Hydrogen Delivery Analysis

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2011 Hydrogen Program Annual Merit Review

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Project ID # PD015

Overview

Timeline

- Start date: FY 2004
- End date: October 2011

(Project continuation and direction determined annually by DOE)

Barriers

- Lack of hydrogen/carrier and infrastructure option analysis (3.2 A)
- Gaseous hydrogen storage and tube trailer delivery costs (3.2 F)

Budget

Funding: 100% DOE Funded

- FY10: $150K
- FY11: $250K

Partners

- Argonne National Lab
- Pacific Northwest National Lab
- Nexant, Inc.
- TIAX
- GTI
- Chevron
- Air Liquide
- Linde
- DTI
- Power and Energy Inc.
- Lummus Technology, a CB&I Company
- H2Pump LLC

Relevance: Objectives

Project Objectives

- Hydrogen delivery cost analysis
- Update and maintenance of the H2A Delivery Components Model
- Design of new delivery components
- New delivery scenarios development
- Support of the other models with delivery data

MYPP

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

Activities: Development of the H2A Delivery Components and Scenario Models, 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 have followed the general H2A approach and guidelines:

✓ Collaborating closely with industry to get and update 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 Addressed

Barriers

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." (p. 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)

Multi-Directional Approach

- ✓ **Future big-volume delivery**: analysis of hydrogen delivery by rail
- ✓ **No hydrogen-dedicated infrastructure build-up option**: analysis of H2 delivery via existing NG infrastructure
- ✓ **Hydrogen as energy carrier**: analysis of the wind energy delivery via producing, liquefying and delivering hydrogen to a major energy demand center

- ✓ **New flexible delivery option**: multi-node delivery scenarios development
- ✓ **Truck Delivery**: review of the federal and local highway regulations for truck delivery
- ✓ **Truck Delivery-new materials:** composite truck trailer delivery analysis

Approach: Milestones

DUE

Due	Milestone	Status
June 2010	Multi-node delivery model development: introduce pipeline branching	✓
September 2010	Rail Delivery Cost Analysis	✓
December 2010	Analysis of delivering hydrogen via natural gas network	✓
December 2010	Composite Truck Delivery Analysis	✓
July 2011	Multi-node delivery scenarios development: build-in (code in) truck delivery components	70 %
September 2011	Analysis of hydrogen as energy carrier: complete wind-to-hydrogen scenarios	20 %

- At NREL, for hydrogen delivery analysis, we use multiple models.

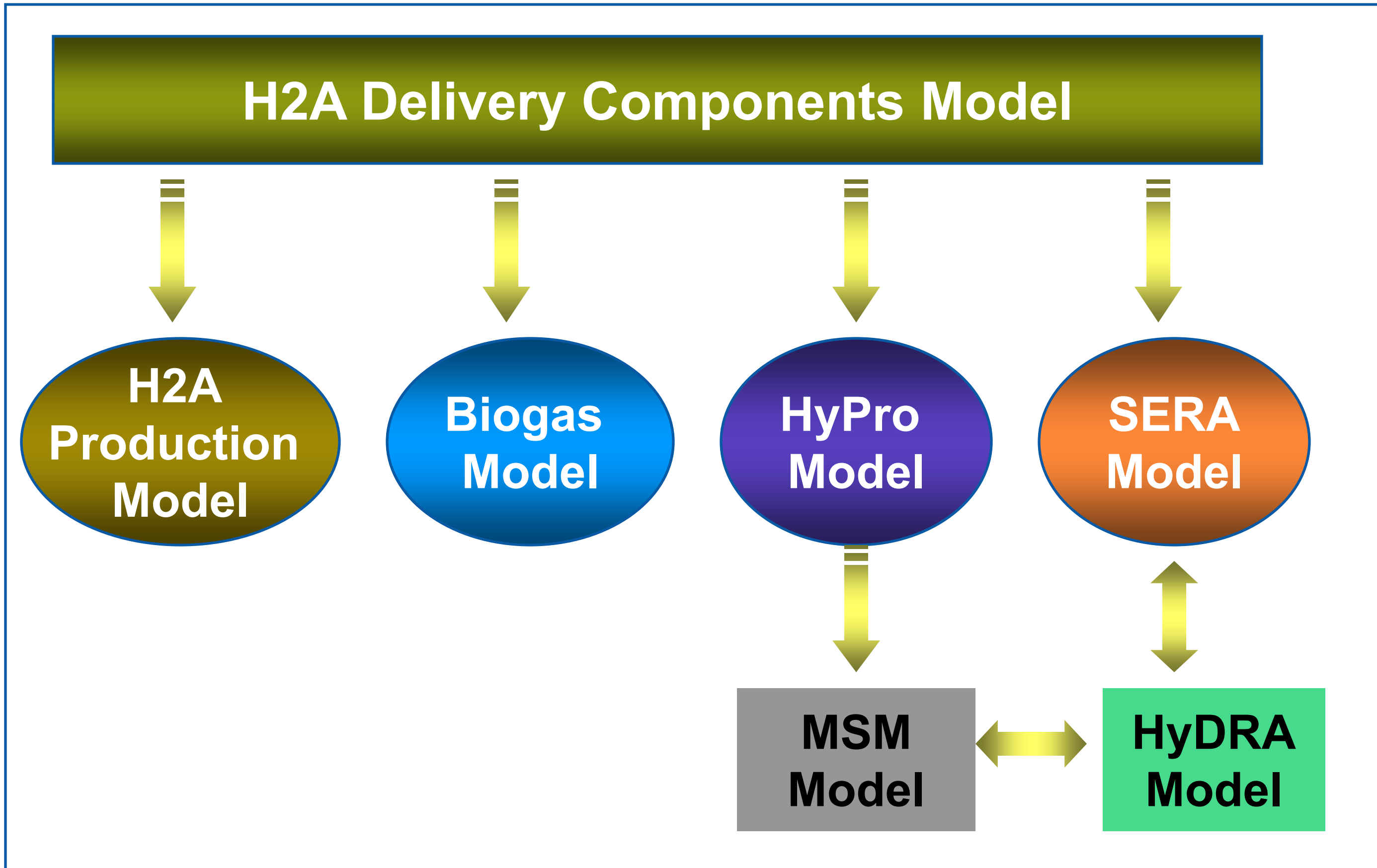
- One of them is the H2A Delivery Components Model

  - we update and maintain it (it's one of the tasks of this project)
  - we use it for various types of analysis
  - data from it are used in various hydrogen models

Let's take a quick look at it…

H2A Delivery Components Model Overview

- Model is used in several other hydrogen models (as delivery cost data source)



Properties

- Calculates hydrogen delivery cost
- Flexible (cost for separate components or the entire pathway)
- Transparent (no password protection)

Also, at NREL, we use the H2A Delivery Components Model in various types of hydrogen delivery analysis

2010 Analysis Tasks included:

Outline

- Rail delivery cost analysis (comparison with other delivery pathways)
- Hydrogen as a carrier for the wind energy: analysis
- Multi-node delivery scenarios development: progress
- Composite truck delivery analysis
- Hydrogen delivery via natural gas pipelines analysis

TASK 1

Rail Delivery Cost Analysis
In Comparison with Other Delivery Pathways

OUTPUTS: Progress Report to DOE (July 2010),
Milestone Presentation to DOE (September 2010)

For what hydrogen market rail is the best delivery option?

We significantly increased demand range for the current analysis, covering hydrogen needs for the early as well as for the mature market

Analysis Tool:

H2A Delivery Components Model

Analysis Ranges:

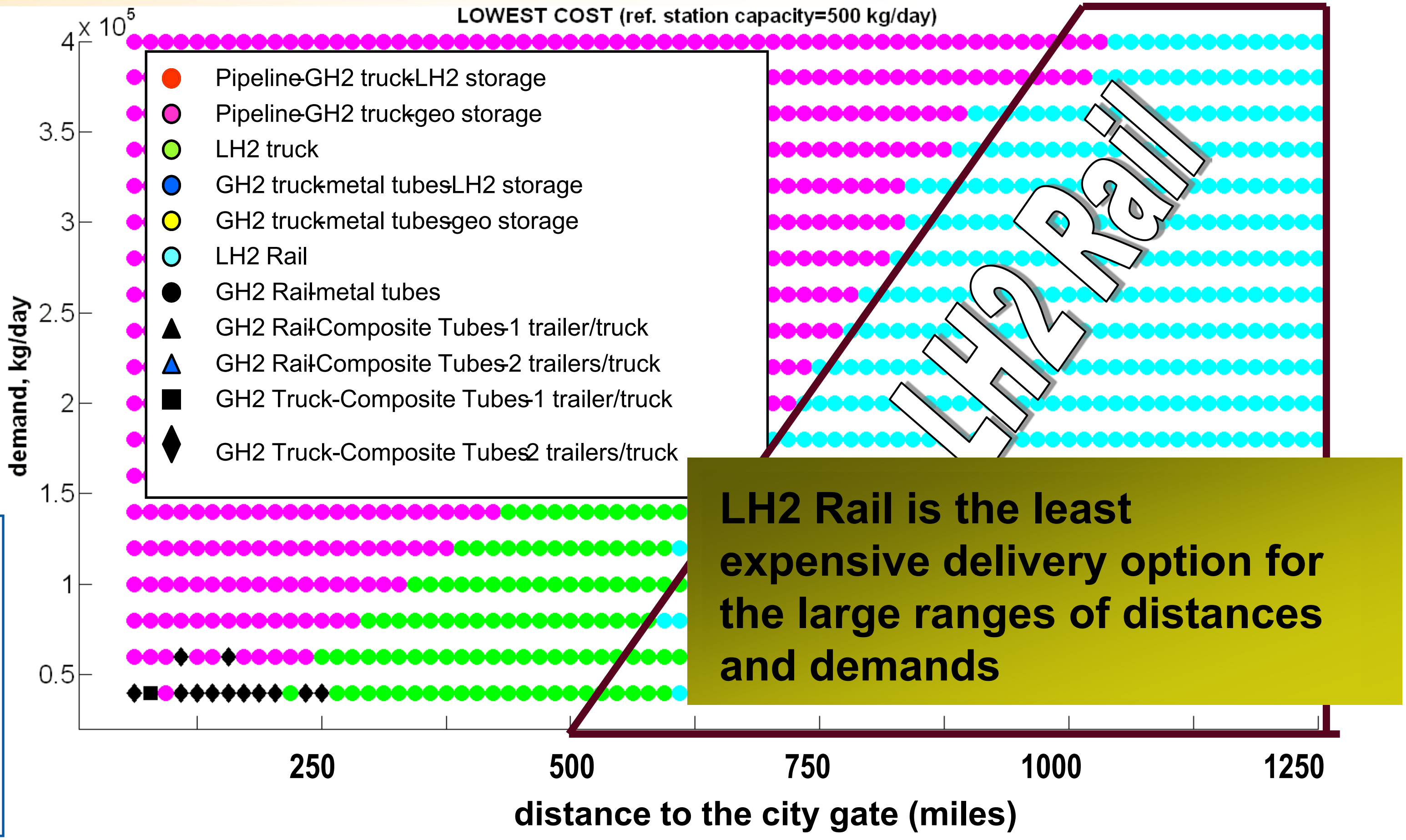
City Demand

40-2600 tonnes/day*

Distance To The City:

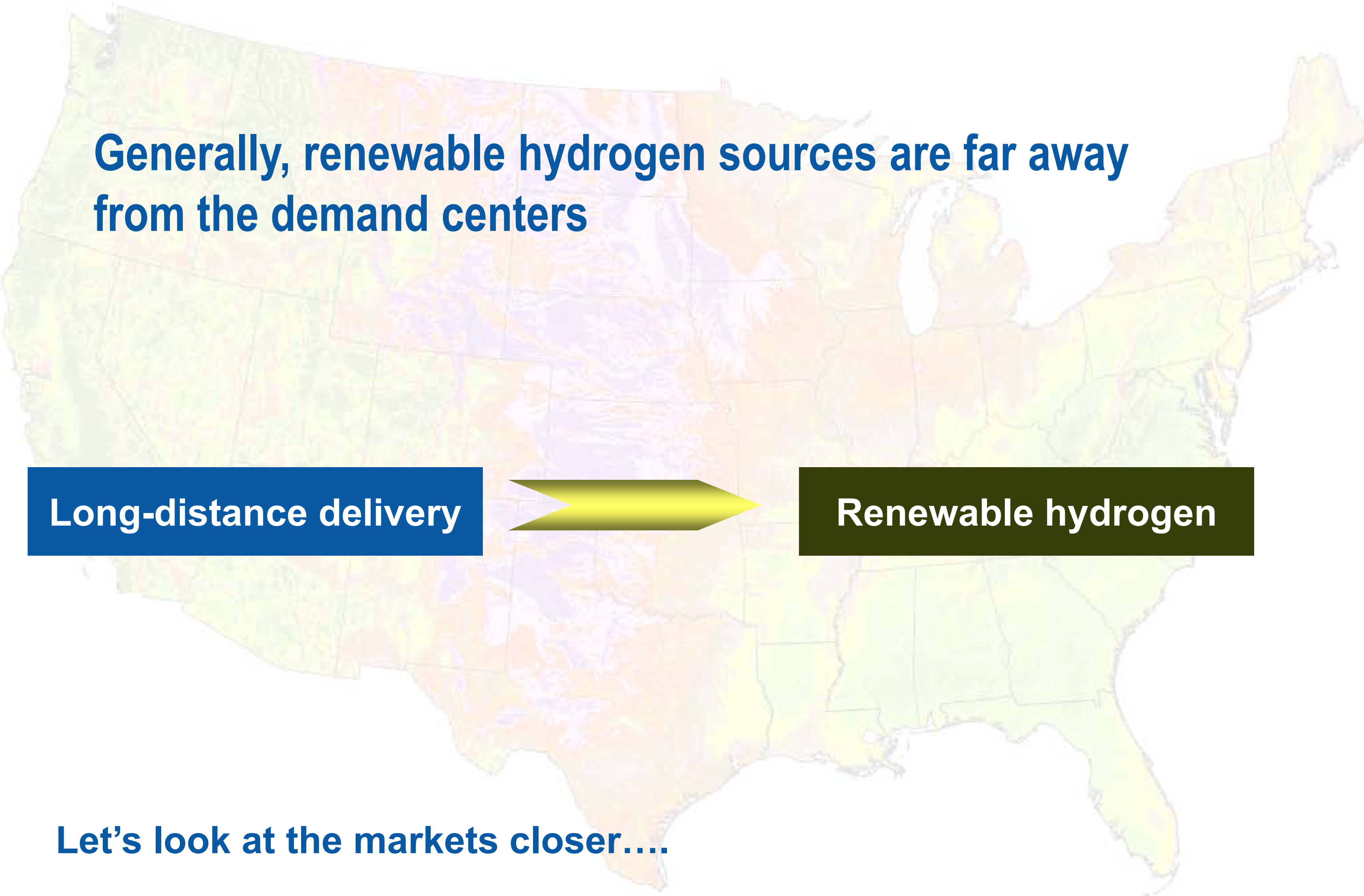
60-2200 miles

The upper limit may correspond to the 50% Market Penetration in the Los Angeles or New-York City Metropolitan areas



* For better resolution, only fractions of demands and distances are shown here. For the full ranges, see supplemental slides.

Why would we need to deliver hydrogen over long distances?



Generally, renewable hydrogen sources are far away from the demand centers

Long-distance delivery → **Renewable hydrogen**

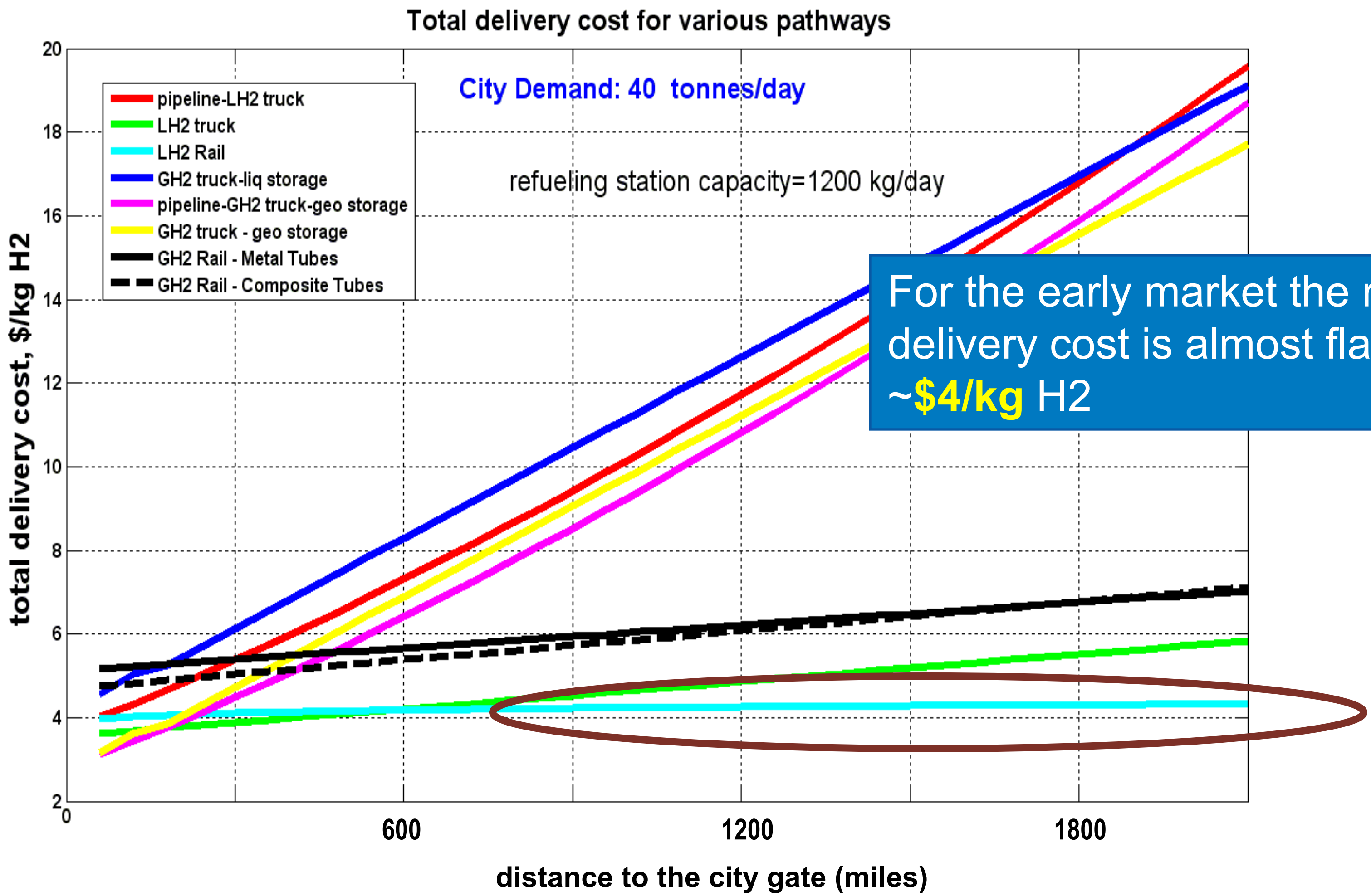
Let's look at the markets closer….

Delivery Cost: Early rollout – 40 tonnes/day

LH2 Rail is the most economic delivery option for *renewable hydrogen* *at early rollout*

Analysis Tool:

H2A Delivery Components Model



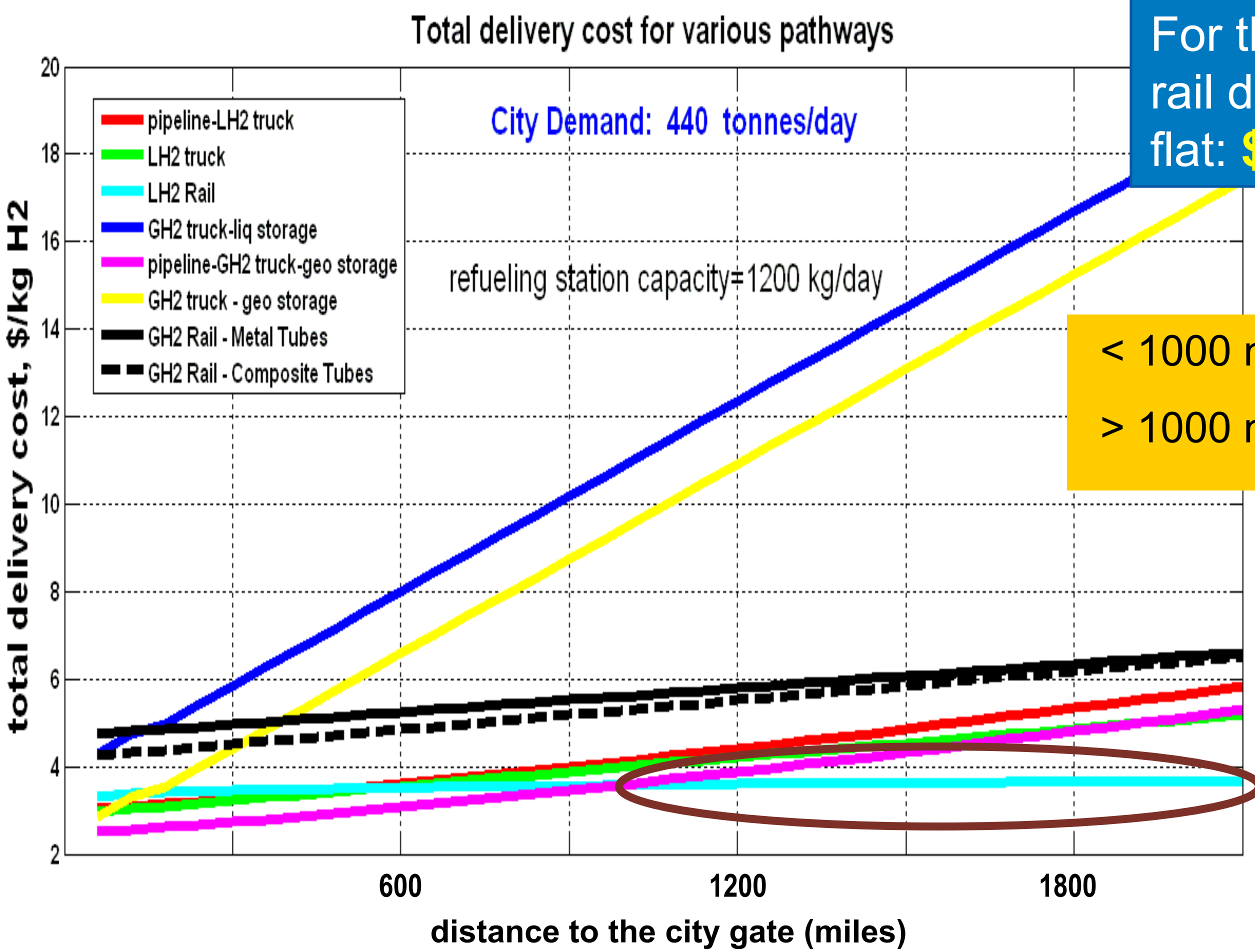
Delivery Cost: Midterm market – 440 tonnes/day

LH2 Rail is the most economic delivery option for *renewable hydrogen* at the *midterm*

Analysis Tool:

H2A Delivery Components Model

For the midterm market the rail delivery cost is almost flat: **$3.5/kg** H2



< 1000 miles: Pipeline

> 1000 miles: LH2 Rail

What about pipeline?

It can be competitive

(up to 1000 miles)

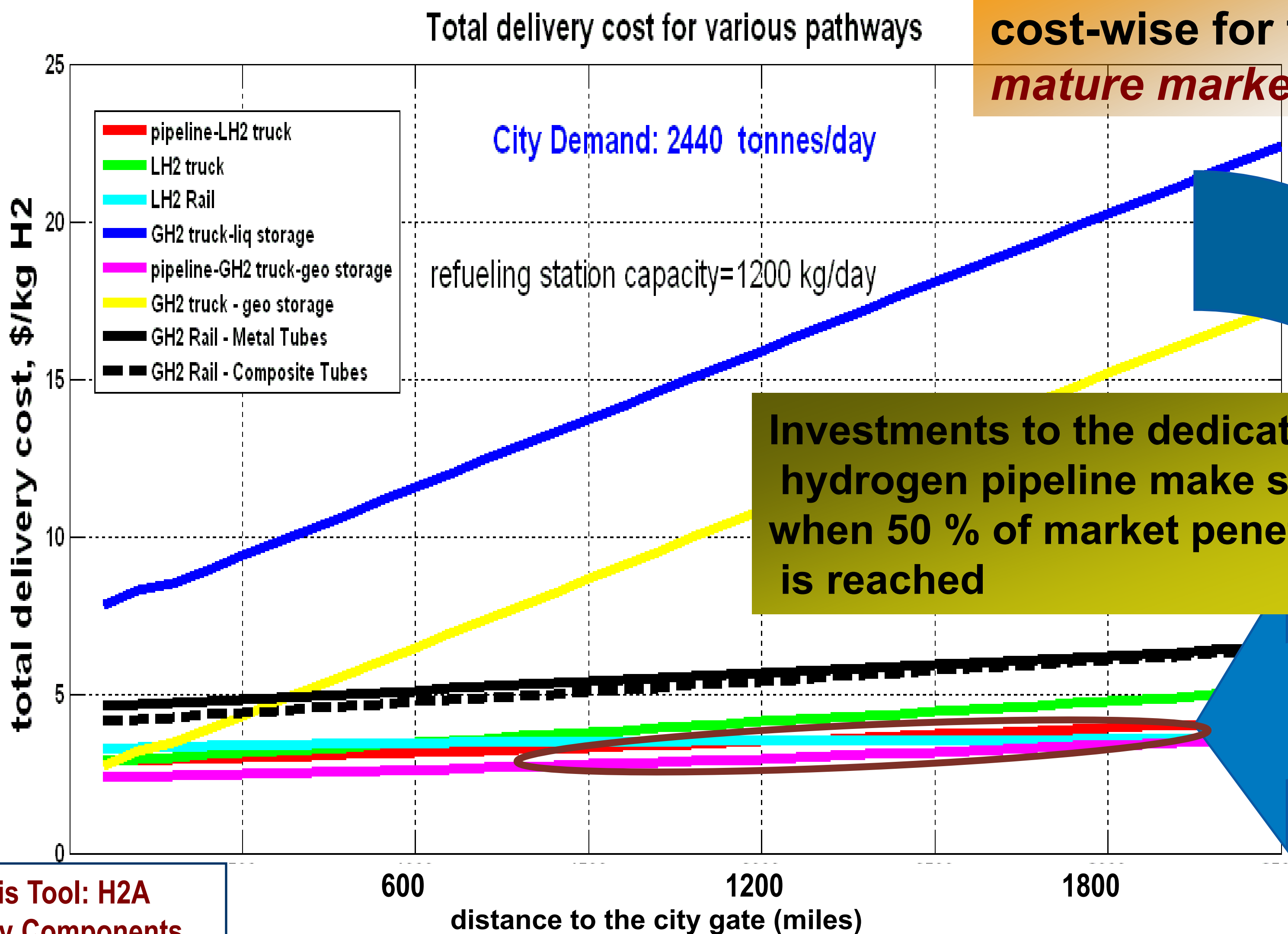
if we find the way for

geologic storage to work

Delivery Cost: Mature market – 2440 tonnes/day

50 % of market penetration

LH2 Rail and Pipeline are comparable options cost-wise for the *mature market*



Investments to the dedicated hydrogen pipeline make sense when 50 % of market penetration is reached

Analysis Tool: H2A Delivery Components Model

US Railroads Congestion Review

If rail is a player cost-wise, is it really viable capacity-wise?

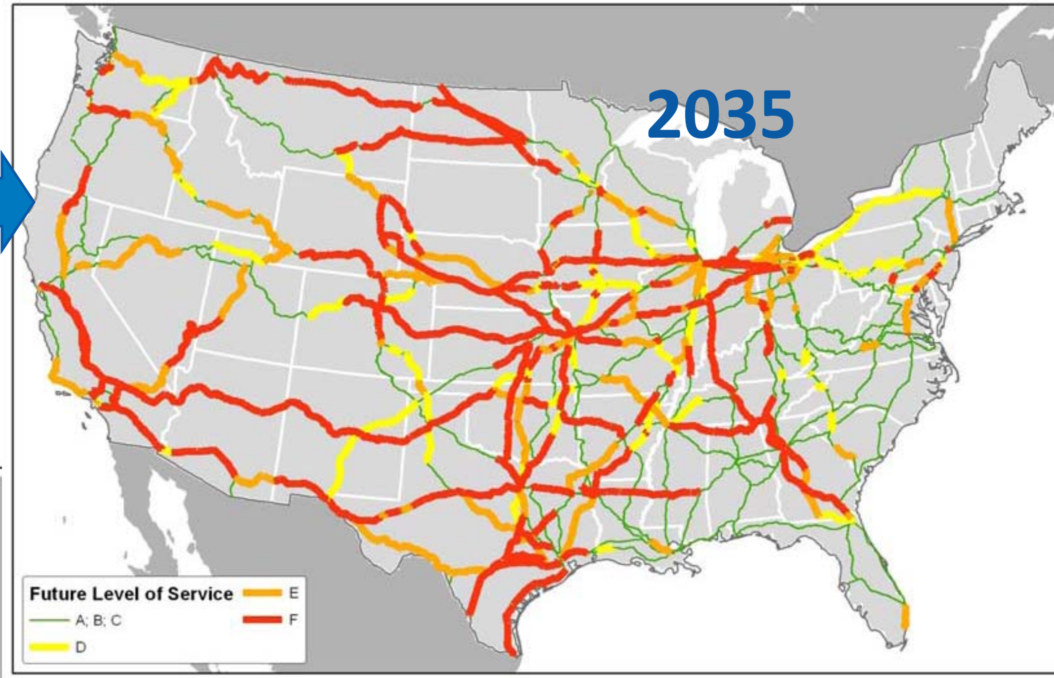
To answer this question, we reviewed the Association of American Railroads study "National Rail Freight Infrastructure Capacity and Investment Study" *

* **"National Rail Freight Infrastructure Capacity and Investment Study,"** ***prepared for*** **Association of American Railroads** ***by*** **Cambridge Systematics, Inc. (2007)**

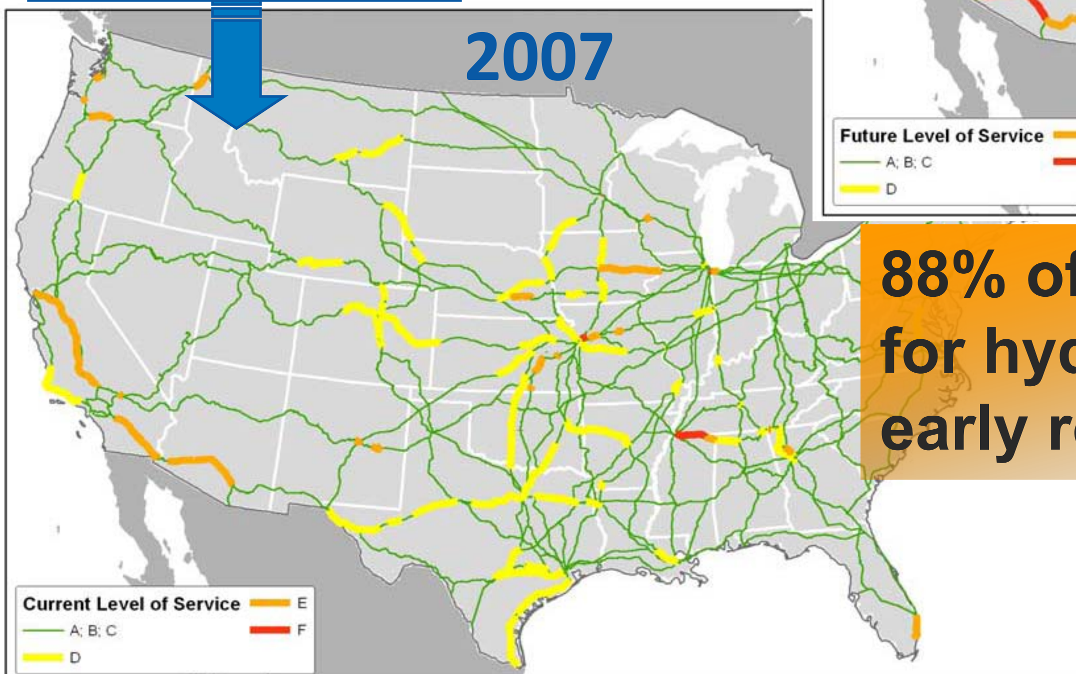
US Railroads Congestion Review

Train Volumes Compared To Current Capacity

45% - below capacity
25% - near or at capacity
30%- above capacity



88% - below capacity
12% - near or at capacity
1%- above capacity



88% of railroads can be used for hydrogen delivery at the early rollout

LOS Grade	Description	Volume/Capacity ratio
A B C	Below Capacity	0.0 to 0.2 0.2 to 0.4 0.4 to 0.7
D	Near Capacity	0.7 to 0.8
E	At Capacity	0.8 to 1.0
F	Above Capacity	>1.0

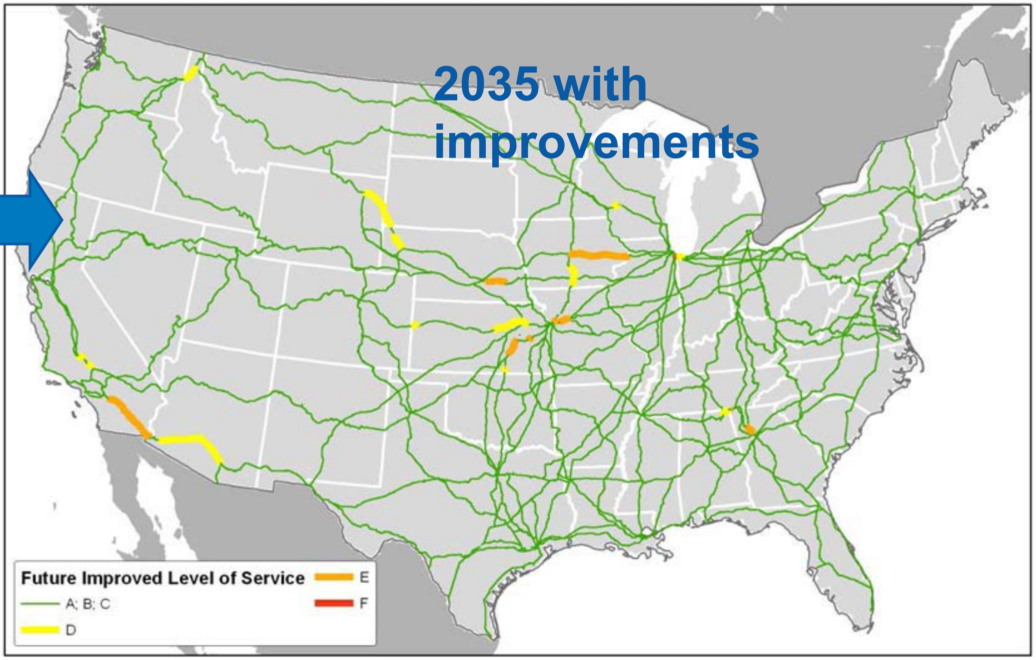
Source: Association of American Railroads, *National Rail Infrastructure Capacity and Investment Study* prepared by Cambridge Systematics, Inc.

US Railroads Congestion Review

AAR determined the areas of railroad improvements by 2035

97% - below capacity
2% - near or at capacity
<1%- above capacity

Future Train Volumes Compared To Future Capacity*



Line expansion:

- Upgrades to mainline tracks and signal control systems
- Improvements to significant rail bridges and tunnels
- Upgrades to Class I railroad secondary mainlines and branch lines to accommodate 286,000-pound freight cars
- Upgrades to short line and regional railroad tracks and bridges to accommodate 286,000-pound freight cars

Facility expansion:

- Expansion of carload terminals, intermodal yards, and international gateway facilities owned by railroads
- Expansion of Class I railroad service and support facilities such as fueling stations and maintenance facilities

Midterm hydrogen rail delivery is viable upon recommended improvements

Total Cost of Improvements was estimated as $147.5 Billions of 2007 Dollars

*2035 train volumes were projected using economic growth and commodity forecasts from the U.S. DOT's Freight Analysis Framework (FAF Version 2.2)

TASK 2

Hydrogen as a carrier for the wind energy: analysis

OUTPUT: Publication with ANL (in review)

Hydrogen as Energy Carrier: Wind-to-Hydrogen Scenarios

In FY10 NREL assessed 2 short-term scenarios:

- grid-independent with seasonal geo storage
- grid-connected

Analysis Tools:

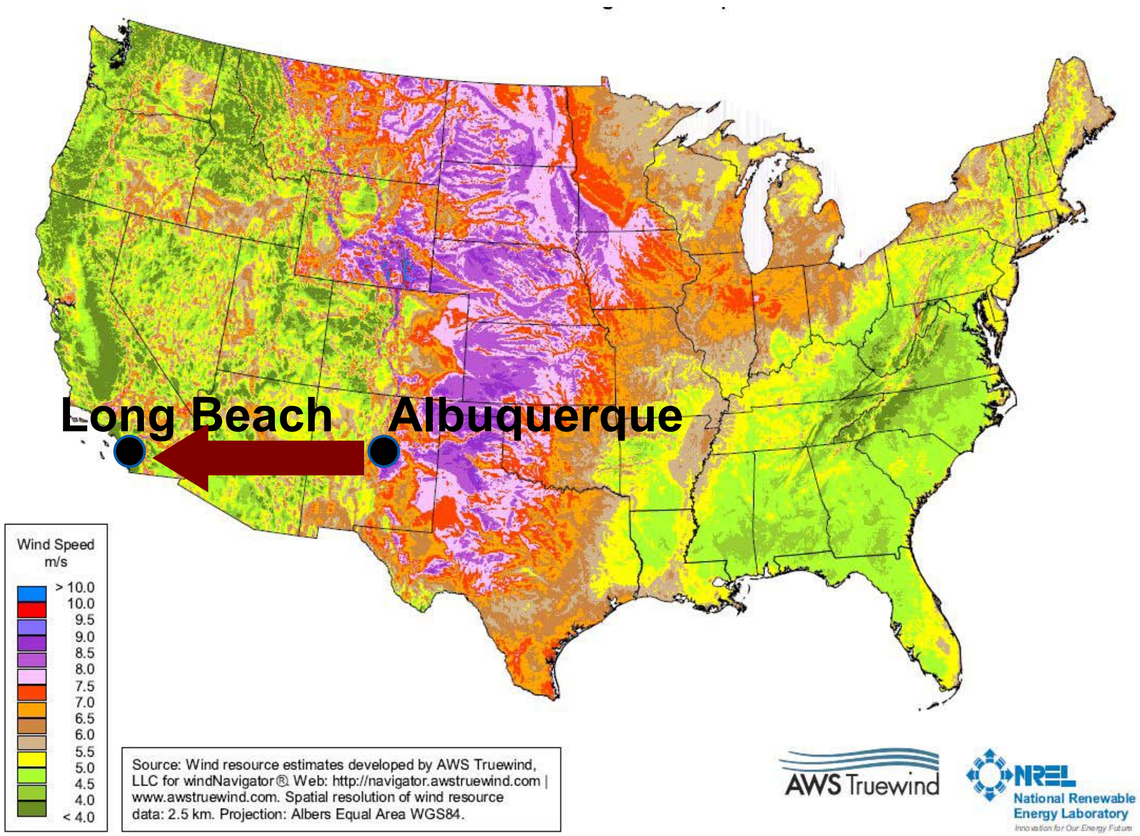
Modified NREL Fuel Cell Power Model

H2A Hydrogen Delivery Components Model

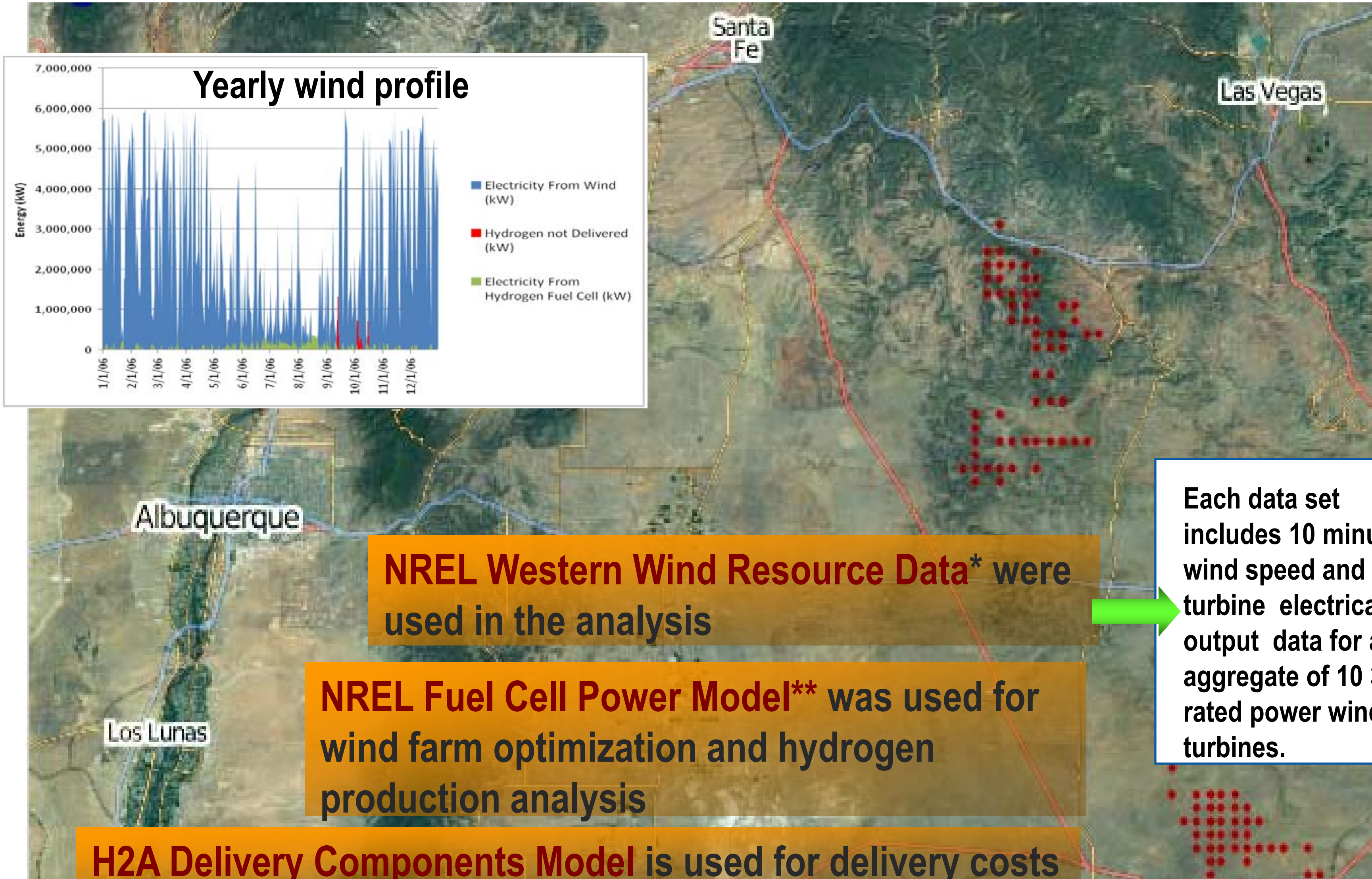
More scenarios will be assessed in FY11

FY10 Scenarios Goal:

- 40,000 kg/day of H_2
- wind farm near Albuquerque
- liquefy
- deliver to the Los Angeles area



Hydrogen as Energy Carrier: Wind-to-Hydrogen Scenarios



NREL Western Wind Resource Data* were used in the analysis

NREL Fuel Cell Power Model** was used for wind farm optimization and hydrogen production analysis

H2A Delivery Components Model is used for delivery costs

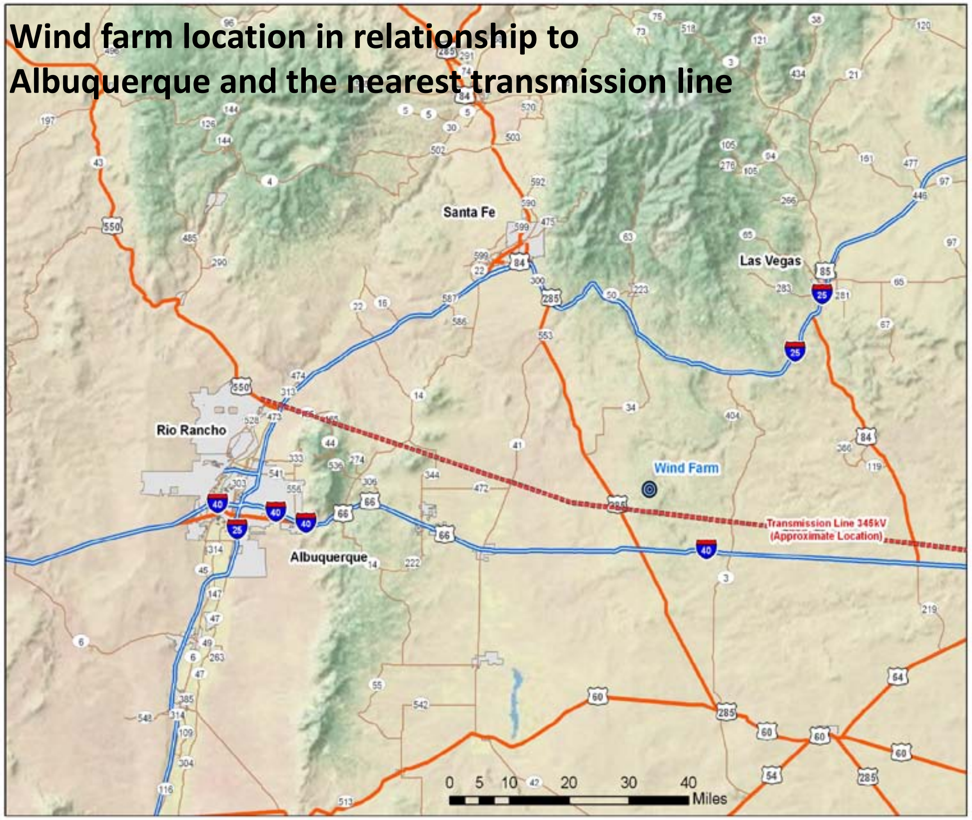
Each data set includes 10 minute wind speed and wind turbine electrical output data for an aggregate of 10 3MW-rated power wind turbines.

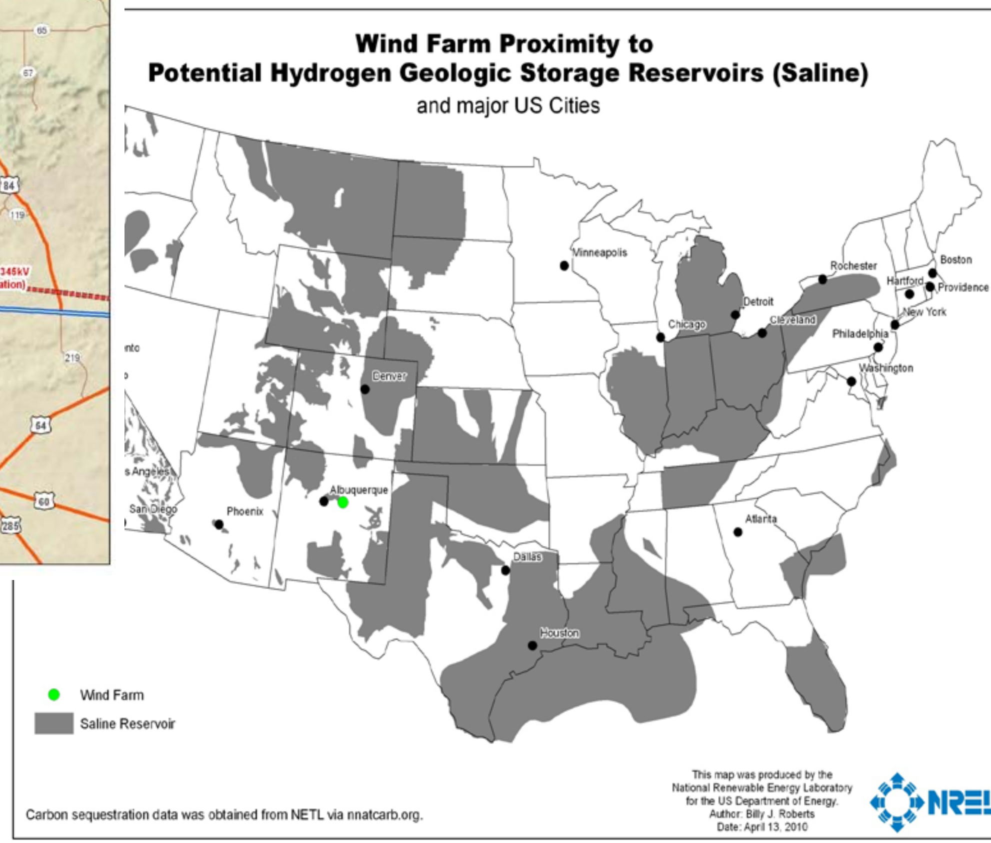
*NREL Western Wind Resource Data: http://www.nrel.gov/wind/integrationdatasets/western/methodology.html

****NREL Fuel Cell and Power Model: http://www.hydrogen.energy.gov/fc_power_analysis.html**

Hydrogen as Energy Carrier: Wind-to-Hydrogen Scenarios

NREL GIS team data were used for geologic storage and transmission lines locations





Hydrogen as Energy Carrier: Wind-to-Hydrogen Scenarios

Wind-to-LH2 Scenarios Results

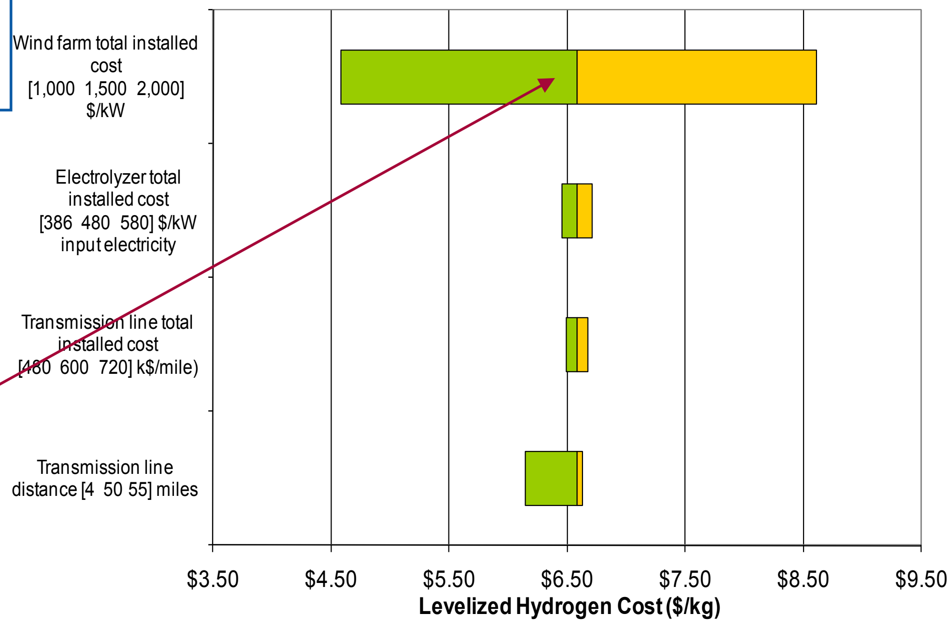
- **Grid-independent**: **$11.3/kg** of dispensed H2
  - production: $6.7/kg
  - liquefaction, storage and delivery: $4.6/kg
  (rail, 1200 kg/day ref. station)

- **Grid-connected**: **$10.6/kg** of dispensed H2
  - production, storage: $6.6/kg
  - liquefaction and delivery: $4.0/kg
  (rail, 1200 kg/day ref. station)

Issues:
90 days of seasonal storage is needed. **Geologic hydrogen storage** is not that feasible and **requires further research and analysis**.

Cost Reduction Possibility:
Production cost is highly dependent on wind turbine capital cost (which has high market volatility). Sensitivity analysis shows that H2 cost **can be reduced by $2/kg** in the case of market lower turbine cost (30% less than average).

Sensitivity Analysis



Details can be found at: "Liquid Hydrogen Production and Delivery from a Dedicated Wind Power Plant ", October 2010 Report to DOE (currently in review)

Technical Accomplishments and Progress

TASK 3

Multi-node delivery scenarios development: progress

OUTPUTS: Progress Report to DOE (May 2010),
Milestone Presentation to DOE (June 2010)

Building Multi-Node Delivery Scenarios

Multi-Node Delivery

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

Benefits

- Delivery Flexibility (ex: storage, pipeline, or plant sharing)
- Geographic resolution

Tools Used:

SERA Model

H2A Hydrogen Delivery Components Model

Approach

Use SERA model

Considering that SERA is not ready yet for this type of scenarios,

Enhance SERA delivery block:

- add pipeline branching
- substitute cost curves by delivery components coded directly into SERA

Building Multi-Node Delivery Scenarios

SERA is a very powerful tool.

At NREL, we use it for various types of analysis.

Here, we will consider the development of multi-node delivery scenarios with the help of SERA only.

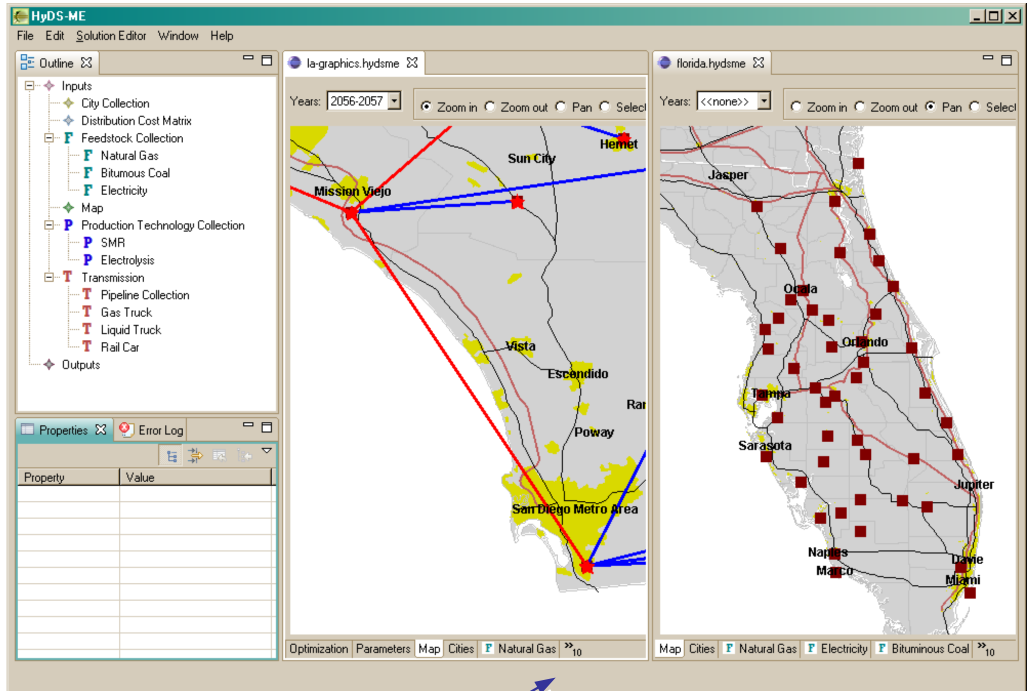
Building Multi-Node Delivery Scenarios

What is SERA Model?

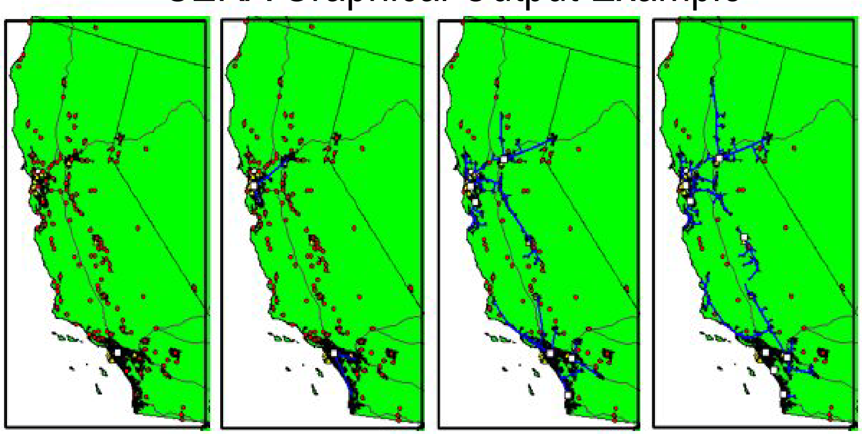
NREL DYNAMIC optimization model:

- GIS-based
- Java-coded software
- Determines the optimal production and delivery infrastructure build-outs
- Traces infrastructure evolution

SERA User Interface Snapshot

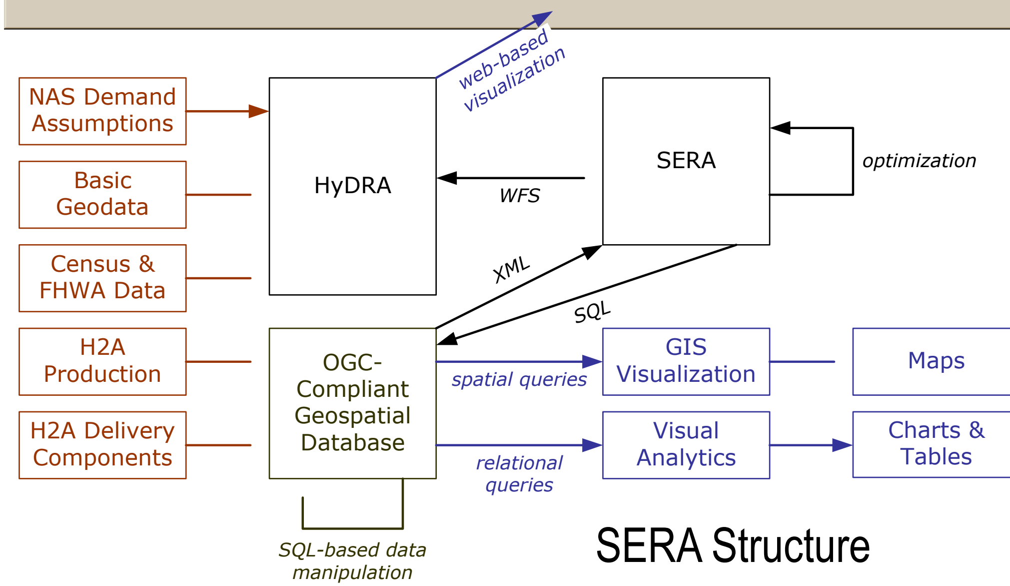


SERA Graphical Output Example



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

Hydrogen infrastructure at various demand levels



SERA Structure

Building Multi-Node Delivery Scenarios

This Year Subtasks Toward Multi-Node Delivery Scenarios Development:

- Enhance SERA pipeline buildup algorithm: introduce branching
- Use H2A Delivery Components (Excel-based) to code them directly into SERA delivery block (Java-based)

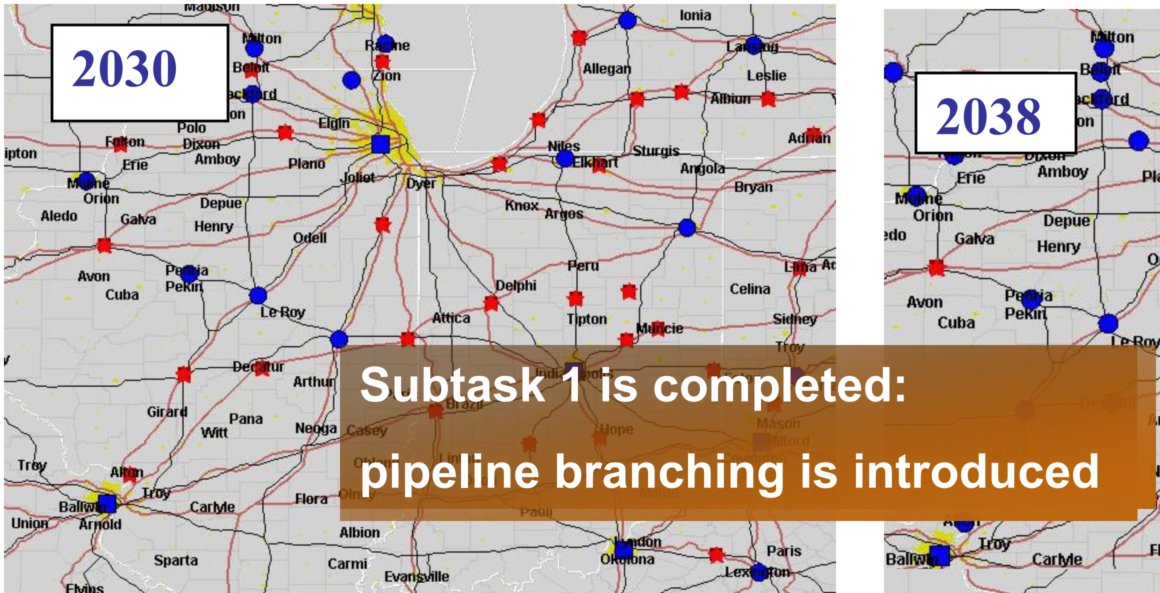
Tools Used:

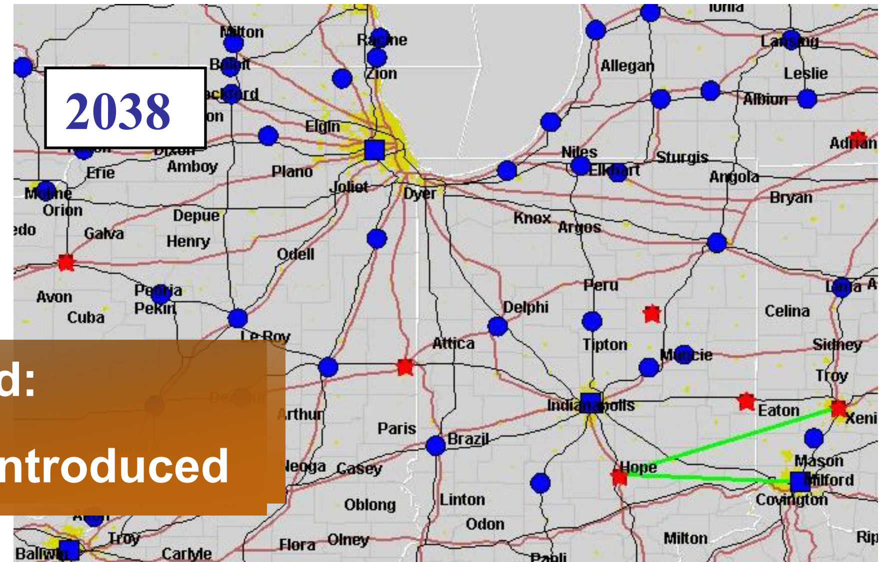
SERA Model

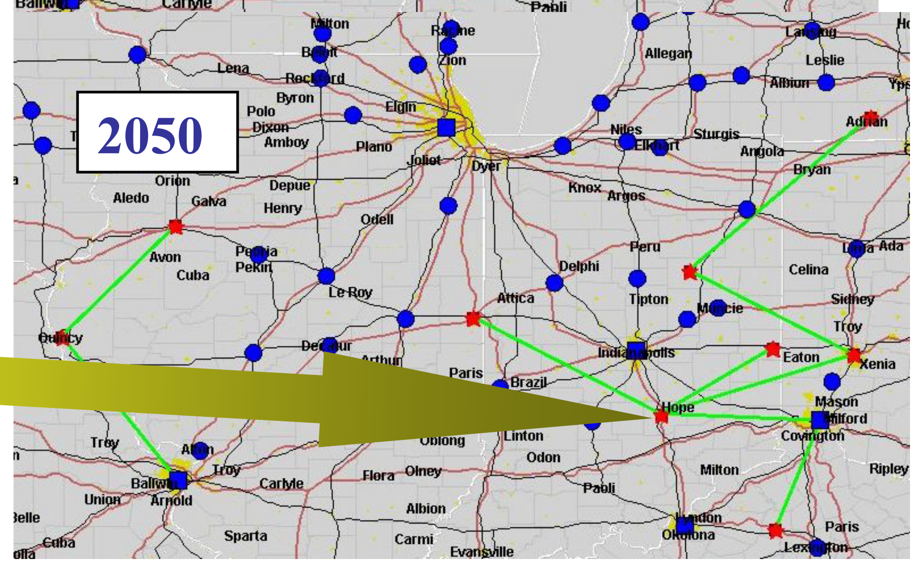
H2A Hydrogen Delivery Components Model

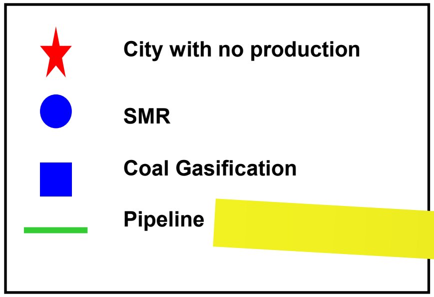
Building Multi-Node Delivery Scenarios

Demonstration of the pipeline network evolution at the Midwestern region. Years 2030-2050.









Remarks: only SMR and coal gasification are chosen as hydrogen production technologies for this demonstration to save on CPU time. Normally, SERA considers all H2 production technologies available in H2A.

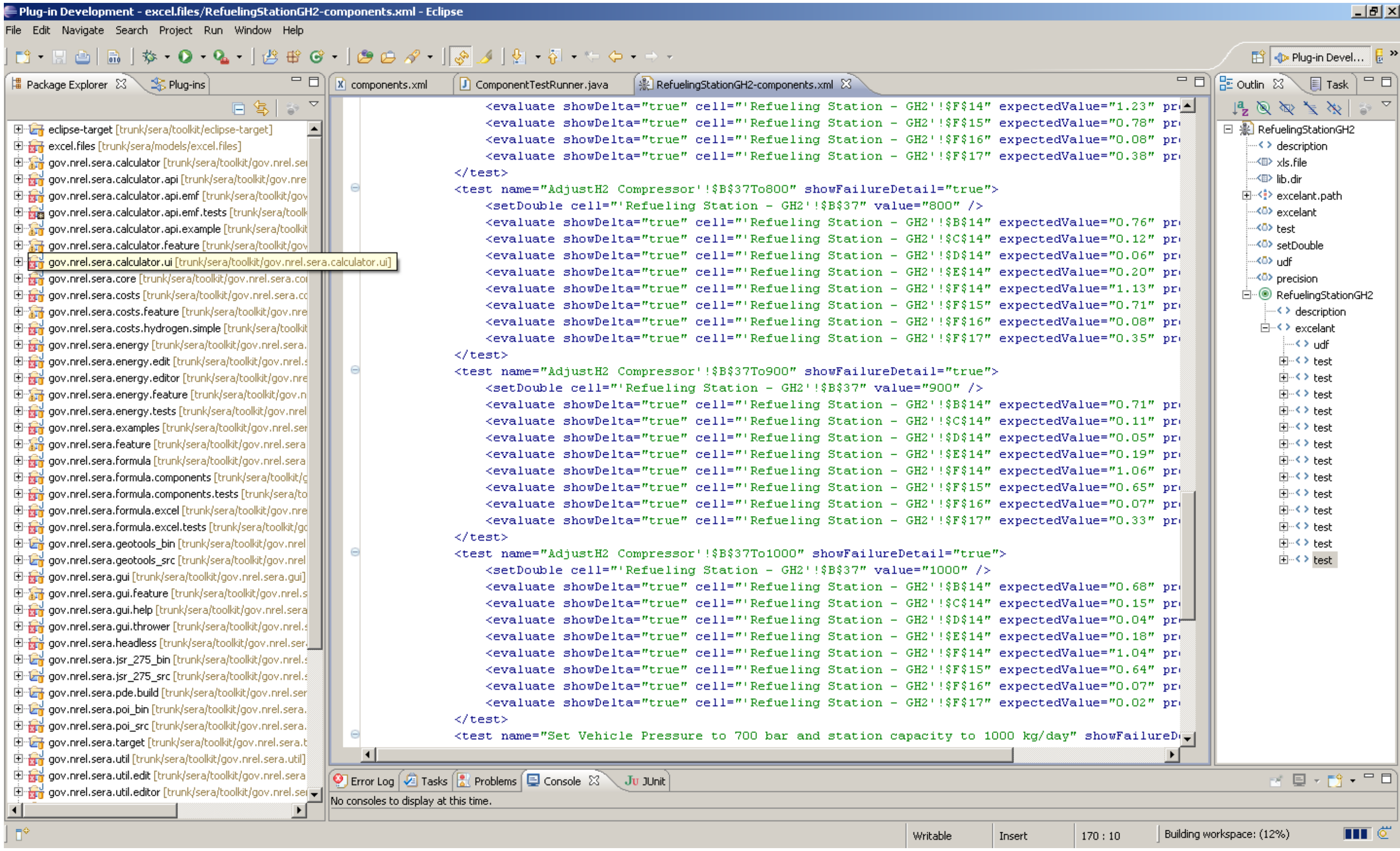
Building Multi-Node Delivery Scenarios

Progress on the Subtask 2:

14 H2A Delivery Components were coded into SERA

Testing Process:

10 of 14 components are tested as of March 11, 2011



SERA Development Interface Snapshot

(components testing XML codes)

Tools Used:

SERA Model

H2A Hydrogen Delivery Components Model

Technical Accomplishments and Progress

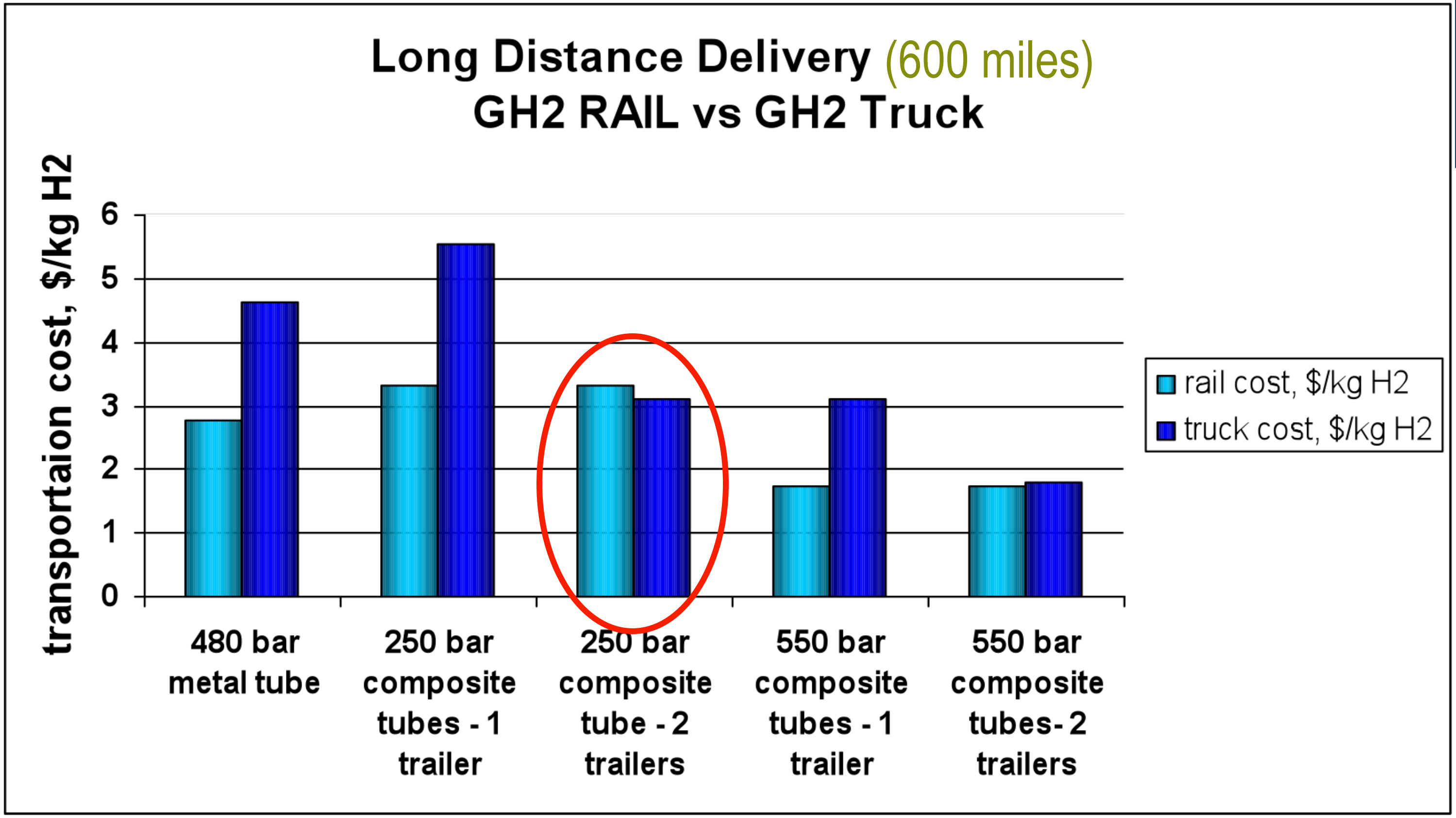
TASK 4

Composite Truck Delivery Analysis

OUTPUTS: Draft Report to DOE (December 2010),
Milestone presentation to DOE (December (2010)

Composite Truck Delivery Analysis

Is composite truck currently competitive for renewable H2 delivery?



Analysis Tool:

H2A Delivery Components Model

Current technology:

550 kg H2/ truck

Other technologies are available

(up to 900 kg/ truck), but they are currently more expensive

Composite truck can be competitive for renewable hydrogen delivery (long-distance) only in the case of allowing for the second trailer

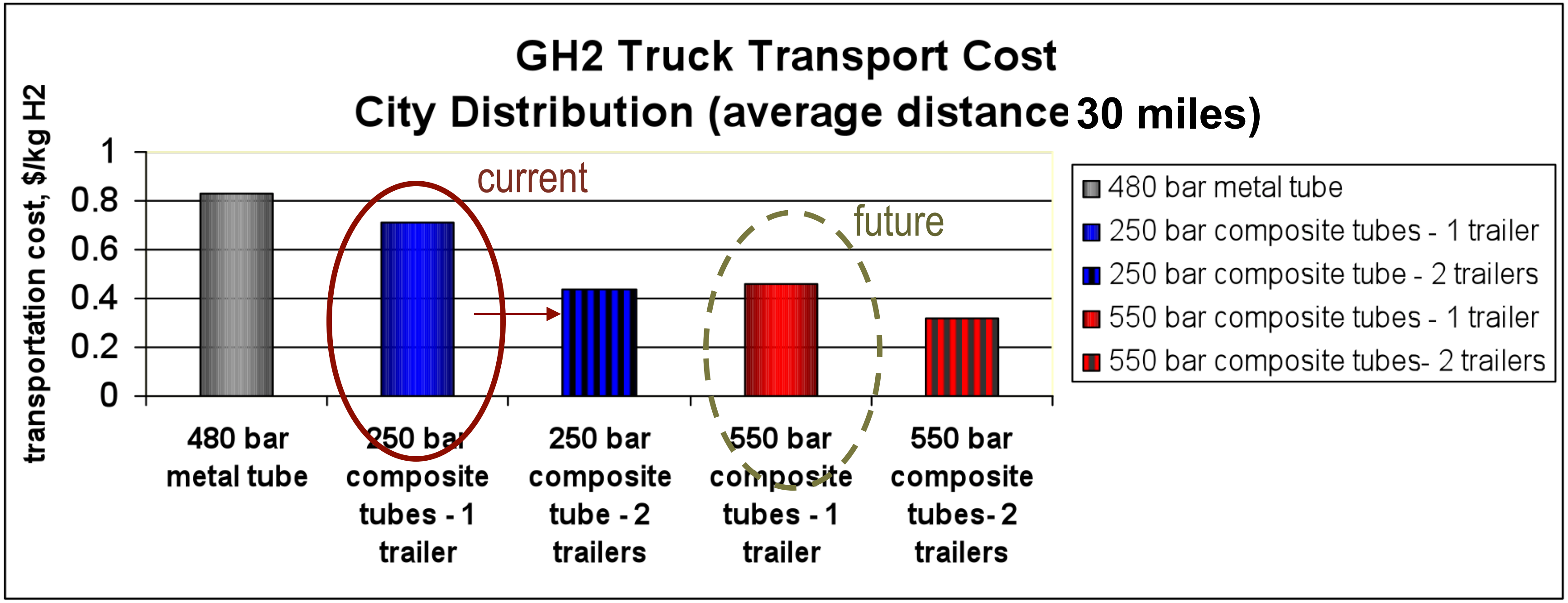
Composite Truck Delivery Analysis

Analysis Tool:

H2A Delivery Components Model

For intra-city delivery, composite truck stands out

Intra-city transportation cost (hydrogen plant at the city gate)



We can significantly drop the cost of transporting H2 by truck, if

- use 2 trailers per truck (induces larger refueling station footprint), or
- raise tube pressure to 550 bar

For cost decrease,

possible technology improvements

are suggested

Composite Truck Delivery Analysis

? Can we even afford 2 bundles (or, 2 trailers) per truck on the US highway system?

➢ To answer this question, we reviewed Federal (**FHWA**) and State (**ISTEA**) highway **regulations** (size and weight limitations per truck)

CONCLUSIONS IN BRIEF

In many "renewable" states* it's possible to carry 2 bundles (or, 2 trailers) per truck

* AK, AR, CO, ID, IN, IA, KS, MO, MT, NV, ND, OH, SD, UT, NM, NY, WY, OR

For reviewers: see details in supplemental slides

Details can be found at: "Analysis of Hydrogen Delivery By Gaseous Composite –Tube -Truck", NREL Report to DOE , December 2010

TASK 5

Hydrogen Delivery Via Existing Natural Gas Pipelines: Analysis

OUTPUTS: Draft Report to DOE (December 2010),
NREL Published Report (currently in review)

Hydrogen Delivery Via Existing Natural Gas Pipelines

Scope of Analysis:

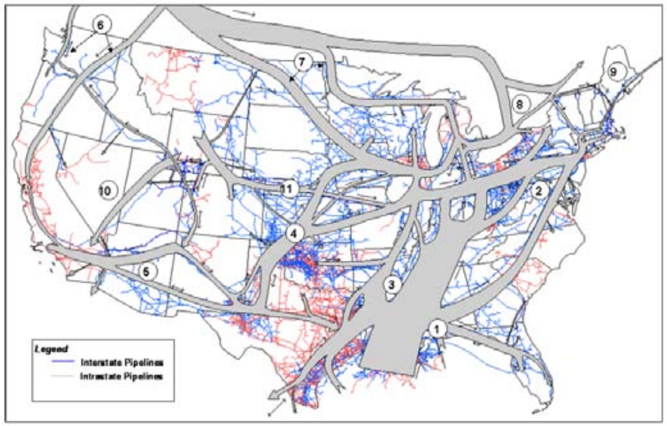
- **Review of NG pipelines system in the US**
- **Review of European (NaturalHy Project) and US studies**
- **Hydrogen extraction technologies overview**
- **Cost assessment of hydrogen extraction**

Hydrogen Delivery Via Existing Natural Gas Pipelines

Scope 1

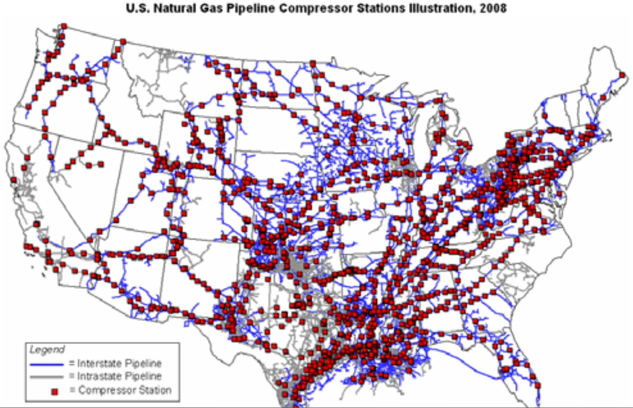
NREL reviewed the U.S. Natural Gas Pipeline Network, based on data from the Energy Information Administration, Office of Oil and Gas Division

Major U.S. Natural Gas Transportation Corridors, 2008



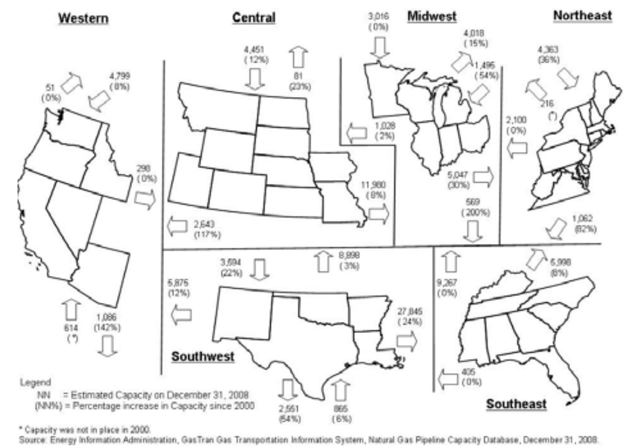
Source: Energy Information Administration, Office of Oil and Gas, Natural Gas Division, GasTran Gas Transportation Information System.

U.S. Natural Gas Pipeline Compressor Stations Illustration, 2008

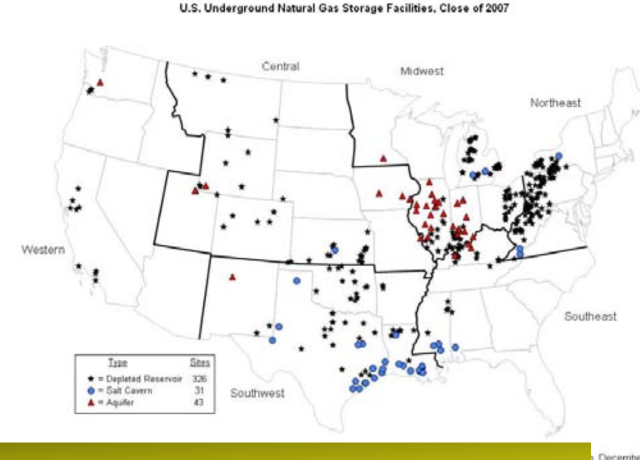


Scope of US NG Network Review:

- US Major Transportation Corridors
- Interstate Grid
- Intrastate Grid
- Capacity and Utilization
- Underground Storage
- Transmission Pipelines
- Distribution Pipelines



U.S. Underground Natural Gas Storage Facilities, Close of 2007



Details can be found at: "Hydrogen Delivery in Natural Gas Networks", NREL Publication (currently in review)

Hydrogen Delivery Via Existing Natural Gas Pipelines

Review of NaturalHy Project and GTI US pipelines assessment

Scope 2

CONCLUSIONS IN BRIEF

Benefits

Air quality improvements

Safety

Up to 20% H_2 is safe for both transmission and distribution pipelines

Leakage

PE distribution mains:
Volume leakage rate is about 3 times higher for H_2 than for NG

Durability

Transmission: No major concern on H_2 induced failures

Distribution: no major concern on aging

Integrity

Transmission:
modifications are not significant (< 50% H_2)

Distribution:
modified integrity management is required

For reviewers: see details in supplemental slides

Details can be found at: "Hydrogen Delivery in Natural Gas Networks", NREL Publication (currently in review)

Hydrogen Delivery Via Existing Natural Gas Pipelines

Scope 3

NREL Assessment of Separation Technologies

NREL assessed three major separation technologies

- Membranes
- Electrochemical Separation
- Pressure Swing Adsorption (PSA)

For reviewers: see details in supplemental slides

CONCLUSION IN BRIEF

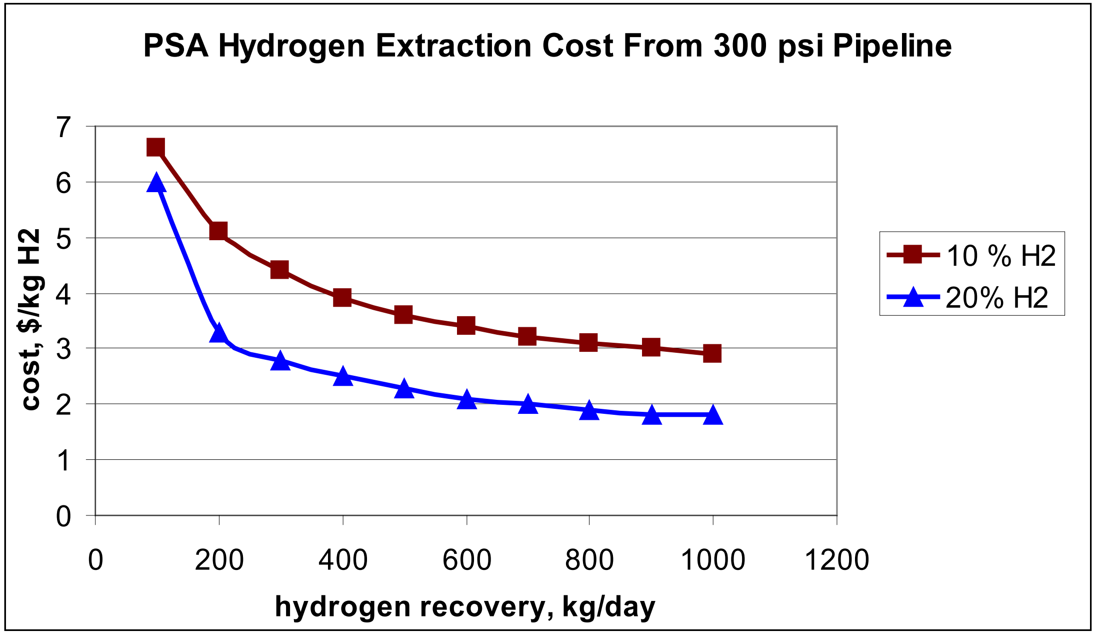
PSA is the most commercially ready technology

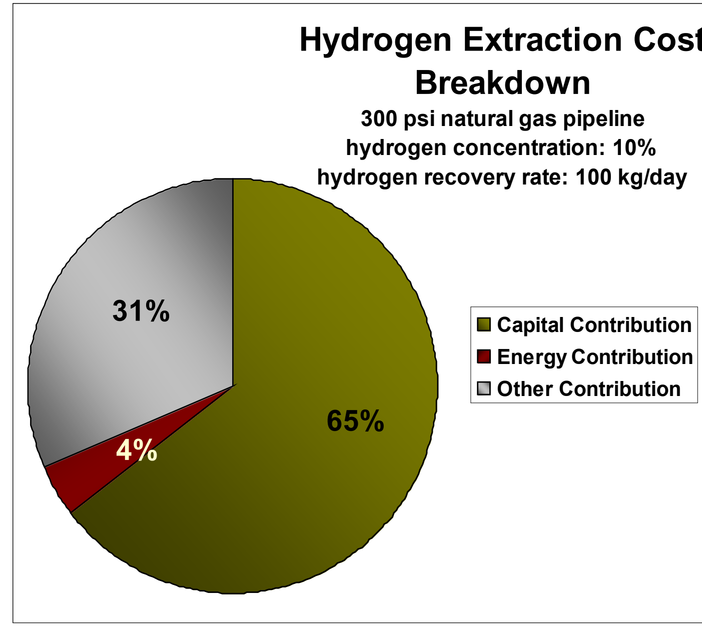
Details can be found at: "Hydrogen Delivery in Natural Gas Networks", NREL Publication (currently in review)

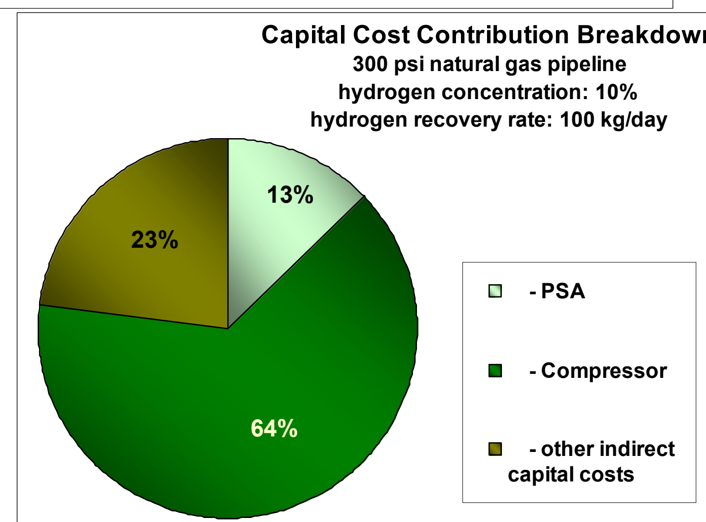
Hydrogen Delivery Via Existing Natural Gas Pipelines

Scope 4

NREL Assessment of Cost of Hydrogen Extraction by PSA Unit *







Hydrogen extraction cost is $2-$6.5/kg, depending on a recovered volume

! Compressor (for NG recompression) capital cost is 64% of the total capital cost of the extraction plant

* Based on Nth plant assumption (mature technology)

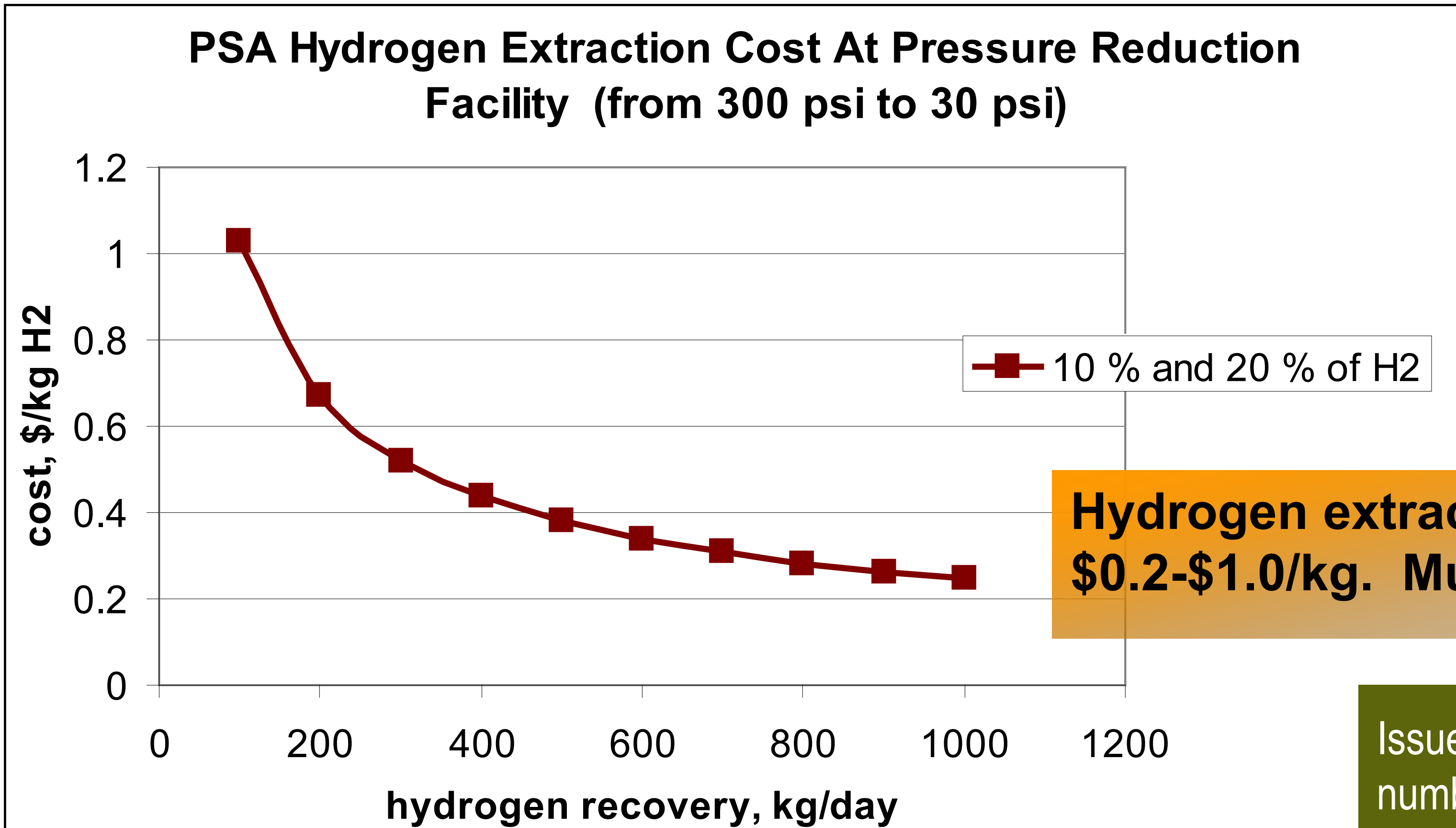
Hydrogen Delivery Via Existing Natural Gas Pipelines

Scope 4

NREL Assessment of Cost of Hydrogen Extraction by PSA Unit *

What if we avoid recompression?

Extract Hydrogen at the Pipeline Pressure Reduction Facility



Hydrogen extraction cost is $0.2-$1.0/kg. Much better!

Issue:
number of these facilities is limited

* Based on Nth plant assumption (mature technology)

Future Work

Milestone due

- Update and maintain H2A Delivery Components Model
  - $2007
  - 2010 and 2020 technologies

- Continue to develop wind-to-hydrogen scenarios
  - various storage types
  - gaseous delivery
  - long-term

  September 2011

- Continue on multi-node scenario model development
  - complete delivery components coding and testing — **July 2011**
  - multi-node pathways constructing — **FY2012**

- Analyze the total pathway cost for delivering hydrogen via NG pipelines
  - pumping in, transporting, extracting and dispensing

  FY2012

Collaborations

Industry

- Linde
- Air Products
- GE Rail Leasing
- Lincoln Composites
- Structural Composites Industries (SCI)
- Union Pacific Railroad
- Konecranes Heavy Lifting Company
- Paceco Corporation
- Power and Energy Inc.
- Lummus Technology, a CB&I Company
- H2Pump LLC

(technical and cost inputs)

(data exchange and review)

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 *(data exchange and review)*
- TIAX *(data exchange and review)*
- Gas Technology Institute (GTI) *(subcontractor)*

Summary

Relevance

- Project activities follow the DOE H2 Program targets

Approach

- Project follows H2A general approach and guidelines

Accomplishments

- Rail delivery analysis in comparison with other delivery options, US railroad congestion review
- Wind-to-liquid hydrogen scenarios assessment
- Multi-node delivery scenarios development: pipeline branching algorithm and delivery components coding and testing
- Composite truck (550 kg H2) cost analysis, and Federal and State highway regulations review
- Analysis of delivering hydrogen in existing NG pipelines

Collaborations

Linde, Air Products, GE Rail Leasing, Lincoln Composites, Union Pacific Railroad,

Structural Composites Industries (SCI),Konecranes Heavy Lifting Company, Paceco Corporation,

ANL, PNNL, DTI, TIAX, GTI, Power and Energy Inc., Lummus Technology- CB&I Company, H2Pump LLC

Future Work

- Update and maintain H2A Delivery Components Model
- Continue on developing multi-node delivery scenarios: pathways development
- Develop more wind-to-hydrogen scenarios with various storage types, and long-term demands
- Analyze the full pathway cost for delivering hydrogen in NG pipelines