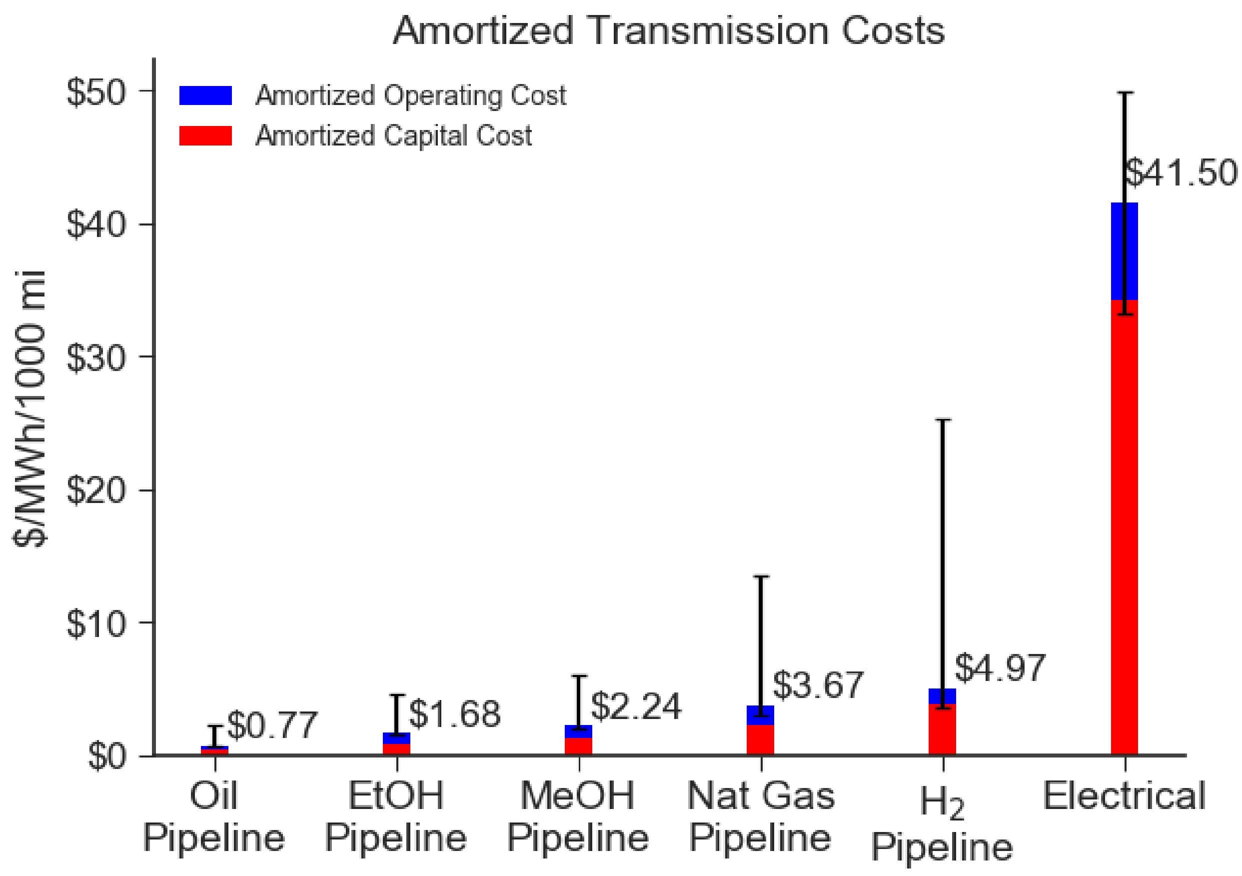
	Electrical	Liquid Pipeline			Gas Pipeline	
Energy Carrier	HVDC	Crude Oil	Methanol	Ethanol	Nat Gas	Hydrogen
Flow (amps,kg/s)	6,000	1,969	1,863	1,859	368.9	69.54
Rated Capacity (MW)	2,656	91,941	37,435	50,116	17,391	8,360
Capital Cost ($M/mile)	$3.9M	$1.47M	$1.92M	$1.92M	$1.69M	$1.38M
Operating Power: Rated Capacity	12.9%	0.78%	2.02%	1.51%	2.67%	1.94%
Capital Cost ($/(mile-MW))	$1,467	$16	$51	$38	$97	$166
Transmission Cost ($/MWh/1000mi)	$41.50	$0.77	$2.2	$1.7	$3.7	$5.0

Electrical transmission faces high cost for sending electricity

- Costs for transmission methods are usually broken down to $/mile
  - It is more useful to consider the cost per distance per *capacity*
- Production method and conversion costs are <u>*not*</u> considered in this analysis
  - Inclusion of those costs could change relative ranking of the options

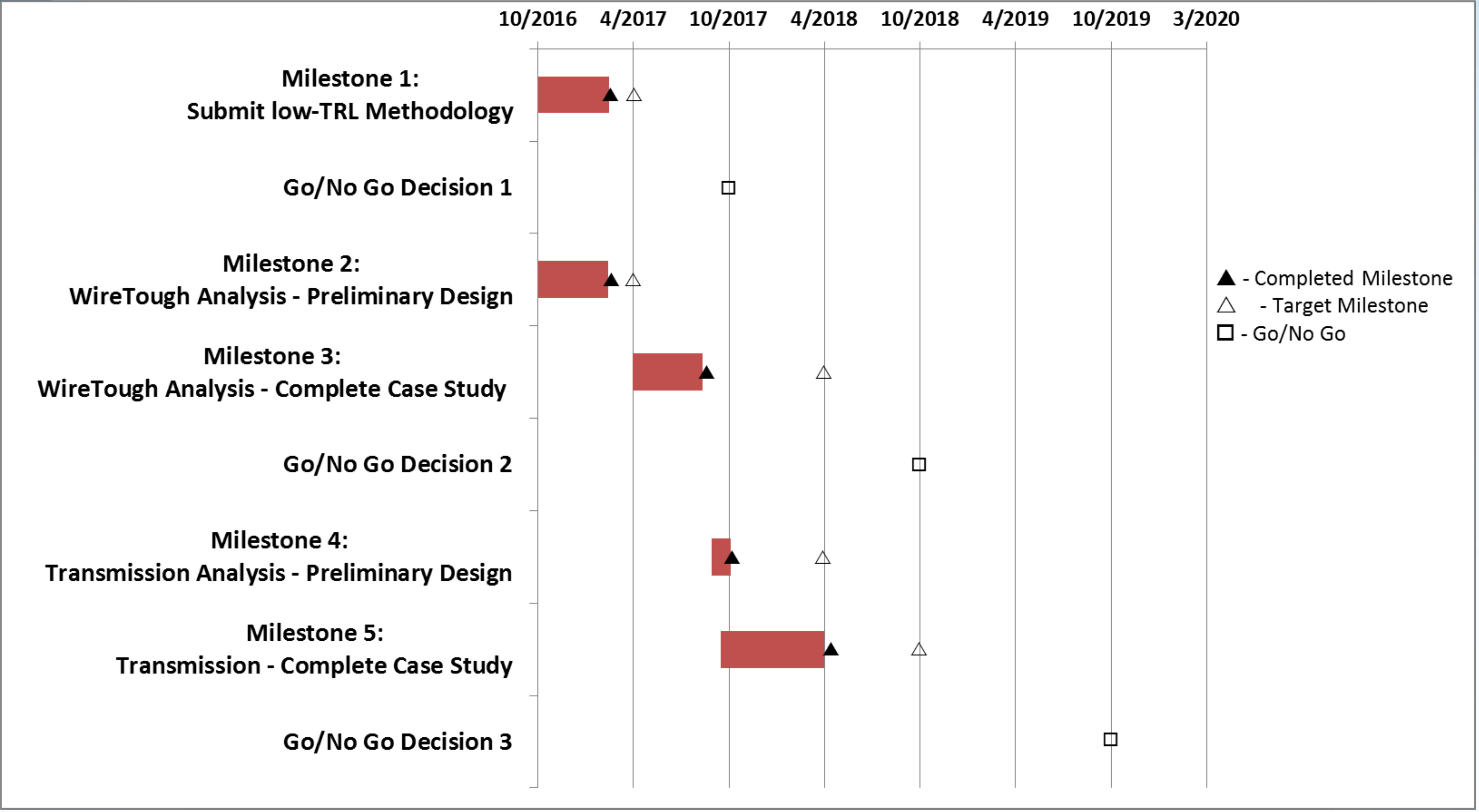
Amortized Transmission Cost

Interest (Discount) Rate	Operating Expenses	Misc. Costs per year	Maintenance Costs per Year	Corporate Tax Rate	Capital Recovery Factor	Equipment Lifetime (Amort. Period)
8%	Pump/Comp. costs + 0.5% of Pipeline Cost	5% of CapEx	5% of CapEx	26.6%	~12%	Pipelines: 33 yrs Elect. Line: 60 yrs



1. **Capital cost is amortized over equipment life time.**
2. **Annual Operational expenses included in amortization.**
3. **Operating cost consist of Pumping/Compression costs and Other Oper. Costs. Pump/Compr. Cost based on calculation of station capital cost and power required. Other Oper. Cost estimated at 0.5% of the capital cost of the pipeline only per year.**

Project Status



Project On-Schedule
Some deliverable tasks completed ahead of schedule

Proposed Future Work

- Production and Delivery analysis of new pathways
  - Photoelectrochemical (PEC) Production of H_2
  - Solar thermochemical (STCH) Production of H_2
  - Update analyses to reflect recent advances in Carbon Capture and Sequestration (CCS)
- H2A updates and case studies
  - NREL has been updating the H2A production model
    - SA assists with case study updates and error checking
  - Cases updated: SMR, Coal, PEM, SOEC, Biomass Gasification, PEC Type 2, PEC Type4, Solar Themo-Chemical Ferrite
- Other P&D cost analysis as directed by DOE
- Continuing coordination between FCTO sub-areas
  - Production and Delivery, Analysis, and Target Setting are all areas that require coordination

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

Response to Reviewer Comments

FY17 Reviewer Comments	FY17 Response to Comment
There is a lack of clarity around technology prioritization by DOE for SA evaluation.	DOE selects cases based on their program objectives and portfolio technologies.
More transparency in milestones and the number of experts polled per technology is desired.	A Gantt Chart with milestones has been added to presentation. In general, SA milestones are completion of preliminary case study design followed by the submission of the final study model and resulting documentation. SA has met its milestones thus far. Further effort has been made to identify the experts used. In some case, (i.e. proprietary technologies) it is difficult to identify and use experts who are knowledgeable. Reviewers identified in Backup slides.
Use of confidential data is a weakness	SA must maintain the confidentiality of sensitive information shared as continued access to such information is vital to an informed analysis. However, every effort is made to openly present as much information as possible. When necessary, IP is used in internal calculations to give accurate results, but the specifics are generalized to preserve confidentiality but to convey approximate assumptions.

Collaborators

Institution	Relationship	Activities and Contributions
National Renewable Energy Laboratory (NREL) • Genevieve Saur	Subcontractor	• Participated in weekly project calls • Assisted with H2A Production Model runs & sensitivity analyses • Drafted and reviewed reporting materials • Managing and arranging H2A Working Group activities
Argonne National Lab (ANL) • Rajesh Ahluwalia • Amgad Elgowainy	Subcontractor	• Participated in select project calls • Vetted process work • Expert review of transmission analysis
Department of Energy (DOE) • Eric Miller • Katie Randolph • Max Lyubovsky	Sponsor	• Participated in some weekly project calls • Assisted with H2A Model and sensitivity parameters • Reviewed reporting materials • Direct contributors to energy transmission work

Summary

- **Overview**
  - Conducted P&D pathways cost analysis for WireTough stationary H_2 storage (Forecourt dispensing) and a cost analysis of transmitting energy over long distances
- **Relevance**
  - Increase analysis and understanding of areas demonstrating information deficiencies
  - Cost analysis is a useful tool because it:
    - Defines a complete production and delivery pathway
    - Identifies key cost-drivers and helps focus research on topics that will lower cost
    - Generates transparent documentation available to the community with relevant data for improved collaboration
- **Approach**
    - Utilize various cost analysis methods for determining system cost: DFMA® and H2A
    - Collaborate with NREL, ANL, DOE, and tech experts to model SOA and future systems
- **Accomplishments**
  - Completed P&D pathway analysis of WireTough storage system
  - Completed an Energy Transmission Cost analysis
    - Incorporates metrics beyond a simple cost per mile analysis
  - H2A Model and Case Study Updates

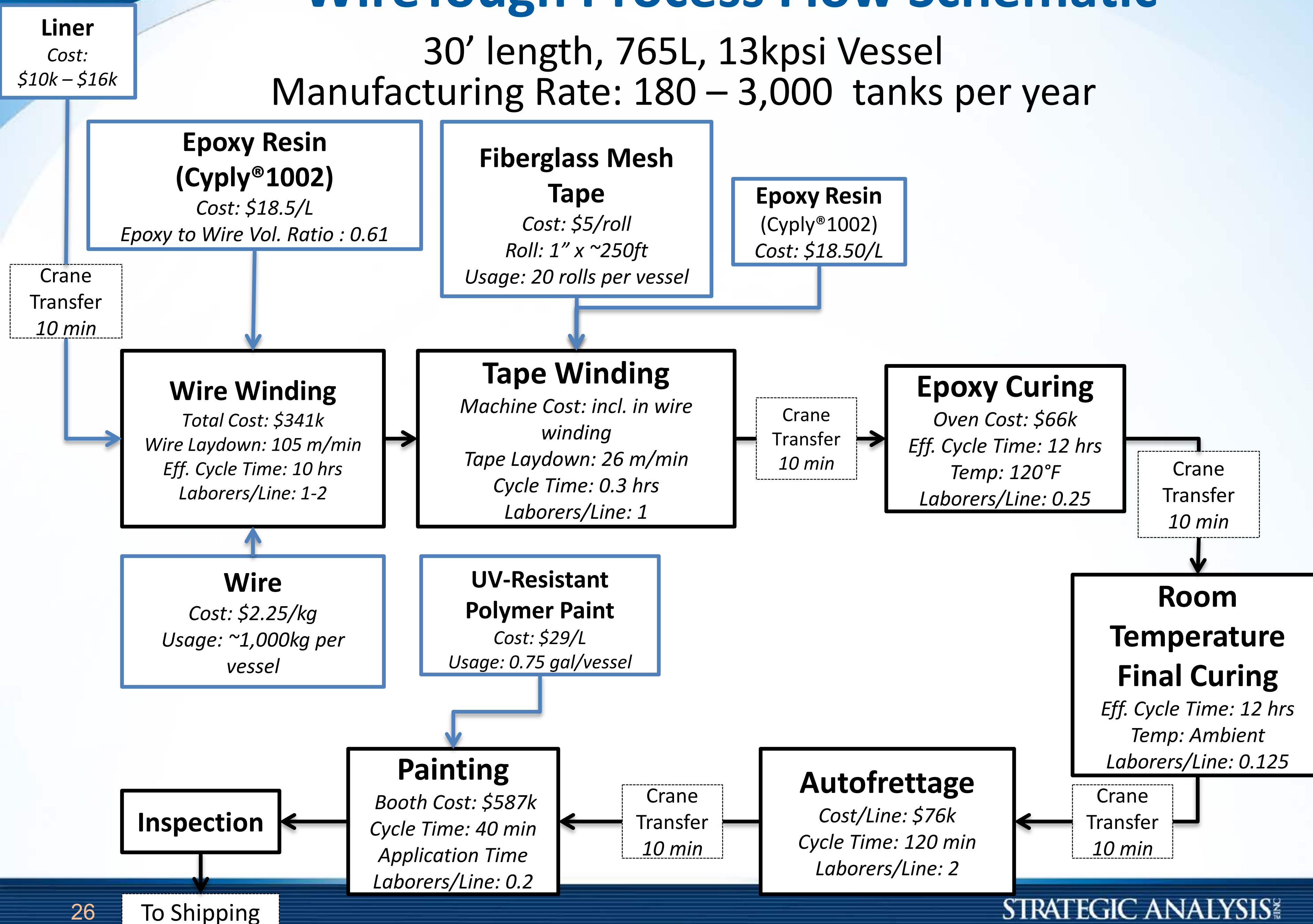
Thank you

- This work funded by the Fuel Cell Technologies Office at DOE/EERE under DOE contract number: DE-EE0006231.
- Special thanks to:
  - Dr. Eric Miller (DOE)
  - Dr. Katie Randolph (DOE)
  - Dr. Max Lyubovsky (DOE)

Backup Slides

WireTough Process Flow Schematic

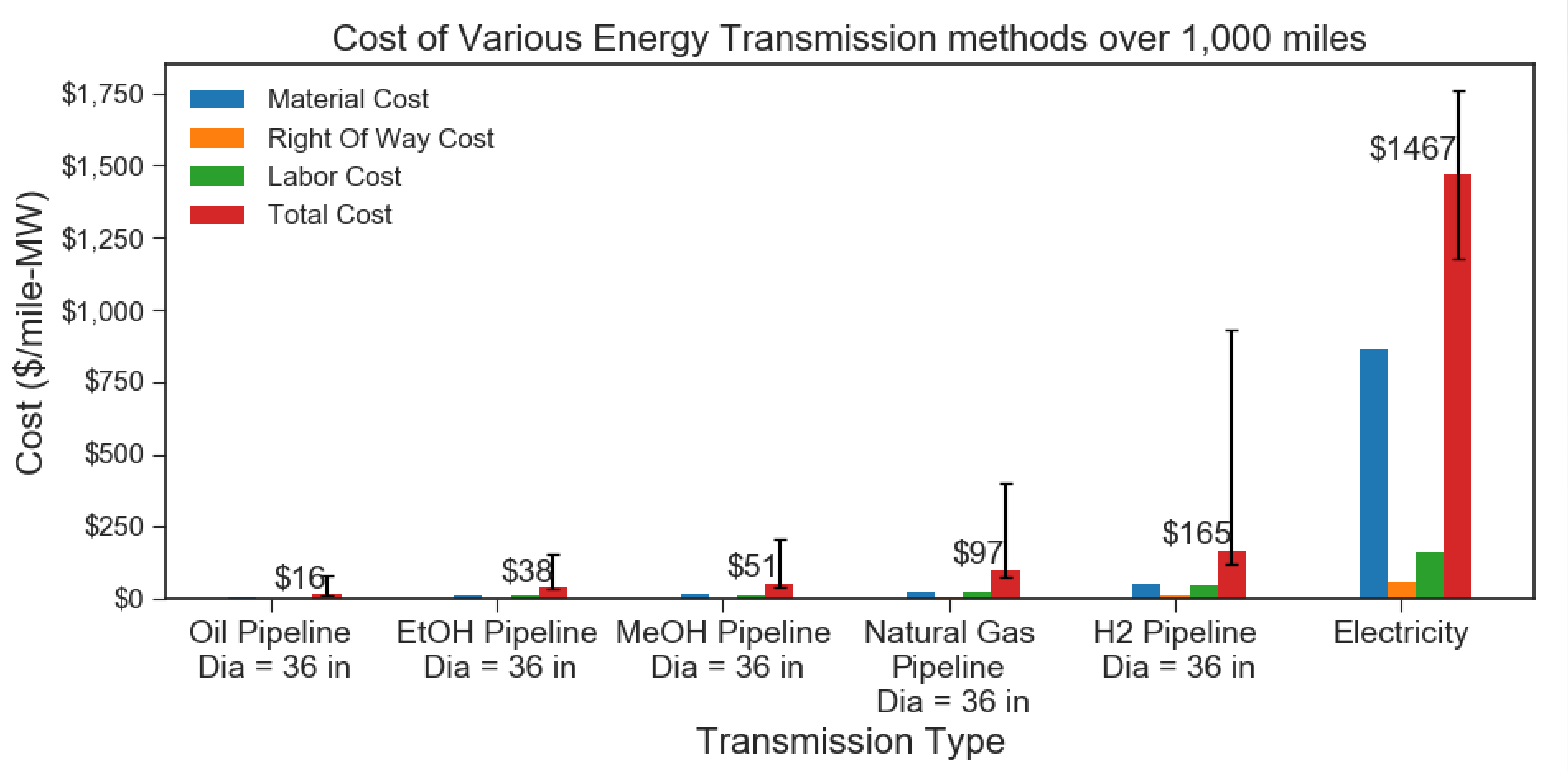
30’ length, 765L, 13kpsi Vessel
Manufacturing Rate: 180 – 3,000 tanks per year



Energy Transmission
Monte Carlo Parameters

Parameter Varied	Units	Randomization Distribution	Lower Limit	Most Likely Value (if applicable)	Upper Limit
Gas Initial Pressure	Bar	Triangular	90	100	130
Liquid Initial Pressure	Bar	Triangular	30	140	160
Liquid Low Pressure	Bar	Triangular	1	5	25
Pump Efficiency	%	Triangular	60	80	90
Compressor Efficiency	%	Triangular	80	85	95
Operational Velocity Factor	-	Triangular	.75	.90	1.0
Pump/Compressor Station Cost Modifier	-	Triangular	0.75	1	1.25
Pipeline Capital Cost Modifier	-	Normal	Normal Distribution of Capital Cost with a 15% standard deviation of the mean		
Model Selection	-	Binary	Brown Model vs. Rui Model		
Construction Region	-	Even Distribution	Even possibility of any given construction region being the location of the entire pipeline		

Results



- Liquid Pipelines are the least expensive option
  - High energy density, low power required for pumping
- Electrical capital cost is more than 10 times as expensive as natural gas and more than 90 times expensive as oil