2016 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Hydrogen Delivery Infrastructure Analysis

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PD 14

Overview

Timeline

- Start: FY 2007
- End: Determined by DOE
- % Complete (FY16): 70%

Budget

- FY15 Funding: $200K
- FY16 Funding: $100K
- 100% DOE funding

Barriers/Challenges

- Lack of hydrogen infrastructure options analysis
- Cost and efficiency of delivery components
- Lack of appropriate models and analytical capability
- Conduct unplanned studies and analyses

Partners and Collaborators

- PNNL
- Fuel Science
- Boyd H2
- Industry Stakeholders

Relevance/Impact

- ❑ Provide platform for comparing impacts of alternative delivery and refueling options on the cost of dispensed hydrogen
  - ✓ Model delivery cost in early and projected long-term FCEVs markets
  - ✓ Evaluate impact of design and economic parameters of various hydrogen delivery options and refueling station (HRS) configurations
  - ✓ Identify cost drivers of current technologies for hydrogen delivery and refueling
  - ✓ Develop estimates of delivery and refueling cost reduction with market penetration
- ❑ Assist FCT Office with planning
  - ✓ Assist FCTO with setting cost and performance targets in MYRD&D planning
  - ✓ Investigate delivery pathways and identify R&D areas with potential to meet cost and performance targets
- ❑ Support existing DOE-sponsored tools (e.g., H2A models, JOBS FC, GREET, MSM)
  - ✓ Collaborate with other model developers and lab partners
  - ✓ Support other DOE sponsored activities (e.g., H2FIRST)
  - ✓ Interact with experts from industry for input and review

Update HDSAM Model to estimate hydrogen delivery cost for different market scenarios – Approach

- **Collaborate** to acquire/review model inputs and examine/review model and results
- **Acquire** current cost of refueling and delivery components from vendors and industry experts
- **Develop** modeling structure to evaluate the impact of market penetration, and economic parameters on hydrogen delivery cost
  - ✓ Evaluate cost reduction of components with production volume
  - ✓ Check methodology through interaction with industry experts
- **Evaluate** performance of various hydrogen supply options and station design configurations
- **Identify** major cost drivers for hydrogen delivery
- **Review** modeling approach and results
  - Checked against cost data in 24 proposals submitted to four California Energy Commission (CEC) solicitations from 2010 to 2014
  - Via collaborators and through briefings to Tech Teams, early releases to DOE lab researchers, and interaction with experts from industry

Evaluated cost reduction of components with market penetration, capturing the impact of production volume, technology advancement and learning – Approach/Accomplishment

– Three technology baskets for delivery components

1. "Mature" technology
2. "Established" technology with potential for innovation
3. "Developing" technologies (in early stage) with higher potential for innovation

– Three market production volumes

1. Low: consistent with today's cost (~200 HRS globally)
2. Mid: mid point between today & large volume markets (5000 HRS)
3. High: consistent with large number of HRS, (10,000 HRS)

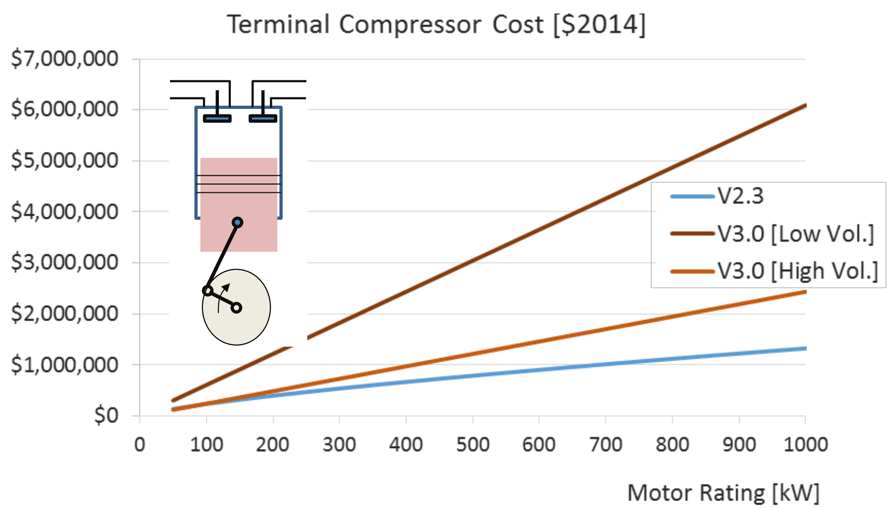
– Cost reduction factors

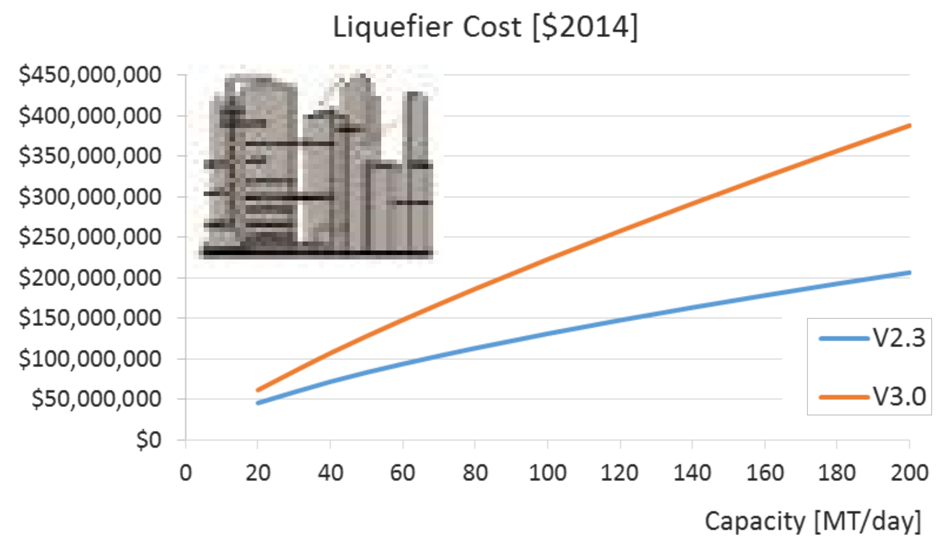
1. 0.95 cost reduction with each volume doubling of mature technologies
2. 0.90 cost reduction with each volume doubling of established technologies
3. 0.85 cost reduction with each volume doubling of developing technologies

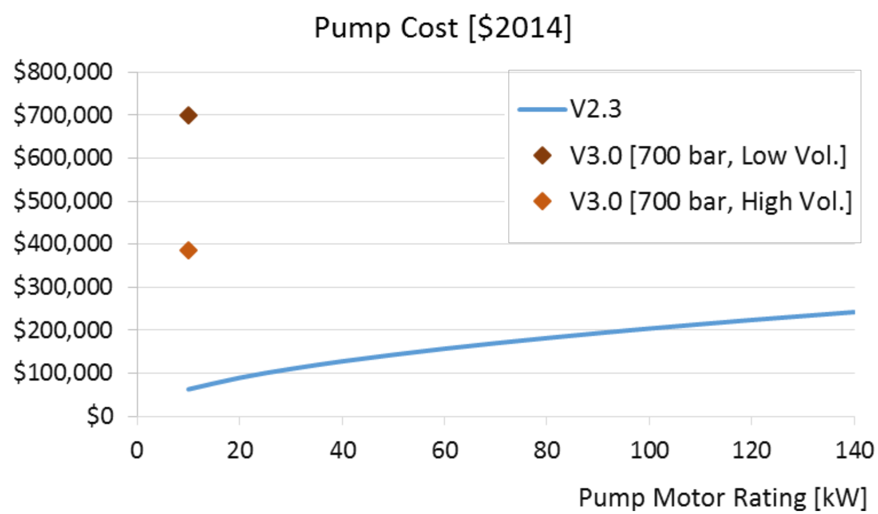
Evaluated cost reduction factors with market maturity, capturing the impact of economies of scale, technology advancement and learning on Hydrogen delivery cost – Accomplishment

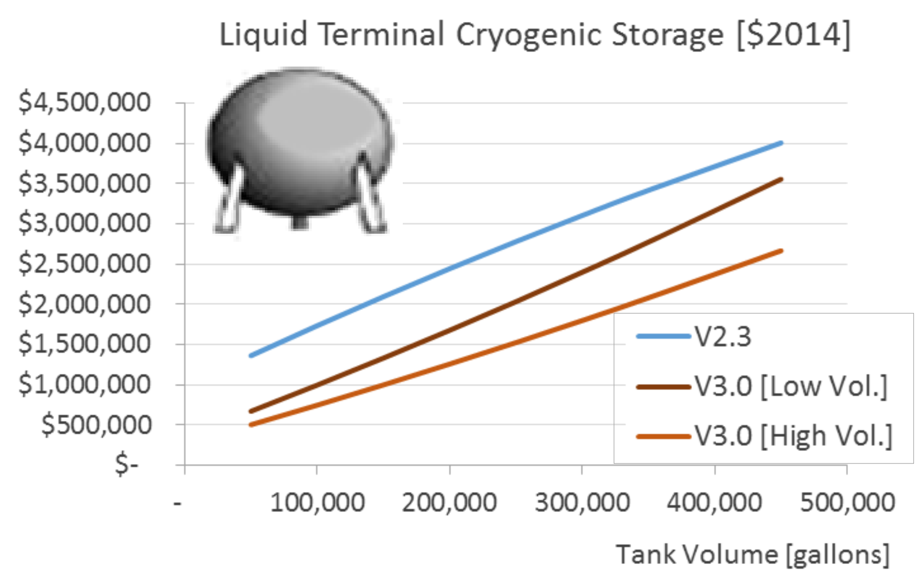
Cost Reduction Factors			
	Market (Production Volume)		
Technology baskets and definitions	Near Term (low volume)	Mid Term	Long Term (large volume)
#1 Mature (low potential for cost reduction) Ex: Low-Pressure Storage, Cryogenic Storage, H_2 Pipeline Cost Premium	**1**	**0.79**	**0.75**
#2 Established (moderate potential for cost reduction) Ex: Station Cascade Storage, Station Refrigeration, Cryogenic Pump, Tube-Trailer Vessel, LH_2 Truck Vessel	**1**	**0.61**	**0.55**
#3 Developing (high potential for cost reduction) Ex: Dispensers, Compressors, Station Controls/Safety Equip	**1**	**0.47**	**0.40**

Developed formulas for today's cost of delivery and refueling components – Accomplishment



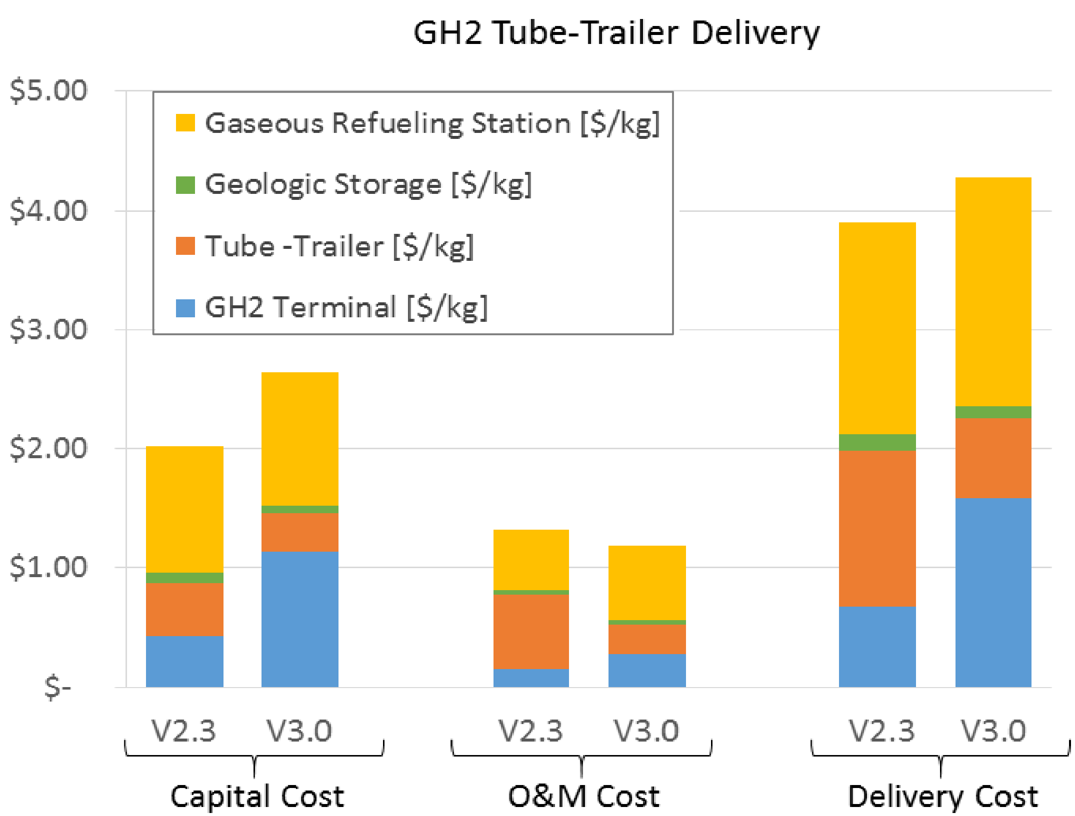






Small change in delivery cost via tube trailer between HDSAM2.3 and HDSAM3.0 versions

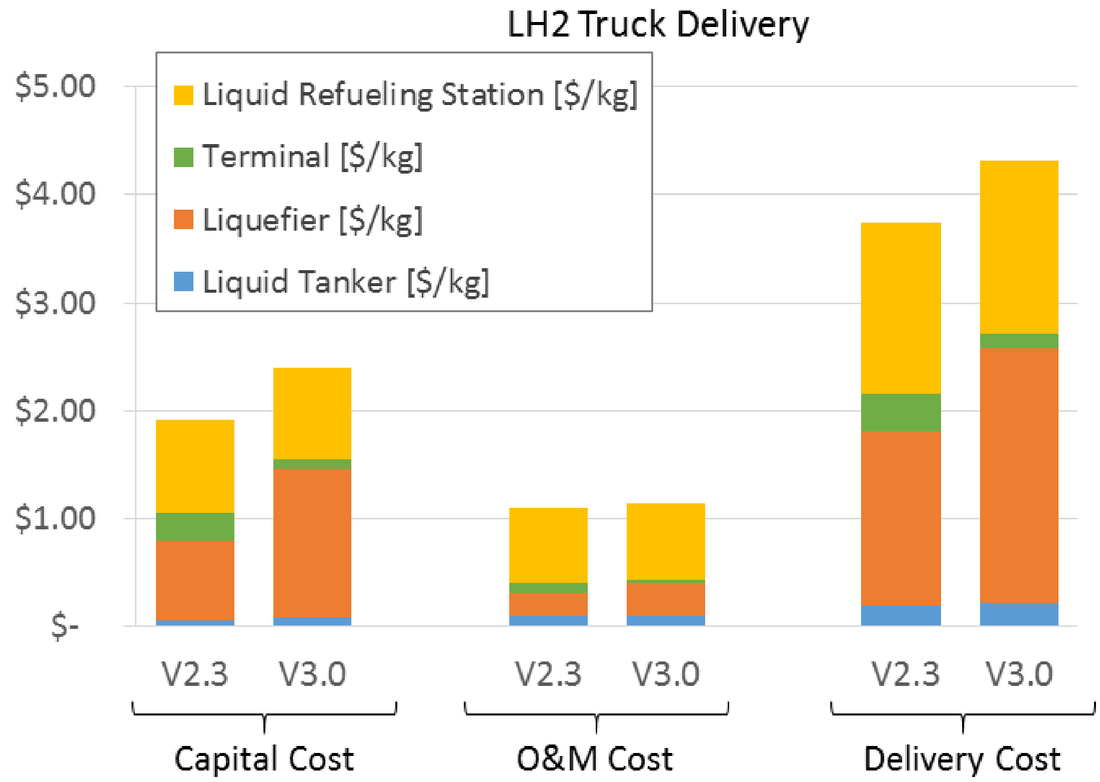
- Higher tube trailer payload negates increase in gaseous H_2 terminal cost



Scenario Parameters	Value
Market	Urban
City	Indianapolis, IN
Market Penetration	10% (80 MT/day)
HRS Capacity	1000 kg/day
Utilization	Full Utilization (80%)
Production volume	High
Analysis Period	30 years
Transmission Distance	60 mi
Refueling	700 bar

Increase in LH_2 delivery cost in V3.0 compared to V2.3

- Lower economies of scale for liquefier
- Accounting for boiloff losses
  - New data suggests that boiloff losses could be as low as 4 kg/day per pump
- Practical limit on pump capacity (120 kg/h)



Scenario Parameters	Value
Market	Urban
City	Indianapolis, IN
Market Penetration	10% (80 MT/day)
HRS Capacity	1000 kg/day
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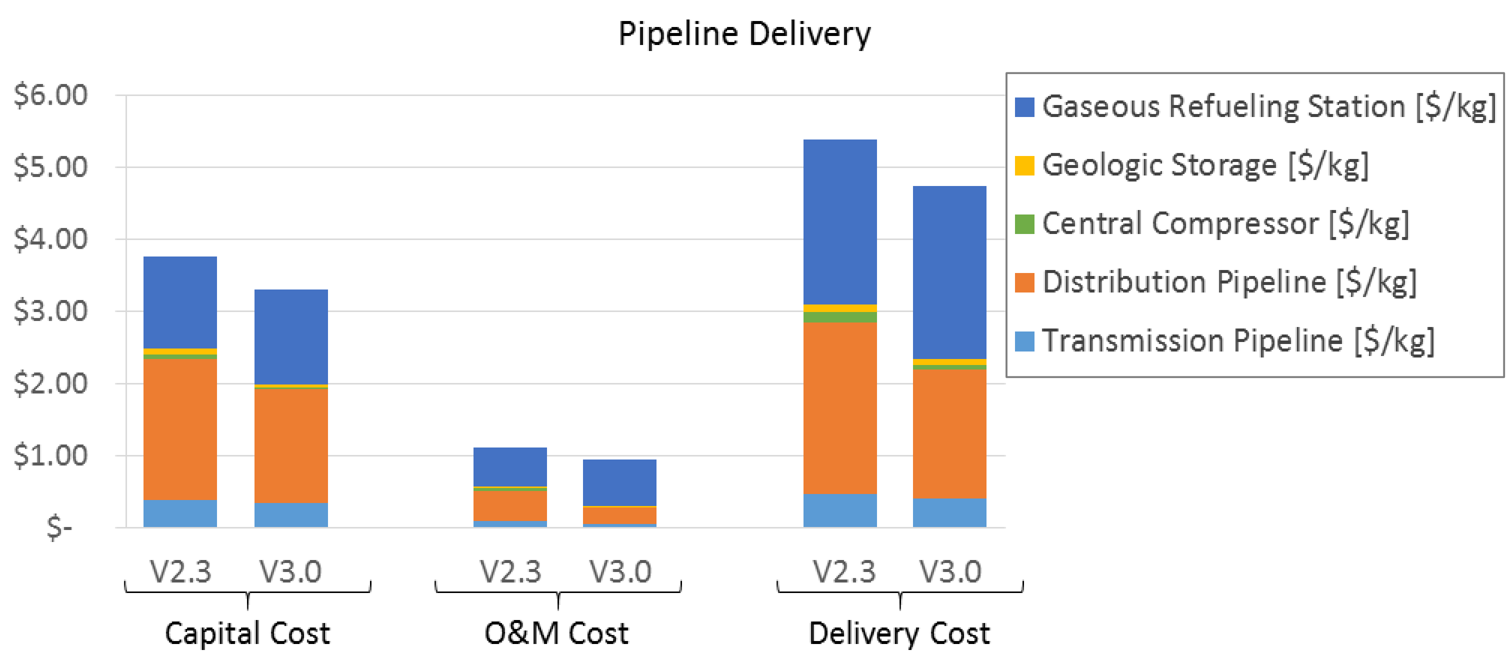
Production volume	High
Analysis Period	30 years
Transmission Distance	60 mi
Refueling	700 bar gaseous (vial liquid pumping)

Lower delivery cost via pipeline in HDSAM 3.0 vs. HDSAM 2.3

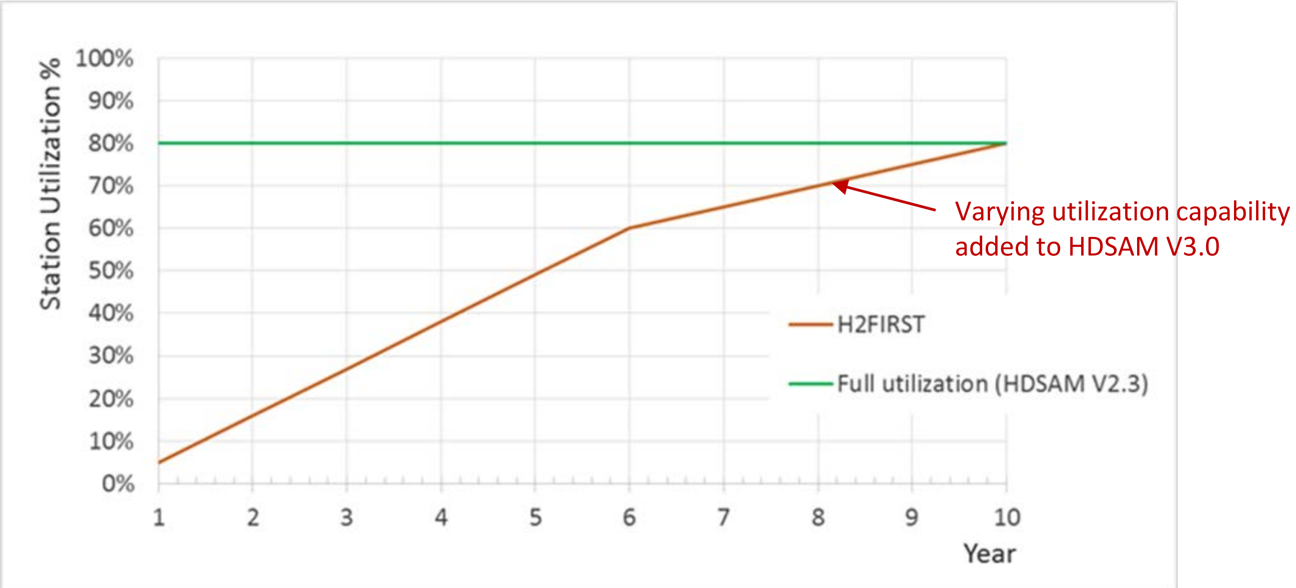
Scenario Parameters	Value
Market	Urban
City	Indianapolis, IN
Market Penetration	10% (80 MT/day)
HRS Capacity	1000 kg/day
Utilization	Full Utilization (80%)
Production volume	High
Analysis Period	30 years
Transmission Distance	60 mi

- ❑ Updated pipeline equations in HDSAM based on PNNL analysis of FERC data from 1980-2009
- ❑ Updated assumption of hydrogen premium based on cost analysis completed by NIST in 2015
  - ✓ Pipelines < 12” at 70 bar not required to be thicker than natural gas lines



Updated key statistics for calculating market demand, electricity prices and cost indices of components –Accomplishment

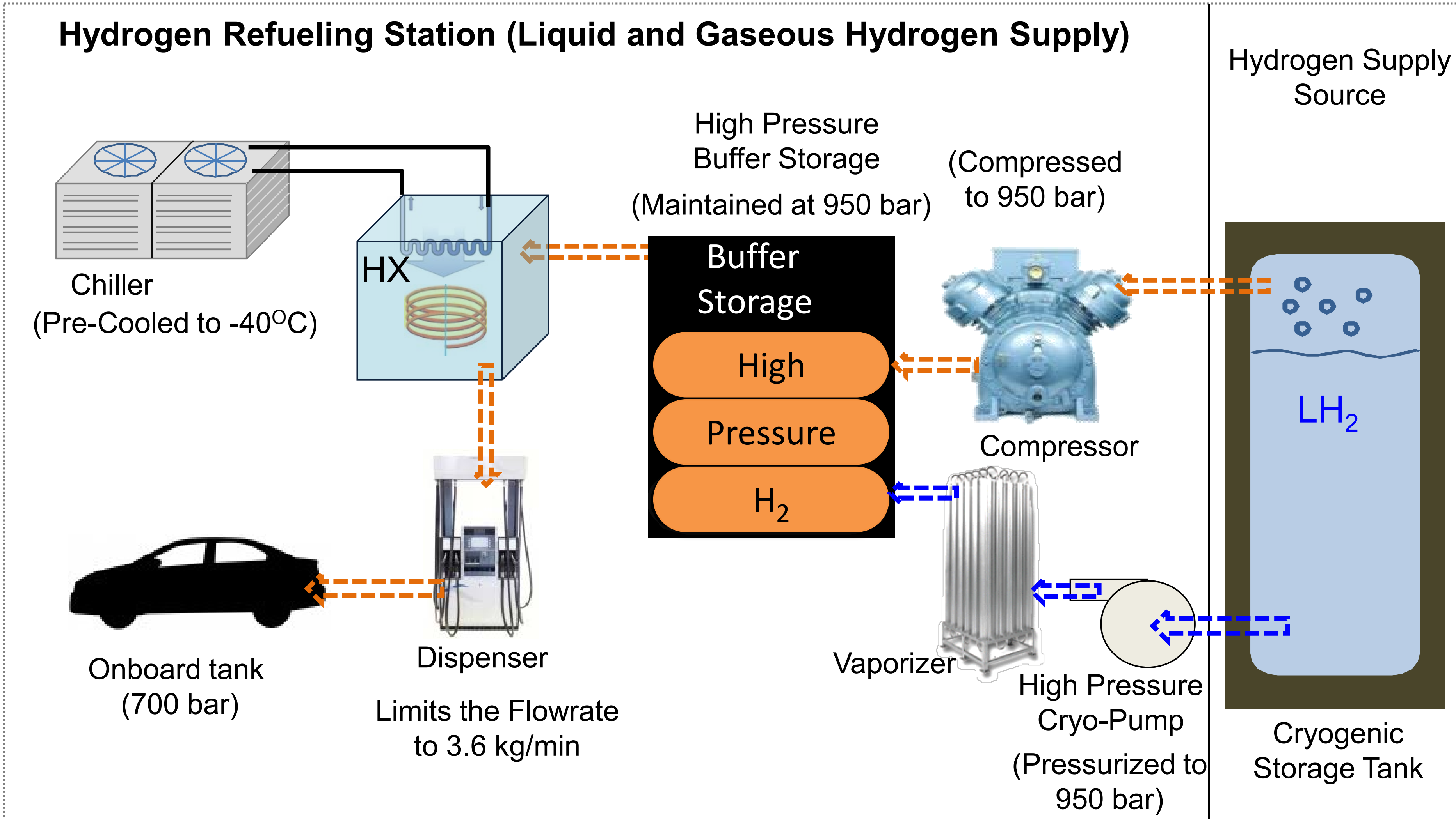
- Updated fuel and electricity prices based on latest EIA/AEO 2015 data
- Updated price and cost indices to allow selection of reference year $ for delivery cost up to [2014$]
- Updated Market parameters like Population, Vehicle ownership rate, Annual miles driven per year, for cities with population greater than 50,000
- Included ability to simulate debt financing, annual utilization rates, and 40-year analysis period.



Chemical Engineering Plant Cost Index (CEPCI)		
	2010 →	2014
Overall Index	1.18	1.23
Equipment	1.21	1.29
Heat Exchanges and Tanks	1.19	1.25
Process Machinery	1.21	1.28
Pipe, valves and fittings	1.31	1.41
Process Instruments	1.10	1.08
Pumps and Compressors	1.20	1.25
Electrical equipment	1.30	1.39
Structural supports	1.18	1.31
Construction Labor	1.07	1.05
Buildings	1.14	1.22
Engineering Supervision	0.98	0.93

Year	Labor Cost Index	GDP Implicit Deflator Price Index
2008	0.99	1.21
2009	1.03	1.22
2010	1.07	1.24
2011	1.09	1.26
2012	1.09	1.28
2013	1.09	1.30
2014	1.09	1.32

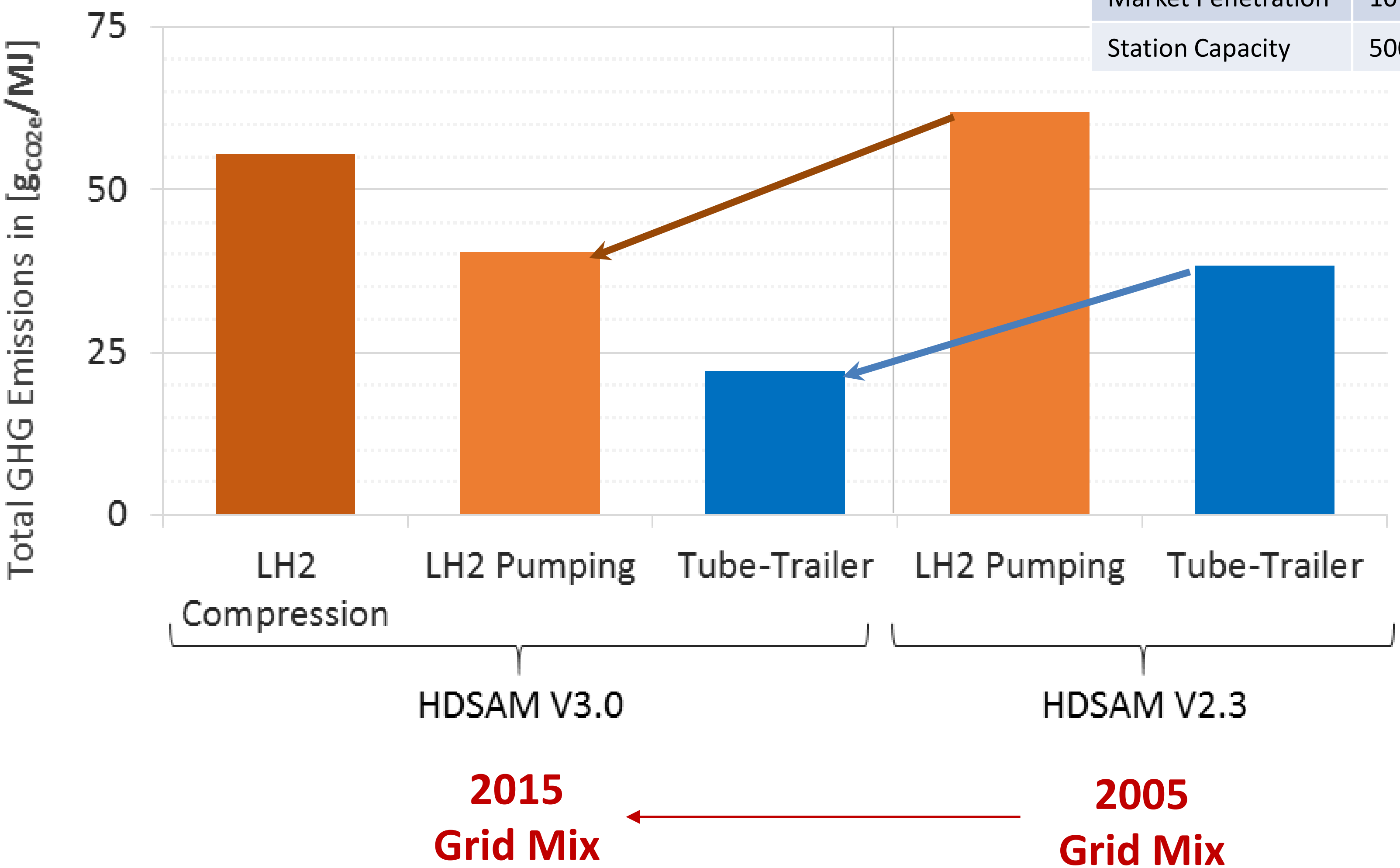
Updated the HRS configurations using compression with liquid delivery in early markets – Accomplishment



Updated GHG emissions estimates for different delivery pathway using GREET™ model - Accomplishment

Scenario Parameters	Value
Market	Urban
City	Indianapolis, IN
Market Penetration	10%
Station Capacity	500 kg/day

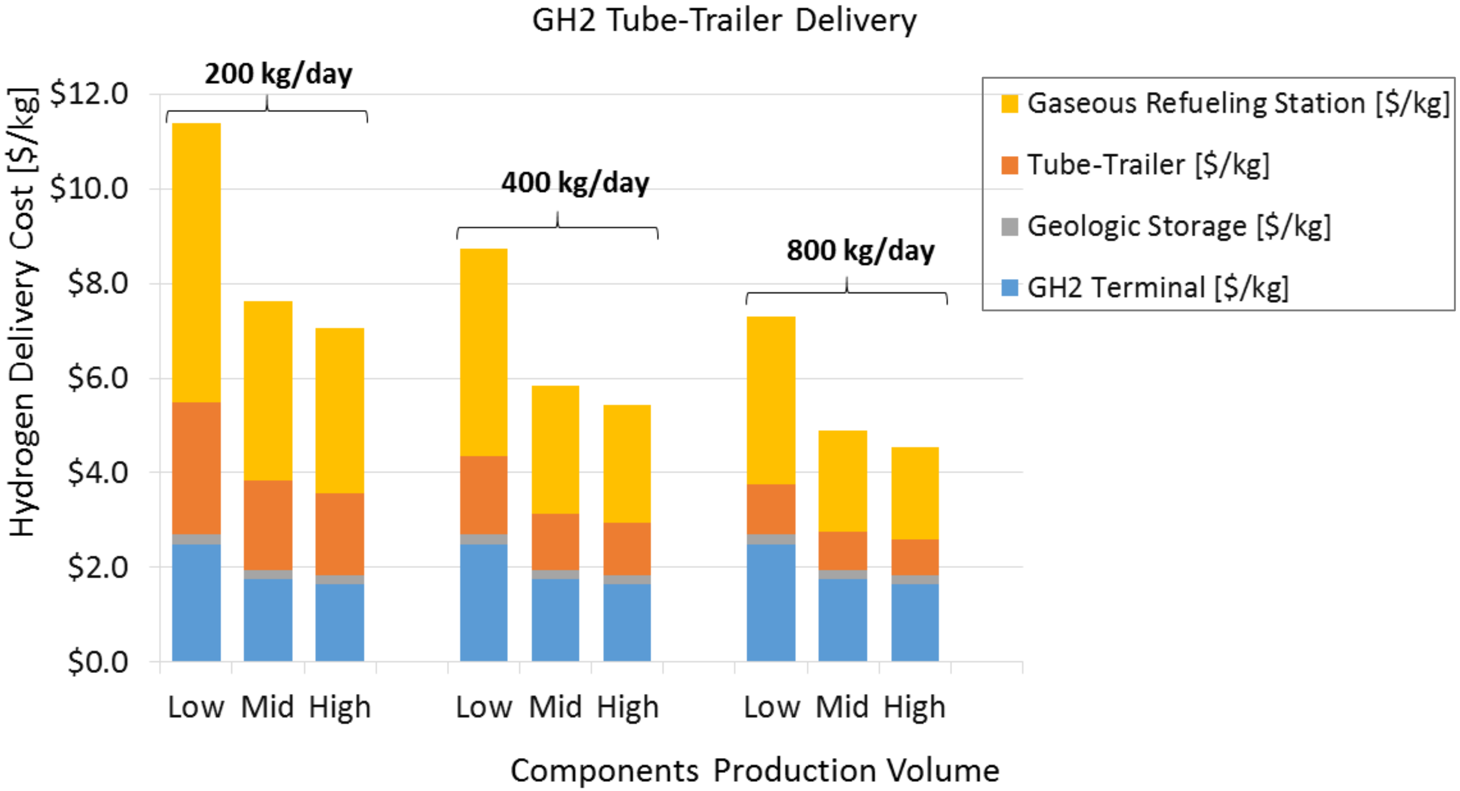
- Cleaner electricity generation mix helps reduce liquefaction and compression carbon footprint



Tube trailer delivery cost drops from ~$11/kg for small HRS at low volume to ~$4/kg for large HRS at high volume -Accomplishment

- Larger station capacities are limited by tube trailer payload and logistics

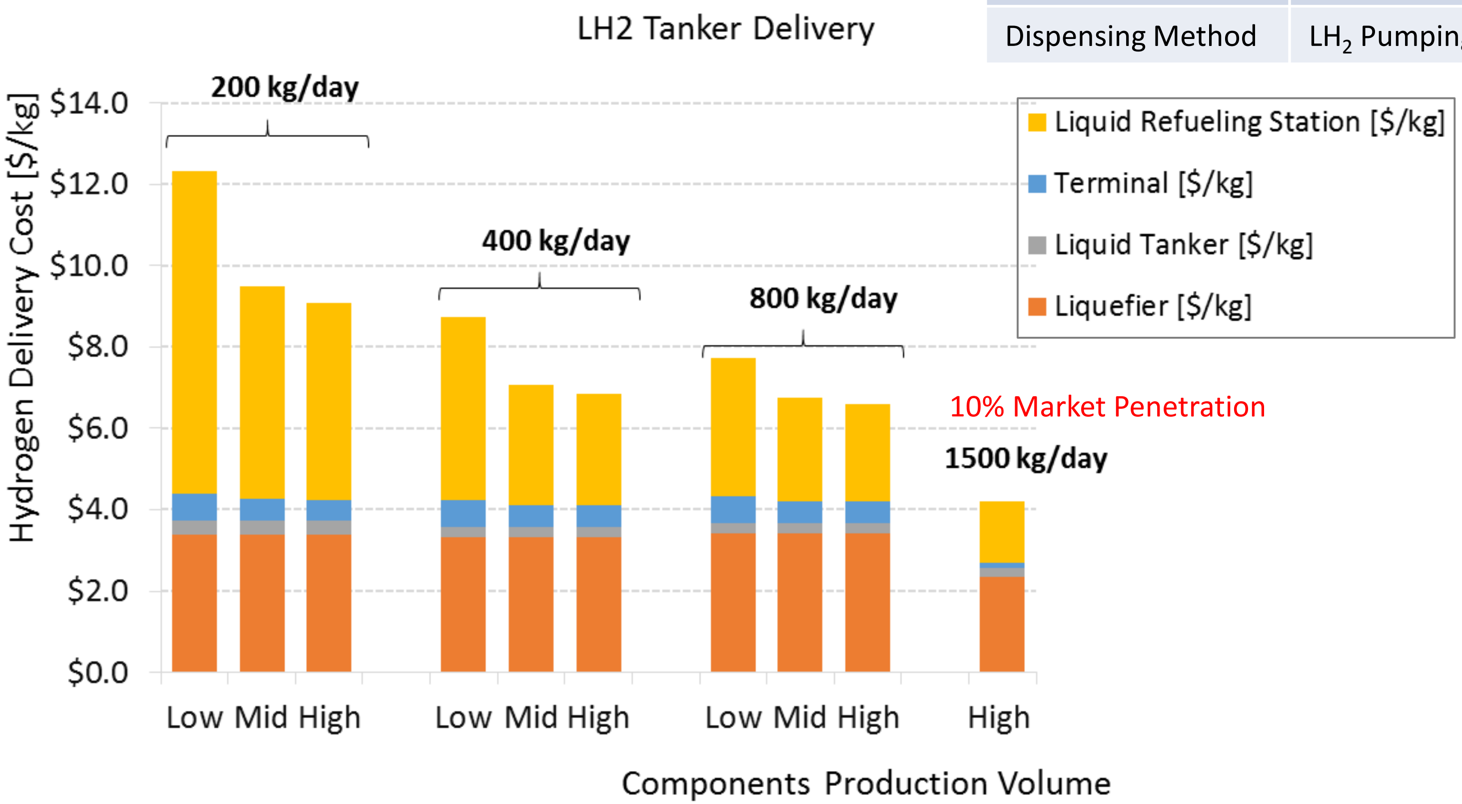
Scenario Parameters	Value
Market	Urban
City	Indianapolis, IN
Market Penetration	2% **(16 MT/day)**
Utilization	Full Utilization (80%)
Analysis Period	30 years



LH_2 delivery cost drops from ~$12/kg for small HRS at low volume to ~$4/kg for large HRS at high volume -*Accomplishment*

➢ Larger station capacities can produce further cost reduction

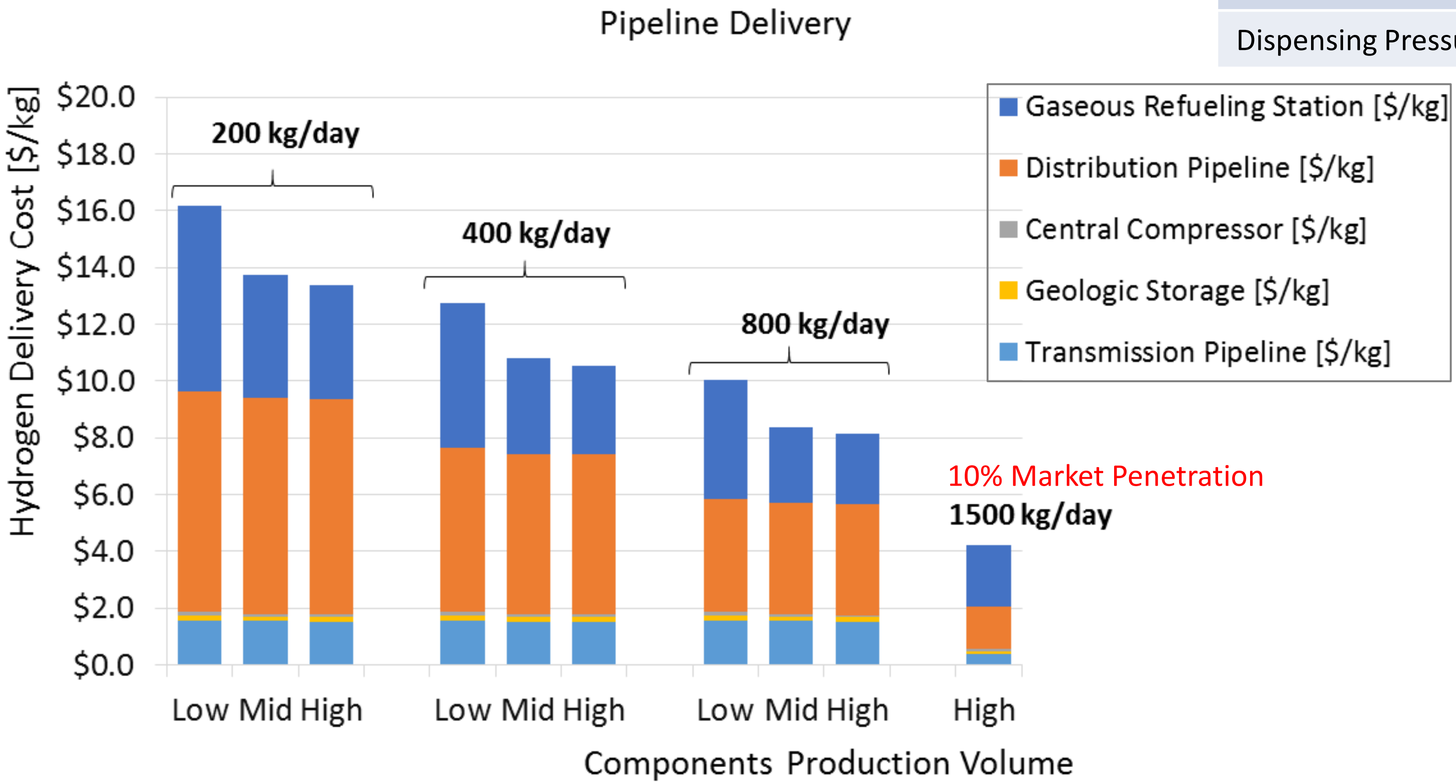
Scenario Parameters	Value
Market	Urban
City	Indianapolis, IN
Market Penetration	2% **(16 MT/day)**
Utilization	Full Utilization (80%)
Analysis Period	30 years
Dispensing Method	LH_2 Pumping to 700bar Gaseous



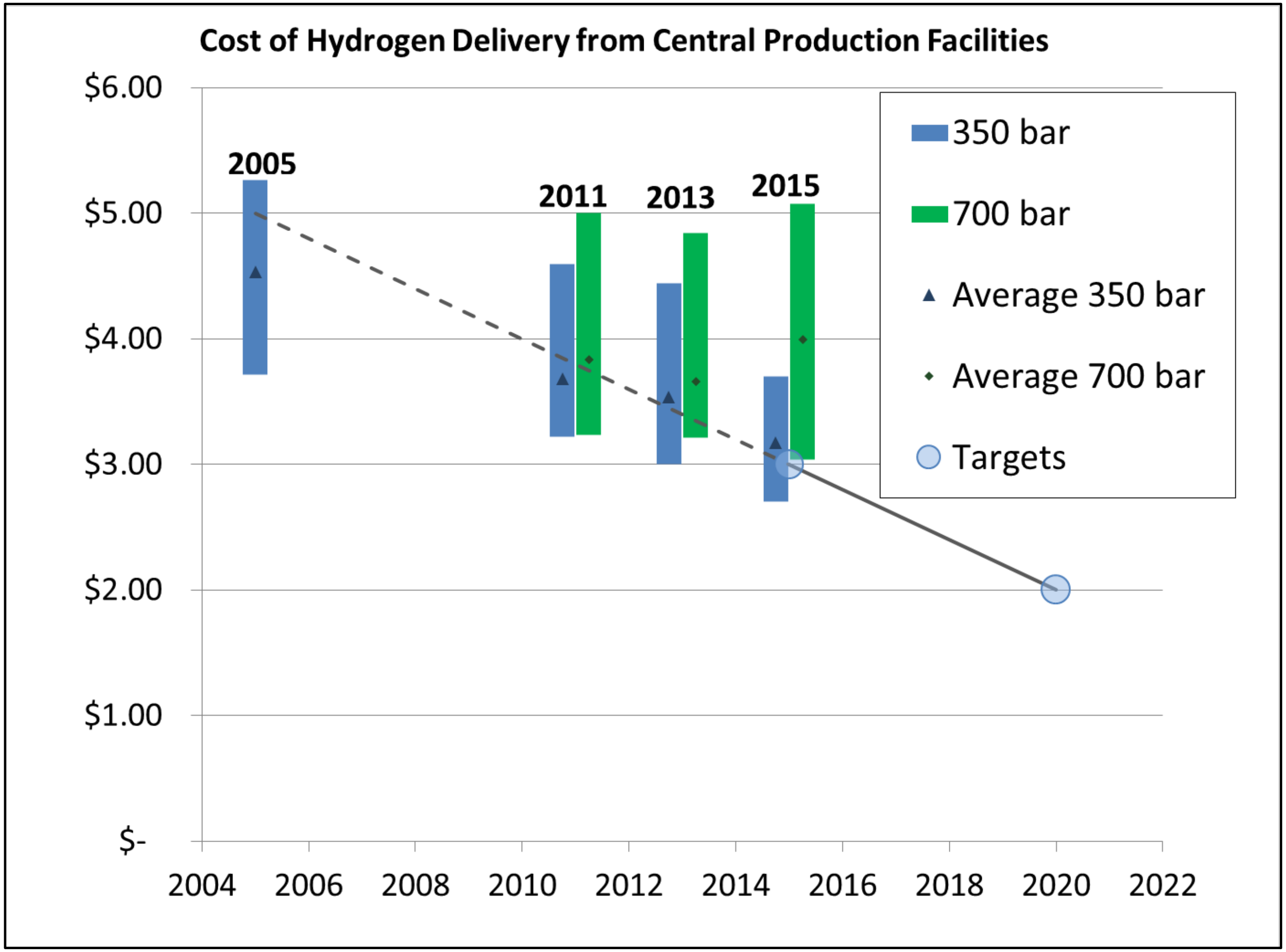
Pipeline delivery cost drops from ~$16/kg for small HRS at low volume to ~$4/kg for large HRS at high volume *-Accomplishment*

Scenario Parameters	Value
Market	Urban
City	Indianapolis, IN
Market Penetration	2% **(16 MT/day)**
Utilization	Full Utilization (80%)
Analysis Period	30 years
Dispensing Pressure	700 bar

- Pipeline cost is a strong function of market demand



HDSAM3.0 used in DOE record of hydrogen delivery cost -Accomplishment



- Increases in the estimates of compression and liquefaction costs increased the average delivery cost, but the tube trailer pathway (with consolidation algorithm) achieved the 2015 delivery cost target of $3.00/gge.

Summary – Progress and Accomplishment

- ❑ A modeling framework (HDSAM3.0) has been updated to examine delivery cost in early and long-term FCEVs markets
  - ❖ Updated formulas for today's cost of delivery and refueling components
  - ❖ Developed means to estimate cost reduction with worldwide HRS market penetration and growth
  - ❖ Demonstrated the strong impact of station economies of scale on H_2 cost
    - ✓ Delivery cost is ~$4/kg$_{H2}$ with today's technologies at high production volume
  - ❖ Tube-trailer supply to HRS is limited to station capacities smaller than delivered payload (a practical limitations on frequency of delivery)
  - ❖ Pipeline cost is a strong function of market demand
  - ❖ Updated user's manual for the version 3.0
- ❑ The model has been peer-reviewed by partners and industry experts
  - ❖ Released in public domain for use by researchers and stakeholders
    - ✓Available at: http://www.hydrogen.energy.gov/h2a_delivery.html

Planned updates to Hydrogen Delivery Scenario Analysis Model (HDSAM) - Future Work

- Update gaseous terminal compression and storage configuration/cost estimates based on recent installations
- Update the liquid delivery pathway with realistic estimates for boil-off losses based on current industry data and practices
- Update cryo-compressed refueling pathway
- Update pipeline modeling and cost information through interaction with pipeline working group
- Update station footprint evaluation (size and cost) in collaboration with Codes and Standards Program
- Post an updated version of HDSAM
- Continue to provide technical support to FCT Office, hydrogen community, and industry stakeholders

Collaborations and Acknowledgments

Collaborators and Partners:

– Daryl Brown, Pacific Northwest National Laboratory: provided updated refueling components cost estimates and price indices; reviewed cost estimates against California CEC projects, conducted model reviews, and developed user manual

– Neha Rustagi, Technology Manager, FCTO: provided modeling information and conducted model reviews

– Boyd H2, Bob Boyd: provided information on configuration of current refueling stations and conducted model reviews

– Fuel Science, George Parks: reviewed cost reduction factors for various production volume/ technology maturity, and conducted model reviews

Project Summary

- **Relevance:** Model delivery cost in early and projected long-term FCEVs markets. Identify cost drivers of current technologies for hydrogen delivery and refueling. Develop estimates of delivery and refueling cost reduction with market penetration. Assist FCTO with setting cost and performance targets in MYRD&D planning. Investigate delivery pathways and identify R&D areas with potential to meet cost and performance targets.
- **Approach:** Collaborate to acquire/review model inputs and examine/review model and results. Acquire current cost of refueling and delivery components from vendors and industry experts. Check model inputs against cost data in early markets (e.g., CA CEC projects). Evaluate cost reduction of components with production volume. Check methodology through interaction with industry experts. Evaluate performance of various hydrogen supply options and station design configurations. Identify major cost drivers for hydrogen delivery/refueling. Review modeling approach and results with partners, Tech Teams, and experts from industry.
- **Collaborations**: Collaborated with researchers from other national labs and interacted with experts from the industry with knowledge and experience on delivery and refueling components relevant to this project. Acquired information needed for the simulations and received valuable input and suggestions to complete our project.
- **Technical accomplishments and summary of findings:**
  - Updated formulas for today's cost of delivery and refueling components
  - Developed means to estimate cost reduction with worldwide HRS market penetration and growth
  - Demonstrated the strong impact of station economies of scale on H_2 cost
  - Delivery cost is ~$4/kg$_{H2}$ with today's technologies at high production volume
  - Tube-trailer supply to HRS is limited to station capacities smaller than delivered payload (a practical limitations on frequency of delivery)
  - Pipeline cost is a strong function of market demand
  - Updated user's manual for the version 3.0
- **Future Research**: Update gaseous terminal compression and storage configuration/cost estimates based on recent installations. Update the liquid delivery pathway with realistic estimates for boil-off losses based on current industry data and practices. Update cryo-compressed refueling pathway. Update pipeline modeling and cost information through interaction with pipeline working group. Update station footprint evaluation (size and cost) in collaboration with Codes and Standards Program. Post an updated version of HDSAM.

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Project: PD14

Publications

- Elgowainy, A., Reddi, K., Brown, D., and Rustagi, N. December 2015. Hydrogen Delivery Scenario Analysis Model (HDSAM), V3.0, available at: http://www.hydrogen.energy.gov/h2a_delivery.html

- Weeda, M., and Elgowainy, A. (2015) “Large Scale Hydrogen Delivery Infrastructure,” International Energy Agency, Hydrogen Implementation Agreement, Final Report, Expert Group Task 28, August. Available at: http://ieahia.org/Activities/Task-28/Task-28-report_final_v2_ECN_12_2_v2.aspx

- Reddi, K., Mintz, M., Elgowainy, A., and Sutherland, E. (2015) “Challenges and Opportunities of Hydrogen Delivery via Pipeline, TubeTrailer, Liquid Tanker and Methanation of Natural Gas Grid,” in D. Stolten and B. Emonts (editors), Hydrogen Science and Engineering: Materials, Processes, Systems and Technology, First Edition, ISBN: 978-3-527-33238-0, Wiley.

Acronyms

- AEO: Annual Energy Outlook
- ANL: Argonne National Laboratory
- CEC: California Energy Commission
- DOE: Department of Energy
- EIA: Energy Information Agency
- FCEV: Fuel Cell Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- GH_2: Gaseous Hydrogen
- GDP: Gross Domestic Product
- GREET: Greenhouse gas, Regulated Emissions, and Energy in Transportation
- H2: Hydrogen
- H2A: Hydrogen Analysis
- H2FIRST: Hydrogen Fueling Infrastructure Research and Station Technology
- HDSAM: Hydrogen Delivery Scenario Analysis Model
- HRS: Hydrogen Refueling Station
- LH_2: Liquid Hydrogen
- MSM: Macro-System Model
- MT: Metric Ton
- MYRD&D: Multi-Year Research, Development, and Demonstration
- PNNL: Pacific Northwest National Laboratory
- R&D: Research and Development
- SNL: Sandia National Laboratory