NATIONAL RENEWABLE ENERGY LABORATORY

H2A Delivery Analysis and H2A Delivery Components Model

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2010 Hydrogen Program Annual Merit Review

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Project ID # PD015

NREL/PR-560-49745

Overview

Timeline

- *Start date:* FY 2004
- *End date:* on-going Project

Budget

- Funding: 100% DOE Funded
- FY09: $200K
- FY10: $150K

Barriers

- Lack of Hydrogen/Carrier and Infrastructure Option Analysis (3.2 A)
- Gaseous Hydrogen Storage and Tube Trailer Delivery Costs (3.2 F)

Partners

- Argonne National Lab
- Pacific Northwest National Lab
- Nexant, Inc.
- TIAX
- GTI
- Chevron
- Air Liquide
- Linde
- DTI

Relevance: Objectives

Project Objectives

- Update and maintain the H2A Delivery Components Model
- Provide Cost Analysis on Hydrogen Delivery Infrastructure
- Support other models and analysis that include delivery costs
- Expand H2A Components Model by designing new components

MYPP

"Activities: Development of the H2A Delivery Components and Scenario Models, MYPP, 2007, p. 3.2-9"

"Analysis: Comprehensive cost and environmental analyses for all delivery options as function of demand, MYPP, 2007, p. 3.2-9"

Outputs

"D3. Output to System Analysis and System Integration: Hydrogen delivery infrastructure analysis results, MYPP, 2007, p. 3.2-29"

Approach

Since 2004 – the project introduction – we were following the general H2A approach and guidelines:

- collaborating closely with industry getting and updating costs and tech specs in the models
- keeping consistency of the cost inputs across all H2A models
- employing H2A standard assumptions *
- maintaining models as publicly available

* http://www.hydrogen.energy.gov/h2a_analysis.html#h2a_project

Approach /Barriers Addressing

Barrier 3.2 A: Lack of Hydrogen/Carrier and Infrastructure Option Analysis
"Additional analysis is needed to better understand the advantages and disadvantages of the various possible approaches." (p. 3.2-18)

Barrier 3.2 F: **Gaseous Hydrogen Storage and Tube Trailer Delivery Costs** "Approaches include increasing the storage pressure, utilizing cold hydrogen gas, and/or utilizing a solid carrier material in the storage vessel. The same technology approaches could be utilized for gaseous tube trailers making them much more attractive for hydrogen transport and distribution." (3.2-20

Milestone 12
"By 2017, reduce the cost of hydrogen delivery from the point of production to the point of use at refueling sites to < $1/gge" (p. 3.2-26)

APPROACH

- Developing new H2 Delivery option: Rail Delivery Components
- Analyzing a possibility to deliver H2 via existing CNG infrastructure
- Building the model capable of calculating delivery costs from multiple sources to multiple demand centers
- Multi-node delivery model will also include storage sharing capability between demand centers, providing overall storage cost decrease
- Analyzing a possibility for delivering H2 by Truck-Trailer in Composite Tubes instead of Metal tubes – increased capacity

Approach/Milestones

Milestone	% of completion, as of March 31, 2010
H2A Delivery Components Model Update: finalize changes to the 700 bar and cryo-compressed dispensing options	95% complete expected completion: end of April 2010
Hydrogen Rail Delivery Cost Analysis	50% complete expected completion: end of FY10
Multi-node delivery scenario model development, stage 1 and 2	50% complete expected completion: end of June 2010
Review: go/no go decision on delivering hydrogen via natural gas pipelines	10% complete expected completion: end of FY10

Technical Accomplishments and Progress

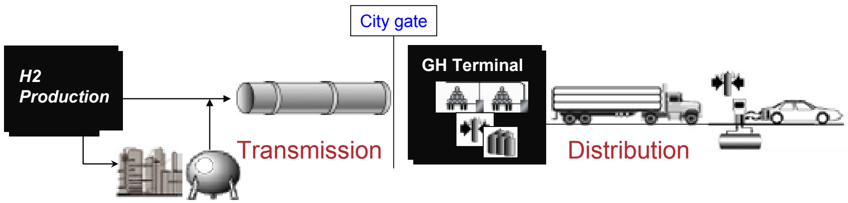
Outline

- H2A Components Model Upgrade and Cost Analysis
- Rail Components development and Cost Analysis
- Building new components for GH2 delivery using composite tubes
- Building multi-node delivery scenario model

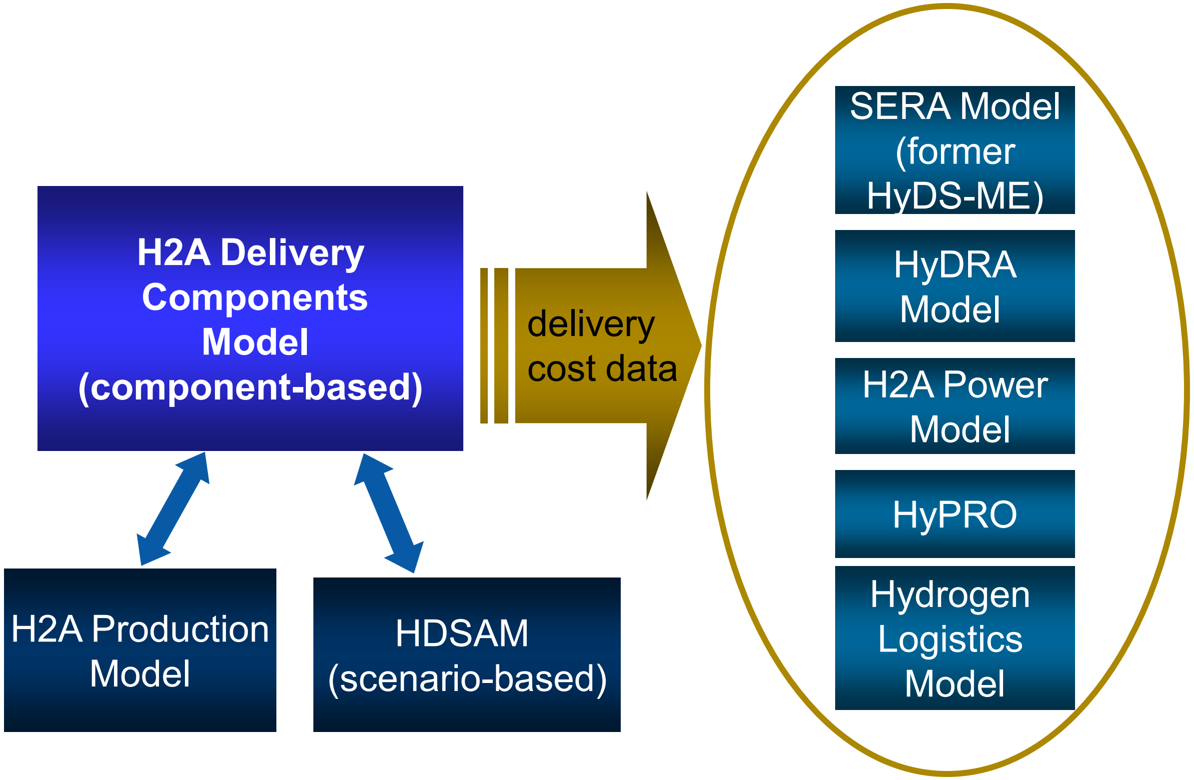
Technical Accomplishments and Progress

H2A Components Model Upgrade and Cost Analysis

H2A DELIVERY COMPONENTS MODEL OVERVIEW



Relation to Other Models



H2A Delivery Components Model provides costs for hydrogen delivery components

- Excel based (availability to public)
- flexible
- can be used to provide inputs for spatially and temporally detailed models

Technical Accomplishments and Progress

H2A Delivery Components Model Upgrade

GH2 Refueling Station Upgrade

dispensing pressure: **350 bar** | **700 bar**

dispensing type:
- 350 bar → cascade
- 700 bar → cascade; booster compressor

tube pressure:
- 350 bar cascade → 180 atm; 480 atm
- 700 bar cascade → 180 atm; 480 atm
- 700 bar booster compressor → 180 atm; 480 atm

LH2 Refueling Station Upgrade

2 dispensing options:

- gas
- liquid or cryo-compressed

Simple Design

Storage
Cryo-Pump
Dispenser

GH2 Tube-Trailer Upgrade

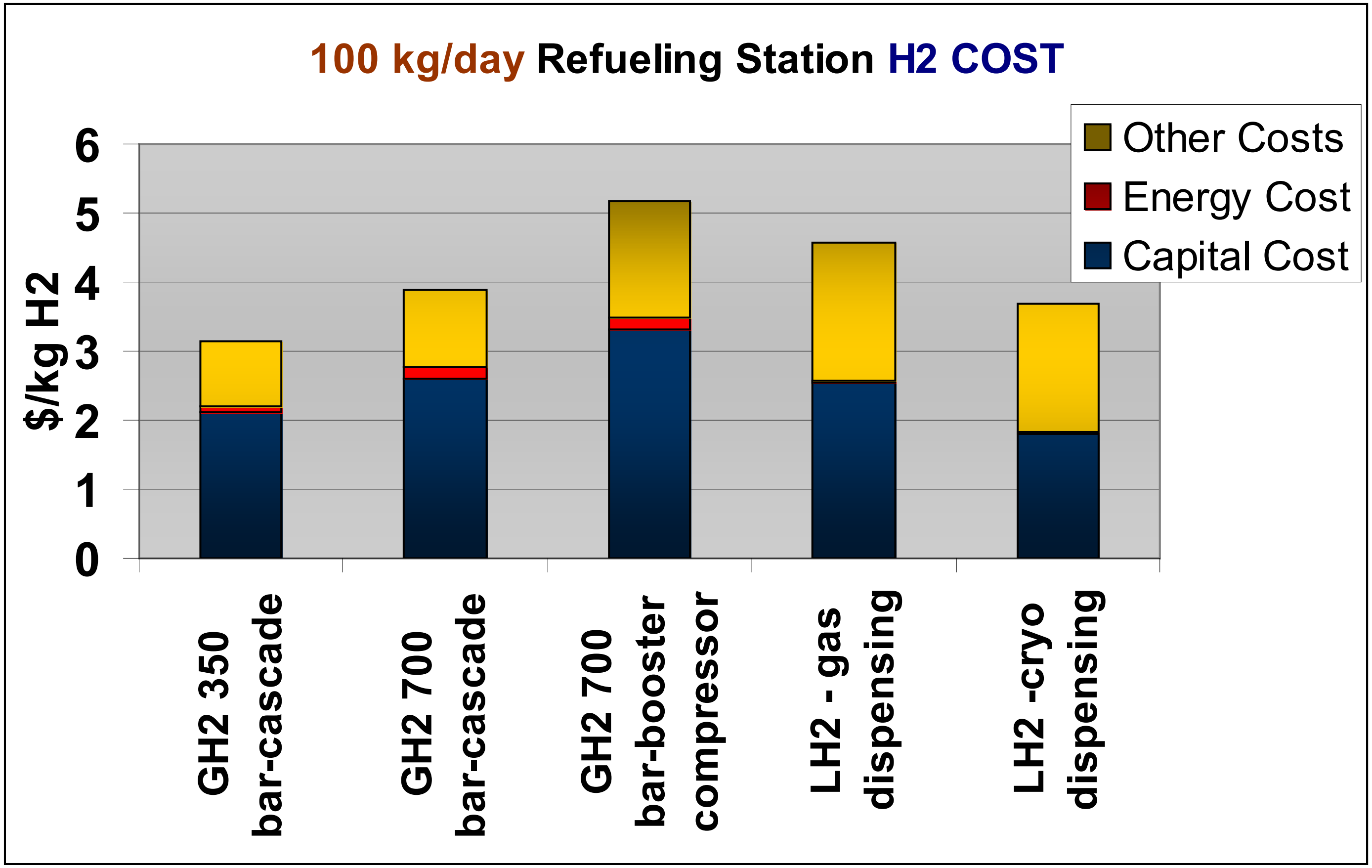
2 options for tube pressure:

- 180 atm
- 480 atm

Technical Accomplishments and Progress

H2A Delivery Components Model Upgrade

Impact on refueling station upgrade

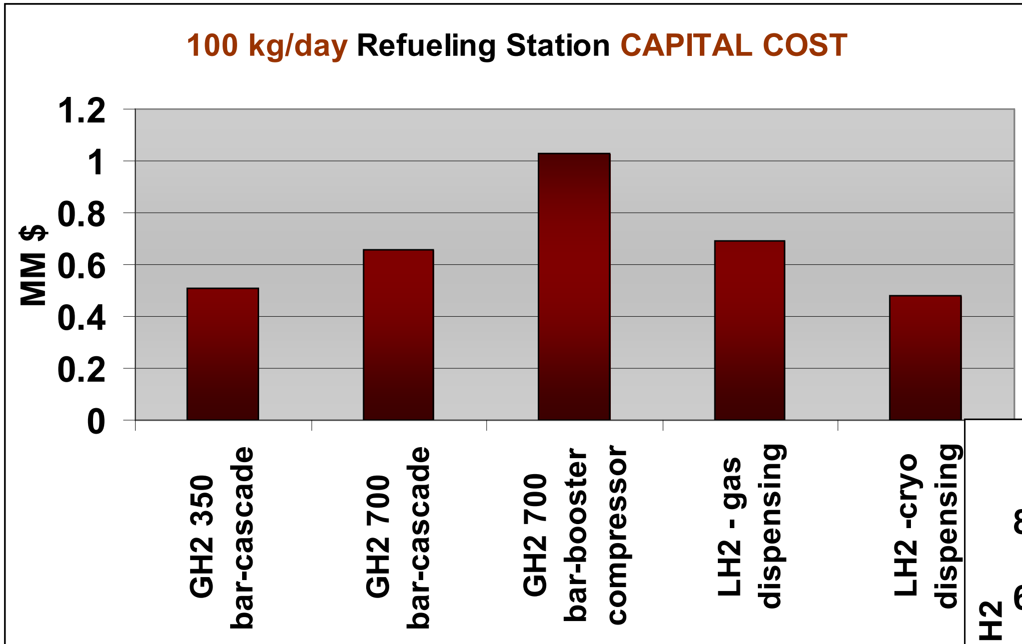


Technical Accomplishments and Progress

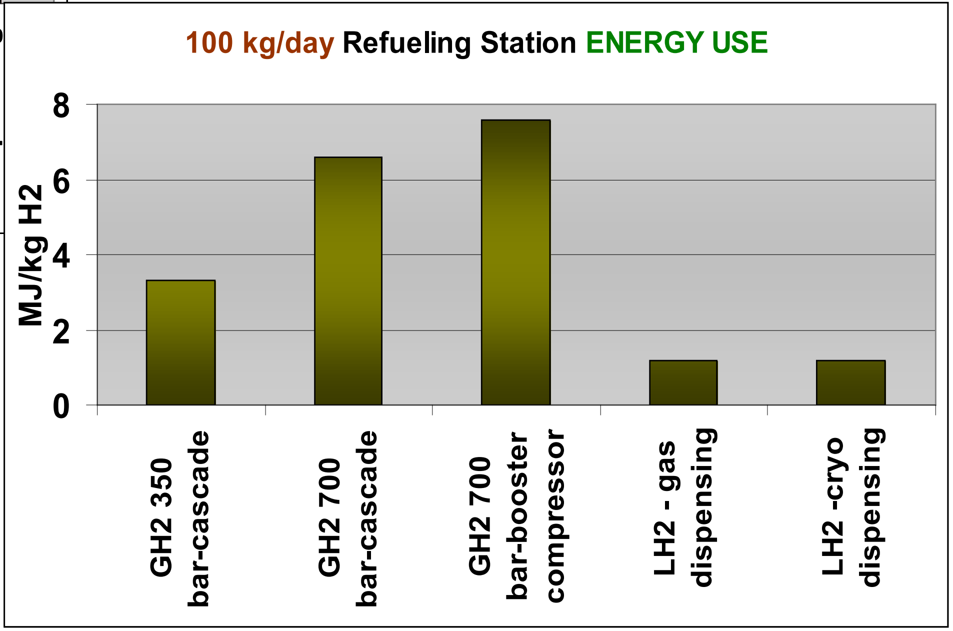
H2A Delivery Components Model Upgrade

How much initial investment needed?

Impact on refueling station upgrade



How energy-effective?

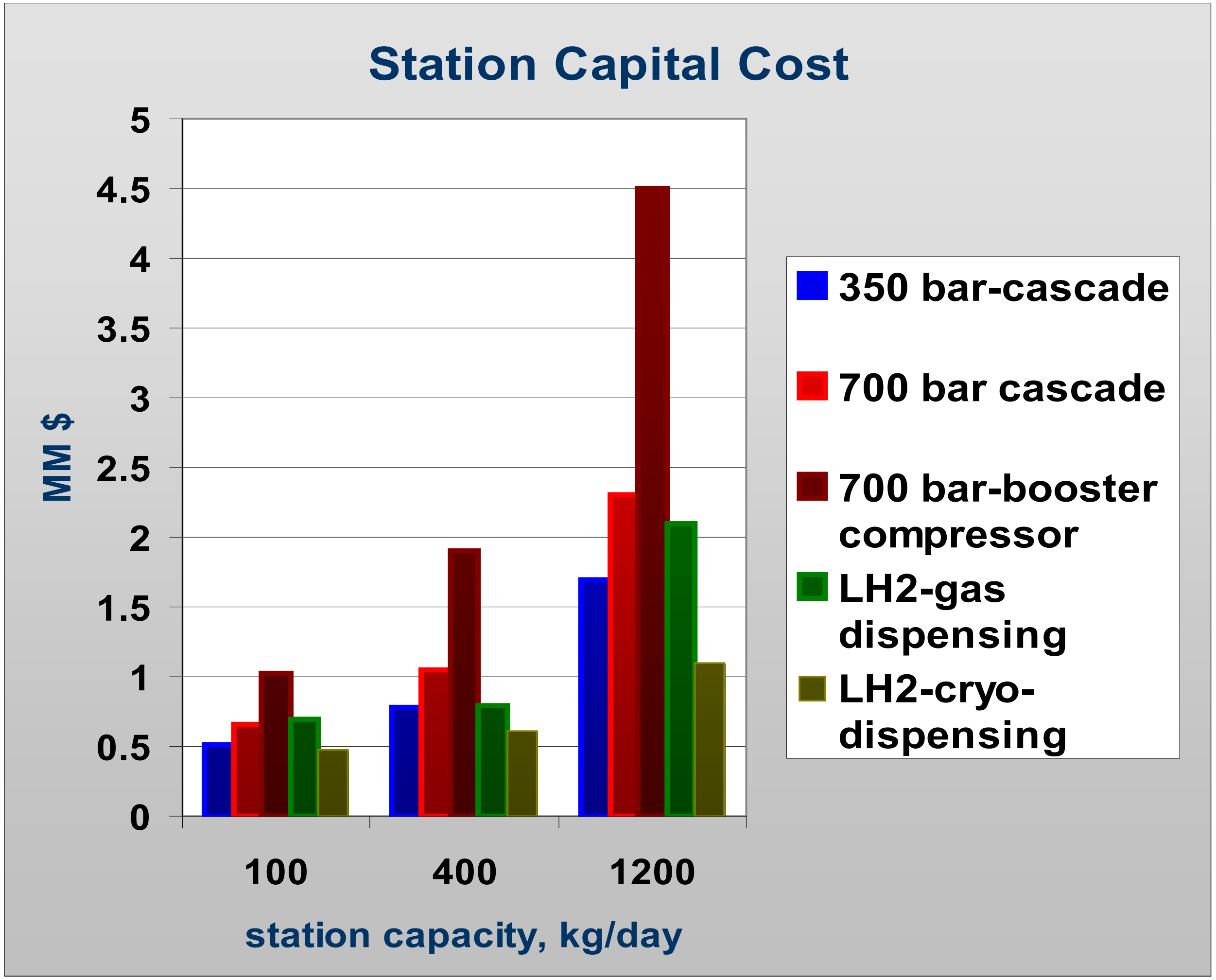


Technical Accomplishments and Progress

H2A Delivery Components Model Upgrade

Station Size Comparison

Larger Station – Bigger Investment



Near term: 100 kg/day

Mid-term: 400 kg/day

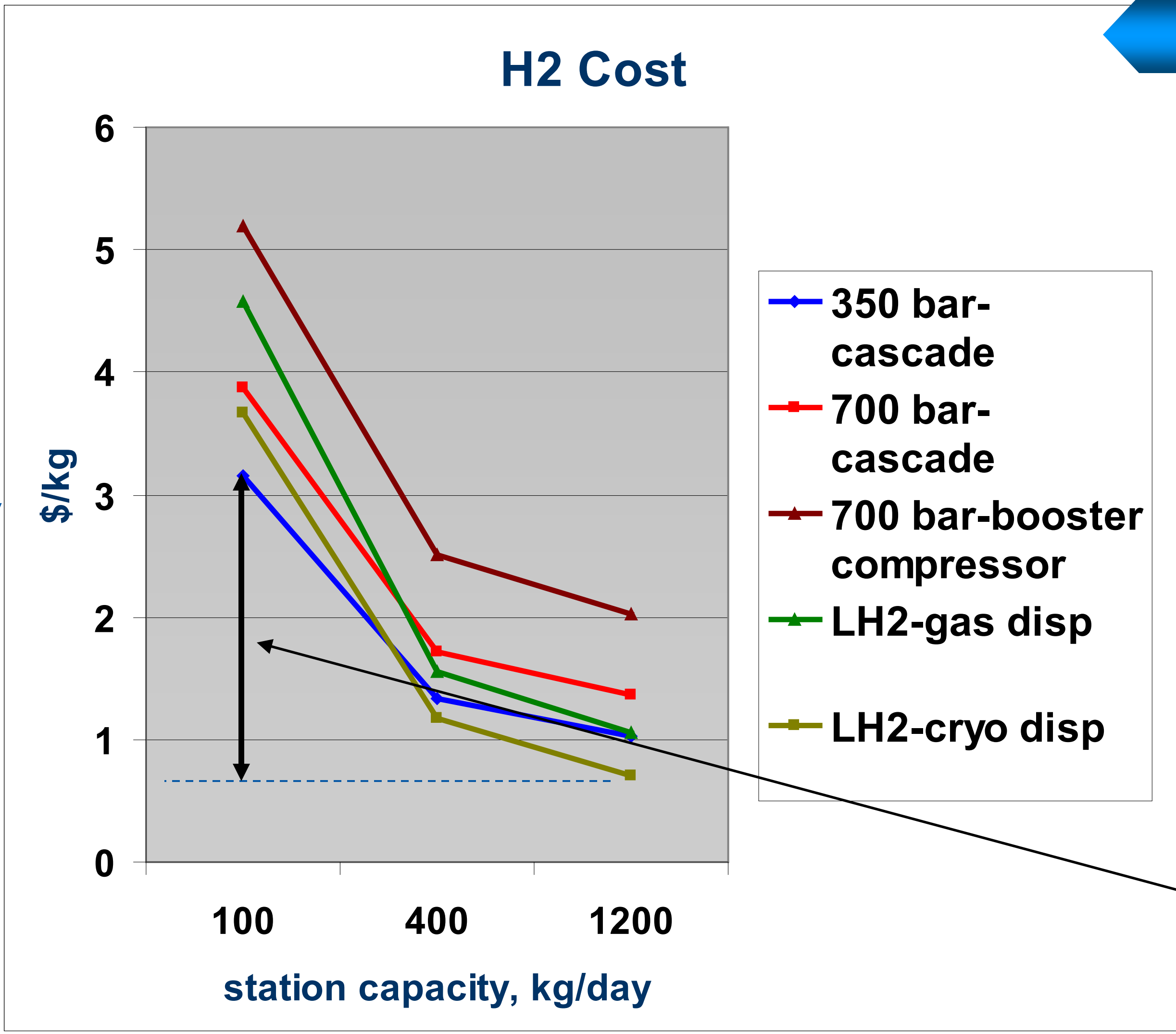
Long-term: 1200 kg/day

cryo-compressed station is the cheapest and has the simplest design

Technical Accomplishments and Progress

H2A Delivery Components Model Upgrade

The larger the station – the cheaper H2



Station Size Comparison

Near term: 100 kg/day

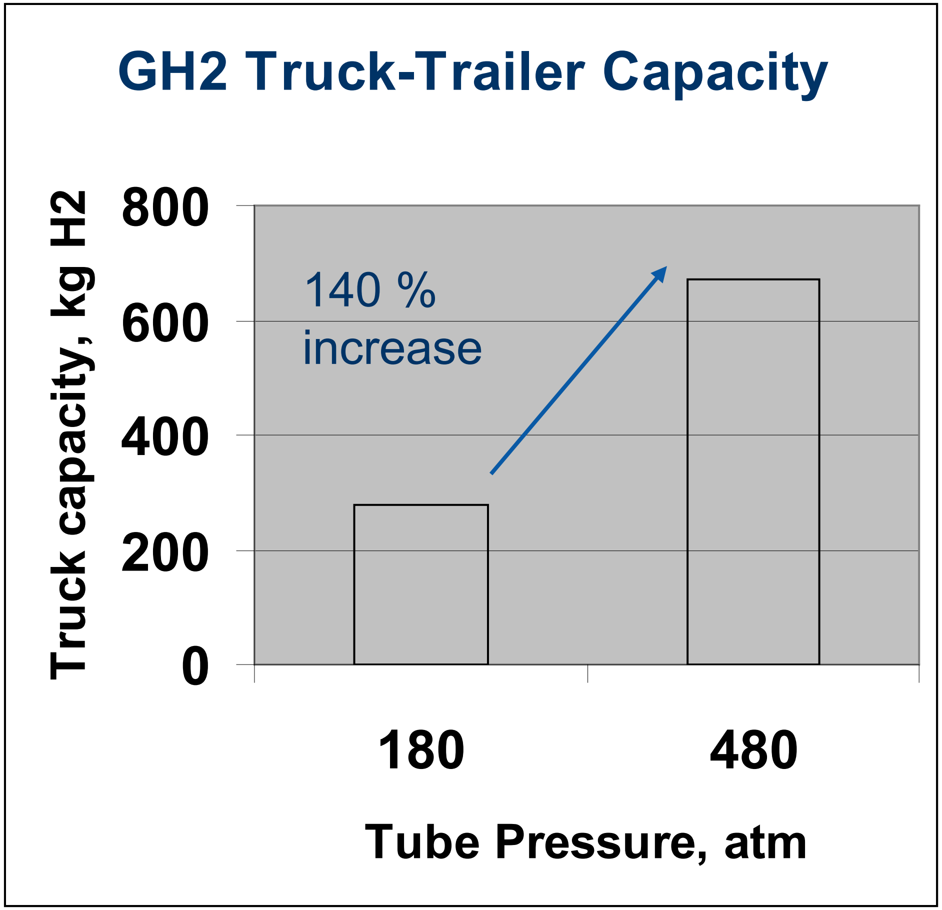
Mid-term: 400 kg/day

Long-term: 1200 kg/day

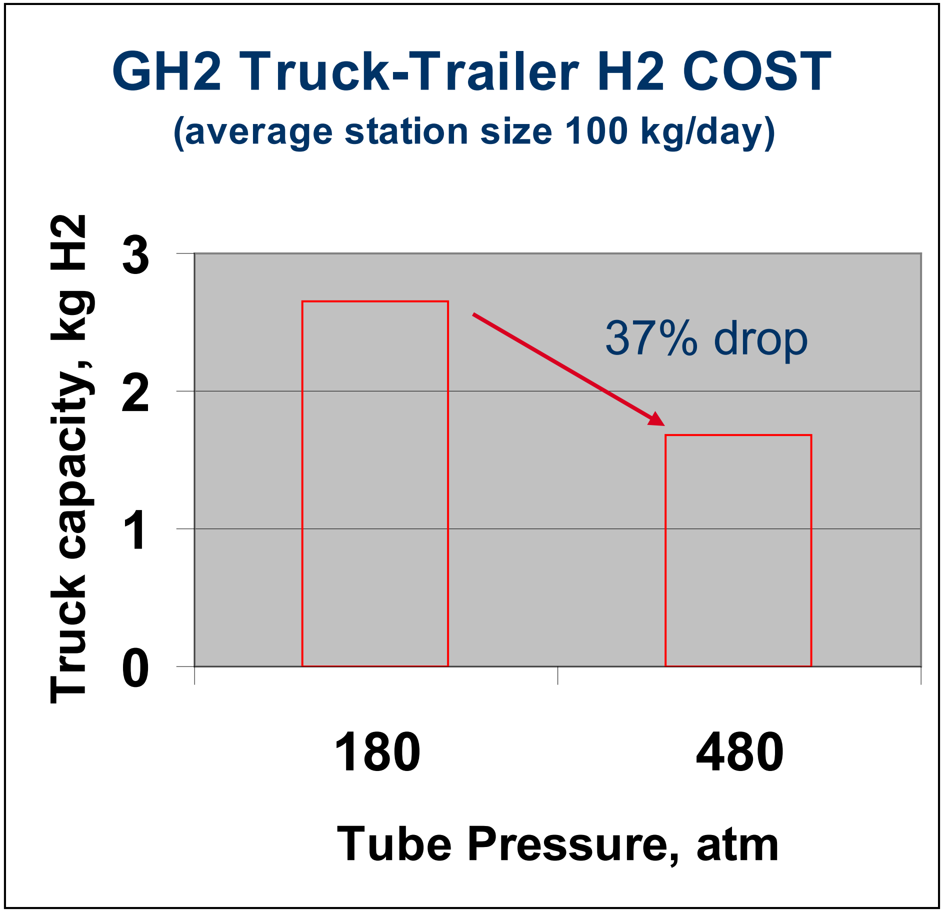
H2 cost drop by Δ=$2.5/kg

Technical Accomplishments and Progress

H2A Delivery Components Model Upgrade



Gaseous H2 Tube Trailer



Technical Accomplishments and Progress

Rail Components Development and Update

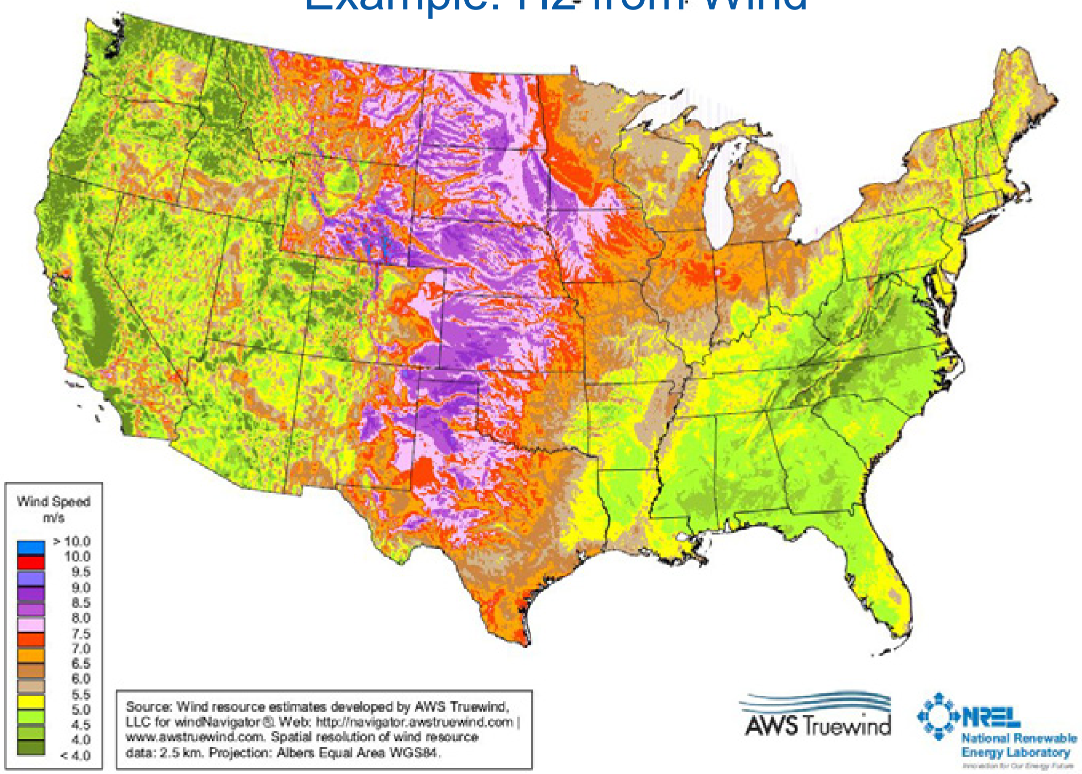
Technical Accomplishments and Progress

H2 Rail Delivery

WHY RAIL?

Rail Delivery may be the most economical option for delivering hydrogen made from renewable sources (long distances+high demand)

Example: H2 from Wind



Estimates of Wind Energy Potential in "purple/red band" states* :

86% of Total US Installed Capacity**

(8,989 GW)

Estimated Annual Generation:

32.4 millions GWh

* IA, KS, MN, MT,NE,NM, ND, OK, SD, TX, WY

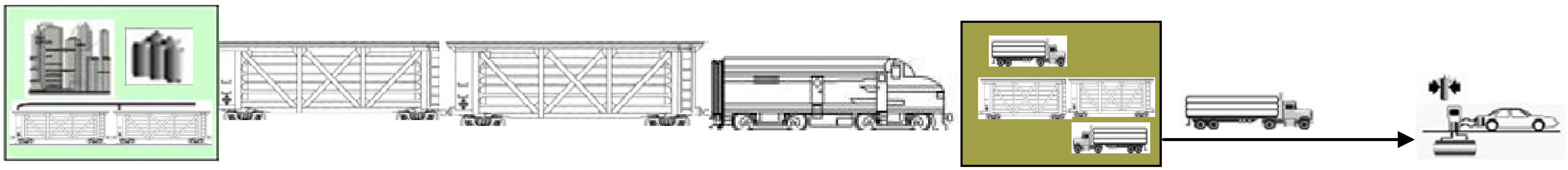
* * 30 % capacity factor at 80 m above ground, assumes 5 MW/km2 of installed nameplate capacity

Source: http://www.windpoweringamerica.gov/pdfs/wind_maps.asp

Technical Accomplishments and Progress

H2 Rail Delivery Pathways

Gaseous Hydrogen Rail Delivery

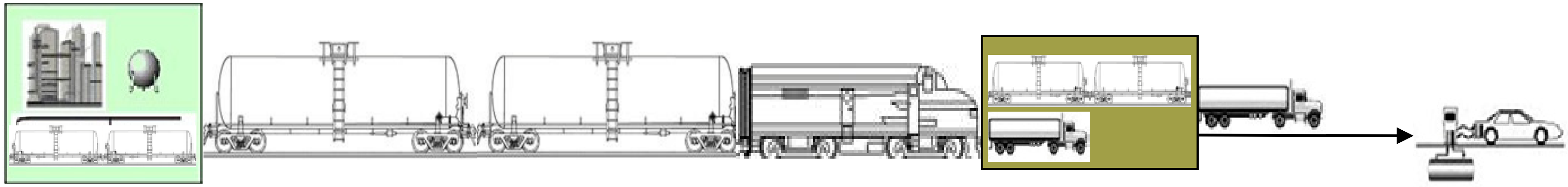


Gaseous Production Site Terminal

Gaseous City Gate Terminal

Gaseous Refueling Station

Liquid Hydrogen Rail Delivery



Liquid Production Site Terminal

Liquid City Gate Terminal

Liquid Refueling Station

Technical Accomplishments and Progress

H2 Rail Delivery Components Update

- ✓ 2 independent reviews (by DTI and PPNL) of the H2 Rail Delivery Components were conducted. The comments and suggestions were incorporated in the updated model.

- ✓ The NREL delivery team collaborated with multiple industry companies in order to refine the input cost and technical data, and to get a better understanding of the logistics of rail delivery:

  - freight data, logistics (Union Pacific Railroads)
  - railcar leasing costs (GE Rail Leasing)
  - intermodal rail crane cost and technical specs (Konecranes Heavy Lifting Company, Paceco)

Technical Accomplishments and Progress

New Components Using Composite Tubes Development

and

Comparative Delivery Cost Analysis

Technical Accomplishments and Progress

New Components: Composite Tubes

To estimate delivery costs using COMPOSITE TUBES

7 new components were added to the H2A Delivery Components Model

1. **GH2 Rail Production Plant Terminal-Composite Tubes** (filling up composite tubes)
2. **GH2 Rail Transport-Composite Tubes** (delivering composite tubes with H2)
3. **GH2 Rail City Gate Terminal-Composite Tubes** (reloading composite tubes to the truck trailer)
4. **Pipeline-GH2 Truck City Gate Terminal-Composite Tubes** (pumping H2 into composite tubes)
5. **GH2 Truck-Trailer Terminal-Composite Tubes** (filling up composite tubes)
6. **GH2 Truck Transport-Composite Tubes** (accommodating composite tubes delivery)
7. **GH2 Refueling Station-Composite Tubes** (accommodating changes in tube pressure and truck capacity)

* all full pathway costs involving composite tubes are preliminary

Rail Components Upgrade

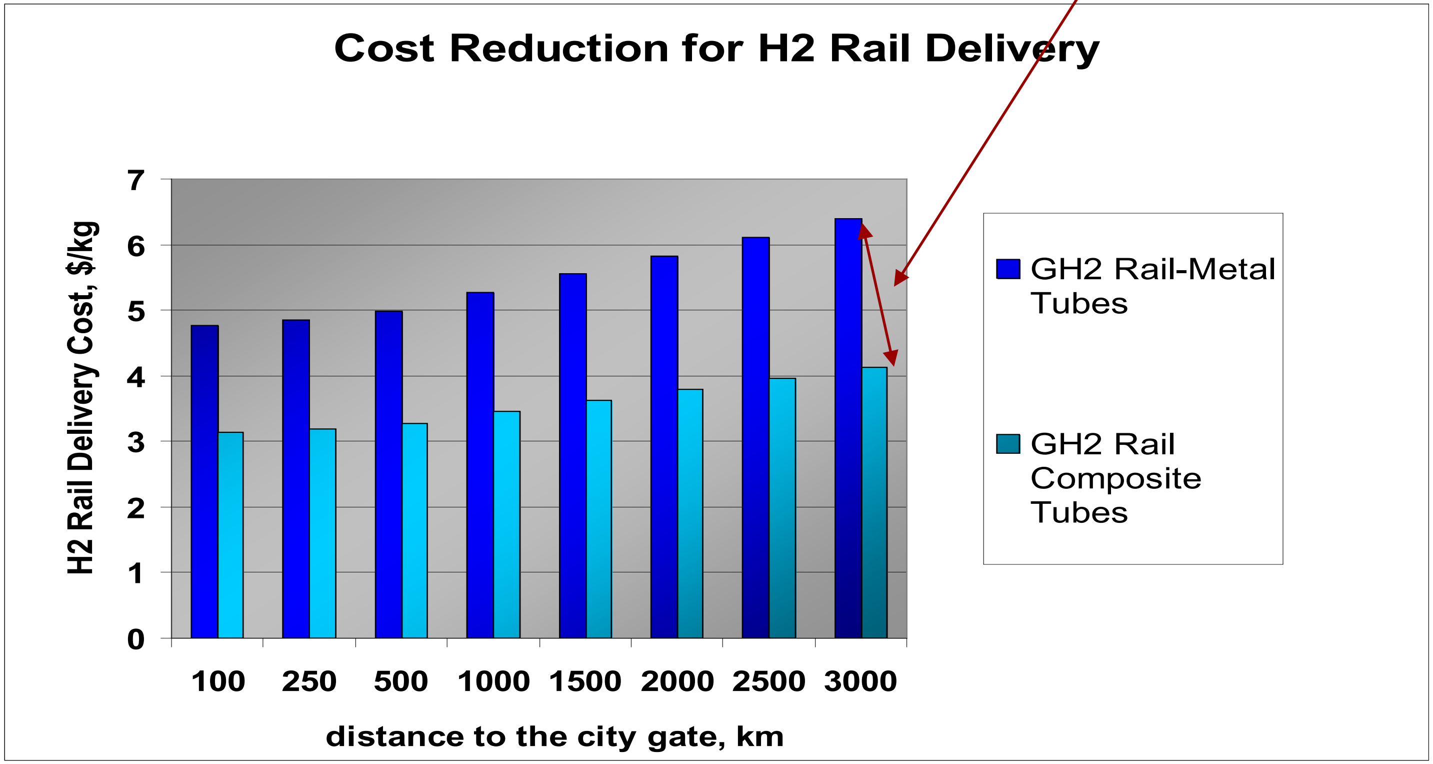
RAIL: From METAL Tubes to COMPOSITE tubes

Increased railcar capacity:

Metal tubes: 2680 kg of H2

Composite tubes: 4400 kg of H2

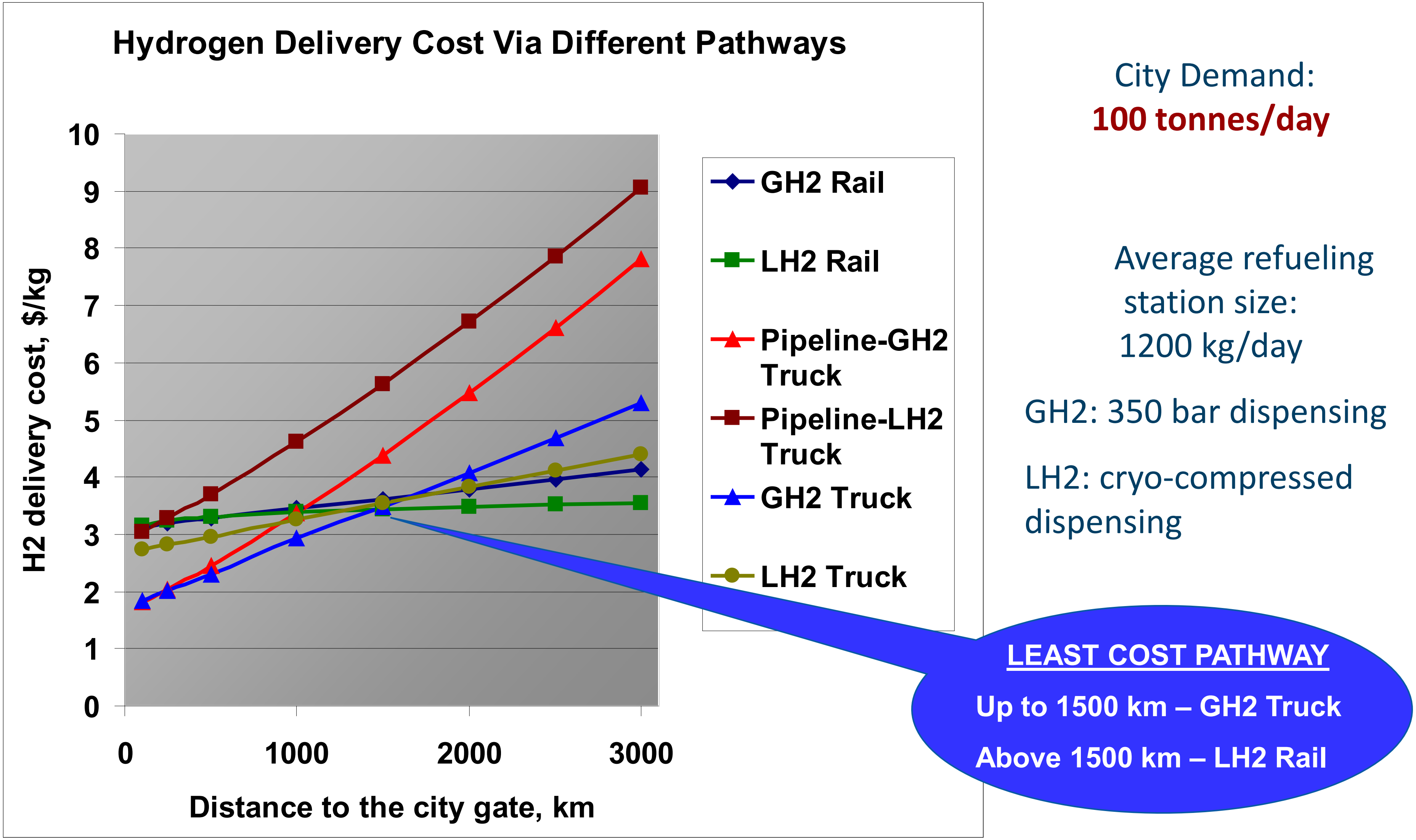
33 % H2 cost reduction for GH2 Rail Delivery



Technical Accomplishments and Progress

Cost Analysis

Distance Sensitivity to the Delivery Cost: Composite Tubes



City Demand:
100 tonnes/day

Average refueling station size:
1200 kg/day

GH2: 350 bar dispensing

LH2: cryo-compressed dispensing

Technical Accomplishments and Progress

Building multi-node delivery scenario model

Technical Accomplishments and Progress

Building Multi-Node Scenario Model

Multi-Node Delivery

from	*to*
multiple plants	single city
multiple plants	multiple cities
single plant	multiple cities

Flexibility

- storage sharing
- branched pipeline networks

Approach

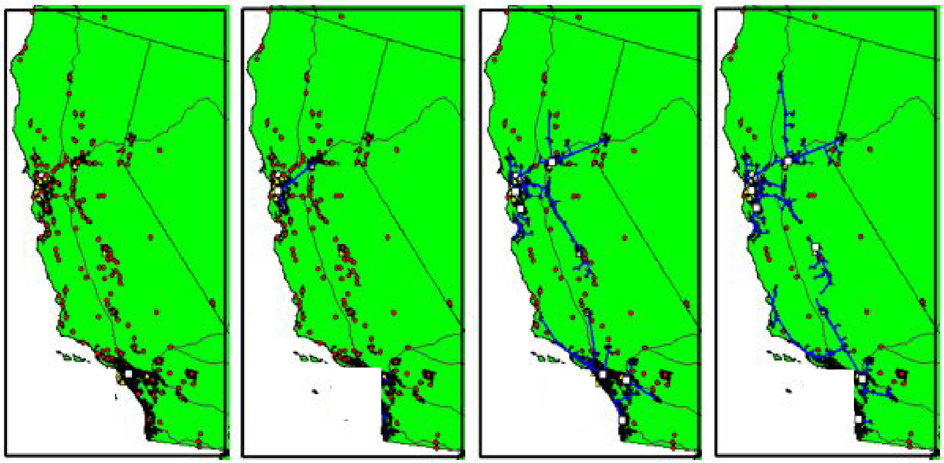
- Using SERA Model (former HyDS-ME) – geo-resolution and optimization
- Substitute cost curves with the delivery component build-ups inside of SERA
- By applying the above: get the flexibility to place components at different geographical locations
- Calculate optimal network and storage
- Trace network evolution
- Develop optimal multi-node scenarios

Technical Accomplishments and Progress

Building Multi-Node Scenario Model

What is SERA Model?

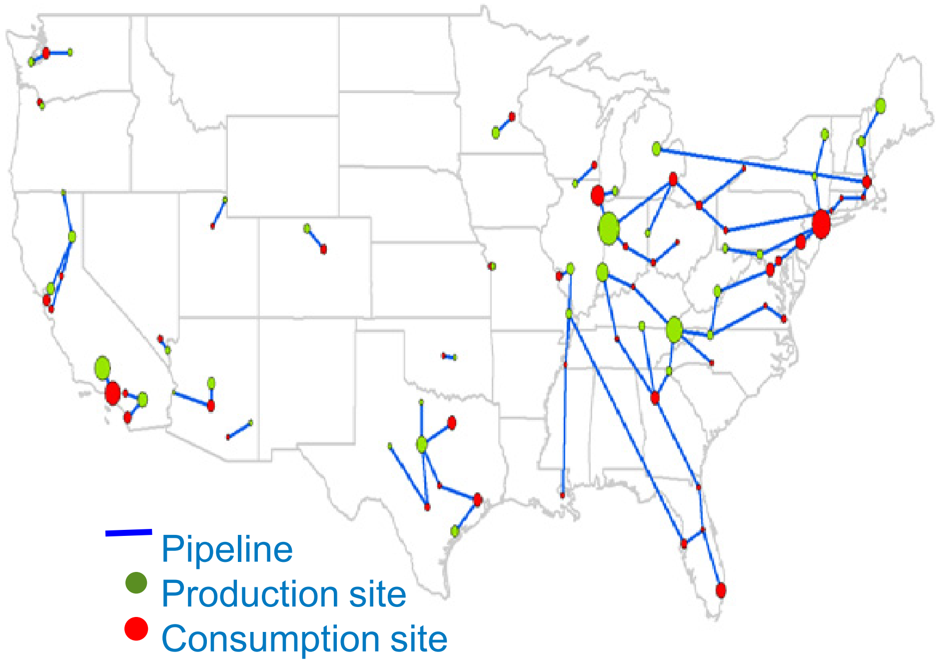
GIS-based DYNAMIC optimization model determines the optimal production and delivery infrastructure build-outs for hydrogen, given resource availability and technology cost.



a. 5% b. 10% c. 50% d. 100%

Hydrogen infrastructure at various demand levels.

Optimal H2 pipeline network build-out example: H2 from Wind Study



– B. Bush, M. Melaina, O. Sozinova, "Optimal Regional Layout of Least-Cost Hydrogen Infrastructure". National Hydrogen Association Conference & Expo 2009.

Technical Accomplishments and Progress

Building Multi-Node Scenario Model

Stage 1: Build delivery components inside SERA

4 components were coded :

- Pipeline Compressor
- Pipeline Transport
- Geological Storage
- Pipeline-GH2 Truck City Gate Terminal

Future Work

Future Work

Building Multi-Node Scenario Model

FY10

Stage 2: Restructure SERA for allowing branched pipelines

FY11

Stage 3: Optimize Delivery Networks

- use restructured SERA Model to perform calculations for identifying optimal infrastructure layout
- identify possible pipeline branching points and storage sharing points

Stage 4: Develop multi-node delivery scenarios

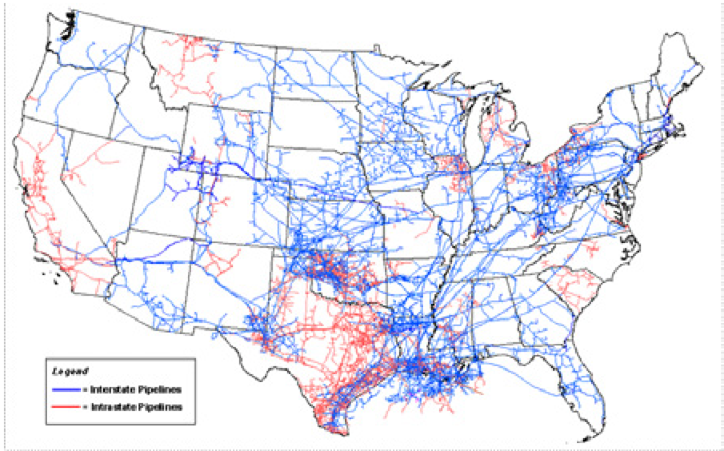
- use the learning curve form Stage 3 to develop multi-node delivery scenarios

Future Work (cont)

Go/ No Go decision on using natural gas pipelines for delivering hydrogen

Is it feasible to use NG pipelines for delivering hydrogen?

TARGET: Review available studies on adding hydrogen (pure or as a mixture with other gases) to the natural gas pipelines



Source: Energy Information Administration, Office of Oil & Gas, Natural Gas Division, Gas Transportation Information System

FOCUS:

- life cycle assessment
- safety
- leakage assessment
- durability
- integrity
- end use: separation, quality
- impacts: environmental and macroeconomic benefits

Milestone Due: Completion expected by the end of FY10

Future Work (cont)

FY10 – FY11

On-Going Efforts

- Update and maintain H2A Delivery Components Model
- Update Rail Delivery components
- Refine delivery components involving composite tubes

Build-up Hydrogen-From-Wind Scenarios

- Identify near term largest demand centers
- Identify potential wind production sites with maximized capacity pertinent to the above demand areas
- Evaluate storage capacity and locations based on actual wind profiles
- Optimize wind farm size for allowing electricity-from-wind use to liquefy hydrogen
- Analyze delivery options for H2 from wind

Collaborations

Industry

- Linde
- Air Products
- GE Rail Leasing
- Lincoln Composites
- Union Pacific Railroad
- Konecranes Heavy Lifting Company
- Paceco Corporation

(technical and cost inputs)

National Labs

- Marianne Mintz - ANL (Delivery Analysis)
- Amgad Elgowainy – ANL (HDSAM)
- Brian Bush - NREL (SERA)
- Daryl Brown - PNNL (Model Review)
- Darlene Steward – NREL (H2A Production Model)
- Mike Penev – NREL (H2A Power Model)

(data exchange and review)

Other Companies

- DTI (HyPro Model) *(data exchange and review)*
- TIAX (Logistics Model) *(data exchange and review)*
- GTI *(subcontract)*

Summary

Relevance

- Project activities follow the DOE H2 Program targets

Approach

- Project follows H2A general approach and guidelines

Accomplishments

- Rail Delivery Components Update with new freight and cost input data
- H2A Components Model Upgrade with 700 bar and cryo-compressed dispensing
- Designed 7 new delivery components for using composite tubes
- Performed comparative cost analysis for various delivery pathways
- Built-up 4 pipeline delivery components into SERA for multi-node scenarios development

Collaborations

Linde, Air Products, GE Rail Leasing, Lincoln Composites, Union Pacific Railroad,
Konecranes Heavy Lifting Company, Paceco Corporation , ANL, PNNL, DTI, TIAX, GTI

Future Work

- Continue developing multi-node delivery scenarios: network optimization and scenarios draft
- Assist DOE in developing go/no go decision on the use of CNG infrastructure for delivering hydrogen
- Build-up Hydrogen-From-Wind Scenarios

SUPPLEMENTAL

Supplemental Slides

FOR THE REVIEWERS ONLY

Responses to Previous Year Reviewers' Comments

SUPPLEMENTAL

- **"It was confusing as to why 100,000 of model runs were needed for HyDS-ME ".**
  - multiple runs were conducted with HDSAM for data being used in HyDS-ME (SERA) as cost inputs.

- **"This project needs calibration with actual installations costs to verify accuracy of predictions".**
  - extensive collaboration with multiple industrial companies during past year allowed us to substantially improve cost input data

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Publications and Presentations

SUPPLEMENTAL

Presentations

- O. Sozinova, “Rail and Pipeline networks as new Hydrogen Delivery Options,” Delivery Tech Team Meeting, Columbia, MA, April 17 2009.
- O. Sozinova, D. Steward, “Wind to Liquid Hydrogen Cost study. Preliminary Results,” Delivery Tech Team Meeting, Washington, DC, April 14, 2010.

Posters

- B. Bush, M. Melaina, O. Sozinova. “Optimal Regional Layout of Least-Cost Hydrogen Infrastructure”. National Hydrogen Association Conference & Expo 2009.

Reports

- B. Bush, M. Melaina, O. Sozinova, D. Thompson. “Hydrogen Deployment System Modeling Environment (HyDS-ME) Notional California Case Study”. National Renewable Energy Laboratory, January 2009.

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Rail Components Assumptions

SUPPLEMENTAL

Where possible, costs for liquefaction and truck pathways have been applied to develop rail components.

Gaseous H2 is pumped into composite tubes (550 bar) at the Production Terminal. The tubes are loaded to the truck-trailer at the City Gate Terminal.

Liquid H2 is loaded into rail tankers at the Production Terminal, then transported, and reloaded to the liquid trucks at the City Gate Terminal.

It is assumed that a single train leaves daily to supply a certain quantity of hydrogen to a single city.

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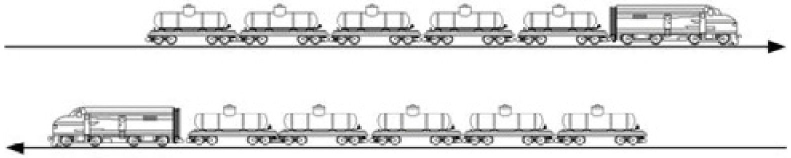
Rail Components Assumptions

SUPPLEMENTAL

It is assumed that a single train leaves daily to supply a certain quantity of hydrogen to a single city

Each day, a loaded train is in transit to the city-gate, and a train with empty tanks is returning



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Technical Accomplishments and Progress

H_2 Rail Delivery

US Railroad Availability

Miles of Road Operated in the U.S.(2006) - 171,077*

Miles of Road Operated Less Trackage Rights - 140,490*

"*Miles of Road* is the aggregate length of roadway, excluding yard tracks and sidings, and does not reflect the fact that a mile of road may include two, three, or more parallel tracks. *Miles of road operated less trackage rights*, which eliminates double-counting caused by more than one railroad operating the same track, is the measure of the rail network."*

***Source: U.S. Freight Railroad Statistics, Association of American Railroads**

http://www.aar.org/PubCommon/Documents/AboutTheIndustry/Statistics.pdf

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Rail Freight Cost

SUPPLEMENTAL

Freight information was taken from the 2008 public Carload Waybill.
http://www.stb.dot.gov/stb/industry/econ_waybill.html

This data includes commodity code, freight charges, transit charges, miscellaneous charges, number of railcars, shipped weight, distance traveled and many other factors. The ‘freight charges’ for the 2008 waybill include fuel surcharge as described in the federal register (http://edocket.access.gpo.gov/2008/E8-26570.htm)

The charges (freight, transit and miscellaneous) were summed and divided by the number of railcars to produce the cost per railcar. This was done for both liquid natural gas and hydrogen gas in order to develop useful rates for moving liquid and gaseous hydrogen. These data were than plotted versus distance traveled to see how the rate varied.

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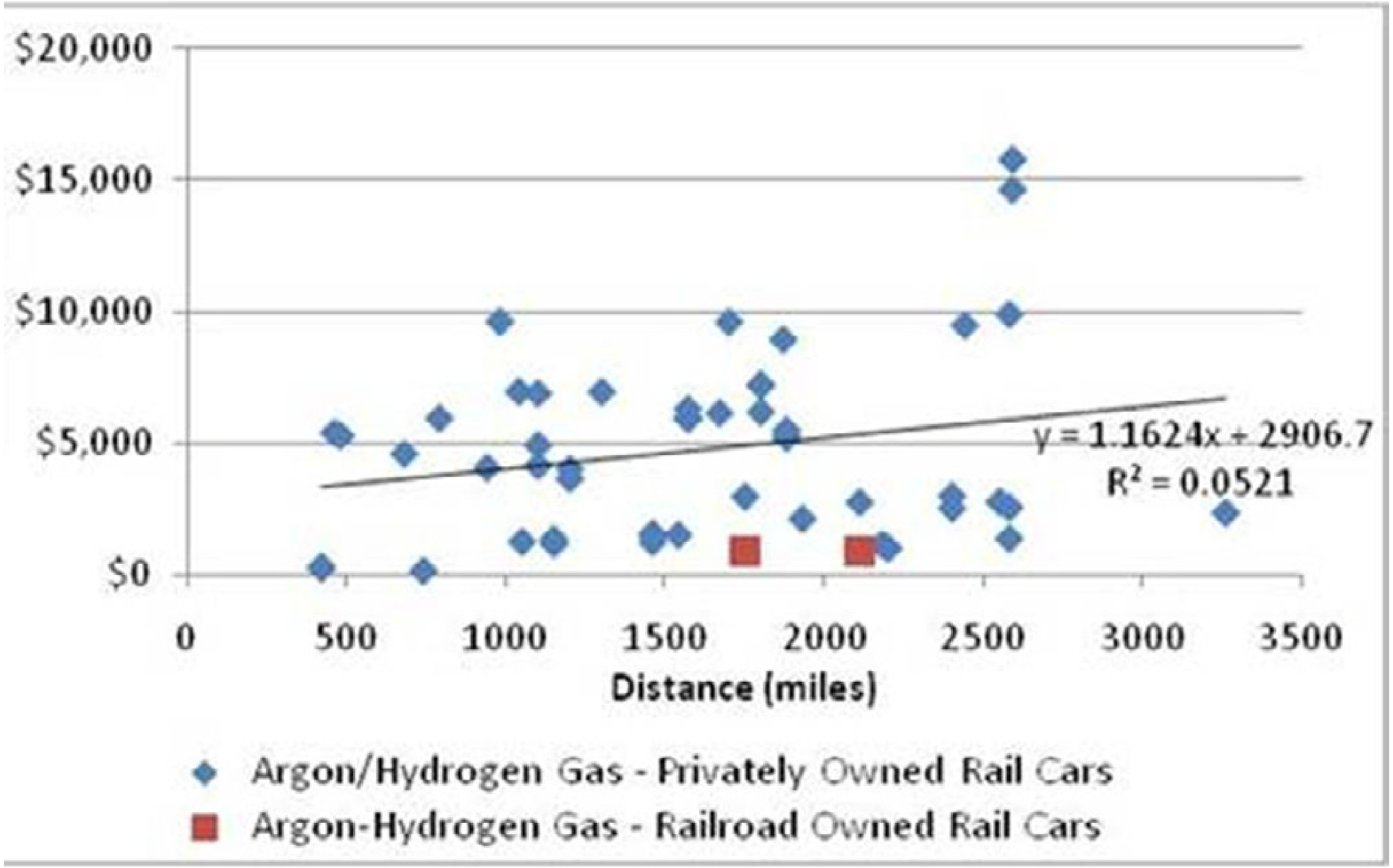
Rail Freight Cost

SUPPLEMENTAL

Gaseous H2 Rail Delivery



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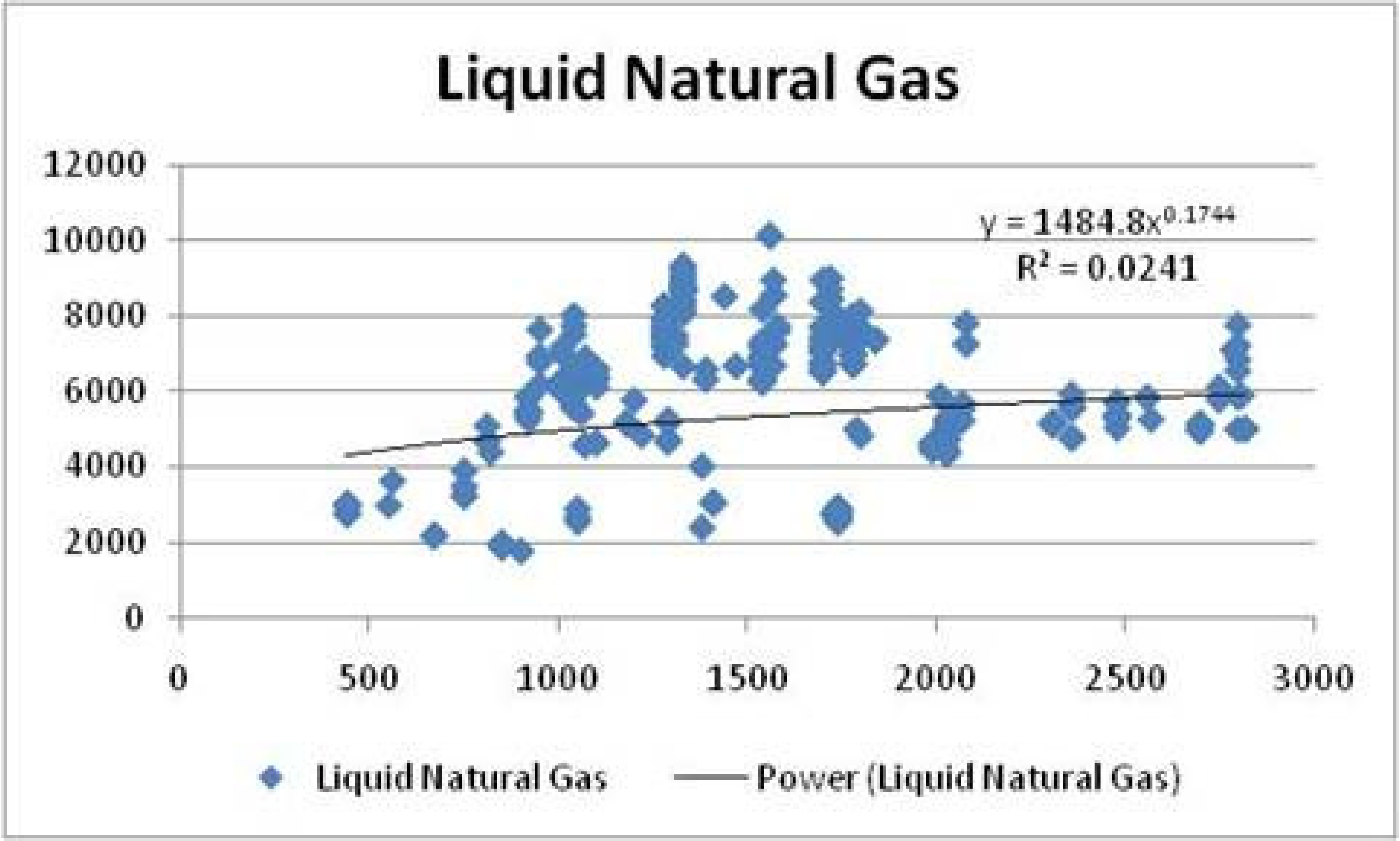
Rail Freight Cost

SUPPLEMENTAL

Liquid H2 Rail Delivery

Freight Rates for LNG



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Railcar leasing costs

SUPPLEMENTAL

Rail Car Leasing

Pressure tank and flat car leasing data were provided by GE Rail Car Leasing
http://www.ge.com/railservices/products/railequipmentbycartype.html

Leasing rates

Flat car	$450/railcar/month
Tanker	$700/railcar/month

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Composite Tubes

SUPPLEMENTAL

TITAN Tank Measurements

Property	SI units
Water volume	8400 L
Diameter	1.08 m
Length	11.6 m

TITAN Module

Property	SI units
Tanks/module	4
Total Water Volume	1.08 m
Module Dimensions	2.44 m*2.44 m*12.2 m
Module Weight (1 bar)	14,500 kg

Source:

TITAN™ LINCOLN COMPOSITES A Member of Hexagon Composites Group

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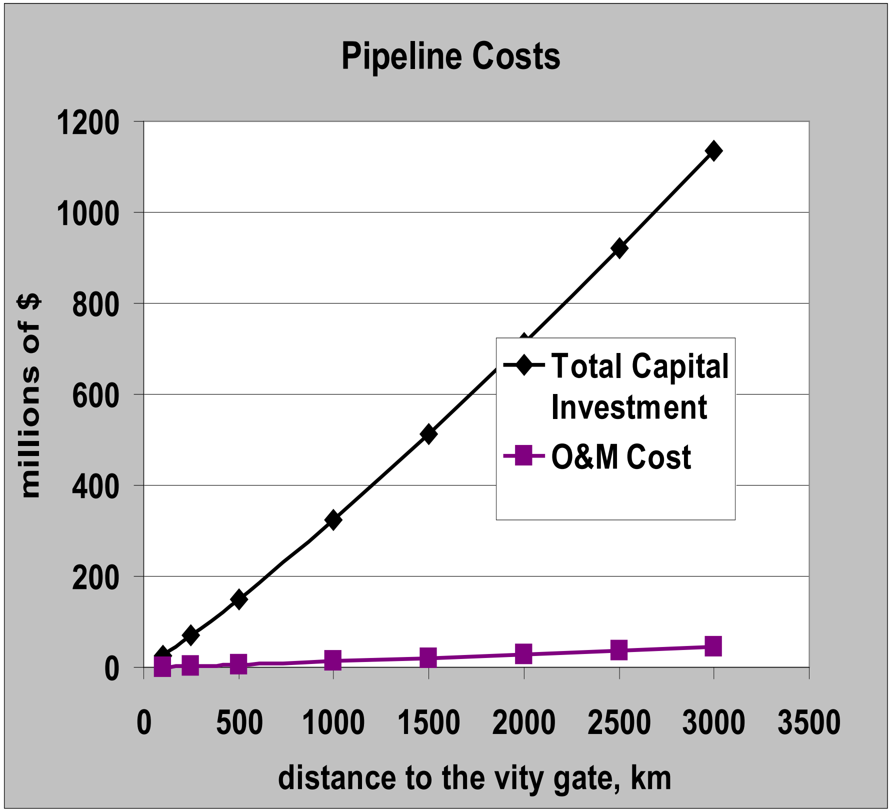
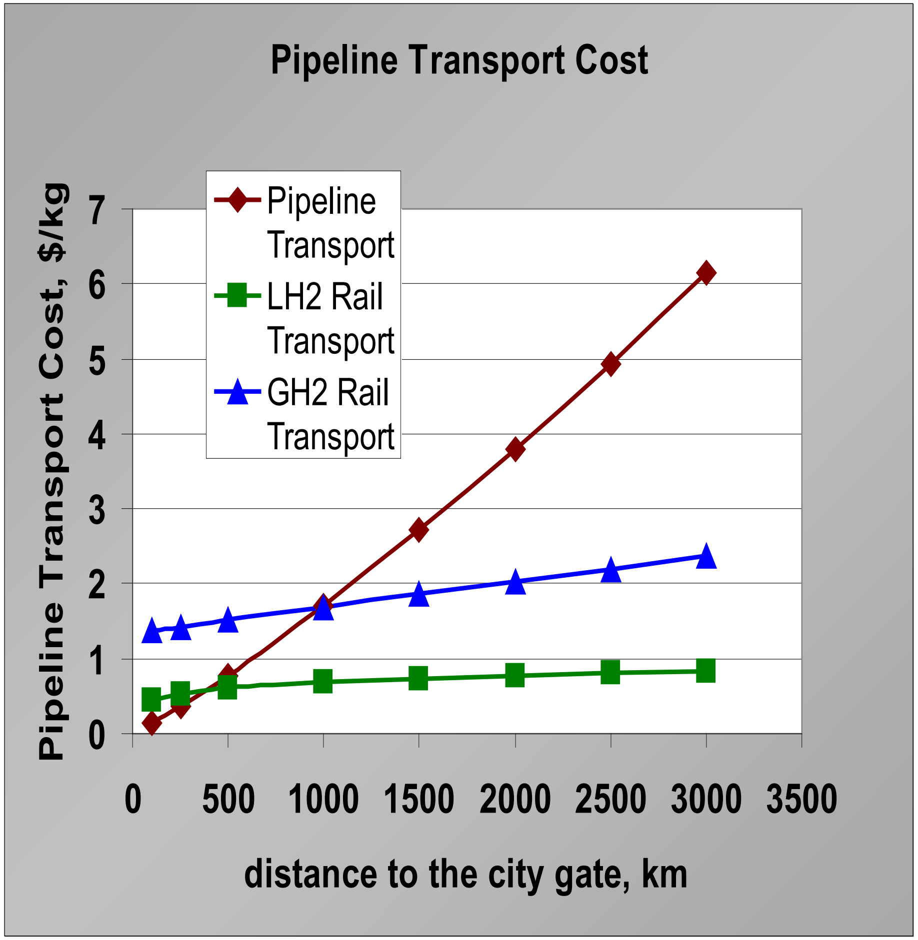
Pipeline Cost Sensitivity to Distance

SUPPLEMENTAL





City Demand: 100 tonnes/day

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