DOE Hydrogen Program
2007 Annual Merit Review
May 15-18, 2007
Washington DC

Hydrogen Delivery Infrastructure Options Analysis

Bruce Kelly

Nexant, Inc.

Project ID: PD12 Kelly

Overview

Timeline

- Start – June 2005
- Finish – March 2008
- 70 percent complete

Budget

- Total project funding
  - o DOE - $1,886,504
  - o Contractor - $0
- 2005 - $570,000
- 2006 - $745,000
- 2007 - $551,000

Barriers

- Delivery systems analysis
- Novel solid / liquid transport
- Delivery storage costs

Targets

- 2007: Delivery infrastructure criteria
- 2012: <$1.70/gge delivery + dispensing
- 2017: <$1.00/gge delivery + dispensing

Partners

- TIAX
- GTI
- Air Liquide
- NREL, ANL, PNNL
- Chevron
- Pinnacle West

Objectives

- Refine technical and cost data in H2A Component and Scenario Models to incorporate additional industrial input and evolving technology improvements
  - Significant data additions
  - Delivery system storage analysis and optimization
- Explore new options to reduce hydrogen delivery cost, including novel carriers
- Expand H2A Component and Scenario Models to include new options leading to Version 2 models
- Provide bases to recommend hydrogen delivery strategies for initial and long term use of hydrogen as a major energy carrier

Approach

- Compile data on liquid and gas fuel distribution methods
- Develop improved and expanded energy requirements, capital costs, and operating costs for 19 hydrogen delivery pathways
- Evaluate capability of existing infrastructure to deliver hydrogen
- Assess greenhouse gas and pollutant emissions for each delivery option
- Compare and rank delivery options
- Recommend hydrogen delivery strategies as a function of market development

Delivery Options

1: Dedicated pipelines for hydrogen gas delivery

2: Convert existing natural gas and oil pipelines to hydrogen gas delivery

3: Blend hydrogen with natural gas for pipeline transmission; separate at city gate

4: Truck delivery of hydrogen gas

5: Truck transport of hydrogen liquid

6: Novel hydrogen carriers

7: Mixed mode pathways

Project Status/Accomplishments

June 2005 to May 2006

- Analyzed hydrogen/natural gas mixing, transmission, and separation utilizing existing natural gas pipeline infrastructure
- Evaluated refurbished natural gas pipelines for hydrogen transmission
- Assembled industrial and commercial data for performance and cost improvements to H2A models and reviewed the V1 H2A Delivery Model

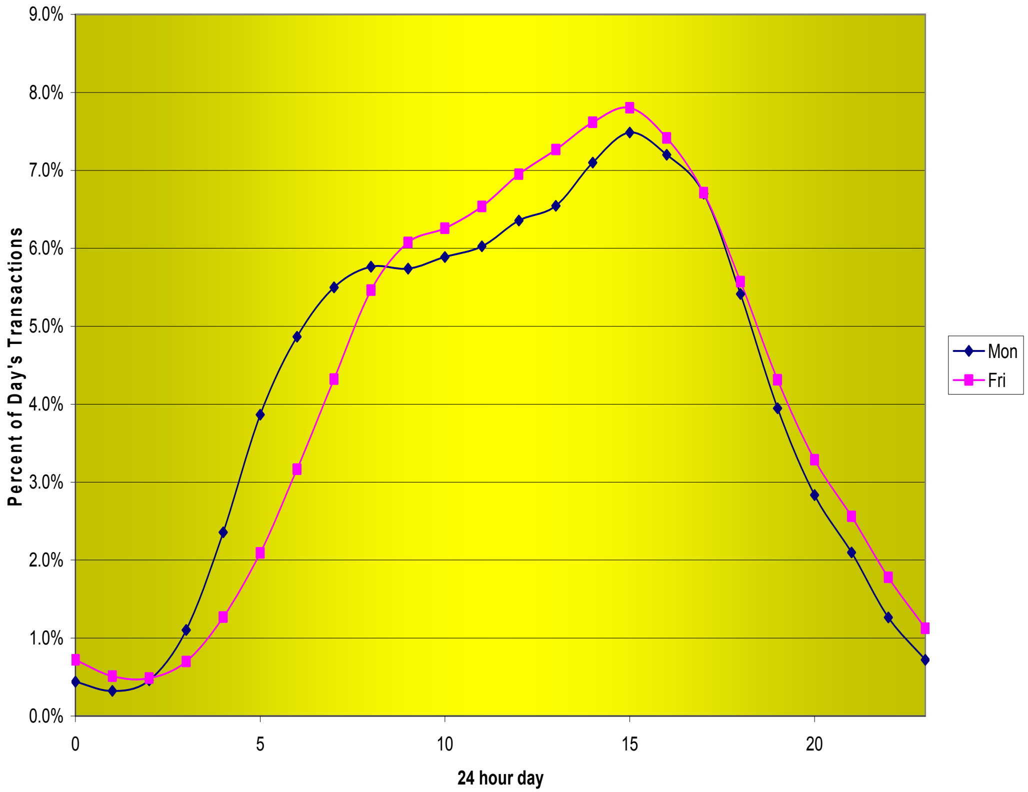
Project Status/Accomplishments

May 2006 to May 2007

- Analysis of market demand and supply variations and delivery systems optimization for storage, compression, dispensing
- Improved hydrogen compressors characterization: capacities and costs at refueling site and terminals
- Improved storage vessel designs and costs at refueling site and terminals
- Improved estimates for hydrogen liquefaction energy requirements and plant costs
- Modeled variable refueling site sizes: compressor capacities, cascade storage capacities, number of dispensers, electric power supply, etc.
- Revamped distribution pipeline costs
- Analyzing novel carrier pathway options

Analysis of market demand and supply variations

- **Supply Side Variations: Central Production Plant Outages**
  - Scheduled yearly maintenance: Typically 5 to 10 consecutive days each year
  - Unscheduled maintenance outages: Indeterminate time and length
  - Natural disasters: A few days?
- **Demand side variations**
  - Hourly at refueling sites
  - Day to day at refueling sites
    - Friday is 8% higher than the average
  - Winter/Summer demand variation
    - Summer is 10% above average; winter is 10% below average



Analysis of Storage Options and Costs

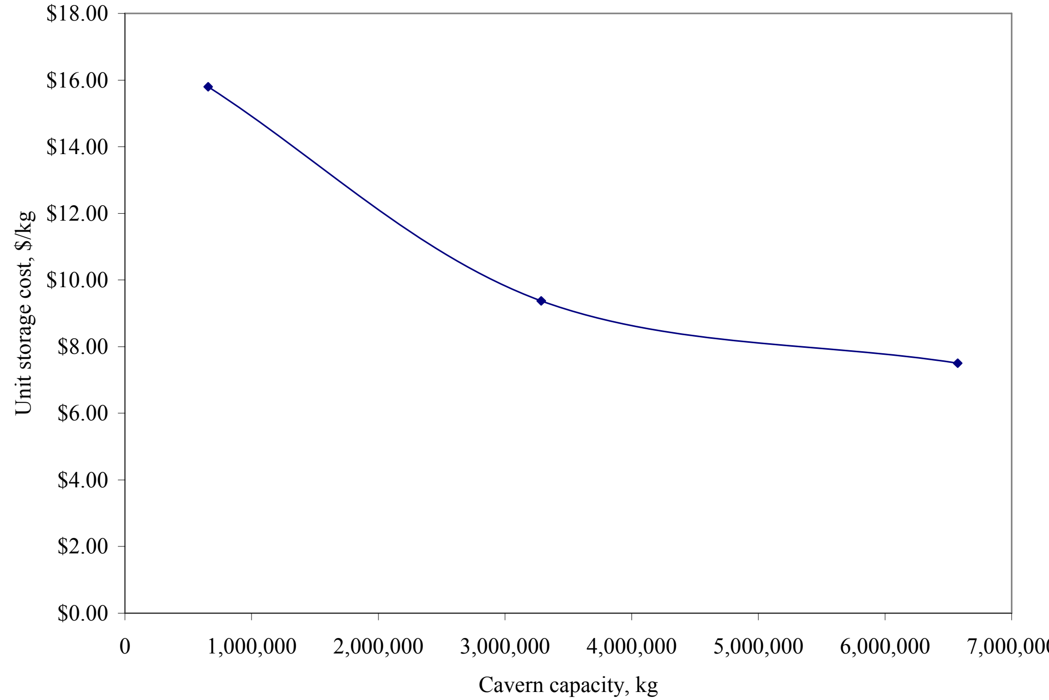
- **Storage Problem**
  - **Production plants operate at constant rate, but demand varies**
- **Storage Options**
  - **Geologic gas storage**
    - **Low cost for very large amounts of hydrogen**
    - **May not be conveniently located**
  - **Liquefaction and liquid storage: Second best for large quantities**
  - **GH2 Tanks: Highest cost, but efficient for small volumes**

❖ ***Storage and compression can add significant cost to hydrogen delivery***

❖ ***Need to find the optimum storage solution***

Geologic GH2 and Liquefaction/LH2 Storage

- Geologic gas storage costs: Two orders-of-magnitude less than steel pressure vessels



- Liquefaction and liquid storage costs: Nominal $45/kg of hydrogen stored for large production plants and storage capacities

- Steel pressure vessels: $1,300 to $1,500/kg of hydrogen stored

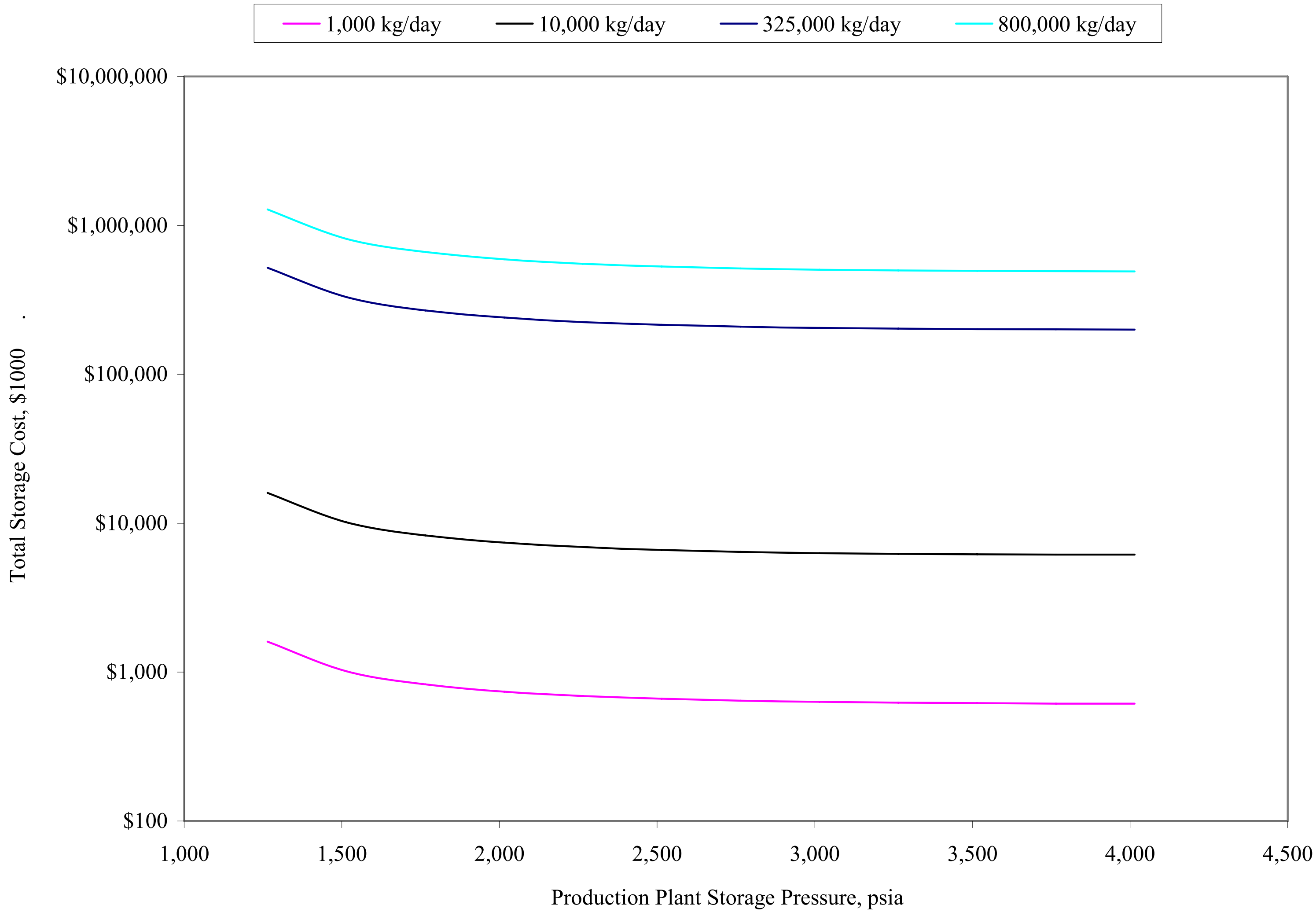
GH2 Hydrogen Vessel Storage

Vessel design options

- SA516, Grade 70; 17,500 psi allowable stress
  - 48 in. diameter; 24 ft. long; 2.5 in. wall thickness
  - $1.91/lb of steel; $980/kg of hydrogen stored
- SA36; 14,000 psia allowable stress
  - 48 in. diameter; 24 ft. long; 3.25 in. wall thickness
  - $1.78/lb of steel; $1,223/kg of hydrogen stored
- SA372, Grade J, Class 70; 40,000 psi allowable stress
  - 24 in. diameter; 25 ft. long (2,800 psi H_2 pressure)
  - $2.75/lb of steel; $596/kg of hydrogen stored

GH2 Vessels as Hourly Storage

Capital and operating cost versus pressure



GH2 Vessel Storage: Conclusions

- **Gas storage vessel design**
  - **SA516, Grade 70; 2,500 psia; 2.5 in. wall thickness**
  - **4.1 ft. diameter, 24.9 ft. long, 91 kg hydrogen capacity**
  - **$2.30/lb of steel; $816/kg of hydrogen stored**
- **Recommended inputs to H2A model**
  - **<u>$1,340/kg of hydrogen stored</u>, including shipping, auxiliaries, installation, engineering, site preparation, contingency, and permit fees**
  - **Independent of capacity**

>90% effective for storage

Refueling Site Cascade Charging/Storage

- ASTM SA372, Grade J, Class 70 low alloy steel
- $843/kg budgetary price from CP Industries
- Vessels are 16 inches diameter, 30 feet long
  - 6250 psia vessel stores 21.3 kg
  - 5000 psia vessel stores 19.4 kg
  - 4000 psia vessel stores 17.2 kg

- $843/kg of hydrogen stored unit price assumed for each vessel
- With shipping, $926/kg of hydrogen stored

Refueling Site Cascade Charging/Storage

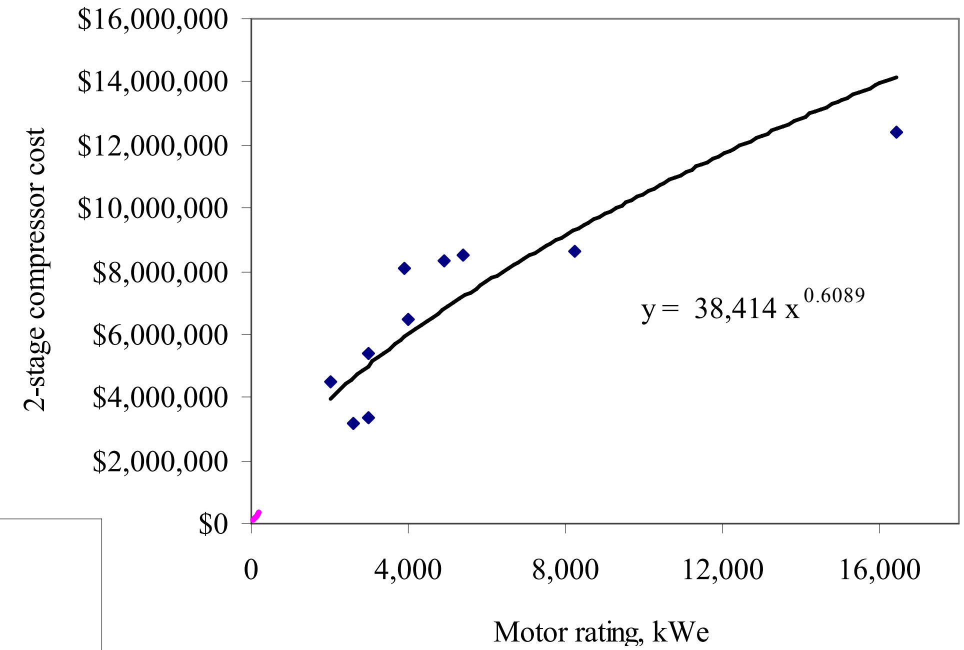
Recommended inputs to H2A models

- $926/kg for vessel assembles, delivered
- $268/kg for storage auxiliaries
- $266/kg for engineering, site preparation, contingency, and permit fees
- <u>$1,460/kg of hydrogen stored</u> total investment cost

Designed for vehicle dispensing: Only ~30% effective for storage

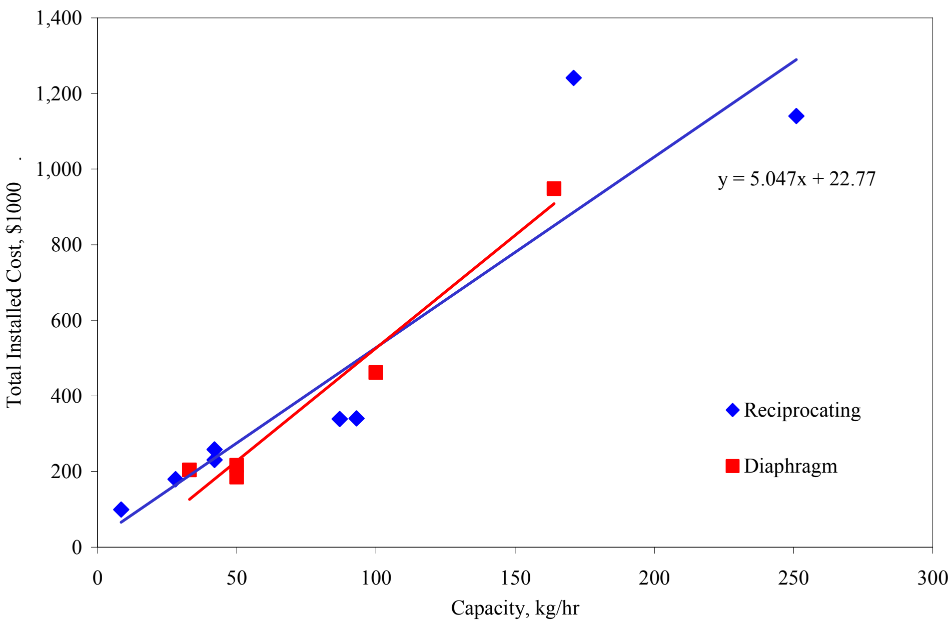
Compressor Costs for Storage and Dispensing

Large reciprocating and refueling site compressors



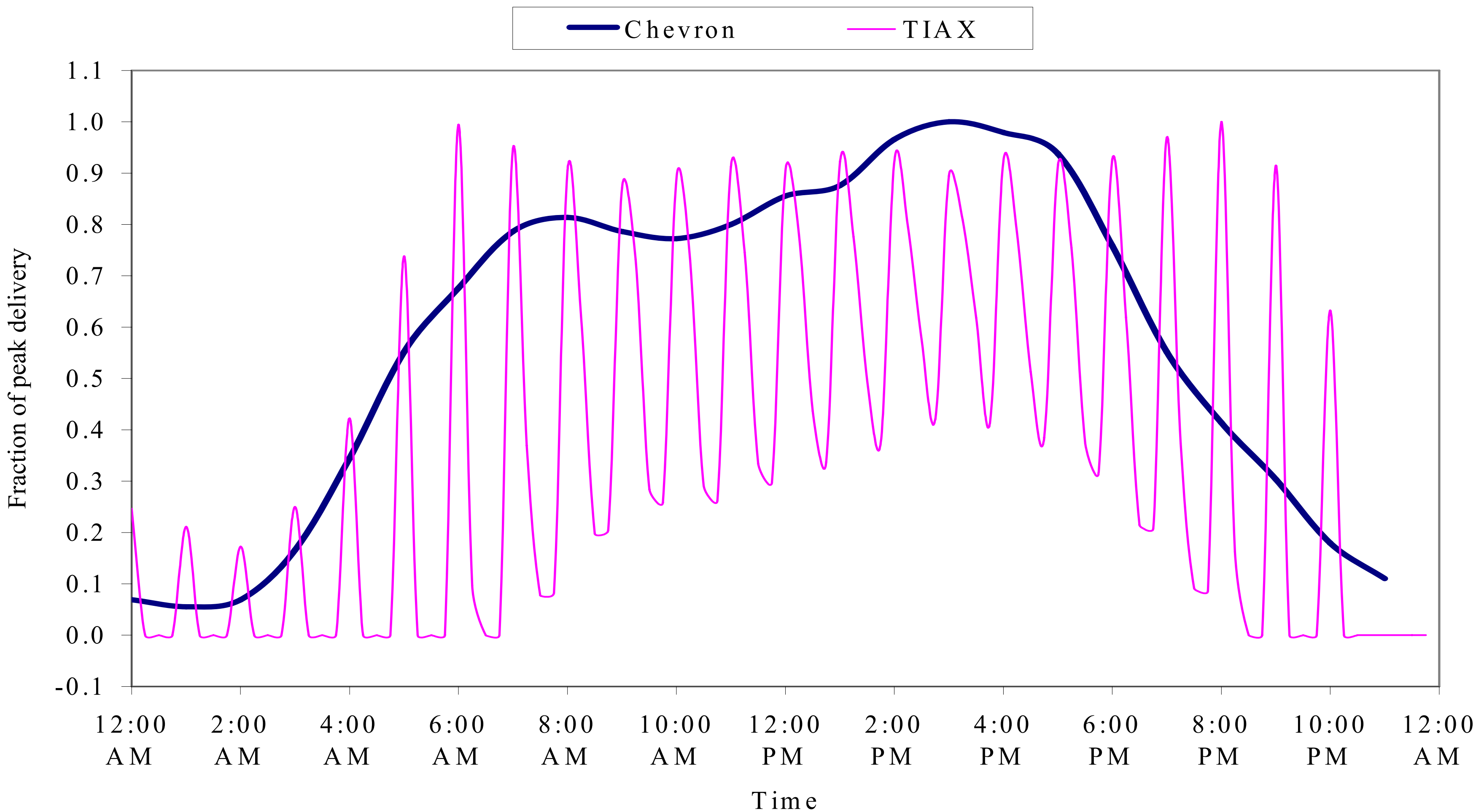
Large Compressors

Small Compressors



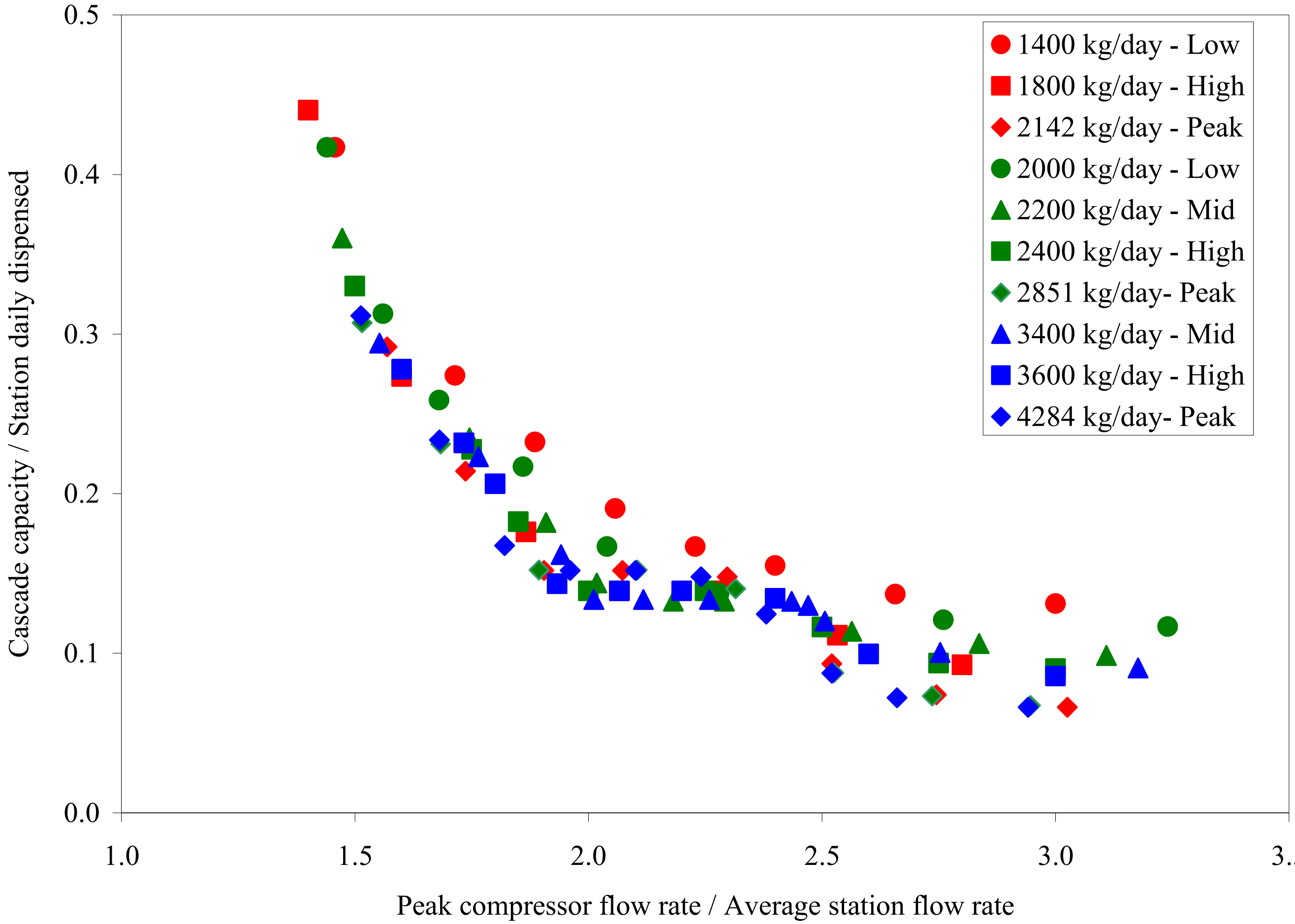
Refueling Site Design and Optimization

Refueling demand shifted to beginning of each hour



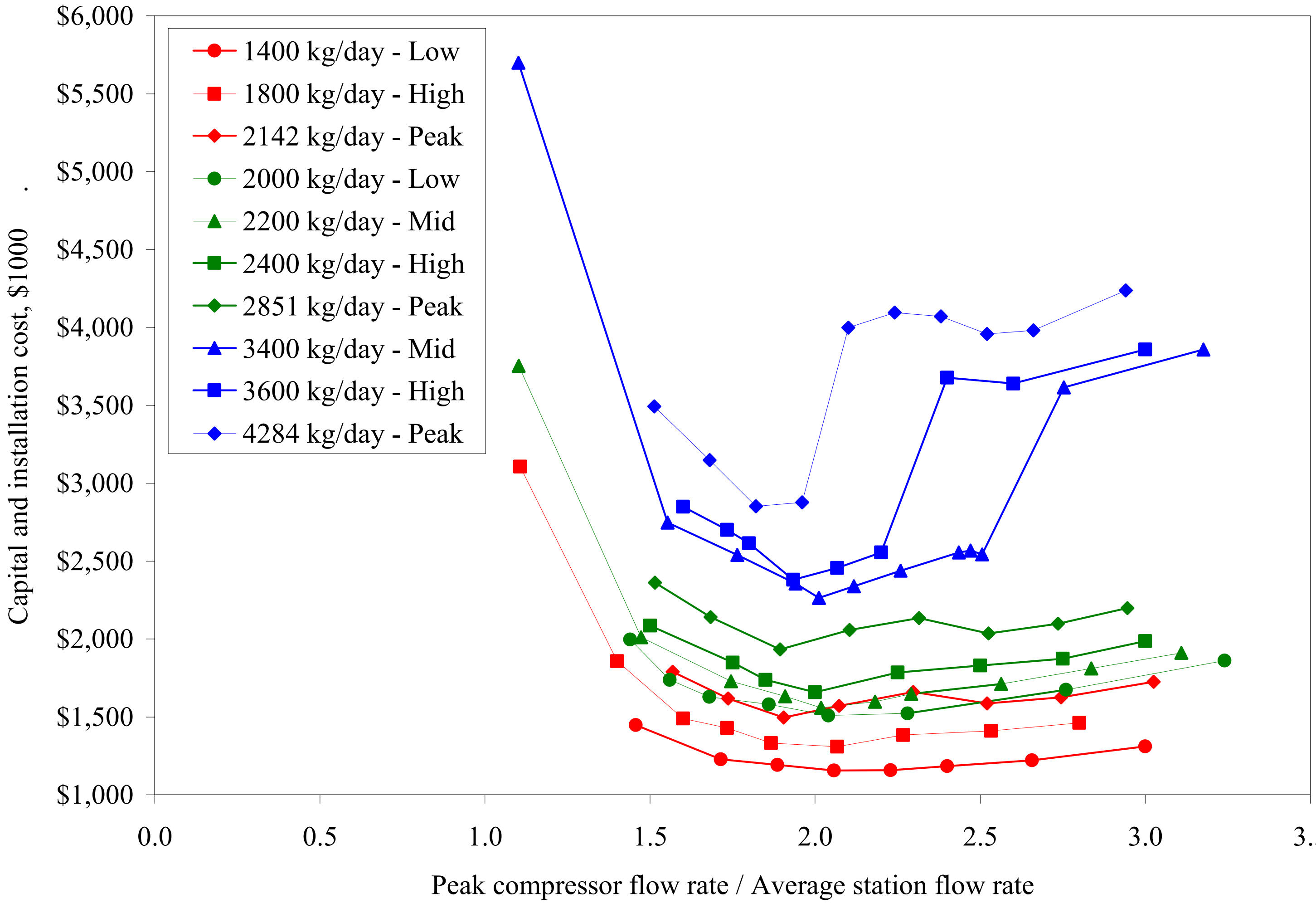
Refueling Site Design and Optimization

Required combinations of refueling site compressor and cascade charging system capacities



Refueling Site Design and Optimization

Refueling site optimization



System Optimization for Hourly Demand Profile

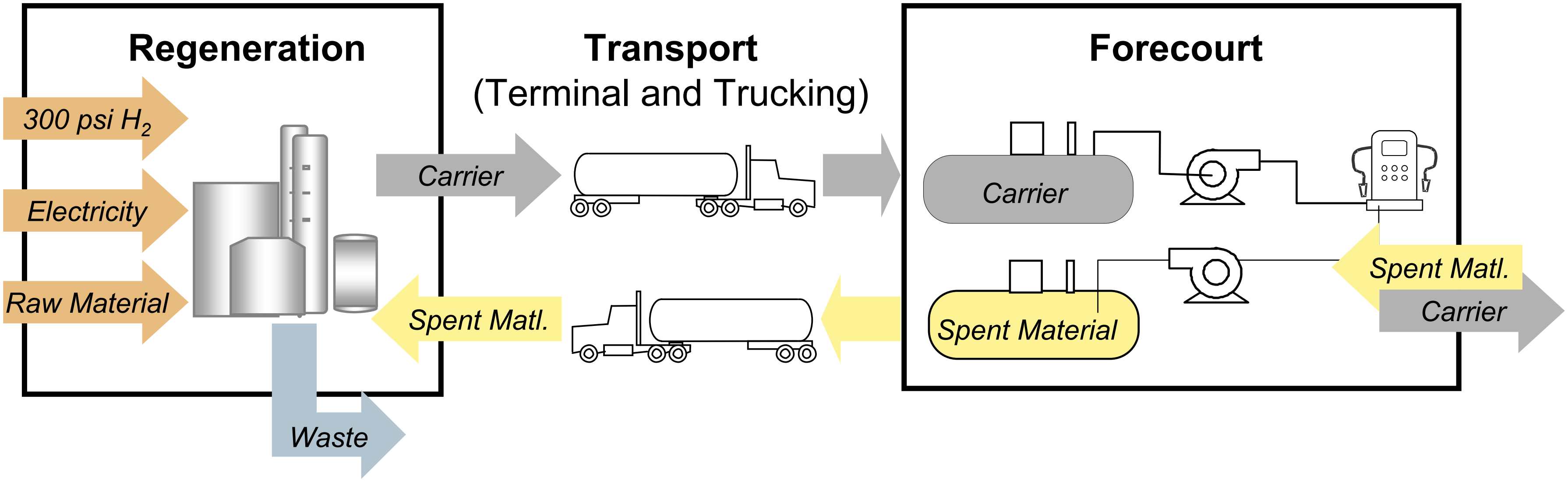
- **Optimized compressor/cascade storage system does not have sufficient storage for full daily profile**
  - **Need an additional 0.3 days of storage**
- **Pipeline Pathway**
  - **Low pressure storage (2500 psi) offers the most efficient and cost effective means for providing storage**
  - **Terminal: Storage compressor, plus low cost land**
  - **Refueling site: One compressor may be suitable; additional land for low pressure storage vessel**
- **Gas Tube Trailer, and Liquefaction/Liquid Truck Pathway**
  - **Tube trailer, or liquid truck, at the refueling site provides 0.3 days of storage**

Novel Hydrogen Carriers

Novel Delivery	Example Materials
Liquid	• **Liquid HC (APCI Material)** • **Ammonia-Borane**
Solid-Liquid Slurry	**All with liquid carrier:** • **Chemical Hydrides (SBH, MgH_2)** • **Metal Hydrides ($NaAlH_4$)** • **Carbons?**
Bricks	• **Chemical Hydrides, Alanates?** • **Metal Hydrides** • **Carbons**
Flowable Powder	• **Metal Hydrides** • **Chemical Hydrides** • **Carbons**

The primary challenges for all novel carriers include cost, density (weight and volume), and energy requirements

Novel Carriers - Modified H2A Tabs



- Major cost contributors: initial capital, continuous material, and energy
- Today's processes may not recycle all spent material

- Transportation of the carrier and spent material in same truck
- Cost inputs include H2 yield, capital costs, and delivery distance

- May include carrier and spent material storage and dispensing (loading and off-loading)
- Alternately, compressed hydrogen dispensing

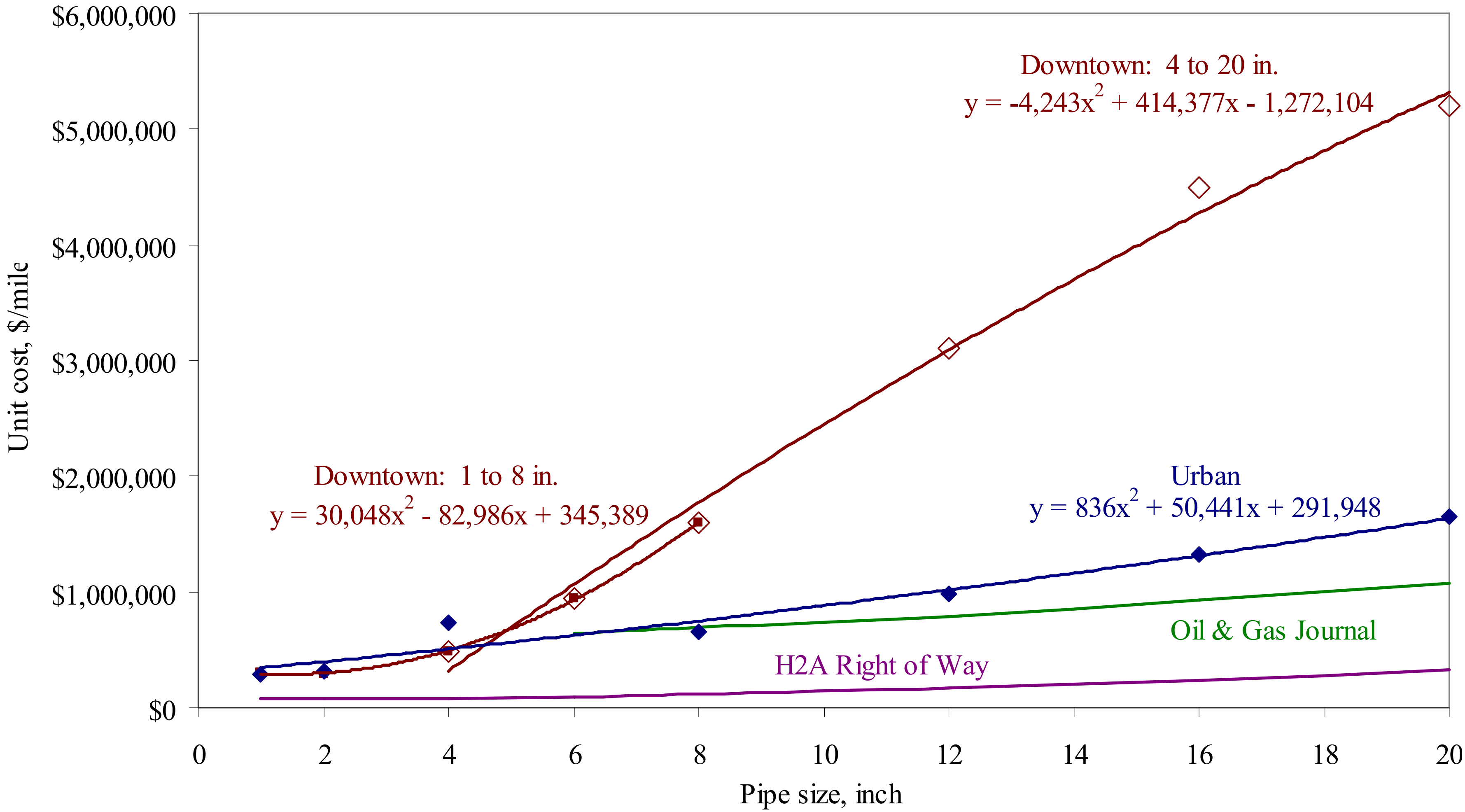
Carrier Objectives, and Some Major Issues

- **Complete a first-phase screening of materials and pathways to determine which are clearly not viable**
- **For carriers deemed viable, create H2A-like tools to consistently evaluate various novel carrier options**
- **Important to avoid making pathway decisions based on the limitations of present technologies and materials**
- **Major issues that remain:**
  - **Are pipelines viable methods of novel carrier transport?**
  - **What is the overall time (days) of a carrier cycle?**
  - **What are the effects of labor costs?**
  - **What is the maximum feasible brick weight?**
  - **Can we better define the equipment used to transport powders?**

Distribution Pipeline Costs

- **Collected historical Oil & Gas Journal data, and surveyed for current urban and downtown data**
- **Verified that historical natural gas pipeline cost data are representative of hydrogen pipeline costs**
- **Better defined regulatory issues and other potential concerns in urban areas and their impact:**
  - **Potential need for odorants or other leak detection technology**
  - **Allowable operating pressures**
  - **Right-of-Way availability**

Distribution Pipeline Costs - Continued



Summary

- H2A model inputs on systems and components optimization, performance, and cost
  - Large hydrogen compressors
  - Refueling site compressors
  - Refueling site cascade storage
  - Hydrogen liquefaction plants
  - Gas storage terminals
  - Distribution pipelines within a city
  - Land areas
  - Variable sized refueling sites: 100-6,000 kg/day average daily capacity
  - Working on novel carriers

Summary - Continued

- **Analysis of market demand and supply variations and delivery systems optimization for storage, compression, and dispensing**
  - **Seasonal demand variations and production plant maintenance: Gas geologic storage, or liquefaction and liquid storage at terminal or plant**
  - **Daily and hourly refueling site: Low pressure (2500 psi) storage at the fueling site or terminal. Could also use oversized transmission pipeline (if >100 miles of transmission pipeline)**

Version 2.0 of the H2A Models will be Published later this year

All this applies to current costs: H2A Models will allow the same principles and optimization for inputted future costs and targets

Future Work

- Complete novel carrier options analyses and incorporate as appropriate
- Incorporate GREET and explicit results for pathway energy efficiency, greenhouse gas and criteria pollutant emissions
- Recommend delivery strategies at each market penetration