2023 DOE Hydrogen and Fuel Cells Program

Annual Merit Review

H_2 DELIVERY TECHNOLOGIES ANALYSIS

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IN025

Overview

Timeline

- Start: October 2005
- End: Determined by DOE
- % complete (FY22): 70%

Barriers to Address

- Inconsistent data, assumptions and guidelines
- Insufficient suite of models and tools
- Stove-piped/Siloed analytical capability for evaluating sustainability

Budget

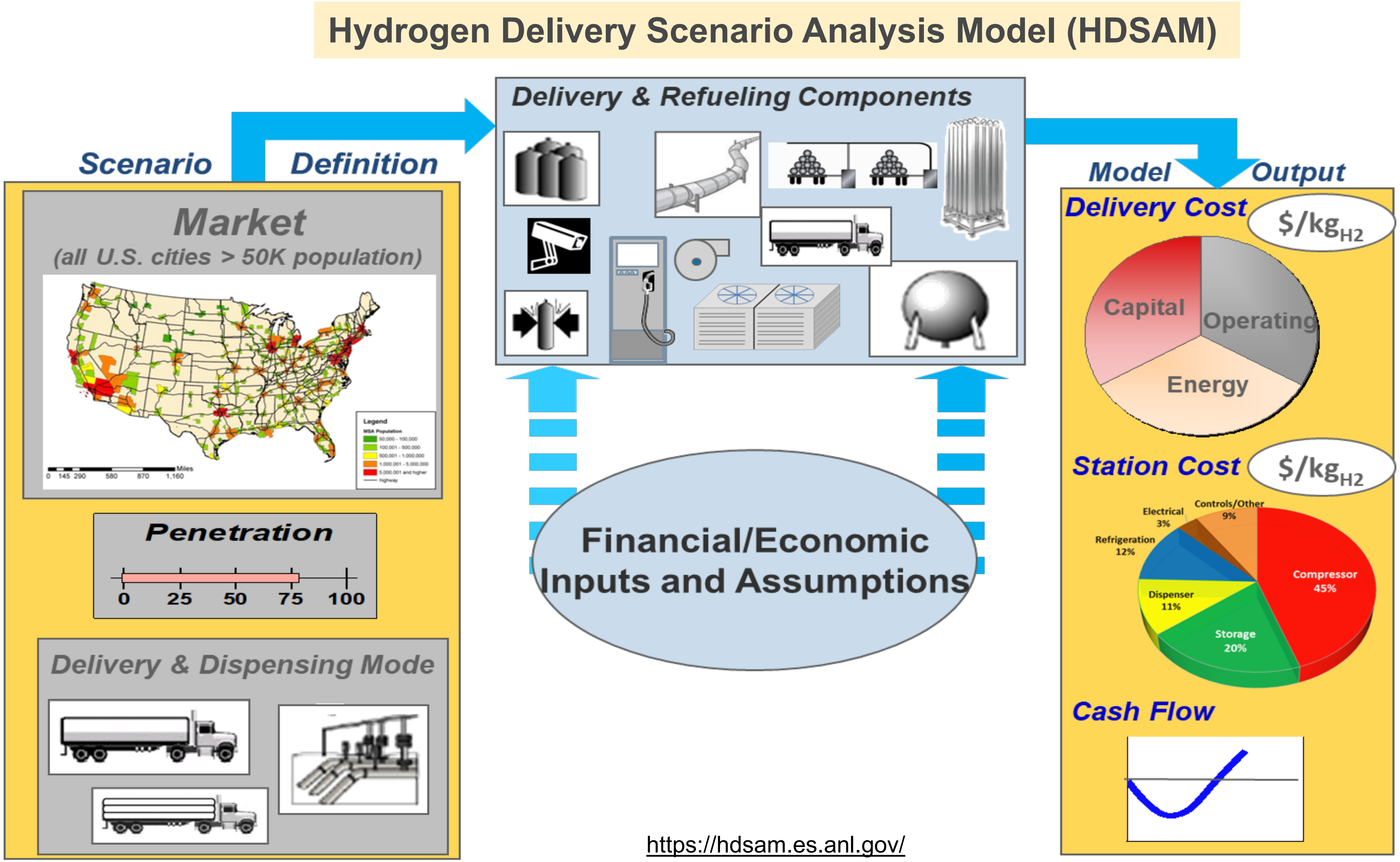
- Funding for FY22: $500K

Partners/Collaborators

- Daryl Brown, Energy Technology Analysis
- Industry partners

Techno-economic modeling and analysis for evaluating cost of hydrogen and ammonia delivery technologies

Goal/Approach/Strategy



https://hdsam.es.anl.gov/

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Updated and expanded HDSAM with most up-to-date cost hydrogen delivery component information

- The HDSAM model has been updated to include the heavy-duty fueling infrastructure with pipeline, tube-trailer and LH_2 Tanker truck delivery
- The cavern costs have been updated in-line with recent DOE funded work[1] on bulk hydrogen storage
  - Cavern construction cost; brine disposal cost; piping, valves and instrumentation cost
- The hydrogen pipeline costs have been updated based on historical cost data on onshore natural gas pipeline projects
  - The data for the nine geographic regions were evaluated and statistically similar groups were combined into six regions.
  - Unique cost estimating equations[2] were developed for the four cost components, including material, labor, miscellaneous and right-of-way, for each of the six remaining groups of states
- Updated the compressor cost data capturing cost reduction with economies of scale
- Updated the compression and storage optimization algorithm improving model performance
- Developed a new model interface to improve reliability and performance

[1]Papadias,D. and Ahluwalia, R.,"Bulk storage of hydrogen", International Journal of Hydrogen Energy, Volume 46, Issue 70, 2021, Pages 34527-34541, ISSN 0360-3199
[2]Brown,D., Reddi,K., Elgowainy, A.,"The development of natural gas and hydrogen pipeline capital cost estimating equations",International Journal of Hydrogen Energy, Volume 47, Issue 79, 2022,vPages 33813-33826

Developed hydrogen pipeline network cost model

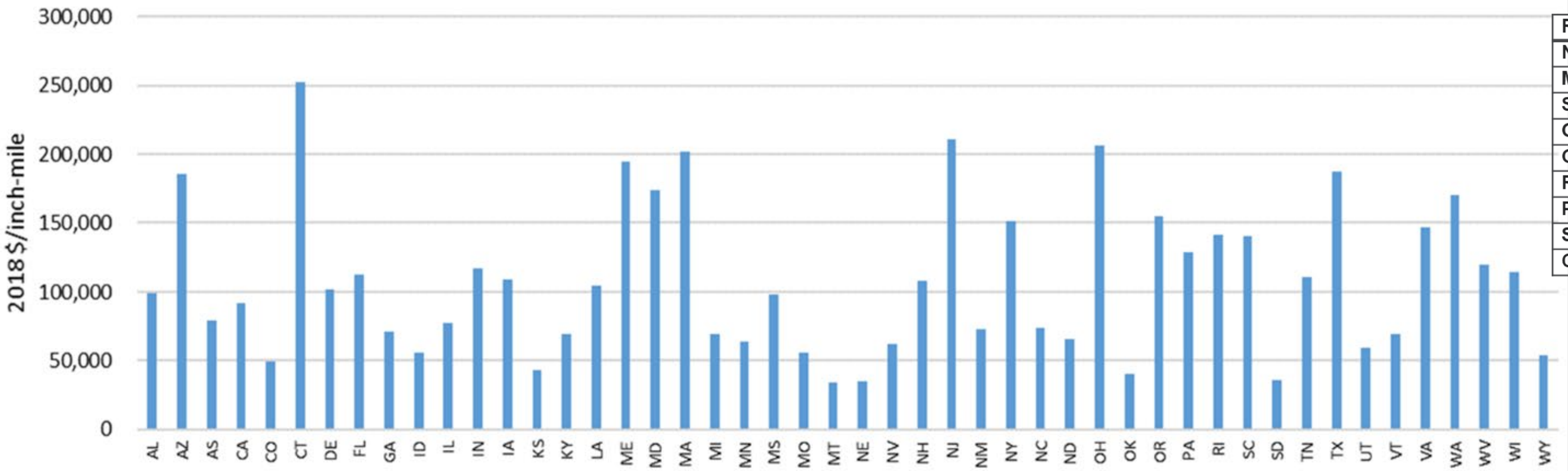
- $9.5 billion Bipartisan Infrastructure Law (BIL) for clean hydrogen, allocating $8 billion to developing regional clean hydrogen hubs[1].
- In a hydrogen hub, there will be multiple end users or demand locations, in addition to one or more hydrogen producers
- A hydrogen pipeline network model connecting the different supply and demand locations is needed to evaluate lowest deployment cost option
- The model identifies pipeline route based on road coordinates and geographic locations of hydrogen producers and consumers
  - Regional hydrogen pipeline cost equations developed from historic natural gas pipeline construction data are used to estimate and optimize the cost of the hydrogen pipeline network
- Pipeline segment diameters are optimized for lowest levelized hydrogen delivery cost
- Optimized compression and piping cost for lowest delivery cost within a network

[1] U.S. Department of Energy, "DOE National Clean Hydrogen Strategy and Roadmap," September 2022. https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

[2] Hydrogen Delivery Scenario Analysis Model (HDSAM) version 4.0. 2022. Argonne National Laboratory. https://hdsam.es.anl.gov/index.php?content=hdsam.

Hydrogen pipeline network modeling approach

- Total pipe network length is optimized based on locations of the supply and demand points using a minimum spanning tree algorithm
- The throughput across all hydrogen segments are calculated and the required pipe diameters and corresponding pressure drop are estimated
- HDSAM model is used to calculate costs of the pipeline network by region
- Compressor is sized to enable the throughput across the pipeline network
- Levelized costs for compressor and pipeline network is calculated
- The delivery cost is optimized for the combined pipeline network and compression stations



Regions	States Included
New England (NE)	ME, NH, VT, MA, CT, RI
Mid-Atlantic (MA)	PA, NY, NJ, WV, MD, DE, VA
Southeast (SE)	KY, TN, NC, SC, GA, FL, AL, MS, LA, AS
Great Lakes (GL)	MI, OH, IN, IL, WI
Great Plains (GP)	ND, SD, NE, KS, OK, MN, IA, MO
Rocky Mountain (RM)	ID, MT, WY, UT, CO, NM, NV
Pacific Northwest (PN)	OR, WA
Southwest (SW)	AZ, TX
California (CA)	CA

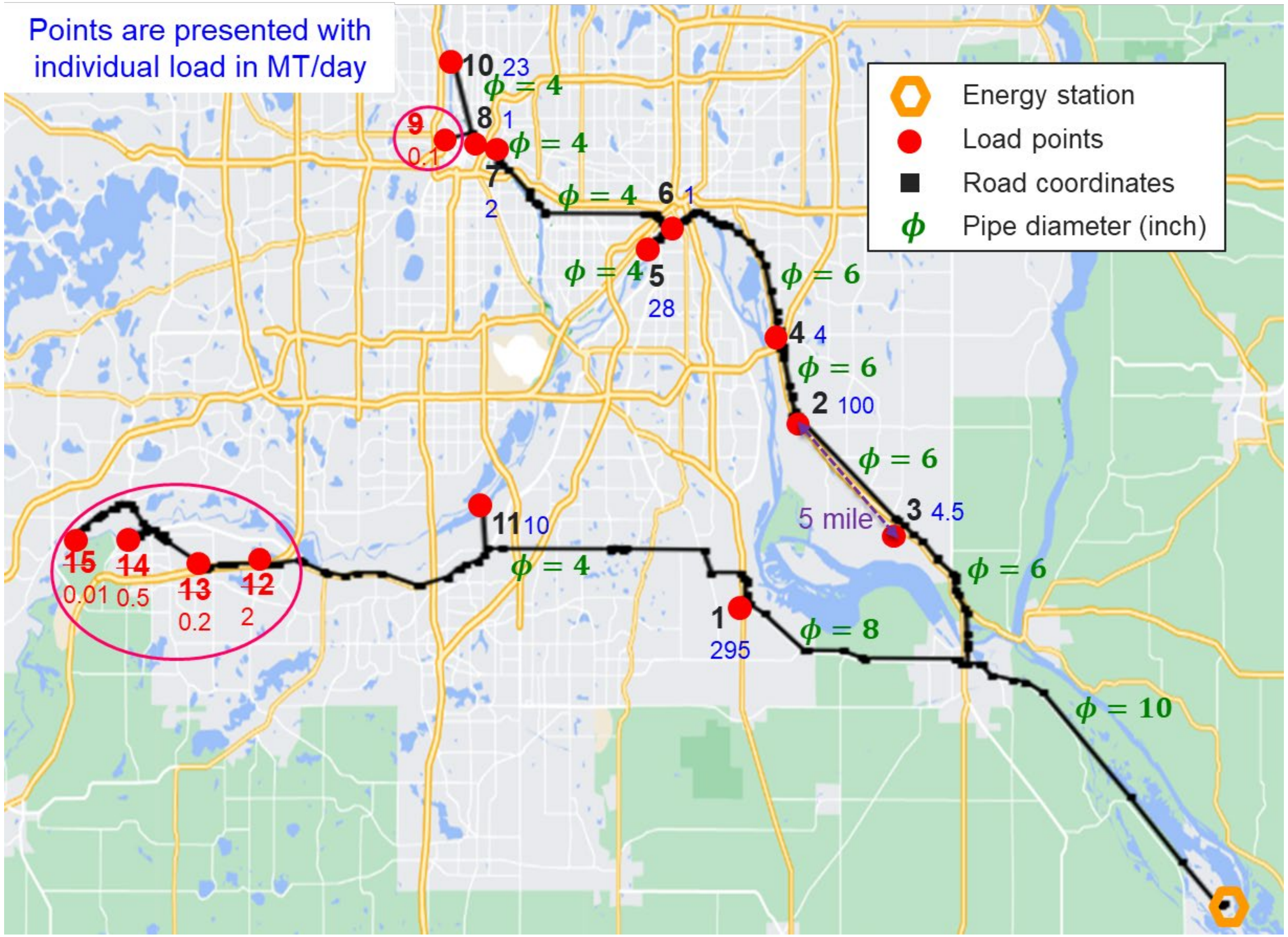
Brown, D., Reddi, K. and A. Elgowainy (2022) "The development of natural gas and hydrogen pipeline capital cost estimating equations," Int. J. of Hydrogen Energy.

Levelized hydrogen delivery cost via pipeline network: hypothetical deployment scenario

Accomplishment

Reference year	2019
Demand pressure:	48 atm
Compressor inlet pressure:	20 atm
Pipline delivery cost:	**$0.02/kg H_2**
Compression cost:	**$0.08/kg H_2**
Required pipeline inlet pressure	**80 atm**

Total initial capital investment	$14,182,620
Pipe material cost	$4,933,232
Pipe miscellaneous cost	$3,082,063
Pipe labor cost	$6,167,326
Total land cost	$786,648



Ammonia is a potential carrier for hydrogen → modeled ammonia road & rail transport

Liquid Ammonia Storage Tank

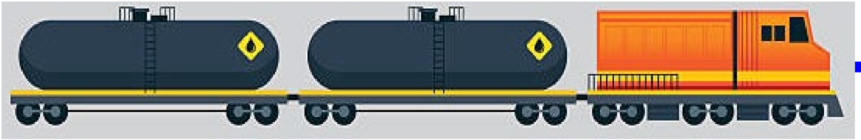
Capital Cost of Storage Tank⁺

Ammonia Loading

Road Transport / Trucking

- Transport in trailer with carbon steel tanks at ambient temperature and high pressure
- Approximately 30 tons-NH_3 per truck

Loading station



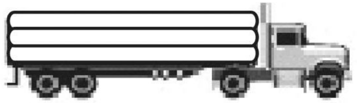
Rail Transport

- Rail Transmission Cost = \$0.088/ton-NH_3-mile based on 2018 Waybill data*
- 1 carload = 13,500 – 33,000 gal
  ~ 32 – 125 tons of NH_3
  ~ 5.4 – 21 tons of H_2 equivalent

City Terminal

Ammonia Storage Tanks

Ammonia Decomposition Plant



Distribution of hydrogen via trucking

Delivery to demand location

**Surface Transportation Board – Carload Waybill Sample: https:// prod.stb.gov/reports-data/waybill/*

⁺ Morgan, E. R. (2013), University of Massachusetts Amherst, https://doi.org/10.7275/11KT-3F59

Ammonia delivery model - NH_3 transport cost

- Trailer Tank Volume = 40.12 m^3 [§]
- Trailer Tank Usable Volume = 87.5%[+]
- Capital Cost of Trailer Tank = $94,950/unit [§]
- Railway transport waybill data of $0.088/ton-$NH_3$-mile for a minimum 4,000 carloads/year ~ 128,000 tons-NH_3/year[‡] is assumed for ammonia transport via rail

NH_3 Demand (ton/day)	Transport Distance (mile)	Transport Cost $/kg-$NH_3$		$/ton-$NH_3$-mile	
		Truck-trailer	Rail	Truck-trailer	Rail
50	50	0.03	0.0044	0.60	0.088
50	200	0.07	0.0176	0.35	0.088
50	500	0.13	0.044	0.26	0.088
200	50	0.03	0.0044	0.60	0.088
200	200	0.06	0.0176	0.30	0.088
200	500	0.13	0.044	0.26	0.088
500	50	0.03	0.0044	0.60	0.088
500	200	0.06	0.0176	0.30	0.088
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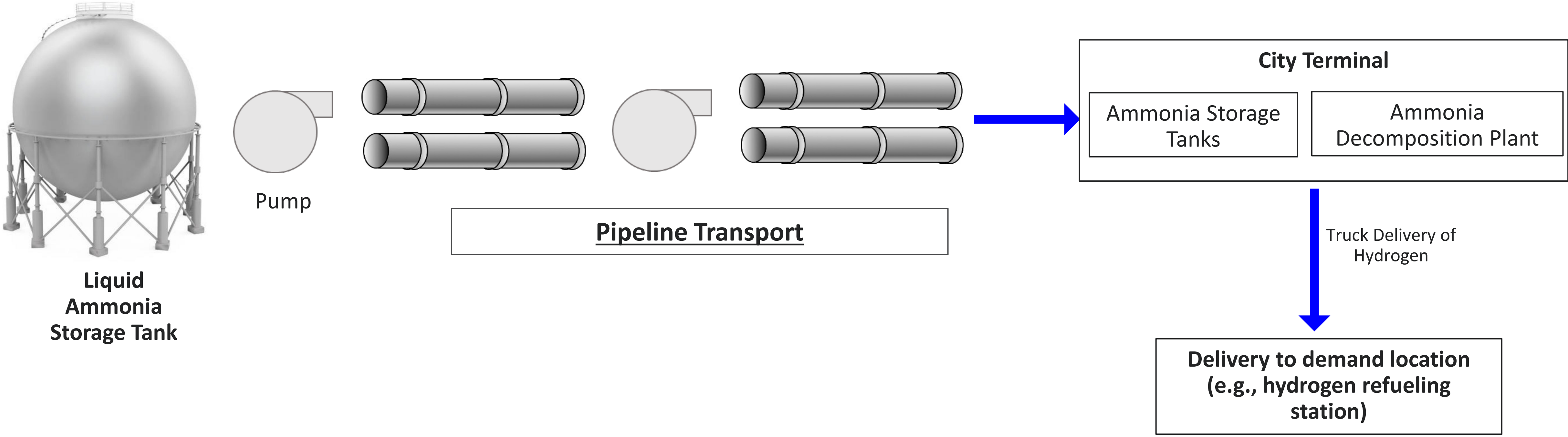
§ https://www.krafttankinventory.com/
+https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.111
**Surface Transportation Board – Carload Waybill Sample: https:// prod.stb.gov/reports-data/waybill/*
‡Papadias et al. (2021). International Journal of Hydrogen Energy, 46(47), 24169-24189.

Ammonia pipeline delivery modeling



- Maximum flow velocity of liquid ammonia in pipeline = 4 m/s*
- Cost of pipe surface coating = $0.033/m^2$* (including coating material, shipping of pipes to and from the coating plant)
- NuStar ammonia pipeline in the US have pipelines with dia. 6, 10 and 16 inches with capacity of 2,600, 6,600, 26,300 tons-NH_3/day and line fill of 20, 56, 144 tons-NH_3/mile, respectively⁺
- Analysis of ammonia transport in pipelines with dia. 16-36" for 30,000-160,000 tons-NH_3/day*

**Papadias et al. (2021). International Journal of Hydrogen Energy, 46(47), 24169-24189*
⁺Pipeline Transportation of Ammonia Helping to Bridge the Gap to a Carbon Free Future November 9, 2021 NuStar

Ammonia pipeline delivery model is developed to estimate NH_3 transport cost

Approach

- Size the pipeline for any ammonia throughput and length (pressure drop) at specific operating temperature
- Liquid ammonia flow properties are calculated using the NIST empirical equation of state[1,2]
- Pipeline diameter is calculated using the Darcy-Weisbach equation
- Optimized levelized pipeline delivery costs by including booster pumps

Model Inputs

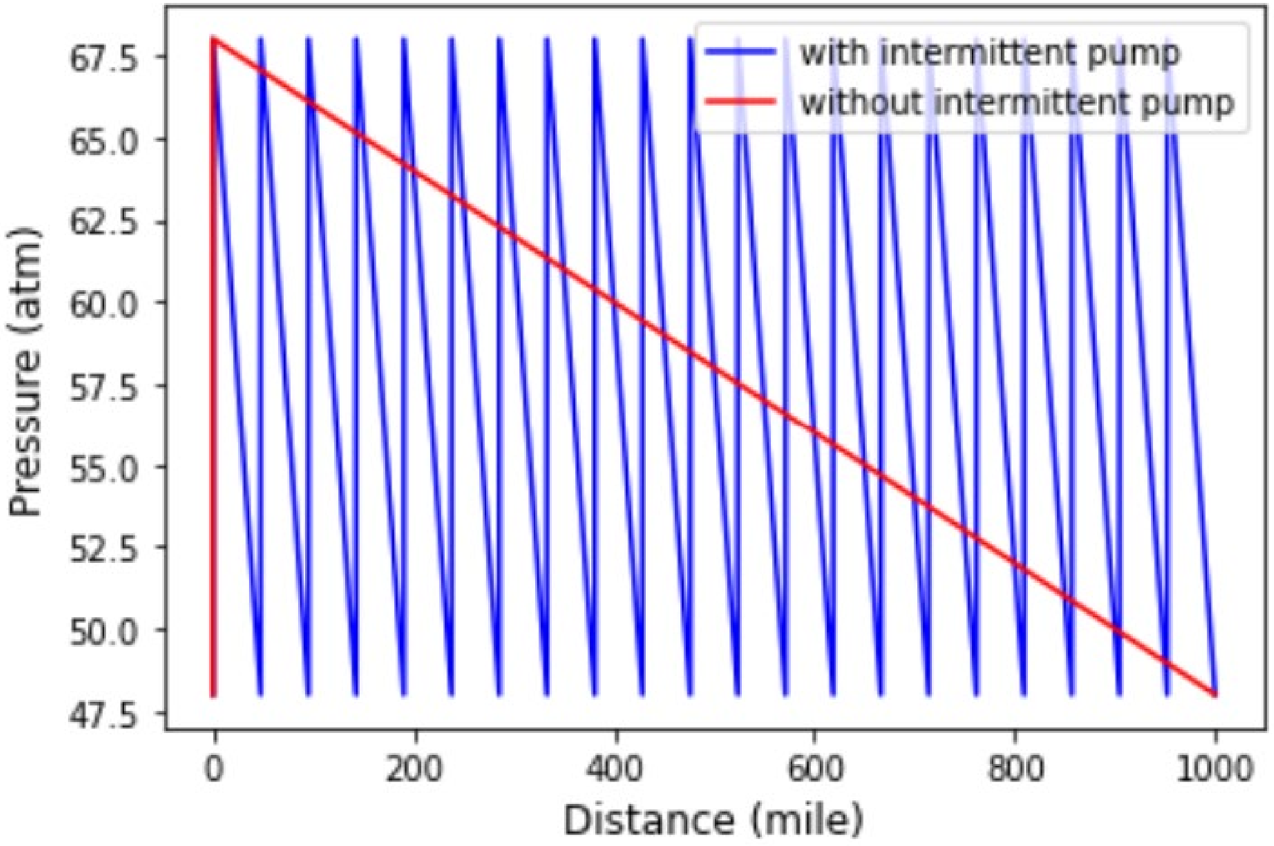
Input Item	Value
Pipe roughness, carbon-steel [m]	4.5E-05
Pipeline Maas Flowrate [tons/day]	11,740
Mean Temperature of Line [°C]	25
Pipeline Length [km]	400
Input Pipeline Inlet Pressure [atm]	68
Input Pipeline Outlet Pressure [atm]	48
Maximum allowable velocity [m/s]	4

Model Outputs

Output Item	Value
Liquid saturation density [kg/m³]	603
Pipeline Diameter [in]	23.87
Standard Diameter [in]	24
Pipeline Diameter [m]	0.61
Liquid viscosity [cP]	0.127
Reynolds number	205,000
Vapor pressure [atm]	9.84
Friction factor	0.016

[1] Gao et al, J Phys Chem Ref Data (2023)
[2] Monogenidou et al, J Phys Chem Ref Data (2018)

NH_3 pipeline model optimizes delivery cost by considering pump cost



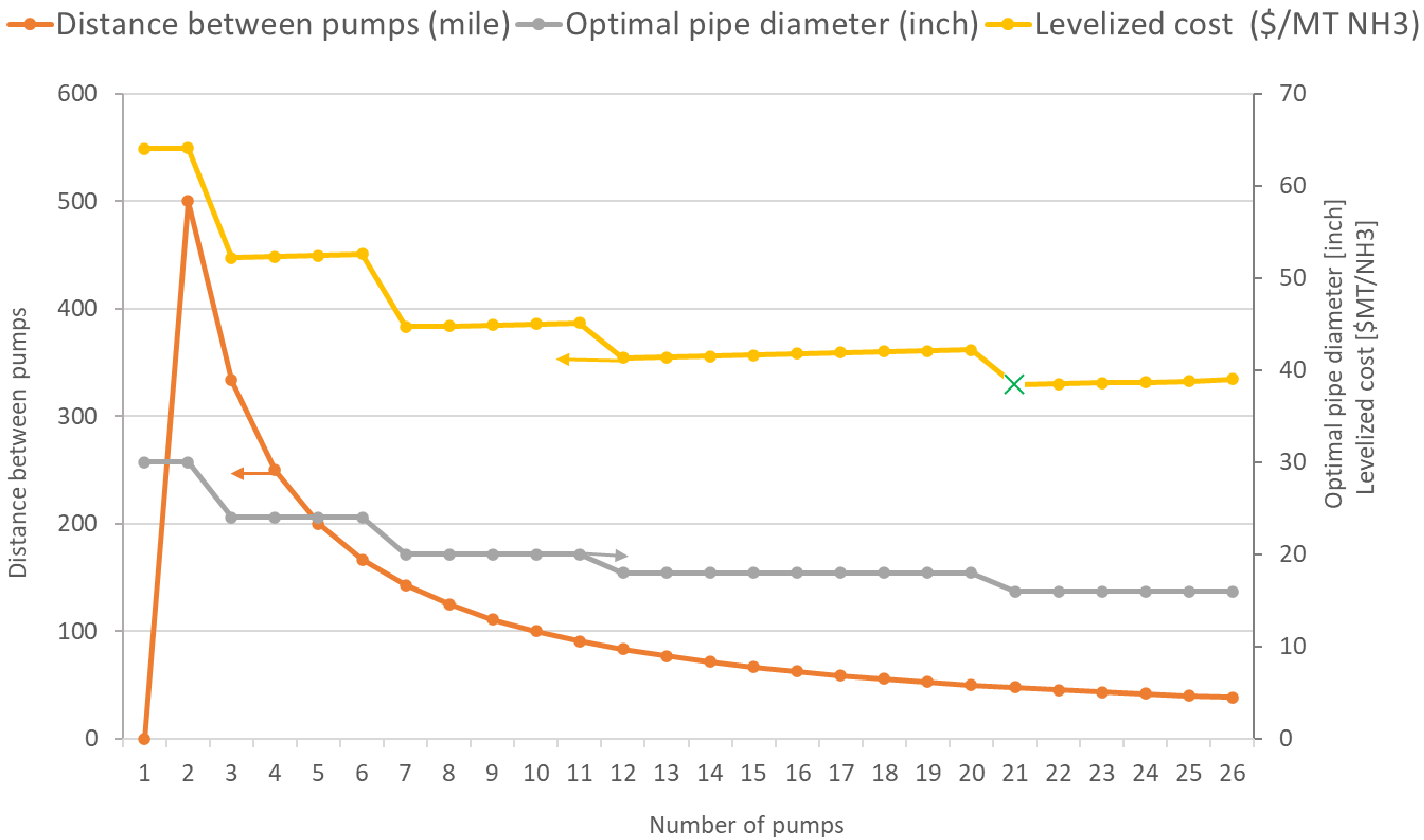
Total NH_3 delivery	= 10,000 MT/day
Total pipeline length	= 1000 mile
Pipeline temperature	= 25 °C
Pipe inlet pressure	= 68 atm
Pipe outlet pressure	= 48 atm
State	= Illinois
Reference year	= 2019
Pump electricity usage rate	= Industrial
Each pump rating	= 300 KW

Preliminary

Piping cost with pump	= $38/MT NH_3
Pumps required	= 40
Pumps at each interval	= 2
Optimum pipe diameter	= 16 inch
Optimum pump intervals	= 48 mile
Piping cost without pump	= $64/MT NH_3
Pipe diameter	= 30 inch

With increase in pumping stations, ammonia pipeline delivery cost can be reduced

Accomplishment



Higher delivery throughout reduces the cost of ammonia transport due to strong economies of scale

Accomplishment

Total NH3 delivery [MT/day]	**5,000**	**10,000**	**20,000**	**50,000**
Piping cost with pump optimization [$/MT_NH$_3$]	58	38	25	15
Number of pumps required	22	40	96	180
Pumps at each interval	1	2	4	10
Optimum pipe diameter [inch]	12	16	20	30
Optimum pump intervals [mile]	44	28	40	53
Piping cost without pump optimization [$/MT_NH$_3$]	104	64	44.3	17.8
Pipe diameter [inch]	24	30	42	42

Challenges and Future Work

- Challenges and barriers
  - Access to cost data for ammonia delivery technology pathways
- Future work
  - Include the cost of terminal loading of ammonia into the rail and tanker trucks
  - Release a standalone model for evaluating ammonia delivery cost
- Summary of accomplishments
  - Developed a hydrogen pipeline network model that connects supply and demand locations in a hub deployment scenario
  - Acquired data for ammonia delivery via rail and trucks
  - Developed ammonia pipeline delivery model
  - Optimum cost exist when considering compression and booster pump stations for hydrogen and ammonia delivery via pipelines

Proposed future work is subject to DOE approval

Collaborations and Acknowledgments

- Energy Technology Analysis who supported acquisition and analysis of pipeline cost data
- Dennis Papadias and Rajesh Ahluwalia from ANL for providing ammonia cost data
- Industry partners who provided cost data and reviewed model inputs and outputs

Project Summary

- **Relevance**:
  - Techno-economic modeling and analysis is needed for evaluating cost of hydrogen and ammonia delivery technologies
  - **Approach**:
  - Bottom-up techno-economic modeling to evaluate delivery cost of hydrogen and ammonia as a hydrogen carrier
- **Collaborations**:
  - Collaborated with consultants and experts from industries
- **Technical accomplishments and summary of findings**:
  - Updated and expanded HDSAM with most up-to-date cost hydrogen delivery component information
  - Developed hydrogen pipeline network cost model for hydrogen hub deployments
  - Modeled ammonia delivery cost via trucks, rail and pipelines
- **Future Research**:
  - Expand the ammonia delivery model to include loading terminals for rail and tanker trucks
  - Release a standalone model for evaluating ammonia delivery cost

TECHNICAL BACKUP AND ADDITIONAL INFORMATION

ACCOMPLISHMENTS AND PROGRESS:
RESPONSES TO PREVIOUS YEAR REVIEWERS' COMMENTS

- Not Applicable: no reviewers comments from 2022 AMR

TECHNOLOGY TRANSFER ACTIVITIES

- Not applicable to this project

SPECIAL RECOGNITIONS AND AWARDS

- None for this project

PUBLICATIONS AND PRESENTATIONS

- Brown, D., Reddi, K. and A. Elgowainy (2022) "The development of natural gas and hydrogen pipeline capital cost estimating equations," International Journal of Hydrogen Energy, Volume 47, Issue 79, Pages 33813-33826, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2022.07.270.

PROGRESS TOWARDS DOE TARGETS OR MILESTONES

Progress towards analysis targets / milestones can be assessed through our contributions to relevant barriers:

1. Barrier, *Insufficient suite of models and tools*
   - Updated and expanded the HDSAM suite of models to evaluate cost of hydrogen and ammonia delivery options

2. Barrier, *Stove-piped / Sioled analytical capability for evaluating sustainability*
   - Evaluated economics of hydrogen delivery technology pathways using consistent modeling frameworks and assumptions

3. Barrier, *Inconsistent data, assumptions, and guidelines*
   - Collected data from literature, models, vendors and industry sources
   - Harmonized assumptions across various modeling platforms
   - Vetted model inputs and analysis output with industry experts